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Physiology of
BREATH-HOLD
DIVING
and THE AMA
OF JAPAN

Symposium on the
"Physiology of
BREATH-HOLD
DIVING
and THE AMA
OF JAPAN

PAPERS PRESENTED
AT A
SYMPOSIUM
AUGUST 31 TO SEPTEMBER 1, 1965
TOKYO, JAPAN

HERMAN RAHN, *Editor*
TETSURO YOKOYAMA, *Assistant Editor*

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PREFACE

Contained within this volume are the papers presented at the "Symposium on the Physiology of Breath-Hold Diving and the Ama of Japan." The Symposium was held in Tokyo, Japan on 31 August - 1 September 1965 in conjunction with the XXIII International Congress of Physiological Sciences, and was conducted under the sponsorship of the International Union of Physiological Sciences, the Office of Naval Research, and the National Academy of Sciences—National Research Council, all of the United States.

The subject is devoted to the description and analysis of the various physiological stresses that confront man as a breath-hold diver. It is not directly concerned with the problems of helmet and self contained underwater breathing apparatus diving (SCUBA) although many areas overlap and are obviously related.

Probably no other environment is so easily accessible and offers so many stresses on various body functions as submersion and diving. It causes subtle changes in pressure distribution within the body and imposes great thermal stresses and large changes in absolute pressure. It places man in a dense supporting medium, which not only restrains his movement but also modifies the normal responses to gravitational forces of his nervous, cardiovascular, and pulmonary systems.

To the physiologist these stresses offer more than an academic challenge since man is increasingly turning to this environment for commercial exploitation, undersea warfare, sport, and sheer relaxation. Recently even the astronaut has turned his attention to flotation in water in order to simulate certain zero gravity conditions; and the modern aquanaut must contemplate living for many days in underwater houses and spending much of his time in this buoyant medium.

Information regarding the adjustments of man to this environment is limited and little is known concerning the adaptations that man is capable of developing under prolonged intermittent exposure to water and pressure. It is, therefore, with the greatest interest that we turn, hopefully, for some of the answers to the Ama of Japan and Korea who have over the centuries developed their professional skills in this aquatic environment. There are today many tens of thousands of women who dive along the coastal waters of Japan and Korea every day to harvest the ocean floor for shellfish and seaweeds. They have developed many diving patterns of great interest. Many of them work throughout the year, perform as many as 30 dives every hour to reach a depth of 20 meters, and during the winter months swim in waters as cold as 10°C. These are indeed remarkable achievements and should provide us with information concerning the acclimation of man to pressure and temperature stresses.

Relatively little has been published about the physiology of these remarkable people and therefore it is hoped in this Symposium to assemble for the first time in the English language the widely scattered information published in the Japanese literature. The Editor is very grateful to his Japanese colleagues for their effort to survey our present knowledge of the Ama, and to his colleagues from other lands who have brought their experience to bear upon this general subject of breath-hold

diving. It is hoped that this collection of reviews will stimulate further work and that we can eventually complete the scientific description of breath-hold diving first given by Professor Gito Teruoka of Tokyo over 30 years ago.

It is a great pleasure to express my sincere thanks to so many of my colleagues who cooperated enthusiastically in making this volume possible, and to the members of the Local Committee, under the Chairmanship of Professor Kentaro Takagi, who organized and planned the arrangements for this Symposium.

I am also greatly indebted to Professor Susumu Harashima for providing the original papers of Dr. Teruoka for reproduction in this volume, to Mrs. Shigeno Iwasaki for allowing me to publish some of Dr. Teruoka's unpublished photographs, to Dr. Tetsuro Yokoyama for his many services in editing and transmitting the Japanese manuscripts, and to Miss Augusta Dustan, in my laboratory, for her administrative help in all the details of this enterprise.

We are all indebted to Dr. Leonard M. Libber, Head of the Physiology Branch of the Office of Naval Research and to Mr. Lee M. Hunt of the National Academy of Sciences—National Research Council for their effort on behalf of the publication of this volume. Finally, we are especially indebted to Mrs. Maxine Sheesley for the many hours spent in the preparation in the final manuscript.

Grateful acknowledgement is made to Springer-Verlag, Berlin, for permission to reproduce the article by Dr. G. Teruoka from *Arbeitsphysiologie*, Vol 5, pp 239-251, 1932.

Hermann Rahn
Editor

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WELCOME

**Kentaro Takagi, M. D.
Chairman of the Local Committee for
The Symposium on Breath-Hold Diving**

Ladies and gentlemen:

It is a great privilege to welcome you to the symposium on the physiology of the diving women of Japan. You represent many different countries and it is gratifying to see that a common bond of interest in one of the fields of biological science can promote the personal friendship and scientific exchange between so many scientists.

I think that you are honoring the home country of the Ama by participating as speakers and guests in the symposium and I hope that our physical facilities will enable you to enjoy the meeting to the fullest.

**GREETINGS FROM THE INTERNATIONAL UNION
OF PHYSIOLOGICAL SCIENCES**

**Wallace O. Fenn
Secretary
International Union of Physiological Sciences**

It is indeed highly appropriate for the International Union of Physiological Sciences to co-sponsor and to encourage, in every way possible, this Symposium which promises to add so much to the study of the Ama and of underwater human activity in general.

Physiologists have always found much to interest them and to demand their expert attention in the use of balloons, airplanes, rocket ships, and submarines, but in many cases these begin as physiological problems and end up as engineering problems. If the engineers can provide in the vehicle the conditions that are normally encountered on earth, then the physiological problems largely vanish. In the type of free dives employed by the Ama the engineering problems appear to be rather simple, and involve chiefly the method of getting the diver up and down quickly so that the time on the bottom can be as long as possible. Most of the problems, however, will always be physiological, and they deal with human responses at the very margin of tolerance limits. It is, therefore, a fascinating situation that merits thorough investigation.

This Symposium started as a cooperative effort between Dr. Hermann Rahn at Buffalo and Drs. Takagi and Yokoyama in Japan. Any effort that results in so much international cooperation is deserving of applause; but this one has resulted already in a very valuable book on the Ama and in this Symposium, which will certainly stimulate a lot more work in the field. If this effort was encouraged in any way by the fact that the XXIII International Congress of Physiological Sciences decided to meet this year in Japan, then this is something in which the officers of the IUPS can take great pride. The Congress was scheduled to meet here just because it was realized that Japan is a country with great intellectual accomplishments and many specialized skills and activities with which physiologists in general should be more familiar. The diving women of Japan represent an excellent example of just this, and much good will result from a more widespread knowledge of their accomplishments and problems.

For all these reasons the International Union of Physiological Sciences is particularly pleased to be able to co-sponsor this program.

GITO TERUOKA, HIS LIFE AND WORK

Susumu Harashima
School of Medicine, Keio University
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Dr. Gito Teruoka was born in 1889, the eldest son in the family of a Buddhist priest, Chief of Seishuji Temple, Teruoka-zan (subsect) in Hyogo Prefecture of the central part of Japan. He himself would have made a very honorable priest had he not taken up the medical profession as his career. Throughout his life he was very active and full of energy, until 1961 when to our most regrettable misfortune he was suddenly stricken by a cerebrovascular accident from which he never fully recovered.

After graduating from the Faculty of Medicine, Tokyo Imperial University, in 1917, he started doing research in the Physiological Laboratory of the University on the synthesis of carbon dioxide, which he recalls was one of the most fascinating physiological problems of the time. Young Dr. Teruoka stayed in the laboratory and worked hard gathering references and reading for one year, when by some odd chance his professor suggested that he take up studies in the field of social medicine from the viewpoint of human physiology.

During the years between 1916 and 1920 the social life and thought of the Japanese changed tremendously as a result of World War I. Japan had many new and difficult problems that required immediate solutions. The leaders of the government as well as politicians were very eager to solve these social problems satisfactorily for the peace of the nation. In order to arrive at a solution they made strong demands and urged the academic experts to cooperate with them in a scientific study.

This was the background of the times contributing to young Teruoka's interest in the social sciences. He was already well acquainted with the western civilization and culture by direct contact with German professors and had learned German at the preparatory school for medical colleges. During his youth he had been well trained and was experienced in Buddhism as a religion, and religious influences in his way of thinking and believing played a noticeable role throughout his life.

After a year's work, during which he enthusiastically engaged in a survey of health conditions of the poor class in one of the sections of the City of Tokyo, he submitted an excellent report to the city authorities. Dr. Teruoka was then introduced by his Professor to Mr. Magosaburo Ohara, who was President of the Kurashiki Cotton Spinning Company and was one of the leaders endeavoring to find solutions for the nation's social problems. He discussed his program with him and offered Dr. Teruoka a position in the Ohara Institute for Study of Social Problems in Osaka as a member in charge of its Medical Division. Dr. Teruoka became thoroughly inspired by Mr. Ohara's purpose and ideal, and enthusiastically started the work which laid the foundation of social medicine and occupational health in Japan.

While preparing for his new work in Osaka Dr. Teruoka was invited by Mr. Ohara to visit his factory at night and was requested to make a scientific study of the health conditions of the young working girls and then to organize a service division in the factory which would allow them to work more efficiently and without hazards. Dr. Teruoka was deeply impressed when he observed young girls of about ten years of age standing up in their work at midnight and working under dim lights. He himself could not see beyond two meters because of fog and cotton dust. It is said that Dr. Teruoka was determined at this moment to devote his whole life to the protection of the health and occupation of workers. Indeed, ever since he has devoted his life to this purpose and has paved the way for better health of the working people in Japan. Today he is seventy-five years old.

The year 1921 saw the inauguration of the Kurashiki Institute for Science of Labour and Dr. Teruoka presided over the Institute until 1951. The Institute was supported by the Kurashiki Cotton Spinning Company at first and later by Mr. Ohara himself. In 1937 it was moved to Tokyo and was reorganized as the Japan Institute for Science of Labour.

As one of the earliest activities of the Institute Dr. Teruoka and his associates began studying industrial fatigue of girls working in the spinning factory, in two shifts of twelve hours each throughout the day and night. His report resulted in the recommendation of abolishment of night work of women and represents the first major protective measures for the working population in the history of Japan. They then became interested in studying the morbidity of young women as affected by factory work. For example, they found that physical and mental development of young girls was very much retarded by factory work and that the morbidity rate was higher, especially in female workers of less than fifteen years of age. These results became the scientific basis for raising the minimum age limit to fifteen years in the labor law standards and regulations. Their physiological studies of female workers were extended further to cover researches of the relationship between factory work and maternity and child care, including breast or bottle feeding of infants and the health of mothers in their pre- and post-natal periods.

As the horizon of interest of the research group of the Institute gradually widened, energy consumption of industrial workers was determined by measuring oxygen intake and carbon dioxide output in each phase of their labor activity. Owing to the series of continued studies by Dr. Teruoka, his associates, and their followers, we have sufficient knowledge and data available for energy consumption of Japanese workers in almost every kind of job in our industry.

It was perhaps at the middle stage of this research work that Dr. Teruoka became interested in studying the Ama since their work takes them far below the surface of the sea. Since Dr. Teruoka had kept his initial interest in women in industry and, furthermore, was involved in deciding the physiological limit of human capability of physical work, it is not surprising that he turned to studying the Ama's work of diving as an example of strenuous physical exertion under extreme conditions of environment. He was fortunate in being able to make full use of the methods which he had already developed so well in the Institute. Dr. Rahn will speak about the contributions of Dr. Teruoka's paper on the physiology of diving by the Ama. Unfortunately his studies of the aspects of social medicine of the Ama remain unpublished.

His scope of interest in occupational health increased as Japan's industrial enterprises developed from the light industry of the twenties of this century to the heavy and chemical industries of the pre-war period. The Institute made many contributions in this later period. To mention a few examples, it set up health standards for heavy muscular work under high temperatures in the steel manufacturing sheds and insisted on installing protective windows in front of the spinning chambers of the rayon and staple fiber plants in order to reduce the amount of noxious gases.

Dr. Teruoka was also endowed with a genius for organizing professional study groups. As early as 1927 he organized the Japanese Association of Industrial Health, which is the oldest organization of its kind and very active in this field at the present time. In 1955 the Asian Association of Occupational Health was organized under his initiative; its fourth conference was held last year in Djakarta, Indonesia.

He was elected honorary member of the Permanent Commission and the International Association of Occupational Health in 1963 in recognition of his long service to the organization as well as for the advancement of occupational health in Japan. He is indeed one of the pioneers in the field in this country and last year, for his work and scientific contributions, Dr. Teruoka was awarded the Asahi Prize, one of the distinguished awards in Japan. In November 1964, the Government of Japan decorated Dr. Teruoka with the Third Order of Merit for his meritorious services to the nation.

It has been my privilege to pay this tribute to Dr. Gito Teruoka; may we pray he will enjoy a long and comfortable life with Mrs. Teruoka, who has always been most trusted and dearest to him.



Figure 1. Dr. Gito Teruoka, Former Director,
Japan Institute for Science of Labour.

G. TERUOKA —
HIS CONTRIBUTION TO THE PHYSIOLOGY OF THE AMA

Hermann Rahn
Department of Physiology
State University of New York at Buffalo
Buffalo, New York

In 1932 a paper appeared in *Arbeitsphysiologie* (Vol 5, 239-251) entitled "Die Ama und ihre Arbeit," by Dr. Teruoka. It was unique in many ways. Not only did it describe a most unusual working environment, but also provided the first scientific description and the first careful measurements of various aspects of breath-hold diving operations. It also illustrated with photographs the actual diving operation, which stirred my romantic heart as a young investigator 20 years ago when Professor W. O. Fenn first called my attention to the work of G. Teruoka. I waited patiently all these years and it was not until 1960 that I was finally introduced, by Dr. K. Tatai, to the Ama of the Shima Peninsula, to watch the actual diving of the Funado and Cachido. From there I went to join Dr. S. K. Hong who had just initiated an intensive program on the physiology of the Korean Ama.

Wherever I traveled it became apparent that many people were unaware of or had forgotten this fundamental contribution. Today it forms the cornerstone of this Symposium, which some 30 years later, has attracted scientists from all over the world. It is probably futile to speculate about the reasons for this long overdue recognition. However, fundamental studies are recognized only when the time is ripe and the scientific mind is prepared to appreciate such a contribution. This was not the case in the 1930's when interest in underwater physiology was limited to the practical considerations of hard-hat diving. However, in the past decade underwater swimming enjoyed a new interest when SCUBA techniques made this environment accessible to everyone. It stimulated many people and scientists to explore this new frontier. The stage was now set for a renewed appreciation of the various physiological problems of submergence. From Japan had come many contributions on various aspects of the life and physiology of the Ama, particularly the Funado. In Korea, Hong and his students began an intensive investigation of the Cachido. In the rest of the world, others became interested in similar studies, spurred on by the problems which confront a long-distance swimmer, man's survival in cold water, and the observations of Scholander on the pearl divers. More recently the space scientists became interested since a floating man represents the closest simulation of some of the gravitational problems which confront the astronaut in orbit.

With so many diverse activities today related to the environment of water and increased pressure it seems appropriate to review not only our present knowledge but to pay homage to Dr. Teruoka, who was the first to describe the unique problems of the Ama in the scientific literature.

In his paper he discussed not only the historical development of goggles but also the limitations in depth of diving which each type presented. He then described in detail the diving patterns, frequency, depth, and duration of dives and how they

vary with the water temperatures of the seasons. He was not content to obtain this information by asking the divers but actually accompanied them on their boats and took careful notes on each dive. It is this thoroughness and careful attention to detail that made his contribution so impressive and of such great value today.

He next described his field measurements from which he was able to calculate the instantaneous velocity of ascent and descent of the Funado to various depths up to 24 meters. Samples of his original paper records were given showing the time and distance markers. The latter were presumably driven by an electrical contact on the pulley which guided the rope as the Ama descended or ascended. Maximal values of 1.81 m/sec were noted although the average values were somewhat lower. He believed that the limiting velocity was determined by the rate with which the middle ear could equalize the changing pressure. His detailed tables and graphs still provide the best description of the diving pattern.

Dr. Teruoka then described the gas exchange by analyzing the first exhalation after returning from dives as deep as 25 meters and lasting as long as 118 seconds. The alveolar CO_2 and O_2 concentrations are recorded in his tables. These values were most unusual in that the CO_2 values as well as the O_2 values were both much lower than would result from an ordinary breath-holding maneuver at the surface. In fact, it was not until Dr. Hong obtained similar values in the Korean divers, and Dr. Lanphier, in simulated dives in a pressure chamber, that we were finally able to understand and interpret the results presented by Teruoka 30 years earlier. In this Symposium we now have several contributions devoted to this topic.

Finally, the effects of the increasing N_2 tension during the dive were briefly discussed. He speculated that during the short period of compression not enough N_2 is dissolved in the blood to produce caisson disease. This notion was generally accepted until a year or two ago. Today we shall be presenting the first evidence that nitrogen gas elimination under certain conditions of repeated breath-hold diving is impaired and may possibly lead to the bends.

In summary, Dr. Teruoka's paper, although not long, was packed with all kinds of information, observations, and suggestions which only today we are finally exploring in more detail. His extensive tables of the diving patterns and alveolar gas concentrations are still the classical studies on breath-hold diving and little can be added. His brief historical sketch of the development of goggles and diving patterns only whet one's appetite for additional historical information, some of which will be provided by the various speakers on this program.

After completion of these studies Dr. Teruoka's attention turned to many other problems during his long and distinguished career. However, he continued a life-long personal interest in the Ama. Even during his later years he always managed to return to the Ama and to continue his observations which he started long before. I believe it became an avocation which he pursued until very recently when his health became impaired. We can only hope that he will be with us today. We have come to his city and to his country from all over the world to pay our tribute and recognition to his pioneering efforts, for which he rightly deserves the title of Father of Ama Physiology.

DIE AMA UND IHRE ARBEIT
(Reproduced from the original)

Gito Teruoka
Tokyo, Japan

(Das Institut für Arbeitswissenschaft Kurasaki, Japan)

Die Ama und ihre Arbeit.

(Vorläufiger Bericht).

(Eine Untersuchung über die japanischen Taucherinnen).

Von
Prof. G. Teruoka.

Mit 11 Textabbildungen.

(Eingegangen am 25. August 1931.)

Die Mechanisierung der modernen Industrie hat unsere traditionellen Produktionsbedingungen mit ihren primitiven und oft pittoresken Arbeitsmethoden zu Grabe getragen, denn die alten Methoden konnten weder nach Schnelligkeit noch nach Umfang in Wettbewerb treten. Eine bedauerliche Folge hiervon war der Versuch, den Menschen den Erfordernissen der Maschine anzupassen, anstatt den Arbeiter dazu zu erziehen, seine Fertigkeit so zu entwickeln, daß sie ihn instand setzt, ökonomisch und dennoch seinem eigenen Tempo gemäß zu arbeiten. Die Anfänge der Industrialisierung kannten andererseits kein Mitgefühl mit den Arbeitern und zwangen ihnen oft ein Arbeitstempo auf, derart, daß sie vorzeitig arbeitsunfähig wurden.

Unser Institut für Arbeitswissenschaft untersucht verschiedene Zweige menschlicher Tätigkeit, die durch die Mechanisierung der Industrie beeinflusst werden, und es hat auch eine Art antiquarischen Interesses an den veralteten und primitiven Methoden, unter denen die der Ama, der Taucherinnen, besonders bemerkenswert sind.

Wir haben natürlich verschiedene physiologische Untersuchungen von der Taucharbeit gemacht und viele Seiten des Lebens der Ama und ihrer Lebensweise erforscht, um diese Töchter der Natur mit ihren überzivilisierten und in Städten wohnenden Schwestern zu vergleichen. Aber dieser Bericht befaßt sich nur mit ihrer eigentlichen Taucharbeit.

A. Gerätschaften.

1. **Kleidung:** Unterkleidung und Lendentuch.
2. **Augengläser.**

Wann der Gebrauch von Augengläsern bei den Ama aufgekommen ist, ist noch ungewiß, aber es ist fast sicher, daß sie am Ende der Tokugawa-Periode, also

Arbeitsphysiologie. Bd. 5.

etwa vor hundert Jahren, noch nicht benutzt worden sind. Sie haben sicher die Arbeitsleistung der Taucherinnen erhöht, und man kann eine allmähliche Verbesserung in 4 Stufen feststellen, für die wir alte und neue Belege gesammelt haben.

a) Brillen, die nicht von den gewöhnlichen Brillen verschieden sind und von einigen Schwimmern getragen wurden. Man kann mit ihnen bis zu einer Tiefe von 3 m arbeiten (s. Abb. 1).

b) Brillen, bei denen der Augenteil mit einem kleinen Metallfutteral verbunden ist, das ein dünnes Gummisäckchen enthält. Dieses wird vor dem Tauchen mit Luft gefüllt, und dadurch wird der auf die Augen ausgeübte Druck reguliert.

c) Eingläser ohne Nasenschutz, eine verbesserte Form von b mit einem Ledersack auf jeder Seite. Dieser einfache Apparat, der noch bis vor 10 Jahren in Gebrauch war, steigerte die Tiefe, bis zu der die Ama tauchen konnte, auf 8 m. Die Ledersäckchen werden, nachdem das Glas aufgesetzt ist, durch ein Gummirohr, das mit dem unteren Teile der Gläser verbunden ist, mit Luft gefüllt. Die Steige-

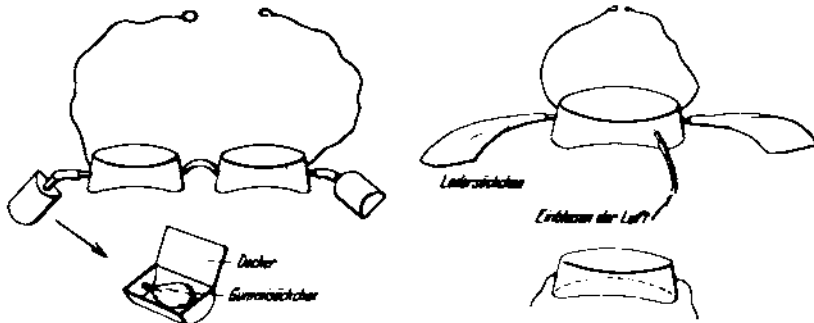


Abb. 1.

rung des inneren Druckes bis zu etwa 2 Atmosphären schützt die Augen vor schwerer Druck- und Blutfüllung, die eintritt, wenn der äußere Wasserdruck die Gläser zu hart gegen das Gesicht drückt.

d) Eingläser mit Nasenschutz. Dieser Apparat, der allmählich während der letzten 10 Jahre in Gebrauch gekommen ist, gestattet ein Hinabgehen bis zu 30 m. Er hat den Vorteil, daß er die Augen des Tauchers gegen übermäßigen Druck und die Naseneingänge vor dem Wasser schützt.

B. Tauchen.

Die letzte Handlung der Ama vor dem Tauchen ist, gerade über der Wasseroberfläche leise zu pfeifen. Aus allen Richtungen des Fischerplatzes werden diese Töne über das Wasser getragen. Aber ihre Bedeutung ist keine musikalische und auch nicht die eines Signals; die Ama bereitet sich zum Tauchen vor, indem sie beim Pfeifen soviel wie möglich Luft aus ihren Lungen herausstößt und dann eine leise, aber tiefe Einatmung macht. Damit ist keine schwere Arbeit des Brustkorbes und des Zwerchfells verbunden, während eine Wiederholung der heftigen und tiefen Atmungen die gesamten Atemmuskeln ermüden würde.

Die wirkliche Arbeit der Ama wird in einem Zustande von Asphyxie verrichtet. Wenn vor dem Beginn der Asphyxie tiefe Atemzüge getan

Die Ama und ihre Arbeit.

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werden können, so kann sie verlängert werden, weil die Lungen durchventiliert sind, genügend CO_2 abgegeben und eine möglichst große Menge von Sauerstoff aufgenommen worden ist. Dies wurde durch experimentelle Untersuchungen im Laboratorium nachgewiesen. Aber die Ama lernt dies durch Übung und Erfahrung (Abb. 2). Ohne Hilfsmittel geht sie in eine Tiefe von etwa 7 m. Je tiefer sie tauchen muß, desto schneller muß sie tauchen, um soviel wie möglich Zeit ihrer Arbeit auf dem Meeresboden widmen zu können. Bis vor 10 Jahren wurde ein 8 m langer Bambusstock in das Wasser gesteckt und als Hilfe beim Abstieg und Aufstieg verwendet. Diese Methode wurde ersetzt durch Benutzung eines Gewichtes, das den Abstieg sehr beschleunigt, während der Auf-



Abb. 2. Der Augenblick des Hineintauchens ins Wasser.

stieg vor sich geht mit Hilfe von Stricken, die am Leibe der Taucherin befestigt sind. Früher wurde ein Stein von etwa 18 kg benutzt, später ein eisernes Gewicht von ungefähr 15 kg, jetzt hat ein eisernes Rohr mit Bleifüllung beides ersetzt; es hat ein Drittel des Gewichtes der Taucherin, die es benutzt.

C. Tauchtiefe.

Die Ama sind angeblich imstande, bis zu einer Tiefe von etwa 45 m zu tauchen, aber unsere Aufzeichnungen registrieren nur etwa 30 m; dort sind die Taucherinnen einem Druck von 4 Atmosphären ausgesetzt.

D. Dauer des Tauchens.

Die Zeit, während der die Taucherinnen unter Wasser bleiben, hängt davon ab, ob sie ihre Beute leicht und in welcher Tiefe sie sie finden. Wir fanden, daß sie ungefähr $2\frac{1}{2}$ Minuten unter Wasser bleiben

17*

können (s. Abb. 3). Sie tauchen durchschnittlich 20mal in 1 Stunde (natürlich in verschiedener Tauchtiefe und Tauchdauer), und die Arbeit je einer Stunde heißt „Nitokura“ oder „Nitokakura“. Die Taucherinnen machen täglich 3 Kakuras, das ist im Durchschnitt 60 und maximal 90 Tauchungen. Eine Pause von 1½ Stunde zwischen je zwei „Kakuras“ wird zur Erholung, Aufwärmung, Säugung und Wartung der Kinder verwendet. Die Dauer einer Arbeitsstunde variiert indessen



Abb. 3. Der Augenblick des Herankommens aus der Wasseroberfläche.

mit der Temperatur des Wassers: im April beträgt sie nur ungefähr 30 Minuten, im Mai und Juni 40 Minuten, vom Juli bis September 60—70 Minuten, im Oktober und November 40 Minuten¹.

E. Tauchgeschwindigkeit.

Tab. 1 zeigt, daß im Falle der Ama A die Höchsttauchgeschwindigkeit 1,28 m je Sekunde beträgt (s. Abb. 4), die Mindestgeschwindigkeit 0,99 m.

¹ Nach *Catsura*. Die Taucher im Westen, die Taucherbeime und ähnliche Apparate bei der Schwammfischerei benutzen, sollen je nach den Arbeitsbedingungen die folgenden Arbeitszeiten haben (zit. nach *Webb* Handbuch):

beim Überdruck von 1,9—2,5	2mal täglich	3 Stunden
„ „ „ 2,5—2,8	„ „	2 „
„ „ „ 2,8—3,0	„ „	1½ Stunde
„ „ „ 3,0—3,4	„ „	1 „
in Tauchtiefe von 15—23 m	Tauchdauer	1 Stunde
„ „ „ 23—30	„ „	15 Minuten
„ „ „ 30—37	„ „	10 „
„ „ „ 37—42	„ „	5 „
„ „ „ 42—45	„ „	3 „
„ „ „ 45—48	„ „	1 Minute

Im Falle der Ama B ist die Höchstgeschwindigkeit 1,45 m, die Mindestgeschwindigkeit 1,10 m. Die durchschnittliche Geschwindigkeit wächst mit der Wassertiefe. B braucht 17,40 Sekunden, um 23,88 m tief zu tauchen, während A 20,60 Sekunden für 24,87 m braucht. Die größte Tauchgeschwindigkeit ist für A 1,76 m je Sekunde beim Tauchen in 24,87 m und 1,81 m für B beim Tauchen in 23,88 m. Die maximale Geschwindigkeit kommt nur etwa im ersten Drittel oder Viertel der Tauchtiefe vor.



F. Tauchgeschwindigkeit und Druckänderungen.

Bei der größten festgestellten Tiefe von 24,87 m beträgt der Totaldruck schätzungsweise 3,5 Atmosphären, wenn die Ama, wie sie sich rühren, imstande wären, bis zu 45 m zu tauchen, so würden sie dort unter einem Druck von 5,5 Atmosphären arbeiten; aber ich zweifle, daß so etwas möglich wäre. Der Faktor, der die Tauchgeschwindigkeit reguliert, ist die Geschwindigkeit (s. Abb. 5, 6), mit der ein Gleichgewichtszustand hergestellt werden kann zwischen dem äußeren Druck des Wassers und dem Luftdruck innerhalb des Ohres. Wenn dieser Gleichgewichtszustand gestört wird, so wird das Trommelfell nach innen gedrückt, und es erfolgt eine Blutfüllung des Trommelfells. Caissonarbeiter sollen imstande sein, eine Steigerung des Luftdruckes von $\frac{1}{10}$ Atmosphäre in 45 Sekunden auszuhalten. Die Ama braucht jedoch viel

Tabelle 1.

	Tauchtiefe in Metern	Zeit für Aufstieg in Sekunden	Durchschnittl. Aufstiegs- geschwindigkeit (meter/sek.)	Max. Aufstiegs- geschwindigkeit (meter/sek.)	Durchschnittl. Zeit für Verhinderung des Wasserdrukks von 1 At- mosphäre (in sek.)	Zeit für Aufstieg	Durchschnittl. Aufstiegs- geschwindigkeit (meter/sek.)	Durchschnittl. Zeit für Verhinderung des Wasserdrukks von 1 At- mosphäre (in sek.)	Gesamt- Tauchdauer
Taucherin A	8,58°	8,55	1,00	1,29	10,00	6,0	1,43	7,41	118,0
	9,23	9,34	0,99	1,19	10,10	7,5	1,23	8,62	22,0
	15,01	12,40	1,21	1,44	8,26	12,5	1,20	8,83	67,0
	16,15	13,00	1,24	1,43	8,06	13,5	1,20	8,83	52,0
	18,67°	15,10	1,23	1,48	8,13	16,0	1,17	9,06	34,0
	19,13	17,26	1,11	1,39	9,01	15,5	1,23	8,50	61,0
	19,74	18,90	1,14	1,49	8,77	13,0	1,52	6,91	71,0
	20,17	17,10	1,18	1,47	8,47	15,5	1,30	8,14	49,0
	21,37°	18,40	1,16	1,54	8,62	15,0	1,43	7,41	70,0
	22,57	17,59	1,28	1,55	7,81	18,5	1,22	8,60	56,0
24,87	20,60	1,21	1,68	7,94	17,0	1,46	7,26	42,0	
24,87	20,60	1,21	1,76	8,26	18,0	1,38	7,68	65,0	
Taucherin B	8,27°	7,20	1,15	1,61	8,70	5,5	1,50	7,06	57,0
	8,95	8,15	1,10	1,35	9,09	8,0	1,12	9,46	53,0
	12,88°	10,48	1,23	1,47	8,13	8,0	2,15	4,93	95,0
	13,44	9,70	1,39	1,81	7,19	9,0	1,77	5,90	87,0
	14,05	10,80	1,30	1,72	7,70	9,0	2,81	3,77	95,0
	14,64	10,85	1,30	1,53	7,70	9,0	2,44	4,34	51,0
	20,15°	15,06	1,33	1,68	7,47	12,0	1,68	6,31	65,5
	22,53	15,55	1,45	1,75	6,90	13,0	1,73	6,13	59,0
	23,88	17,40	1,37	1,75	7,30	13,5	1,77	5,90	56,0

weniger Zeit als diese. Tab. 3 zeigt, daß Ama A (s. Abb. 7, 8) eine Drucksteigerung von $\frac{1}{10}$ Atmosphäre in 1,0 Sekunden in einer geringen Tiefe und in 0,7—0,8 Sekunden in einer Tiefe von 25 m aushält. Ama B hat dieselbe Drucksteigerung in 0,69 Sekunden bei einer Tauchtiefe von 22,5 m ausgehalten. Es ist bemerkenswert, daß sie keine Schädigung erfuhren. Ein Unterschied zwischen der Ama und dem Caissonarbeiter ist jedoch der, daß dieser frei in komprimierter Luft arbeitet und atmet, während die Ama in einem Zustande der Asphyxie taucht und arbeitet. Während sie taucht, wird die rasche Steigerung des äußeren Druckes ausgeglichen durch die Drucksteigerung in dem kleinen Raum der Augengläser und der Atmungsorgane, die durch die Tuba auditiva mit dem inneren Ohr verbunden sind. Tab. 3 zeigt die Zeiten, die bei maximaler Tauchgeschwindigkeit zur Überwindung einer Drucksteigerung um $\frac{1}{10}$ Atmosphäre gebraucht werden. Es wäre zu bemerken, daß die Geschwindigkeit sich im ersten Viertel oder Drittel der zurückzulegenden Entfernung rasch ändert, nachher aber konstant bleibt oder sich sogar vermindert. Dies ist wohl auf die Zunahme der Reibung des Mediums zurückzuführen, die natürlich bei höherer Geschwindigkeit größer ist

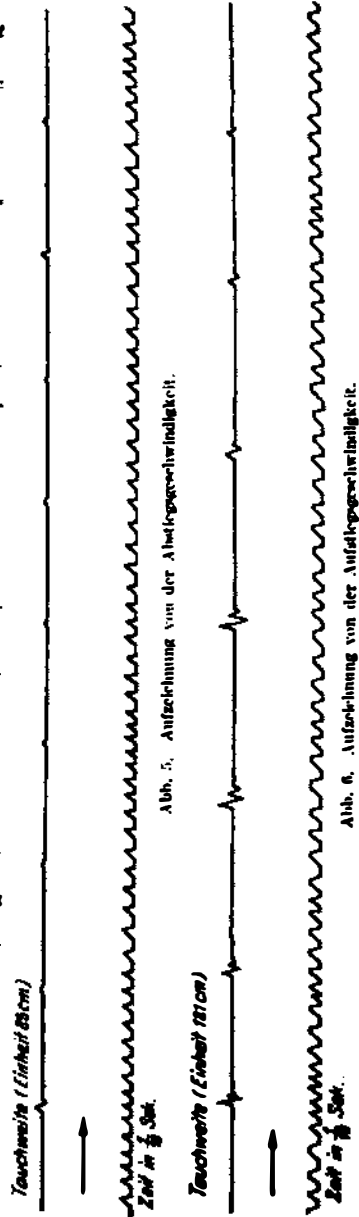
Tabelle 2.

Tiefe, in welcher die Maximalgeschwindigkeit vorkommt
 (bei Taucherin A).

Tauchtiefe (Meter)	A	B	A B × 10
	Tauchtiefe (Meter)	Max. Geschwin- digkeit — Vor- kommen in Tiefe (Meter)	
20—25	24,87	3,40	1,4
	22,57	8,80	3,9
	21,37	6,50	3,0
	20,68	3,17	1,5
	20,32	6,06	3,0
	20,17	5,02	2,5
Durchschnitt	21,68	5,49	2,6
15—20	19,26	6,94	3,6
	19,13	5,11	2,7
	18,67	10,55	5,7
	18,62	6,81	3,7
	16,15	3,83	2,4
	15,01	7,51	5,0
Durchschnitt	17,81	6,79	3,9
unter 10	9,23	2,30	2,5
	8,58	3,16	3,7
Durchschnitt	8,91	2,73	3,1

Tabelle 3.

	Max. Ge- schwindigkeit (m / Sek.)	Zeit für Verände- rung der $\frac{1}{10}$ Atm. Drucksteigerung	Größe der Drucksteigerung innerhalb 1 Sek.
Taucherin A	1,759	0,57	0,1759
	1,678	0,60	0,1678
	1,545	0,65	0,1545
	1,474	0,68	0,1474
	1,441	0,69	0,1441
	1,288	0,78	0,1288
Taucherin B	1,747	0,57	0,1747
	1,746	0,57	0,1746
	1,723	0,58	0,1723
	1,700	0,59	0,1700
	1,349	0,74	0,1349



oder darauf, daß die Ama versucht, sich selbst dem von ihr gespürten größeren Druck anzupassen.

G. Aufstiegs- und Druckänderungen.

Wenn die Ama an die Oberfläche zurückzukehren wünscht, so gibt sie dies ihrem Manne im Boot zu erkennen mittels des Strickers, der an ihrem Leibe befestigt ist, und der sie mit ihm verbindet. Sobald er diesem Zeichen empfangen und erkannt hat, zieht er sie mit Hilfe eines Flauchzuges herauf. Die Schnelligkeit ihres Auftauchens ist mehr vom guten Willen ihres Gatten und der Kraft seiner Arme abhängig, als von ihren eigenen Anstrengungen oder der Tiefe des Wassers, so daß die Geschwindigkeit ziemlich auf allen Punkten der Reise konstant ist. Natürlich werden nun die Druckänderungen von der Taucherin in umgekehrter Reihenfolge wiederum erlebt, sie muß sich ihnen anpassen, und hierbei ist zu bemerken, daß die Geschwindigkeit des Aufstiegs größer ist als die des Abstiegs. Obgleich das Gewicht der Ama und die Anstrengungen ihres Mannes die Aufstiegs- und Abstiegsgeschwindigkeit verändern, ist sie doch fast stets größer als die Abstiegsgeschwindigkeit, und dies ist vielleicht so zu erklären, daß die Druckverminderung weniger Beschwerden verursacht als eine Druckvermehrung. Die größte Aufstiegs- und Abstiegsgeschwindigkeit der Ama A ist 1,52 m je Sekunde, die geringste 1,20 m je Sekunde. Für Ama B waren es 2,81 und 1,12 m. A brauchte bei ihrer Minimalgeschwindigkeit 0,9 Sekunden und bei ihrer Maximalgeschwindigkeit 0,69 Sekunden, um eine Druckverminderung von $\frac{1}{10}$ Atmosphäre zu passieren, während Ama B hierfür 0,38 und 0,95 Sekunden brauchte.

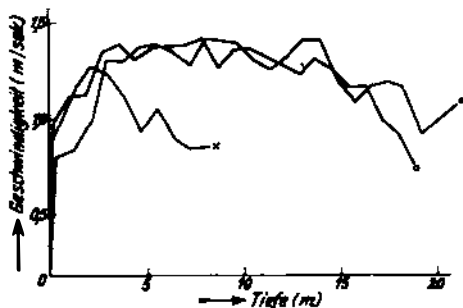


Abb. 7.
Tauchtiefe und Tauchgeschwindigkeit (Taucherin A).

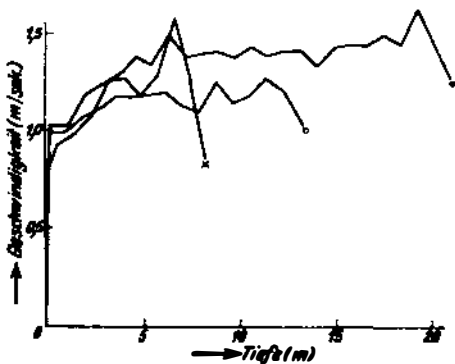


Abb. 8.
Tauchtiefe und Tauchgeschwindigkeit (Taucherin B).

als die Abstiegsgeschwindigkeit, und dies ist vielleicht so zu erklären, daß die Druckverminderung weniger Beschwerden verursacht als eine Druckvermehrung. Die größte Aufstiegs- und Abstiegsgeschwindigkeit der Ama A ist 1,52 m je Sekunde, die geringste 1,20 m je Sekunde. Für Ama B waren es 2,81 und 1,12 m. A brauchte bei ihrer Minimalgeschwindigkeit 0,9 Sekunden und bei ihrer Maximalgeschwindigkeit 0,69 Sekunden, um eine Druckverminderung von $\frac{1}{10}$ Atmosphäre zu passieren, während Ama B hierfür 0,38 und 0,95 Sekunden brauchte.

H. Respiratorische Funktionen während des Tauchens.

Es wurde bereits erwähnt, daß die Ama vor dem Tauchen pfeift und die Lungen vollkommen ventiliert, bevor sie einen keil, aber tiefen Atemzug tut, um die Periode, während deren sie unter Wasser bleiben kann, zu verlängern. Ihre Arbeit, unter einem Druck von 3—4 Atmosphären, in einem Zustande der Asphyxie, dauert etwa 2 $\frac{1}{2}$ Minuten. Die Ergebnisse der Messung und Analyse der 1.—6. Ausatemungsluft wurden aufgezeichnet, aber hier beschäftigen uns nur die Ergebnisse für die 1. Ausatemungsluft (Tab. 4).

Tabelle 4.

	Tauch- tiefe	Tauch- dauer	Vol. der 1. Ate- at.-Luft	O ₂ -Ver- brauch	O ₂ - Ge- halt	CO ₂ - Ge- halt	Verbrauchte O ₂ in mm ³ Tauchzeit	Produzierte CO ₂ in mm ³ der Tauch- zeit	O ₂ -Ver- brauch in 1 Sek.	CO ₂ in 1 Sek.
	m	sek.	l	%	%	%	cm ³	cm ³	cm ³	cm ³
Taucherin A	18,7	34	1,675	13,81	7,09	6,86	231,3	114,2	6,80	3,36
	25,0	42	2,001	11,21	7,69	5,80	224,3	115,3	5,34	2,75
	20,5	49	1,279	13,65	7,35	6,17	173,3	78,3	3,54	1,62
	22,6	56	2,263	11,13	9,77	6,06	250,8	135,6	4,48	2,42
	16,5	61	1,361	15,13	6,29	6,33	205,9	85,6	3,38	1,40
	19,5	61	1,810	16,20	4,70	6,79	202,0	84,2	3,31	1,38
	24,9	65	1,890	9,58	11,3	5,73	180,1	107,0	2,77	1,63
	15,5	67	0,924	16,58	4,65	6,80	150,1	62,5	2,24	0,93
	21,5	70	1,374	12,52	8,38	5,11	172,5	69,2	2,46	0,99
	19,8	71	1,393	15,67	5,23	6,37	218,3	88,2	3,06	1,24
9,0	118	1,576	15,61	5,29	6,18	246,4	96,9	2,09	0,82	
Taucherin B	14,7	51	2,130	14,21	6,69	5,16	302,6	109,1	5,93	2,14
	9,0	53	1,634	12,23	8,67	5,61	199,8	91,0	3,77	1,72
	24,0	56	1,816	13,72	7,18	5,27	249,2	95,0	4,45	1,70
	8,5	57	1,932	13,72	7,18	5,76	265,1	110,5	4,65	1,94
	22,5	59	1,657	14,99	5,91	6,20	248,4	102,1	4,21	1,73
	20,5	65	2,001	16,71	4,19	5,47	336,0	109,2	5,17	1,68
	13,5	87	1,532	17,60	3,30	5,64	269,6	85,8	3,10	0,99
	14,1	95	1,934	14,81	6,09	5,76	286,4	110,6	3,02	1,16
	12,9	95	2,069	17,24	3,66	5,42	356,7	111,3	3,76	1,17

A. Man fand, daß das Volum der 1. Ausatemungsluft (s. Abb. 9) in keiner Beziehung steht zur Tiefe oder zur Dauer des Tauchens. Nimmt der Wasserdruck schnell zu, so wird der Rumpf zusammengedrückt und das Volum der Luft, die sich im Glas und Atmungsorgan befindet, vermindert sich. Tatsächlich stößt die Ama einen Luftüberchuß in ihrem Tauchglas und ihren Atmungsorganen durch eine kleine Spalte aus, die sich zwischen ihrem Gesicht und dem Augenglasse befindet, und zwar vermittels einer kleinen Bewegung der Gesichtsmuskeln beim Herabgehen. Bei größeren Tiefen veranlaßt der größere Druck sie, mehr Luft auszustößen, und infolgedessen ist bei der Rückkehr das

Volumen der 1. Ausatmung kleiner als das Volumen der letzten, dem Tauchen vorhergehenden Einatmung, vorausgesetzt, daß keine sonstigen Änderungen statthatten.

B. Kohlensäure.

Bei den Ama A und B beträgt der CO_2 -Gehalt in der 1. Ausatemungsluft zwischen 5 und 7%. Dieser CO_2 -Gehalt scheint keine Beziehung zu haben zur Dauer oder zur Tiefe des Tauchens (s. Abb. 10), mag aber

tiefte.



Heraufnahme des tievlichten.

Taucherin
Gummihülle für
Ausatemungsluft
Tauch-
geschwindigkeitmeßapparat

Abb. 9.

innerhalb sehr enger Grenzen sich verändern. Es zeigt sich nur eine geringe Zunahme mit der Ausdehnung der Tauchzeit (s. Abb. 11). Dies kann zusammenhängen mit der unvollständigen Verbrennung in den Geweben, die vom fortschreitenden Sauerstoffmangel in dem Blut herührt. Infolge dessen würde die CO_2 -Spannung in den Geweben durch eine Verlängerung der Tauchdauer nicht vermehrt werden, und folglich ist auch die Abgabe von CO_2 durch das Blut an die Lungen gering. Obwohl die Tauchdauer den Kohlensäuregehalt der 1. Ausatemungsluft nicht beeinflusst, ist er doch natürlich beeinflusst durch die Tiefe des letzten dem Tauchen vorhergehenden Tiefatemzuges, die Tauchgeschwindigkeit, die Größe der auf dem Grunde zu verrichtenden Arbeit und die Temperatur des Wassers.

C. O_2 -Gehalt der 1. Ausatemungsluft.

Der O_2 -Gehalt regelt sich natürlich in ganz anderer Weise als der CO_2 -Gehalt. Es ist im allgemeinen bei einer Verlängerung der Tauchzeit herabgesetzt, aber er ändert sich auch mit der Schnelligkeit des Auf- und Abstieges, mit der Menge und der Art der auf dem Grunde zu verrichtenden Arbeit und der Wassertemperatur. Der O_2 -Gehalt der 1. Ausatemungsluft vermindert sich auf 3,3%, und dies entspricht einem partiellen Druck von 23,6 mm Quecksilber in den Alveolen.

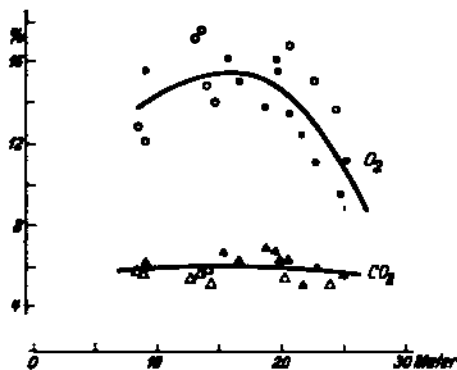


Abb. 10.
 O_2 -Verbrauch und CO_2 -Abgabe bei verschiedener Tauchtiefe.

●▲---Taucherin A
○△---Taucherin B

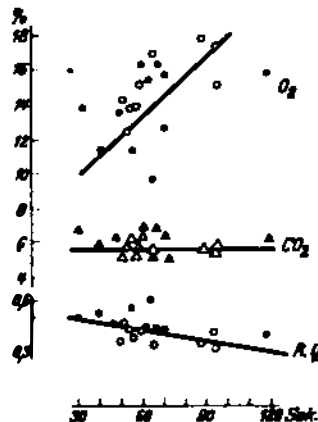


Abb. 11.
 O_2 -Verbrauch und CO_2 -Menge in verschiedener Tauchdauer.

Abb. 4 zeigt, wie er abnimmt, wenn die Tauchdauer verringert wird; es muß jedoch daran erinnert werden, daß hierbei auch andere Ursachen im Spiele sind: die Schwierigkeit der auf dem Grunde zu verrichtenden Arbeit, die Tauchgeschwindigkeit usw. Zieht man all dies in Betracht, so ist es immerhin bemerkenswert, daß der O_2 -Verbrauch bei lang- und bei kurzdauernder Arbeit nicht sehr verschieden ist. Man kann nur sagen, daß eine Tendenz vorliegt, zu wachsen, wenn die Dauer des Tauchens wächst. Ama A hatte beim Tauchen in 18,7 m und bei einer Tauchdauer von 34 Sekunden einen durchschnittlichen O_2 -Verbrauch von 3,36 ccm je Sekunde, aber beim Tauchen in 21,5 m mit einer Dauer von 70 Sekunden war dieser Betrag 0,99 ccm¹. Dies kann folgendermaßen erklärt werden:

¹ Haldane berichtet, daß in seinem Experiment über eine 77 Sekunden dauernde Asphyxie der O_2 -Gehalt der Alveolarluft auf 6,12% vermindert war. Versore berichtet, daß nach einer 4 Minuten und 5 Sekunden dauernden Asphyxie der O_2 -Gehalt auf 3,7% herabgesetzt war.

Wenn die Dauer der Asphyxie verlängert wird, vermindert sich der O_2 -Gehalt in der Lungenluft. Der partielle Druck des Sauerstoffs in den Alveolen nimmt ab, und der Sauerstoffsättigungsgrad des Blutes wird gleichfalls geringer. Hierzu kommt, wie man aus der Tab. 4 und Abb. 4 sehen kann, daß, während der Zustrom von CO_2 aus dem Blut in die Alveolen sich nicht gemäß der Tauschdauer vergrößert, die Anhäufung von CO_2 in den Geweben und im Blut gradweise zunimmt; daher wird die Absorption von O_2 durch das Blut schwierig und die Rate sinkt¹.

In solchen Fällen, in denen die Ama eine mehr als 1 Minute dauernde Asphyxie durchmacht, fällt ihr O_2 -Verbrauch auf 2—3 ccm je Sekunde, das ist meiner Meinung nach ein erstaunlich geringer Betrag. Während der O_2 -Gehalt der Ausatemungsluft auf 3,3% herabgesetzt ist, wächst der Kohlensäuregehalt bis zu einer gewissen Grenze, ohne aber sie zu überschreiten. Unter diesen Umständen verrichtet die Ama, woran nochmals erinnert sei, anstrengende Muskelarbeit, behindert durch einen Druck von 25 m Wasser, und dennoch ist ihr durchschnittlicher Sauerstoffverbrauch nicht mehr als 2—3 ccm je Sekunde, und der O_2 -Gehalt der Alveolarluft ist 3,0%.

D. Stickstoff.

Es wurde schon erwähnt, daß die Ama unter einem Druck von etwa $3\frac{1}{2}$ Atmosphären arbeitet, aus dem sie im Laufe von 13—18 Sekunden in den normalen atmosphärischen Druck zurückkehrt. Die Zeit, in der sie Unterschiede von $\frac{1}{10}$ Atmosphäre passiert, beträgt nur 0,5—0,7 Sekunden. Trotz dieser heftigen Druckänderungen arbeitet sie tüchtig und erleidet keine Gesundheitsschädigung.

Nach Haldane sind Caimonarbeiter imstande, ohne Gefährdung unter einem totalen Atmosphärendruck von 1—1,5 zu arbeiten. Nach einer Verminderung des Druckes von 2 auf 1 wird das überschüssige in den Geweben befindliche Gas in einen Zustand der Übersättigung übergeführt, aber es bildet niemals Luftblasen. Bei einer Verminderung des Druckes von 6 auf 3 oder von 4 auf 2 Atmosphären, mit anderen Worten bei einer Druckverminderung auf die Hälfte des vorherigen Totaldruckes besteht keine Gefahr, wenn der Prozeß 2—3 Minuten dauert, vorausgesetzt, daß der partielle Druck von N_2 im Blut nicht größer ist als das Doppelte des Druckes von N_2 in der Ausatemungsluft.

Die Ama arbeitet ungefähr $2\frac{1}{2}$ Minuten unter hohem Wasserdruck im Zustand der Asphyxie. Sie atmet nicht, wie der Caimonarbeiter, komprimierte Luft ein, aber sie hat komprimierte Luft in dem kleinen Raum ihrer Atmungsorgane (und der Augengläser). Daher hat diese Luft wahrscheinlich einigen Einfluß auf den partiellen Druck von N_2 in der Alveolarluft, und wahrscheinlich wird ein gewisser Betrag von

¹ Eine experimentelle Untersuchung hierüber wurde ausgeführt. Die Resultate werden später veröffentlicht.

Stickstoff, der in dieser geringen Menge von komprimierter Luft enthalten ist, im Blute gelöst. Wenn die Lungen einem Druck durch komprimierte Luft von 3,5 Atmosphären für so kurze Zeit, wie die Ama sie braucht, ausgesetzt sind, so verursacht dies keine Störungen, solange die Lungen nicht zum Einatmen gezwungen sind.

Zusammenfassung.

Die Untersuchung der Arbeit der japanischen Ama oder Taucherin zeigte, daß sie durch Training, Übung und eine maximale Anpassung an die in ihrer Umgebung vor sich gehenden Änderungen und ohne andere Hilfsmittel als einen Glasschutz für Augen und Nase, unter einem totalen Wasserdruck von 3,5 Atmosphären während etwa $2\frac{1}{2}$ Minuten in einem Zustande der Asphyxie zu arbeiten vermag. Sie kann anstrengende Muskelarbeit verrichten trotz eines so extremen Mangels an O_2 , wie er durch einen Sauerstoffgehalt von nur 3,3% in der Ausatemungsluft angezeigt wird. Der CO_2 -Gehalt der Ausatemungsluft nimmt mit der Tauchdauer innerhalb gewisser Grenzen nicht zu. Die Geschwindigkeit des Abstiegs ist etwas größer als die des Aufstiegs. Trotz der raschen Rückkehr von hohen auf normale Druckverhältnisse in nur 13—18 Sekunden und wieder zurück in nur 17—20 Sekunden, kann die Taucherin sich diesen Veränderungen so gut anpassen, daß sie keine Schädigungen erleidet.

Über andere Einzelheiten aus dem Leben und der Arbeit der Ama wird später berichtet werden.

HISTORICAL DEVELOPMENT OF THE AMA'S DIVING ACTIVITIES

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Introduction

Many ancient references indicate that the Ama have existed for at least 2000 years. One of the oldest references which refers to the Ama is the Gishi-Wajin-Den, which is believed to have been published in the year 268 B. C.

In the old Japanese language the word originally meant the ocean or the sky. Later the meaning of the word Ama was transferred to the diving fishers. In Japan today Ama only refers to the diving fishers, including either male or female divers. Using different Chinese characters the Japanese were able to distinguish in their writings between male and female divers. The Chinese character indicating the male Ama was equivalent to "sea warrior" or the "samurai of the sea." The Japanese word "samurai" refers to the ancient warriors of Japan. The Chinese character for the female Ama means "sea-women." The ancient literature used many different Chinese characters to represent the Ama but the sex was not always clearly indicated. There are also many synonyms for the Ama, such as "Suijin," "Kazuki," "Osaiso," "Umibito," "Mogurime," and "Umiko."

As shown in Table I, the male and female Ama engage in different practices. The male Ama is concerned with catching fish, either with use of a spear or grabbing them by hand. The female Ama collect shellfish and seaweed from the bottom of the sea. In this paper the author will concern himself primarily with the female Ama, who can be described as a person who uses no special diving equipment for her protection except goggles, collects plants or animals from the bottom of the sea, and derives her income entirely or in part from this activity.

Presently there are about 18,000 Ama in Japan. However, it should be pointed out that this number has recently decreased because fewer young girls are entering this activity. Young girls today prefer to work in factories or the pearl industry because the income is better and the work less arduous.

The greatest numbers of Ama are found in Mie Prefecture followed by Chiba, Fukui, Niigata, Shizuoka, and Ishikawa Prefectures, in decreasing order. There are also some seasonal Ama in Hyogo, Okayama, Shimane Prefectures and in Hokkaido. These seasonal Ama migrate to special places only during the diving season. In Kumamoto, Ehime, and Ibaragi Prefectures there are some male Ama.

There are several conditions which are necessary for the establishment of good diving localities. For example:

TABLE I
Sexual Specialization of the Ama's Diving Activities

Sex	Fishing Method
Male Ama	1. Diving to grab fish by hand 2. Diving for spear fishing
Female Ama	3. Diving to collect shellfish and seaweed

1. The water temperature must be suitable for the growth and the reproduction of the biological flora.
2. The water temperature should be warm enough for prolonged diving for long periods of the year.
3. The water current must not be too fast and must be safe enough for diving.
4. The absence of harmful animals, like the shark.
5. The structures of the sea bottom must be suitable for the biological flora.
6. The market or other economic organization should be located nearby so that the Ama may easily sell her harvest.
7. The diving area should not be too far from the Ama village.

There is one interesting exception to this last rule. In Wajima all the inhabitants leave their Ama village during the diving season and migrate to Hekura Island located 60 km from the village.

Figure 1 indicates the distribution of the Ama in Japan. As one can see, Japan stretches geographically over a wide area from north to south so that there are significant differences in the climate, such as temperature, humidity, and amount of rainfall. From the meteorological point of view one can divide Japan into three parts, the frigid zone, the temperate zone, and the subtropical zone. The Ama villages are distributed in the temperate and the subtropical zones, but not in the frigid zone. The northern limits of the Ama villages coincide with the line representing the average annual air temperature of 12°C. It is interesting to realize that this northern limit nearly coincides with the northern limit of the cultivated tangerine or the Japanese tea plants.

There are many towns which in the past must have been Ama villages but where today no Ama live. These places can be recognized by their names such as Ama-machi or Kaishi-machi.

The Origins of the Women's Role in Diving

In the ancient shell mounds or middens one may today find many shells which must have been collected in fairly deep water, which suggests that they were obtained by diving and without the use of special tools. Although this work requires great skill, the author does not believe that this skill is inherited since it is well known that farmers' children can be trained to become excellent divers.

The ancient shell mounds have also revealed animal bones, fish bones, harpoons, and fish hooks made from animal bones. These facts suggest that in ancient times there was no particular specialization in hunting or fishing. It might naturally be assumed that some hunted while others fished, and that these occupations were pursued by both men and women since much of their time was spent in gathering food. Only later with greater specialization in the art of hunting and fishing did the art of diving and collecting shellfish and seaweed fall into the province of the women.

To understand this specialization it is useful first to discuss the migration of the Japanese people. It is believed that they came from islands southwest of Japan. They had boats and were presumably fishermen who came to the shores of the main island to exchange their products with the people who practiced hunting or agriculture. Seaweed were an important item for they supplied not only food but also salt.

These migrating fishermen settled along the shores of the main islands where they continued their fishing while the women collected the shellfish and seaweed near the shore. Thus possibly the women became associated with collecting these particular items, which not only supplied certain salt requirements but which

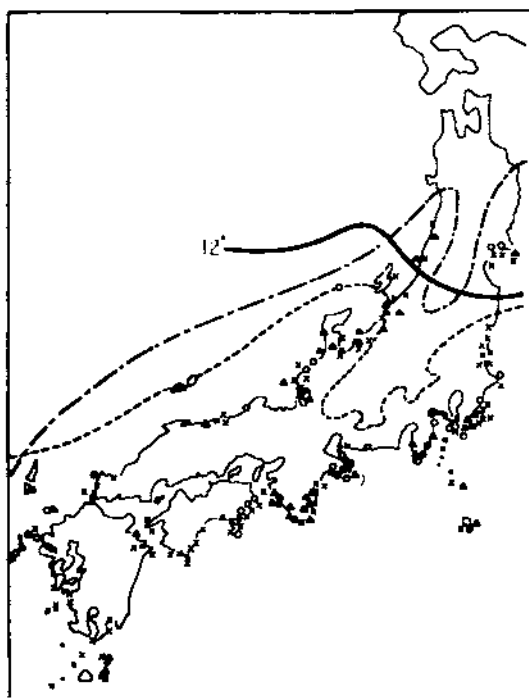


Figure 1. The Distribution of the Ama Villages (June 1956).

- Ooisodo
- △ Nakaisodo
- Koisodo
- x Male Ama
- The iso-thermal line for the annual average air temperature of 12°C
- The northern limit of the cultivated tangerine
- The northern limit of the cultivated Japanese tea plant

were also used in certain religious ceremonies. The abalone or the turbo were used in religious rites of the Emperor's family; even today they are offered at the Ise-Shinto Shrine, a practice that started about 1000 years ago.

Some Ama also collected pearls or the abalone shell to use as trinkets. In the Muromachi era (781-1185) the Japanese enjoyed a peaceful period and elegant living and appreciated the trinkets made of pearl and abalone shells. Until the advent of the cultured pearl the abalone shells were important products of the Ama.

The Harvest of the Ama

While the men were thus engaged in off-shore fishing or as sailors on ships, the Ama stayed at home, and took up diving to supplement the farming harvest from the land. This custom has remained to this day.

The harvest of the Ama are listed below:

A. Shellfish

Haliotis (Euhaliotis) gigantea Gmelin
Turbo (Batillus) cornutus Solander
Haliotis japonica Reeve
Pteria (Pinctada) martensii (Dunker)
Cristaria plicata spatiosa (Clessin)
Mytilus crassitesta Lischke

B. Animals

Heliocidaris crassispina group
Stichopus japonicus group

C. Plants

Gelidium Amansii Lamour
Ceramium hypnaeoides (J. Agardh) Okamura
Gelidium japonicum (Harvey) Okamura
Acanthopeltis japonica Okamura
Undaria pinnatifida Suringar
Laminaria japonica Areschoug
Ecklonia cava Kjelluman

The Ama's Diving Pattern

As mentioned above, the Ama are distributed in the area of Japan where the annual average air temperature exceeds 12°C. In this region the water temperature exceeds 20°C frequently enough to make harvesting a practical operation. At this temperature or above she can stay submersed for relatively long periods without excessive chilling. From the beginning of May until the end of October the average water temperature during the day will remain at 20°C or above and therefore most of the diving is done during this period.

In order to achieve the maximum harvest with a minimum effort the Ama developed various skills and methods. She was concerned with the following:

1. shortening her time for descent,
2. prolonging her bottom time for harvest,
3. shortening her time for ascent,
4. developing methods and tools for carrying the harvest to the surface and placing it in the boat,
5. developing the best position for controlling her breathing while resting at the surface,
6. developing convenient devices for better underwater vision, and
7. finding and locating productive diving areas.

It is difficult to trace these developments in the ancient literature. But one may assume that originally the Ama dived in a very primitive way without the use of special equipment. Over the centuries they learned efficient and safe methods of diving and through this experience handed down their art from generation to generation. Since the Ama in each village were geographically isolated, their traditional methods and practices varied from place to place.

In the 17th and 18th centuries the Ama were half naked during their dives, wearing only a skirt. This is well illustrated in the "Ukiyoe," the old Japanese woodcuts. Most of the Ama along the shore of the Japan Sea still dive naked today (Fig. 2), while those along the shores of the Pacific Ocean use cotton shirts to cover their bodies and cotton shorts or knitted drawers instead of skirts (Figs. 3, 4). Very recently a few Ama have started to wear foam-rubber suits to prevent excessive heat loss.

The underwater goggles were not introduced until about one hundred years ago. In the early goggles the sidewalls were made from bamboo. However, these simple "two-piece" goggles were uncompensated and produced pain or bleeding when certain depths were reached. The next step was the development of pressure compensating devices which were attached to the goggles. These were made from soft leather or rubber (Figs. 2, 5, 6). Some of the Ama use the "single-piece goggles," which cover both eyes (Fig. 6). One type of these single-piece goggles covers the nose as well as the eyes, while the other type of the goggles does not cover the nose. The latter type of the single-piece goggles has the pressure control device just like the two-piece goggles (Fig. 6). The Ama on the shores of the Japan Sea use the two-piece goggles, while the Ama on the Pacific Ocean side use the single-piece goggles (compare Figs. 2 and 4).

The Ama carries a metal scoop or pallet for various types of diving. This is called a "Kaigane" and is used to remove the abalone or other shells from the rocks, and serves as a counterweight during her descent (Fig. 7). The "Kaigane" has different shapes and sizes which vary with the localities of each Ama village. Some of the "Kaigane" have wooden handles. In ancient times "Kaigane" was very precious and was given to the Ama by the Emperor or by the rich people in return for her services. It was also carried to protect her from evil.



Figure 2. Koisodo from Hekura Island. She dives without clothes. Note pressure compensating bulbs attached to goggles. Hair style is typical for a diving Ama.



Figure 3. Nakaisodo from Shima Peninsula on the Pacific Ocean side. Here they use a cotton suit. Note hair style and net bag attached to her waist.



Figure 4. Koisodo from Shima Peninsula. Note the single-piece goggles pushed back on top of her head and her cotton suit.



Figure 5. Close-up of two Nakaisodos scanning the bottom just prior to a dive. Note rubber bulbs attached to their goggles.

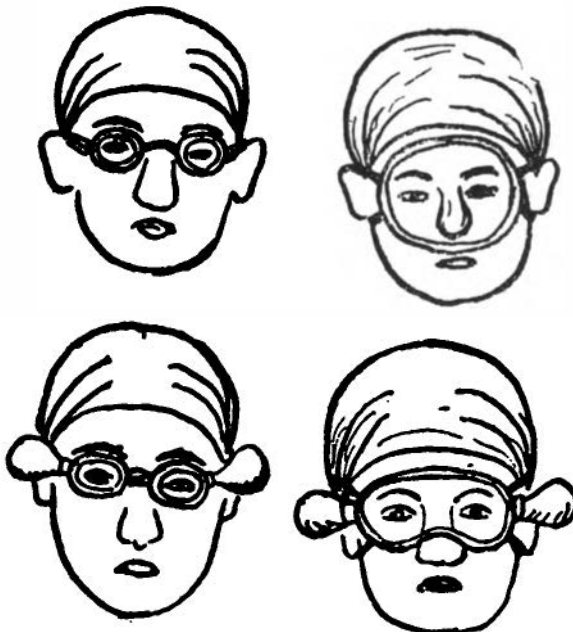


Figure 6. Different types of goggles. Upper left: 2-piece goggles — uncompensated; lower left: 2-piece goggles with compensating bulbs; upper right: face plate with compensation achieved by compensation through the nose; lower right: 1-piece goggles with compensating bulbs.

There are three different diving patterns which the Ama has developed:

1. Koisodo (Figs. 8, 9, 10, 11). The Koisodo does not use a boat and walks on the beach to the diving places. She dives to relatively shallow depths of two to four meters. The Koisodo is also called "Iso-katsugi," "Okaama," "Ko-ama," "Isodo," "Cachido," or "Kachi-iso." The Koisodo will carry a wash tub or a piece of board, to which the net bag is attached as a container for a harvest. They will dive around these floats and place their harvest in them during their repeated dives. These floats are usually connected to the Ama by a rope to avoid drifting away. This kind of diving activity is usually done by the young girls who are in training. The old Ama who can no longer dive deeper may also be included in this group.

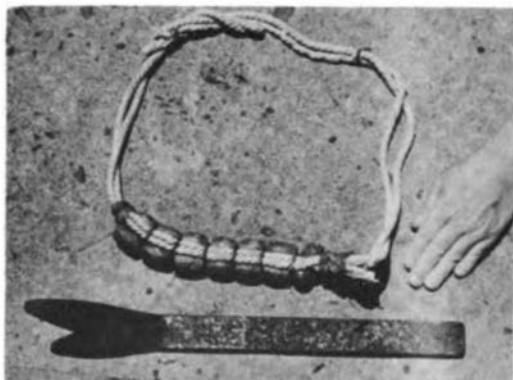


Figure 7. The "Kaigane" used by the Ama of Hekura Island for breaking loose the shellfish from the rock. Note also the lead weights used as a counterweight. They are strung like beads on a belt rope.

2. Nakaisodo (Figs. 5, 12, 13, 14). The Nakaisodo is also called "Funedo," "Funado;" "Okazuki;" "Okicama," or "Funekazuki." This group of Ama is more capable than the Koisodo. Only young girls who have already been trained as Koisodo for a few years are allowed to work as Nakaisodo. Many of the Nakaisodo are between 15 and 20 years old. The old Ooisodo may also be included in this group of the Nakaisodo. The Nakaisodo makes active dives down to four to

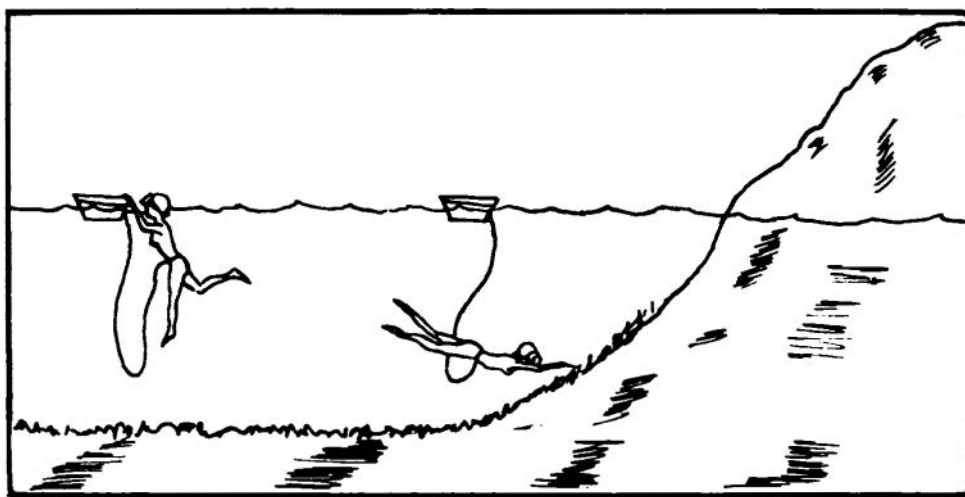
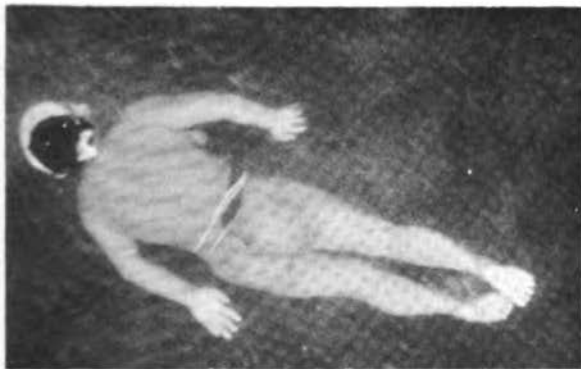


Figure 8. Diving pattern of the Koisodo. These are young girls in training. They dive two to four meters, close to shore.



Figures 9, 10, 11. Sequence from top to bottom during descent, on the bottom looking for harvest, and during ascent.

seven meters. They make up a group of five to ten Ama and get aboard a boat controlled by one or two boatmen. These men also work as watchmen for the safety of the diving Ama. The Nakaisodo also use wash tubs which are connected to the Ama by a rope. The wash tub is used as a container for their harvest as well as for the float for resting between dives.

When the Nakaisodo feel chilly, after excessive loss of body heat, they return to the beach and warm themselves by the fire.

3. Ooisodo (Figs. 15, 16, 17, 18, 19). The Ooisodo is also called "Okicama," "Oo-ama," "Ookazuki," "Funa-ama," or "Funado." The Ooisodo is the most capable Ama and can expect the best income. After finishing the junior high school the young girl will first be trained as a Koisodo and as a Nakaisodo before she becomes an Ooisodo. The Ooisodo is usually more than 20 years old and becomes technically and physically most efficient between the ages of 25 and 40 years. It is believed that the Ooisodo already existed more than 1000 years ago.

The Ooisodo usually dives to depths of 10 to 25 meters and she has a particularly long breath-hold time. Since she goes down to such depths, she usually uses special devices to decrease her ascent and descent times. The Ama in Kanegasaki of Kyushu Island or on Hekura Island uses a belt of lead as a counterweight (Fig. 7). Each

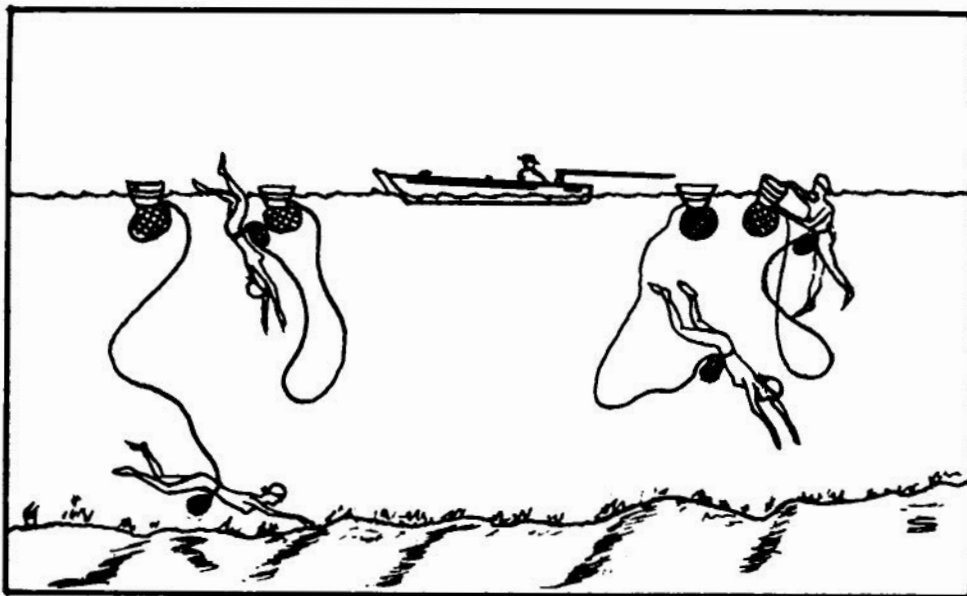


Figure 12. Diving pattern of the Nakaisodo. These operate in groups from a boat and dive four to seven meters. Note the collecting nets attached to their belts and the larger ones suspended from the floating tubs.



Figure 13. Diving activities of the Nakaisodo on Hekura Island: Group of Ama preparing for diving.



Figure 14. Diving activities of the Nakaisodo on Hekura Island: The boatman watching the diving operation. Note three tub floats in front of the boat.

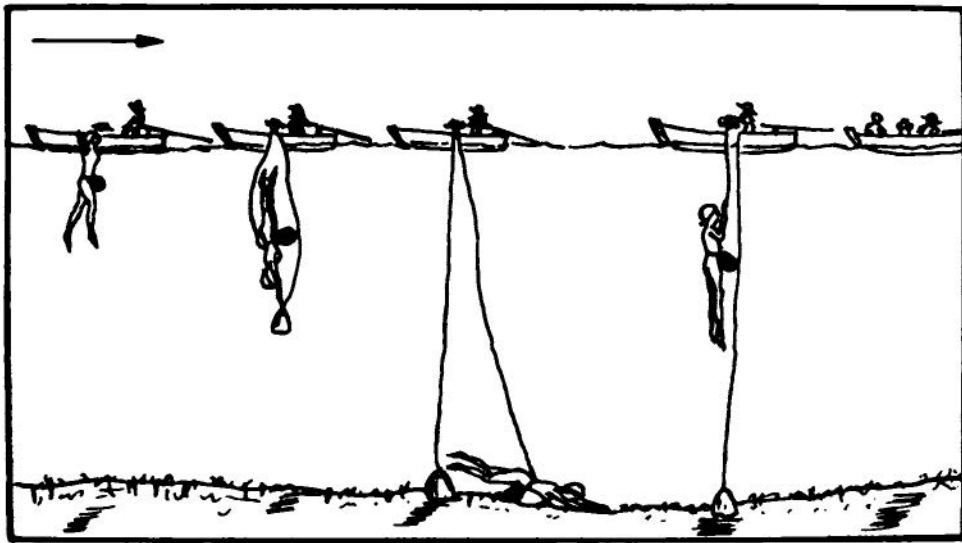


Figure 15. Diving pattern of the Ooisodo. This is the most advanced type of diving with one Ama per boat. She descends rapidly with a counterweight and after the harvest is pulled up to the surface. She can dive to depths of 25 meters. On Hekura Island she descends head-first as shown here; in other localities she descends feet-first.



Figure 16. Activities of the Ooisodo: Ama resting between dives at the side of the boat.

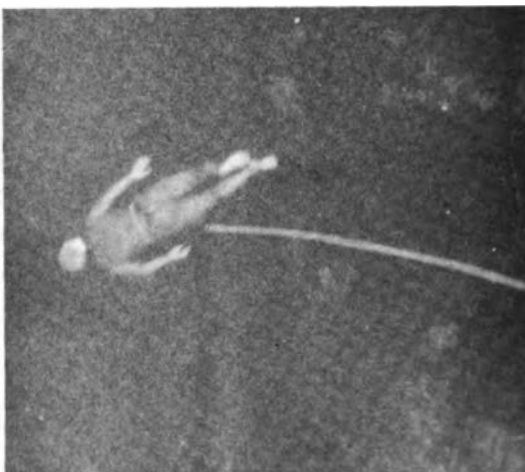


Figure 17. Activities of the Ooisodo: Ooisodo from Hekura Island descending head-first.



Figure 18. Activities of the Ooisodo: Her partner pulling up the Ama.



Figure 19. Activities of the Ooisodo: The Ama breaks the surface.

piece of this lead counterweight has an oval form of 3 cm in diameter and 5 cm in length. In addition to this she will carry the Kaigane of about 3 kg (Figs. 7, 20).

The other method is to carry by hand a counterweight of 11 to 15 kg which is made of stone, copper, or iron. This counterweight is called a "Haikara" or "Kuri-ikari" (Fig. 21). The counterweight is connected to the boat with a rope. This rope goes through a pulley fixed at the side of the boat (Figs. 18, 19). The Ama dives holding this counterweight down to the bottom so that she may obtain a high descent velocity. At the bottom the Ama releases the counterweight and

swims around looking for harvest. After collecting her harvest she pulls her life rope to signal her partner on board and he pulls her up to the surface using a pulley. On the Ooisodo's boat an Ama is usually accompanied by one or two men who control the boat, pull up the Ama, and handle the counterweight. The counterweight is pulled up while the Ama is working at the bottom. The partner is usually the Ama's husband, brother, father, or other near relative.

Between dives the Ama rests, holding onto the side of the boat, and prepares for the next dive by regulating her breathing (Fig. 16).

The time schedule during the repeated dives of the Ooisodo is shown in Figure 22. This figure indicates the descent time, the bottom time, and the ascent time as well as the resting time between dives. The Ama repeats such dives 50 times in the morning, followed by another 50 dives in the afternoon. A series of photographs indicates the method of diving by the Ooisodo.

The boat carries a sunken fire pit which the Ooisodo will use to warm her body after a series of dives (Fig. 23). The Ama always changes her clothes before warming her body.

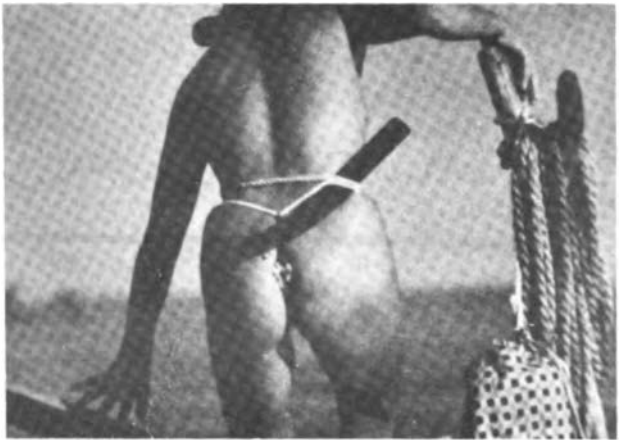


Figure 20. Ooisoso of Hekura Island ready for a dive. Note the "Kaigane" carried on her rope belt.

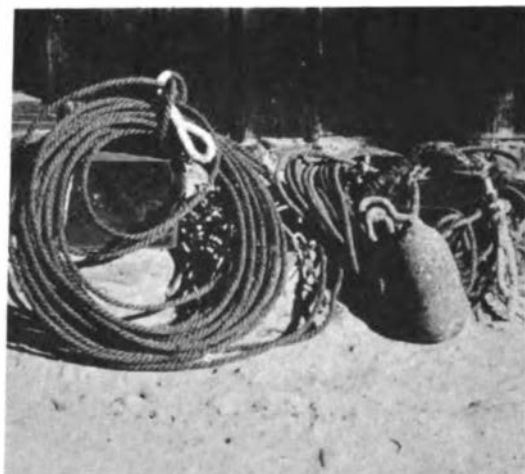


Figure 21. A counterweight and rope used by the Ooisodo.



Figure 23. Fire pit in bottom of boat used for rearming the Ama and boiling tea.

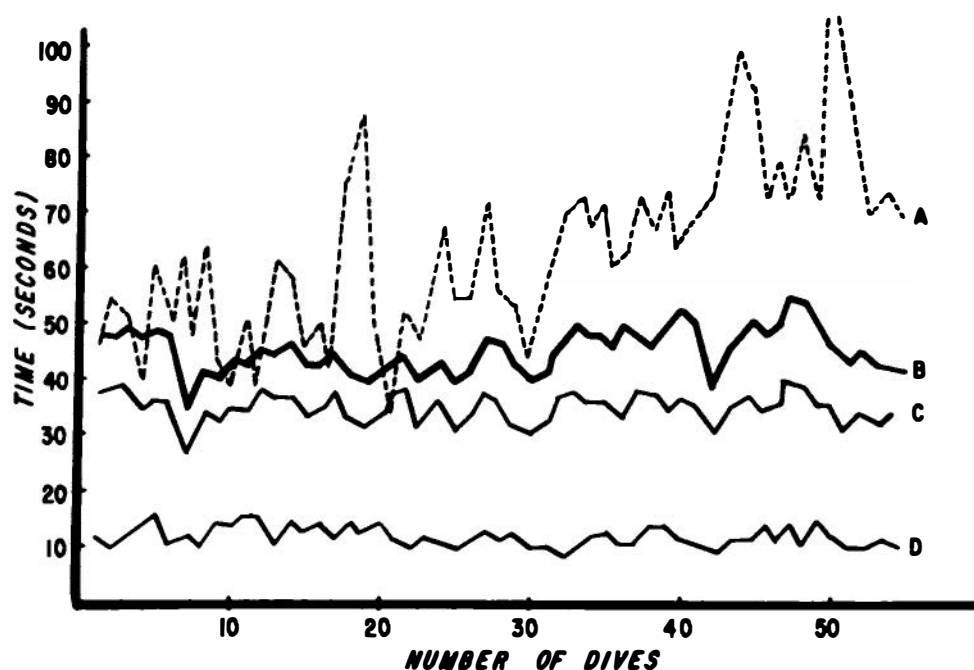


Figure 22. The time schedule of the Ooisodo, showing the total diving time (line B) and the resting time (line A). Lines C and D indicate the subdivision of the total diving time. The distance between the abscissa and line D indicates the descending time; the distance between lines D and C indicates the bottom time; the distance between lines C and B indicates the time for ascent.

TABLE II
Classification of Ama

Classification	Depth of work - (meters)	Age for work (years)	Note
Ooisodo	8 - 25	20 - 50 sometimes over 50	the most skillful Ama
Nakaisodo	4 - 7	18 - 25	the Ama of moderate skill
Koisodo	2 - 4	15 - 20 over 60	the junior Ama in training

Summary

The author has briefly discussed the historical development of the Ama and her diving activities, which have become a very interesting topic in the Japanese folklore. As mentioned, the Ama in every Ama village have their own traditional methods of diving patterns and activities and it was not possible to refer in detail to all the variations. It is hoped, nevertheless, that this brief manuscript will contribute to an understanding of these traditional diving activities which have developed during their 2000 year history.

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REVIEW OF ACTIVITIES: HARVEST, SEASONS, AND DIVING PATTERNS

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INTRODUCTION

The Ama, professional women skin divers, have existed from very early times and are widely distributed along the shores of Japan. They may be either male or female, but ordinarily the word is applied to the female divers. The Ama are thus women laborers who collect submarine plants and animals fixed to reefs by breath-hold diving and who live partially or almost completely on the income from these harvests.

The Ama have been studied from various standpoints, because of the interest in their lives and work. However, almost all of these studies have been carried out in ethnological fields, with the recording of personal observations or folklore.

At present, the Ama are often regarded as a tourist attraction and much has been written about them from this point of view. Since she works from the rocky reefs along the picturesque seashore, the places near large cities are gradually becoming show places. There she dives as a performer for tourists instead of carrying out her original job as a diver. Thus, the life of the Ama is gradually being changed by journalists and tourists. The real activities of the Ama can be observed only in some remote corners of the country.

The scientific reports concerning the Ama activities in Japan are almost always restricted to local customs which vary widely from place to place. It is thus difficult to review the Ama activities and generalizations must include the following:

1. The wide geographical distribution of the Ama long the sea-shores of Japan which causes many local differences.
2. There have been extensive migrations of the Ama group in the past even though they live at present in permanent places. There is, therefore, a diverse ancestry in diving activities and living manners.
3. Diving patterns differ depending on the flora and fauna to be harvested and on varying geographic conditions.

The harvest, seasons and diving patterns of the Ama are therefore described only in a very general way.

HARVEST

The harvest of the Ama differ with the location and the skill of the individual. In general, the harvests are of the submarine fauna and flora which can be reached by breath-hold diving, ranging to a depth of 20 meters. The main harvests are as follows: (See also Figs. 1 and 2.)

FLORA

RHODOPHYCEAE (Floridae)

Gelidiales

Gelidiaceae

Gelidium Amansii Lamouroux: "Makusa" or "Tengusa,"
raw material of agar-agar.

G. japonicum (Harvey) Okamura: "Onikusa."

Acanthopeltis japonica Okamura: "Yuikiri."

Ceramiales

Ceramiaceae

Ceramium hypnaeoides (J. Agardh) Okamura: "Egonori."

Gigartinales

Gigartinaceae

Gigartina tenella Harvey: "Suginori."

Rhodophyllidaceae

Euclidean muricatum f. *depauperata* Weber van Bosse: "Kirinsai."

Gracilariaceae

Gracilaria confervoides Greville: "Ogonori."

PHAEOPHYCEAE

Laminariales

Laminariaceae

Undaria pinnatifida Suringar: "Wakame," foodstuff.

Laminaria japonica Areschoug: "Makombu" or "Kombu."

Ecklonia cava Kjellman: "Norokajime" or "Kajime,"
raw material of iodine.

FAUNA

MOLLUSCA

Bivaldia

Anisomyaria

Pteria (Pinctada) martensi (Dunker): "Akoyagai," pearl
oyster.

Mytilus crassiteata Lischke: "Igai," foodstuff.

Gastropoda

Archeogastropoda

Haliotis (Euhaliotis) gigantea Gmelin: "Awabi," abalone,
foodstuff.

H. japonica Reeve: "Tokobushi."

Turbo (Batillus) cornutus Solander: "Sazae," wreath shell.

ECHINODERMA

Holothurioidea

Actinopoda

Stichopus japonicus Selenka: "Manamako" or "Namako,"
sea slug.

Echinoidea

Regularia (Sea urchin)

Strongylocentrotus pulcherrimus (A. Agassiz). "Bafun-uni."
Heliocidaris crassispira (A. Agassiz). "Murasaki-uni."

Among the plant harvests, some kinds of seaweeds, as the raw material of agar-agar (vegetable jelly), are most important. Agar-agar is not only consumed abundantly in this country but also is exported to foreign countries. At present seaweed as raw material must be imported from Korea to replenish the shortage in Japan.

Seaweed of the "Tengusa" type is the main harvest of the Ama. At present, however, in the shallow sea with a relatively flat bed these weeds are collected by ships equipped with rope-drawn rakes. Thus the range of the Ama activities is gradually being reduced, but the deeper or very uneven and jagged places are still the field of monopoly of the Ama. There they can pick the weeds of better quality. Of course, seaweed which has been cast upon the shore by waves or are floating in the sea after storms, can be collected without diving. "Wakame" and "Kombu," seaweed commonly eaten in Japan is picked mainly by reaping hooks or rakes with long poles from ships instead of by diving. The Ama participate little in this job. Among the seaweed harvest of the Ama, weeds of the "tengusa" group are so important that they have special divers named "Kusa-ama" (sea-weed divers).

Among the animal harvests, "Awabi" has been the most important since ancient times. "Awabi" is one of the most precious foods in Japan and dried "Awabi" is also exported to China. At present, "Awabi" is found only in the deeper waters because of over-harvesting. The harvest is thus limited to the best divers. Furthermore, picking "Awabi" is very difficult and long experience is necessary to acquire the technique. A skilled Ama can occasionally earn as much as 10,000 yen (about \$28.00) a day, a considerable sum of money for an ordinary Japanese.

As the artificial cultivation of "Awabi" is not yet practical, "Awabi" harvesting is a veritable gold mine for the Ama. Among the Ama there are thus specialists called "Kai-ama" (shell-fish Ama). Although "Awabi" is the most important marine animal harvested by the Ama several other animals are also harvested.

"Sazae," "Tokobushi" and "Igai" are highly valued as foodstuff, but are relatively cheaper because of their easier harvest in shallow water. "Akoya-gai" are the most famous among the mother-of-pearl shells in Japan. They are not harvested by the Ama for natural pearls but for pearl cultivation. However, instead of gathering the baby shells as in ancient times, the larvae of "Akoya-gai" are collected by special equipment. These are cultivated to a certain size and are then disseminated within certain zones of the shallow sea. The Ama collect



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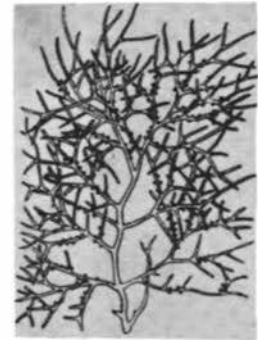
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Figure 1. Vegetable Harvests of the Ama. 1. *Gelidium amansii* Lamouroux; 2. *G. japonicum* (Harvey) Okamura; 3. *Acanthopeltis japonica* Okamura; 4. *Ceranium hypnaeoides* (J. Agardh) Okamura; 5. *Gigartina tenella* Harvey; 6. *Eucheuma muricatum* f. *depauperata* Weber van Bosse; 7. *Gracilaria confervoides* Greville; 8. *Undaria pinnatifida* Suringer; 9. *Laminaria japonica* Areschoung; 10. *Ecklonia cava* Kjellman.



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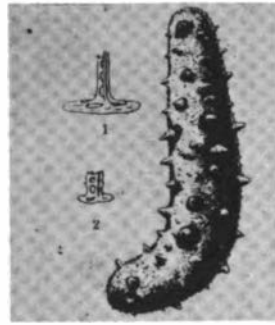
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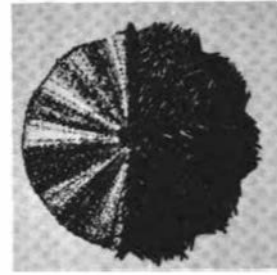
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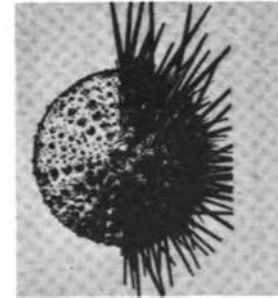
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Figure 2. Animal Harvests of the Ama. 1. *Pteria (Pinctada) martensi* (Dunker); 2. *Mytilus crassiteata* Lischke; 3. *Haliotis (Euhaliotis) gigantea* Gmelin; 4. *H. japonica* Reeve; 5. *Turbo (Batillus) cornutus* Solander; 6. *Stichopus japonicus* Selenka; 7. *Strongylocentrotus pulcherrimus* (A. Agassiz); 8. *Heliocidaris crassispina* (A. Agassiz).

them after they have reached the requisite size for insertion of the pearl nuclei at the factories near the shore. These inoculated shells are then cultivated in metal wire baskets or strung on rops suspended from rafts. Thus the Ama in pearl cultivation works much as an agricultural or factory laborer. The pearl Ama at present are not real Ama in the sense that they are not self-employed.

"Uni" and "Namako" are also precious foodstuffs eaten uncooked or processed. Dried "Namako" are exported abundantly to China. These are also products harvested by the Ama, but there are no specialists for these harvests.

SEASONS

The working seasons of the Ama correspond with the best harvest seasons. Out of season there is little return even with a great deal of work. In general, the season is four or five months from spring to autumn but best in the summer. In ancient times, it is said that the Ama worked whenever any harvest could be expected, but nowadays they generally work only in restricted seasons. Factors conditioning the harvest season are as follows:

Natural Factors

1. Abundant presence of the harvests.
2. Adequate water temperature for frequent diving (higher than about 20°C).
3. Adequate air temperature so the Ama does not feel cold after leaving the water.
4. Transparency of the water which facilitates the sighting of objects in the sea.
5. No danger for diving or navigation because of tides, winds or waves.
6. Absence of dangerous animals — such as shark or jelly fish which invade at certain seasons.

Artificial Factors

1. Fishing seasons provided by the central or local government.
2. Fishing seasons arbitrarily designated by cooperatives or trade unions to which the Ama belong.

(Fishing seasons of the categories 1 and 2 are provided in order to prevent the over-harvesting and to conserve the natural resources.)

3. Limitation by the local agricultural calendar. Part-time Ama who have other jobs, especially farm work, do not dive during the busy farming season.

Therefore the harvest season differs with location and harvest. At any given location the Ama observe the rule strictly.

DIVING PATTERNS

The costume and equipment of the Ama are very simple and convenient for diving.

Costume

Head and Face: In general, the Ama arrange their hair in special styles to keep it in order during diving and cover their head with a handkerchief ("Tenugui"). In some places they also cover their cheeks with a towel.

Body: The Ama wear undershirts or Japanese-styled underwear of cotton or wool with long sleeves. In some places, however, they wear nothing but pants or loincloth ("Fundoshi" — a long narrow piece of cloth that is wrapped around the waist and the lower part of the body). Such Ama are called "Hadaka-ama" (nude Ama). Outside of the pants or loincloth, a "Koshimaki," a rectangular piece of cloth, tied around the waist and descending nearly to the ankles, is often worn.

Diving suits of foam rubber — wet suit — such as used in aqua-lung diving, are not used by the Ama and prohibited by the code of local cooperatives or trade unions of divers. These are used only by the male divers. The women divers wear at most the foam rubber pants. Because of the heat insulating function of such a material, the women divers, who are more tolerant of cold water than the male divers, gain an advantage over the male divers. This also accelerates over-harvesting.

Fingers: In general, the Ama work with bare hands, but for the "Tengusa" picking, finger caps are often used to prevent injuries.

Feet: Generally the feet are bare. In some cases, "Tabi" (Japanese socks) or "Zori" (straw sandals) are used so as not to slip or injure the feet.

Equipment

Goggles: At present, all Ama use diving goggles. The most popular ones are as follows (Fig. 3):

1. Twin-glassed goggles without rubber bulbs; these are used only in very shallow seas for beginners.
2. Twin-glassed goggles with rubber bulbs; these goggles are used for deeper diving. Each eye piece is provided with a small pear-shaped rubber bulb. This bulb is the air reservoir. When it is squeezed by the water pressure in the sea, the air in the bulb is compressed to the eye piece and the atmospheric pressure in the chamber is automatically compensated with the water pressure so as to prevent the "squeeze."

However, at the depth where this bulb is collapsed, the pressure compensation effect disappears. That is to say that there is the limit of depth for these



Figure 3. Goggles of the Ama.

1. Twin-glassed goggles without rubber bulb.
2. Twin-glassed goggles with rubber bulb.
3. One-glassed goggles — head piece.

goggles. To dive deeper, the dead space of the eye-piece chamber must be smaller. This also decreases the water resistance during the diving. Deeper depths may also be reached with larger bulbs, but in this case, the water resistance increases and it is more convenient to reach the lower depths.

3. **Face masks, the headpiece familiar in western countries; (a large glass covering both eyes and nose).** In this case, the inner atmospheric pressure of the headpiece is balanced against the water pressure at any depth by the expiration from the nose to the chamber.

The expiration is carried out easily as the thorax is being pressed by the water pressure. Furthermore, the inner pressure of the tympanic cavity is balanced with the pressure of the goggles, i. e., the water pressure, so injury of the ear drum is prevented and hearing loss because of tympanic injury rarely occurs except in those with auditory tube stenosis.

The limit of diving depth is much greater than that with twin-glassed goggles with rubber bulbs. Because of this depth limitation of the goggles the single glass headpiece has gradually come into wide use.

Belt of the Ballast Weight: In some places, a belt with lumps of lead, like a necklace, is tied around the waist to serve as ballast to aid a rapid descent.

"Tegane" or "Isogane": This is a sharp spatula-like iron tool used to detach the "Awabi" shells from the rocks. The Ama stick it in their belt like a warrior putting on his sword. A large-sized instrument also aids as a ballast for rapid diving.

Containers for the Harvest: A net bag or a bamboo basket is used to hold the harvest. The bag may be hung from the neck or the waist. If it is desired not to weaken or kill the harvest, the bag may be hung from the bottom of the buoy described below.

Buoy: A large sized wooden board, barrel or large tub of wood is used as a buoy to facilitate swimming from the shore to the diving place. The tub may also be used as a small boat which the Ama row with a bamboo pole. They rest holding onto the buoy.

The Ama and her buoy are connected by a long rope to keep the buoy from floating away. If the diving place is far from the shore the buoy may be carried in the boat with the Ama.

Life Rope: When diving deep, the Ama ties a rope about 20 m long around her waist. With this she is hauled to the surface at the end of her dive by her boatman. The rope is very important not only in case of danger but also for rapid ascent.

Diving Patterns

The Ama are classified into three groups according to their diving abilities. Of course, it often happens that the Ama work in a lower grade because of the weather or for health reasons.

1. Junior Class: Young girl beginners and old women just before retirement. They dive only two to three meters deep. They reach their diving place by walking into the sea and swimming with the aid of the buoy mentioned above. When they feel tired or cold they go to shore and rest around a blazing fire.

2. Middle Class: Cachido, girls younger than 20 years of age who have finished junior class training. They dive four to seven meters deep. One group of five or six girls go to their diving place on board a small boat with a boatman. There they work using their buoys and harvest containers. The harvests are brought to the tub or the basket after each dive or kept in a net bag attached to the waist. After each dive they rest holding the buoy. After a series of dives (20-30 times), they go on board their boat and rest around the fire on board which the boatman has prepared and chat with each other. There are several diving shifts per day.

The characteristic of the middle class Ama is the group transportation to their diving place by a boat and their unassisted diving and ascent without a ballast weight or the assistance of a boatman such as is the case with the senior class Ama. The junior class Ama, in contrast, go to their diving place individually by wading and swimming. (Fig. 4).

3. Senior Class: Funado, the most experienced and skillful divers of 20 to 50 years of age. They dive 8 to 20 meters deep. An Ama goes to her diving place on board a small boat in partnership with a boatman. In some cases there is also an additional male assistant.

As the diving time is limited by breath holding (40-50 seconds, at longest, about one minute), it is desirable to shorten the time of diving and ascent in order to stay on the sea bed as long as possible. For this reason, they have developed special diving patterns.

1. They wear a ballast belt (2-3 kg weight);
2. carry a heavy "isogane" (1.5-2 kg weight);
3. sink down with a heavy weight. This is a stone or iron weight weighing 10-15 kg connected with a rope through a pulley on one side of the boat. The Ama holds on to this weight and sinks down quickly with it, either head up, or, in some cases, head down.

Reaching the sea bed she releases the weight and swims away. As soon as she arrives at the sea bottom, her boatman takes the rope of the weight off the pulley and puts her life rope in its place. He then waits for her ascent signal, one or two slight tugs on the rope. On receiving the diver's signal, the boatman pulls her quickly to the surface (Figs. 5 and 6).

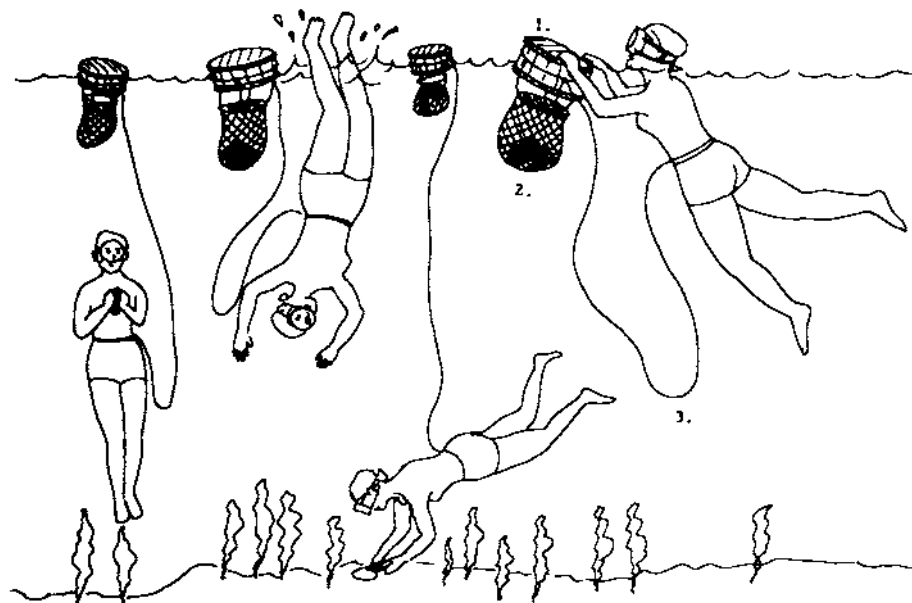


Figure 4. Shallow Diving of the Cachido.

1. Barrel as a buoy.
2. Net bag for the harvest.
3. Rope connecting the diver and barrel.

The boatman is very busy. He is responsible for controlling the location of his boat and managing the life rope and the weight rope as well as the anchor rope. He must further concentrate his attention on handling the weight and pulling up his partner. He, therefore, often has an assistant, generally a young boy, who handles the weight and the life rope. The men on board the boat often feel more tired than their diver.

The team work between the diver and her boatman (and assistant) is extremely important for effective diving and the prevention of accidents. In almost all cases, therefore, the boatman or the assistant is the father, husband, brother of the diver. This arrangement for the senior class Ama is in contrast with that of the middle class Ama.

Diving is carried out generally in the following manner: The divers regulate their respiration before diving. Then they dive rapidly, perpendicularly head down, stroking the water with both arms either alternating or simultaneously. They hold both legs in a posture of minimum water resistance and move with minimum physical effort, saving their breath.

Ascent is carried out in a similar manner, holding the legs together and the arms at the sides in order to offer a minimum of resistance. The hands are rarely used for ascent since they are generally full of harvest.

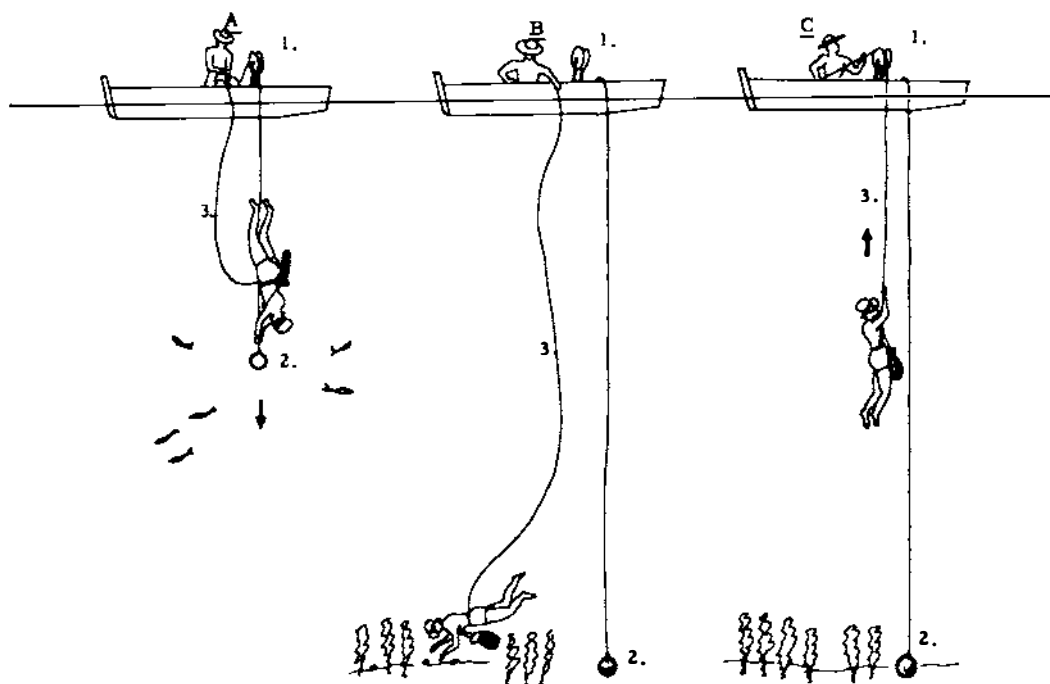


Figure 5. Deep Diving of the Funado.

- A. Rapid sinking.
- B. Working at the sea bottom.
- C. Rapid ascent.
- 1. Pulley; 2. Weight; 3. Life rope.

The senior Ama dive head up though they sometimes dive head down. Just after their arrival at the surface, they breathe with a characteristic whistle, which the Ama believe is very effective for regaining their breath.

CONCLUSIONS

The harvest, seasons, and diving patterns of the Ama of Japan have been described. However, as was discussed in the introduction of this paper, it is very difficult to express the general features of the Ama, since these depend on the local circumstances.

As for the diving ability of the Ama, their cardio-respiratory functions, hematological characters, etc. are very similar to that of the ordinary Japanese women. In any case, they are healthy women. Of course, even women who live in Ama regions do not become Ama, or drop out of the group, if they are not qualified because of weakness or sickness. Thus, it is undeniable that there is a certain selection.

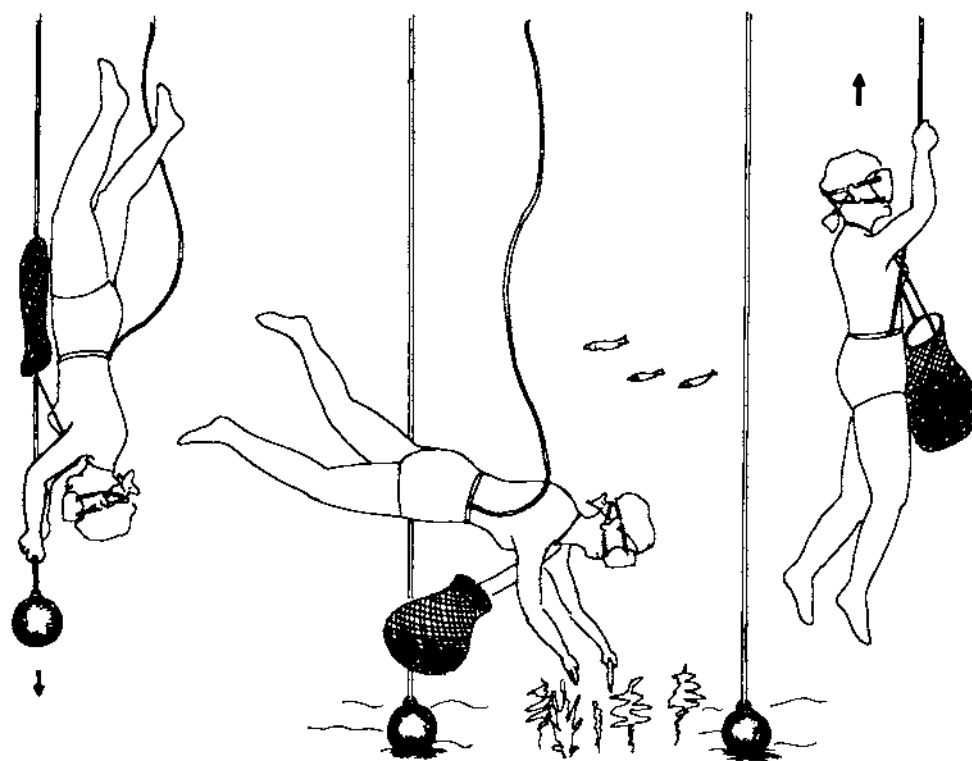


Figure 6. Deep Diving.

The most important attribute of the best Ama is not necessarily good health. It is the perseverance to continue diving exercises for many years, the mental power to continue patiently breath holding and to increase the skillfulness of their respiratory control.

A single dive is quite short (at most about one minute, even with senior class Ama). For the repeated diving which they do it is more advantageous to dive frequently for short periods. If they dive too long at one time, it is difficult to dive again immediately and they are obliged to rest for a relatively longer time to recover from fatigue and to compensate the respiration.

However, diving time, frequency, resting time and other activities are principally determined by the physical condition of the Ama and by other environmental conditions. The job of the Ama may be regarded as an independent, self-employed laborer as opposed to the employed laborer of a factory.

Further study on the breathing efficiency of the Ama may be one of the very interesting future problems in the physiology of respiration.

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GEOGRAPHIC DISTRIBUTION OF AMA IN JAPAN

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During their long history and migration the Ama of Japan have settled in various areas along the coast. In each locality they adapted their techniques to the local conditions of harvest and physical features of the seashore. It is, therefore, not surprising that the local customs, diving techniques, and diving patterns vary from place to place, which makes generalization difficult.

Before discussing the geographic distribution it is therefore helpful to provide a general scheme of classification of the Ama according to the kind of harvest and, secondly, according to the harvesting method, and then to describe their typical diving pattern and work schedule.

Classification Based on the Kinds of Harvests

- A. Kusa-ama collecting raw materials for agar-agar (kusa denotes grass or, more specifically here, marine plant). The more important marine plants for making agar-agar are tengusa (agar-agar plant; Gelidium amansii, G. pacificum, G. linoides), hirakusa (G. subcostatum), onikusa (G. japonicum), dorakusa (Perocladia capillacea), toriashi (Acanthopeltis japonicum), ego (Ceramium hypnaeoides).
- B. Kai-ama collecting shellfish sold as the more precious sea food (kai denotes shellfish). Main harvests are awabi (abalone; Haliotis gigantea), sazae (top shell). Some other marine products such as uni (sea urchin; Echinoidea), namako (sea cucumber; Holothuroidea), and igai (sea mussel; Mytilus erassitesta) are also harvested by kai-ama.

Classification Based on Harvesting Methods

- A. Taru-ama (miscellaneously called ita-ama, oka-ama, cachido, isodo, etc.) consisting of two sub-types:
- A1. Okedo who go to the fishing ground in groups by boats.
- A2. Eijin who go to the fishing ground from coast by swimming.
- In these two cases, taru-ama dives down to the sea bottom supported by a wooden floating cask called taru.
- B. Giri-ama (miscellaneously called oki-ama, funado, hon-ama, etc.) consisting of two sub-types:
- B1. Hitotsu-moguri-ama (hitokashira-ama, ippa-kalsugi, etc.) taking a rest on a boat after each dive.

TABLE I

Diving Patterns and Work Schedule of Ama

	Taru-ama (Cachido)	Giri-ama (Funado)
Breath-holding time during dive	45-120 seconds	60-120 seconds (ippa-kalsugi, 240 sec)
time for descent	variable	10-15 seconds
time for ascent	variable	8-13 seconds
time for harvest, bottom time	variable	30-60 seconds
Depth of the sea bottom	3-10 meters	10-27 meters
Number of dives per day	variable	105-150 times (3 or more shifts or work units)
Working hours for harvesting per day	6 hours (10 hours when busy)	6 hours (10 hours when busy)
Time schedule of harvesting work	irregular	Ama rest in the water on the side of a boat for 45-80 seconds, after each dive of 45-80 seconds. After one work shift of 1-2 hours, Ama warm themselves by fire on the boat or on the beach. One shift (<u>hitoori or ikkai</u>) = 35 dives for 1-2 hours. Harvest work consists of 3 daily shifts but in midsummer may perform 150 dives per day
Age of Ama (see Table II)	15-75 years old	17-50 years old

58

Table I (cont'd)

Tools	<u>Taru</u> casks as floats and for storing harvests. <u>Sukari</u> or <u>tamari</u> nets for storing harvests. Diving goggles.	Boats with or without power, less than 3 tons. Anchor made of iron. Rope (<u>inochizuna</u> or life rope) for pulling up Ama from sea bottom. Diving goggles. Firewood for heating. <u>Sukari</u> or <u>tamari</u> . <u>Isogane</u> or <u>awabi-okoshi</u> for catching <u>awabi</u> (ear shell or abalone)
Dress	Juban (kimono-like Japanese diving wear, similar to a slip). Diving drawers. <u>Koshimaki</u> (Japanese loincloth).	Same as Taru-ama.
Partner	None	Husband or father
Per-day productivity	5-70 kg (<u>tengusa</u>). Mean - 16 kg.	50-240 kg (<u>tengusa</u>). Mean = 80 kg in Izu, 30 in Shima. In case of ear shell, 26 kg. In Izu, 15-58 kg in Shima. In Yamaguchi Pref, 56 kg of ear shell and top shell.
Harvesting season and working days	From end of April to end of October, 72-75 days in total for Izu and 150 days for Shima.	Same as Taru-ama.
Seasonal arrangement of other occupations	There are no significant differences between Taru-ama and Giri-ama.	
in winter	Harvest of lavel (<u>iwanori</u>) and vegetables; seeding of wheat and barley; manuring; treading of young wheat plants to check early growth in winter; collecting of firewood in mountains; making straw bags for packing; charcoal making; flower growing.	

Table I (cont'd)

in spring	Cutting of <u>wakame</u> (seaweed), then dried in open field; vegetable seeding; transplanting of rice sprouts.
in summer	Harvest of wheat and barley; transplanting of rice sprouts and sweet-potato sprouts; weeding of paddy fields; vegetable seeding, harvest of agar-agar plants, ear shell and top shell by diving.
in autumn	Harvest and threshing of rice; vine cutting of sweet potato; harvest of garden peas which are famous as a truck farming product.
all the year around	Household affairs; feeding of small animals such as hens and pigs.

TABLE II

Age Distribution of Ama in Different Areas

	-20	21-30	31-40	41-50	51-60	61-70
	(percent)	(percent)	(percent)	(percent)	(percent)	(percent)
Fuseda (1964)	0	1	16	31	45	7
Goza (1964)	1	2	24	33	35	5
Shima (1936)	19	31	24	15	8	3

B2. Hyaku-moguri-ama taking a rest on a boat after many divings. In summer, divings are repeated even for two hours before taking a rest on a small boat.

C. Mensen. Since the simple diving apparatus was introduced, some giri-ama began using this, and are called mensen.

In these cases, both Ama and her husband or father work together.

Geographic Distribution

There have been no special censuses concerning the population of Ama in Japan. Numbers of both full-time and part-time Ama depending mainly upon maritime products, however, are estimated to be not so large. Rather, most of the Ama are spare-time divers. So in the census, these Ama are classified as agricultural or unemployed in terms of occupation. Therefore, exact population of Ama cannot be obtained. The writer, however, attempts to estimate the number of Ama including part-time and spare-time ones as shown in Table III.

TABLE III

Total Estimated Population of Ama in Japan

Year	Ama (women divers)	Kaishi (men divers)
1921	12,913	11,744 (data by Chiba Pref Off)
1934	10,128	7,499 (data by Mr. Nishi)
1938	10,002	6,777 (data by Mr. Tokuhisa)
1949	15,000	6,500 (est. by the author)
1963	7,000	6,000 (est. by the author)

Distribution of Ama extends along the Pacific coasts from Chiba Prefecture to Ôita Prefecture and also along the coasts of the Japan Sea from the Oga Peninsula in Akita Prefecture to the many scattered islands of Nagasaki Prefecture in Kyûshû. Of these, the Pacific-facing coastal belt stretching from the Bôsô Peninsula in Chiba Prefecture to Tokushima Prefecture in eastern Shikoku shows the densest concentration of Ama in the general distribution pattern, together with two major areas on the Japan Sea side, i. e., from the Noto Peninsula in Ishikawa Prefecture to the Yosano Peninsula, Kyôto Prefecture and from the northwestern part of Yamaguchi Prefecture to the Islands of Nagasaki Prefecture. Even in Iwate Prefecture, northeastern Tôhoku District facing the Oyashio, there are two Ama villages isolated from all other Ama villages of Japan.

It is a remarkable feature that no Ama areas are distributed in southern Kyūshū, Setouchi Inland Sea area, Hokkaidō, northern tip of Honshū, coastal regions from southern Iwate Prefecture to northern Chiba Prefecture, and the Izu Islands south of Tōkyō which are quite noted for its abundance of marine plants. As mentioned above, the spotted distribution of Ama villages in Iwate Prefecture is very interesting.

TABLE IV
 Core Areas or Villages of Ama Concentration

	Population of Ama			number of villages
	before WW II	after WW II	today	
1. Shima Peninsula, esp. its rocky coasts and the four small islands facing the ocean.	5,500	6,500	4,000	31
2. Izu Pen., esp. southern rocky coast	800	1,100	1,000	25
3. Southern Bōsō Pen. esp. southern rocky coast	3,000	2,000	1,000	36
4. Echizen rocky coasts from Oshima to Kinosaki-ura in Fukui Pref.	1,900	?	?	?
5. Hekura Island and Wajima, Ishikawa Pref.	350	?	?	2
6. Kanegasaki, Fukuoka Pref.	130	?	?	1
7. Ōura, Yamaguchi Pref.	130	?	?	1
8. Sodeshi, Kyōto Pref.	60	?	?	1
9. Abu and Shiwaki, Tokushima Pref.	107	?	?	5
10. Saganoseki, Ōita Pref.	60	?	?	1

Except for the Peninsulas of Shima and Izu, it is almost impossible to describe the distribution of Giri-ama (Funado) and Taru-ama, because of the absence of data. In the Shima Peninsula, Funado are concentrated on the southern rocky coasts facing the Pacific, and Cachido are concentrated on the islands and rocky coasts at the mouth of Ise Bay. Most of the Ama in Hekura Island and the Wajima in Ishikawa Prefecture are classified as Kai-ama which belong in this case to the Funado (Giri-ama). On the Izu Peninsula, the core area of Giri-ama is largely determined by the distribution pattern of tengusa, the most useful marine plant for making agar-agar. Many Taru-ama are also found on the central and southern rocky coasts of this Peninsula.

The place of origin of the diving Ama in Japan is not known, but two or three places have been suggested. Many ethnologists presume that at least some of the Kanegasaki Ama group in northern Kyūshū drifted in small boats down from the Cheju (Saishū) Island in southern Korea on the Tsushima Current and settled in the Kanegasaki area a long time ago. Some of them are thought to have migrated there intentionally. Ama of Shima in Mie Prefecture and those of Kada, Wakayama Prefecture, both on the Pacific side are presumed to be of different origin.

One reason for the recognition of the difference in origin between these two groups of Ama is indicated by their diving wear. Ama of the Kanegasaki group generally wear a saiji, which is quite similar to a man's loincloth, whereas Ama of the Shima group put on a koshimaki, a kind of petticoat. Since the end of Taishō era (1926), many Ama began wearing a juban, which is similar to a slip or undershirt, with diving trunks. Ama of Wajima near the top of the Noto Peninsula dive with a saiji (a kind of loincloth) even at present.

In the Meiji era (1867-1912), there were Ama migrations from Shima to the Japan Sea coasts as seasonal divers. In early Shōwa era (1926-), Korean Ama undertook successive migrations both to the Korean Peninsula and to the coastal villages of Honshū facing the Japan Sea from the Cheju Island which is the largest concentration center of Ama in the Far East.

Factors Affecting the Geographical Distribution of Ama

These factors can be broadly divided into physical and socio-economic ones. Physical factors include:

1. Enrichment patterns of marine plants caused by topographic eddy systems and back eddy systems.
2. Optimum water temperature ranging from 10°C in winter to 26°C in summer.
3. Absence of large river mouths on the coast which lower the salinity.
4. High transparency and the absence of water pollution. Coastal industrial development is not welcome to Ama diving.
5. A large area of shallow sea bottom not deeper than 30 meters.

6. Presence of rugged, rocky sea bottoms.

As to human factors, traditional customs held by practically all people in Ama villages are conspicuous, since they have produced specific patterns in the communities concerned. Among these is the custom of honko, under which the heads of Ama households possess a special right in the use of common lands and common fishing grounds. They also control to a large degree harvesting days, harvesting methods, and the sale of products. In some communities, even the profits from marine products are shared only among honko.

Harvest season of marine products is limited to the warm season. Moreover, the amount of products is usually unstable, since bad harvests are quite likely due to the periodic changes of marine conditions. To overcome these handicaps and by attempting better use of labor in off seasons, agriculture plays an important role in their livelihood, although it is of more or less subsistence type on a small scale.

Another economic factor affecting the distribution of Japanese Ama is the overwhelmingly general distribution of patchy arable lands on the rocky coasts. Size of these arable lands per household ranges only from one-quarter of an acre to one acre. The arable lands are usually distributed on abrasion platforms, upheaved marine terraces, or valley bottoms along small rivers. Some are found on steep mountain slopes as terraced fields, however. Though small in size and operation, the Ama households are supported by combination of diving, fishing, and farming. The author calls this type the Shirahama-type farming household. (Shirahama is a fishing-farming village on the southeastern coast of the Izu Peninsula.)

Recent Trends

Ama, diving women, are to be divided into three types based on their harvesting methods, i. e., Taru-ama, Giri-ama, and Ama with a simple diving apparatus. Per-day productivity of seaweed harvests by types is as follows: Taru-ama 1; Giri-ama 5; Ama with a simple diving apparatus 24, if that of Taru-ama is rated to be 1. In the case of shellfish catching, productivity of Ama with a simple diving apparatus is evaluated to be 10-20, when that of Giri-ama is evaluated as 1.

In 1951, modern diving apparatus was introduced. This is the simple diving apparatus which covers the head of a diver only. With this apparatus which has an air pipe from the boat, some Mensen are now able to dive for a much longer time than Tau-ama and Giri-ama thus raising efficiency to a considerable degree. In recent years, however, many young girls who would have otherwise become Ama have now been engaged in other occupations than fishing as a result of rapid urbanization and the growing tourist industry. Consequently, the population of Ama has been decreasing, resulting in a smaller number of younger Ama, especially in resort areas such as Izu, Bôsô or Shima.



Figure 1. Distribution of the Japanese Ama.

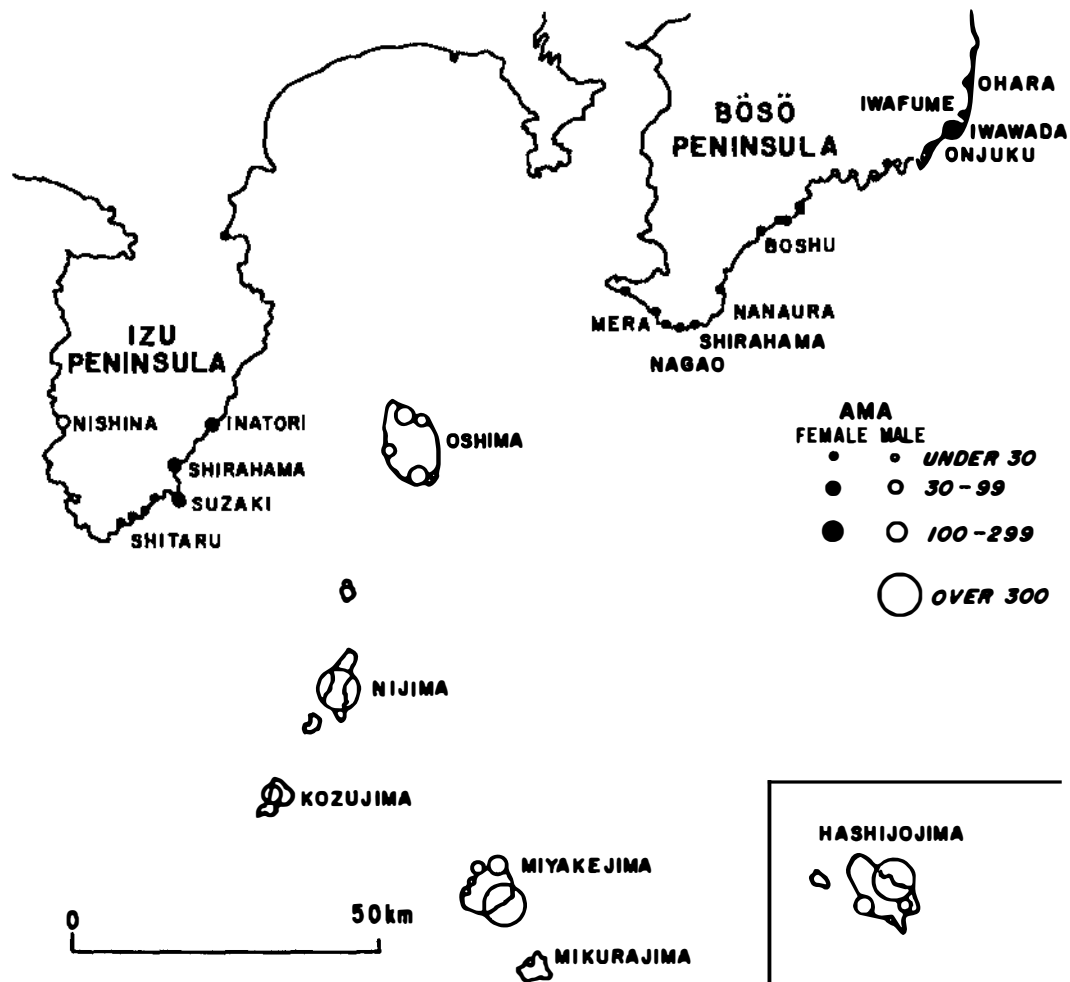


Figure 2. Distribution of Ama in Southern Kanto and Izu Province.

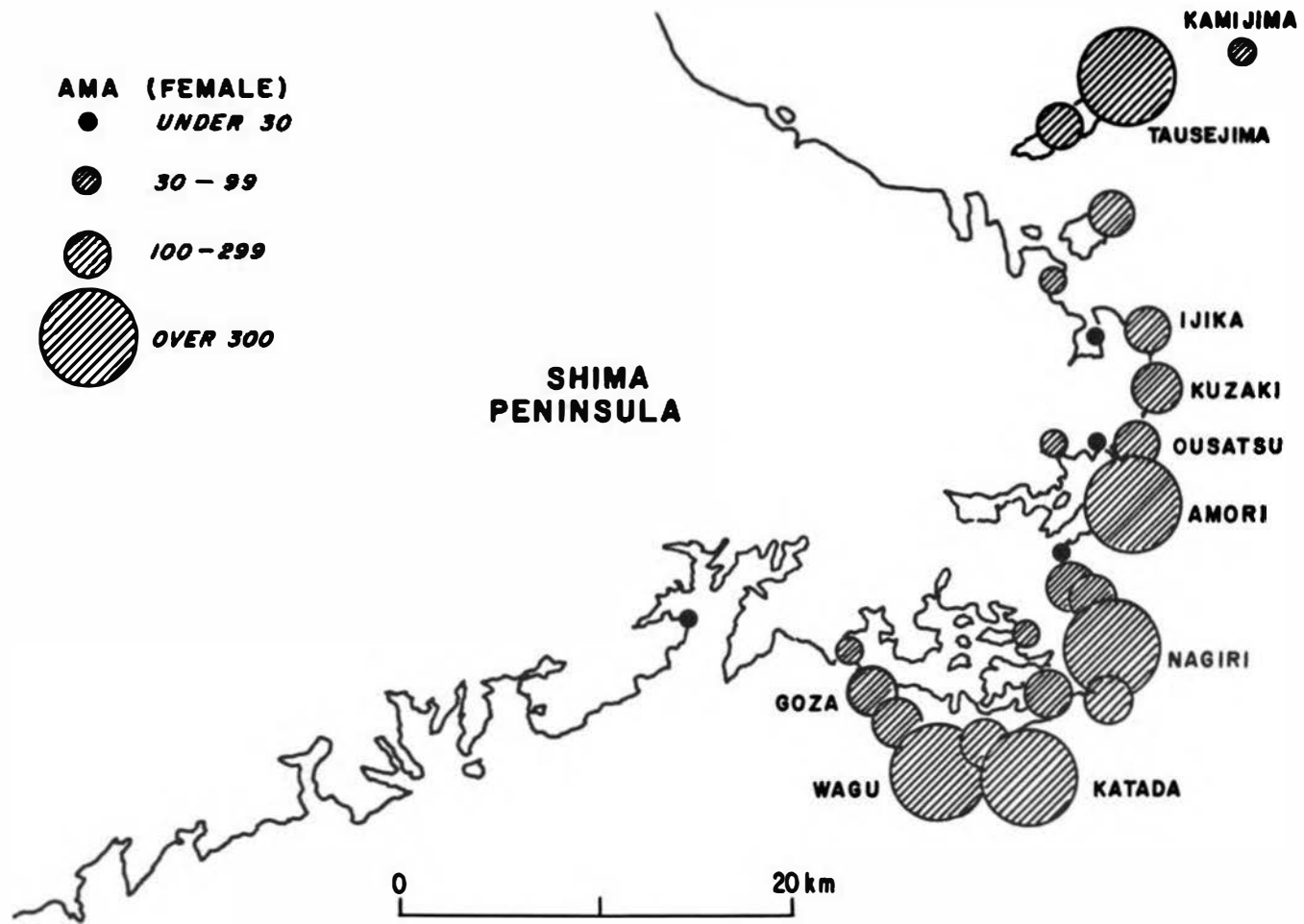


Figure 3. Distribution of Ama in Shima Province.

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ANTHROPOMETRIC STUDIES ON THE JAPANESE AMA

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More than thirty years have passed since Teruoka and his collaborators made their first studies on the physiological attributes of female fishing divers or Ama in Japan. Since then, several anthropometric studies have been added. During the past thirty-five years, Japan has undergone a tremendous social and industrial change, which inevitably affected the development of the physical standards among Japanese people. When discussing the anthropometric data one has to consider the general trend of their physical development during this lapse of time. During the first decade, from 1930 to 1940, the body size was gradually increased. During World War II and the few years immediately thereafter, however, this trend stopped or even reversed. In the past ten years, it is again increasing steadily, presumably because of the nutritional improvement. Keeping this trend in mind, we will review the studies on the Ama including the results which we have obtained recently.

In 1961 Nukada⁽⁴⁾ made a map which indicated the distribution of male and female Ama all over Japan. On the map, which was modified here in Figure 1, the authors have indicated three places, where the anthropometric studies were done, viz., Shima, Abu, and Boso. Shima is a peninsula located in the middle of Honshu Island. Abu is located on Shikoku Island which lies on the Inland Sea with the main island (Honshu) at the southwest of Japan. Boso is close to Tokyo, the capital of Japan, located at the eastern part of Honshu.

I. STUDIES ON AMA IN SHIMA

The location has been indicated on the map (Fig. 1). The harvest season for shellfish is regularly from April through October, but sometimes starts in March and continues to November. The first anthropometric study on Shima-ama was reported by Ogawa⁽⁵⁾ in 1929. In the report the physical characteristics of the Shima-ama were compared with those of the female textile workers. The results are summarized in Table I. Although the statistical significance was not expressed in this report, he concluded that height, weight, sitting height, chest circumference, leg length, and vital capacity were greater in Ama compared with the textile women, but shoulder- and hip-width did not reveal any differences. Since the vital capacity is proportional to the body heights, the ratio of vital capacity to the body height was taken as a parameter. The parameter in the Ama was also significantly larger than that of the textile workers. The vital capacity

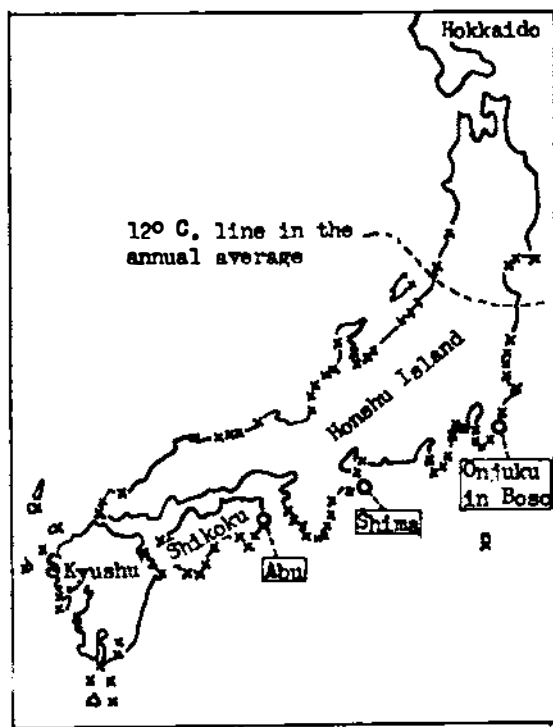


Figure 1. The distribution of skin divers (male and female Ama) in Japan as shown by the crosses. The circles mark the three places which served as a basis for the anthropometric studies reported in this review. (Modified from Nukada(4).)

of Ama was even larger than that of the average Japanese female inhabitants at the age of 20-49 years, whose vital capacity is a little larger than that of the textile women(3).

The second report on Shima-ama by Yamamoto(17) appeared in 1936. He measured weight, height, and chest circumference in 1012 Ama and 1003 non-Ama in the wide age distribution from 15 to 60 years. The mean values are tabulated in Table II, and divided into five age groups. All the values appeared to be larger in Ama than those in non-Ama.

The third anthropometric study was made by Tatai(11) in 1957, particularly as concerns the ventilatory capacities. The values obtained from Ama were compared with those obtained from nurses and telephone operators. The Ama group was physically most active, while the third group was most sedentary. The results are shown in Table III, divided into three occupational groups and two age groups. The air velocity index of Gaensler(2) is a function of airway resistance. As to vital capacity, maximal breathing capacity, respiratory rate during

MBC, as well as air velocity index, the difference between all three groups was statistically significant with $P < .01$, excepting vital capacity between nurses and telephone operators. Thus, here again, the greater ventilatory functions of the Ama were observed.

II. STUDIES ON AMA AT ABU

Abu is a small village located in Shikoku Island. The harvest time is allegedly from May to October. At Abu there live both male and female Ama. There, Oka et al(6, 7) made extensive studies in 1952 and reported a comparison of physical characteristics between male and female Ama as well as between Ama and non-Ama living in the same village. The results are shown in Table IV. Unfortunately the age distribution of the population was not mentioned. Both in male and female Ama the chest circumference, vital capacity, grip strength, and weight were greater than in non-Ama, while no difference was noted in chest expansion, back muscle strength, and resting pulse rate. The statistical significance

TABLE I

Physical Characteristics of Shima-Ama in Comparison
 with Textile Workwomen in 1929. From Ogawa(5).

	Ama		Textile Workwomen	
	No.	$\bar{m} \pm S. D.$	No.	$\bar{m} \pm S. D.$
Height, cm	154	151.5±4.18	411	146.5±2.52
Weight, kg	"	50.7±4.99	"	45.3±4.87
Sitting height, cm	"	84.0±2.27	"	81.5±2.58
Chest circum, cm	"	83.9±3.28	"	80.0±3.70
Shoulder width, cm	"	32.9±1.39	"	33.0±1.39
Hip width, cm	"	25.1±1.56	"	26.9±1.29
Leg height, cm	"	67.3±3.45	"	64.9±3.58
Vital capacity, l/m	190	2.67±0.423	107	1.91±0.264

TABLE II

Body Characteristics by Age of Shima-Ama and
 Non-Ama in 1936. From Yamamoto(17).

Age, years	No. subjects	Weight, kg	Height, cm	Chest circum. cm
AMA				
15-20	158	47.8	147.6	81.7
21-30	274	51.4	150.2	85.6
31-40	298	51.0	149.3	85.0
41-50	219	50.6	149.6	84.8
51-60	63	49.7	148.2	80.9
NON-AMA*				
15-20	239	46.5	146.9	77.5
21-30	214	47.9	147.7	81.6
31-40	185	47.3	146.1	81.2
41-50	201	46.0	145.1	80.5
51-60	164	43.6	144.3	76.6

*764 women in general and 239 working women.

TABLE III

Comparison of Various Measurements in Three Different Occupational Groups and Two Age Ranges. From Tatai(11).

	Ama		Nurses		Telephone operators	
	20-29	30-39	20-29	30-39	20-29	30-39
Age, years	20-29	30-39	20-29	30-39	20-29	30-39
No. subjects	23	12	161	105	53	31
Height, m	1.52	1.54	1.51	1.52	1.52	1.52
Weight, kg	54.4	54.9	49.1	51.0	47.2	49.2
Body surface area, m ²	1.51	1.53	1.44	1.47	1.42	1.45
Vital capacity, l/m	1.85±.021	1.88±.021	1.76±.020	1.68±.021	1.71±.029	1.68±.036
Max. breath. capacity, l/min/m ²	67.6±2.39	67.0±2.75	54.3±.932	47.5±.991	45.4±1.53	37.4±1.41
Max. breath. rate, /min	36.5±1.26	35.7±1.44	29.5±.525	27.1±.571	25.0±.369	21.7±.733
Air velocity index	1.24±.046	1.27±.054	1.08±.022	1.01±.021	.91±.034	.80±.035

Mean or mean ± S. E.

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TABLE IV
Physical Characteristics of Abu-Ama.
Mean Values. From Oka(6).

	Men		Women	
	Ama	Non-Ama	Ama	Non-Ama
No. subjects	44	72	34	46
Weight/height, kg/m	33.8	32.8	33.4	31.9*
Sitting height/height, cm/m	54.0	53.7	54.9	54.4
Chest circum/height, cm/m	53.3	51.9*	54.4	53.4
Chest expansion/height, cm/m	3.1	3.4	3.1	3.1
Vital capacity/height, ml/cm	23.2	22.1	18.0	16.5*
Vital capacity/weight, ml/kg	69.1	67.3	53.7	51.5
Grip strength (aver 1+r), kg	42.0	40.5**	29.6	27.5**
Back muscle strength/height, kg/m	85	85	58	55
Pulse rate at rest, min	78.3	74.2	81.4	83.0
Syst blood pressure, mmHg	123.6	126.6	118.9	126.4*
Diast blood pressure mmHg	76.5	72.0*	74.9	74.7
Mean blood pressure, mmHg	100.0	101.4	96.8	99.8
Pulse pressure	47.0	54.4*	44.0	51.8**

*P < .05.
 **P < .01.

or P-value was added to the table. These observers concluded that the male Ama were better fit for diving activities than the female Ama because of their larger vital capacity, back muscle strength, and grip strength(6). In their later report(7) they further observed a longer breath-holding time in female Ama than in female non-Ama and higher maximal inspiratory and expiratory pressures in Ama than in non-Ama of either sex.

III. STUDIES ON AMA IN BOSO

The Peninsula of Chiba which is a neighboring prefecture of Tokyo is commonly called Boso Peninsula. Along the eastern shore of the Boso Peninsula, directly facing the Pacific Ocean, there are a number of small villages of male and female Ama.

In 1951 Shibuya and Sukegawa⁽⁸⁾ made a gynecological and anthropometric study on female Ama in one village called Onjuku, and the results were reported in 1953. The number of subjects was 51 and the age was distributed from 18 to 40 years. The anthropometric results are given in Table V. The superior physical development, especially of their body size, of the Ama compared with the farmers or of the female office workers was observed. On the basis of their measurements they made a unique conclusion, viz., that the Ama's vital capacity was excellent although their muscular strength was poorer than that of the farmers or the female office workers. However, it should be remembered that, at the time of their study, the physical development was still largely influenced by the poor socio-economic conditions during and after the war and, therefore, it might be better to reserve judgment on the physical characteristics. It is obviously desirable to repeat these particular studies on the Ama and for this purpose, the present authors repeated an extensive anthropometric study in the same village. This study was done in September of 1964 and is briefly reported here. The details will be given elsewhere⁽¹⁵⁾.

In this study it was desired to make a comparison of the Ama with that of the average female in the same community and similar economic conditions. Fortunately it was possible to pick a group of farmers living in the same village. The number of farmers was slightly less than that of Ama but their age distribution was similar.

The results are tabulated in Tables VI and VII. Most of the data are presented by the mean values \pm S. E. except for the skin-fold thickness and blood pressure, which are presented by their mean values and range. The body weight and height, the sitting height, and the chest or the upper arm circumference were definitely greater in the Ama, although there was no difference in the lower thigh.

The muscular power, which was represented by the grip strength and by the back muscle strength, was definitely stronger in the Ama than those in the farmers. Especially the superiority of the back muscle strength was remarkable. There was also significant difference in the diastolic blood pressure, the pulse rate, and the breath-holding time. In the Ama the pulse rate was lower and their diastolic blood pressure higher than in the farmers, suggesting a difference in their autonomic adjustment. The difference of the breath-holding time was significant, but smaller than expected.

As for the ventilatory function tests, the authors used a modified Collins respirometer. As expected from other reports, the vital capacity and the maximum breathing capacity were definitely larger in the Ama than in the farmers. Although the vital capacity was larger, the time required for the maximal expiration was significantly shorter. The average air velocity index was similar in both groups. Thus, the greater respiratory capacity as seen in the vital capacity and the maximal breathing capacity of the Ama seems to be related to her greater muscular power. There was no significant difference in the tidal volume or in the expiratory reserve volume between two groups. However, the inspiratory reserve volume was definitely larger in the Ama as has been reported in Korean Ama by Song et al⁽⁹⁾ and probably accounts for the greater vital capacity.

TABLE V
Physical Characteristics of Onjuku-Ama in 1951(8)

Age, years	18-40
No. subjects	51
Height, cm	151.9 ± .74
Weight, kg	50.4 ± .94
Chest circum, cm	83.3 ± .66
Sitting height, cm	84.4 ± .47
Upper arm circum, aver, cm	24.4 ± .24
Grip strength, sum, kg	52.4 ± 1.15
Back muscle strength, kg	80.4 ± 2.84
Vital capacity, ml	2832 ± 58.8
Shoulder width, cm	34.7 ± .24
Hip width, cm	28.9 ± .16
Hip circum, cm	78.8 ± .81
External conjugation, cm	18.7 ± .09
Cristal distance, cm	26.1 ± .20
Spinal distance, cm	24.1 ± .19
Syst. blood pressure, mmHg	113 ± 1.41
Diast blood pressure, mmHg	63 ± 1.35
Pulse rate, min	67 ± 1.32

TABLE VI
 Physical Characteristics of Onjuku-Ama in 1964(15)¹⁾

	Ama	Farmers
Number of subjects	76	49
Age, years	34	36
Height, cm	154.0±.549	149.7±.980*
Weight, kg	54.1±.899	47.0±.697*
Surface area, m ²	1.52±.015	1.41±.015*
Chest circum, cm	86.4±.863	81.2±.745*
Sitting height, cm	84.9±.322	82.4±.390*
Upper arm circum, cm, r	26.3±.322	24.6±.223*
Upper arm circum, cm, l	25.9±.337	24.1±.218*
Skin fold thickness, mm ²) ²⁾		
Upper arm	31.5(31.3-31.6)	28.9(28.8-29.0)*
Side abdomen	24.3(24.2-24.5)	20.0(19.8-20.1)*
Lower thigh	26.5(26.4-26.7)	27.0(26.9-27.2)
Grip strength, kg ²⁾	59.1±.974	52.5±1.47*
Back muscle strength, kg	99.5±2.06	83.8±2.78*
Blood pressure, mmHg ³⁾		
Syst.	113.3(112.0-114.5)	114(112.0-116.0)
Diast.	67.8(66.7-68.9)	60.0(57.8-62.2)*
Resting pulse rate, min	67.6±1.08	73.6±1.83*
Breath-holding time, sec	39.0±1.87	37.1±2.09*
Vital capacity, l/m ²	1.79±.039	1.54±.027*
Time for max expir, sec	3.30±.125	3.80±.195**
Max breath cap, l/min/m ²	62.4±1.88	53.7±1.52*
Insp reserve vol, l/m ²	.798±.028	.562±.007*
Tidal vol, l/m ²	.366±.015	.368±.020
Exp reserve vol, l/m ²	.621±.025	.610±.029
Air velocity index	1.25	1.25

1) Values are mostly tabulated by mean ± S. E.

2) Sum of right and left sides.

3) Logarithmic treatment.

* P < .01.

** P < .05.

TABLE VII

Age Difference of Ventilatory Volumes in Ama and Farmer at Onjuku⁽¹⁵⁾, Presented by Mean \pm S. E.

Age, years	20-29	30-39	40-49
<u>Ama</u>			
No. subjects	14	45	17
Vital capacity, l/m	1.92 \pm .010	1.80 \pm .039	1.62 \pm .085
Time for max expir, sec	2.88 \pm .267	3.40 \pm .168	3.39 \pm .254
Insp reserve vol, l/m	.897 \pm .070	.797 \pm .034	.715 \pm .056
Tidal vol, l/m	.364 \pm .040	.370 \pm .031	.359 \pm .037
Expir reserve vol, l/m	.664 \pm .064	.635 \pm .032	.548 \pm .052
Max breath capacity, l/min/m ²	70.3 \pm 4.54	61.8 \pm 2.13	48.0 \pm .76
<u>Farmers</u>			
No. subjects	13	21	15
Vital capacity, l/m	1.61 \pm .046	1.56 \pm .054	1.44 \pm .047
Time for max expir, sec	3.50 \pm .255	4.08 \pm .375	3.67 \pm .289
Insp reserve vol, l/m	.522 \pm .022	.604 \pm .014	.510 \pm .015
Tidal vol, l/m	.370 \pm .033	.360 \pm .037	.338 \pm .027
Exp reserve vol, l/m	.690 \pm .056	.586 \pm .042	.573 \pm .055
Max breath capacity, l/min/m ²	60.9 \pm 1.79	52.6 \pm 2.59	49.5 \pm 2.86

With regard to the greater maximal breathing capacity, one of us suggested that this may be due to a decrease in the air-way resistance or an increase in the muscular strength⁽¹¹⁾. On the basis of the ventilatory function studies done at Onjuku, we are now inclined to regard the increase in muscular strength as a primary cause of the larger maximum breathing capacity of the Ama.

The thicker skin fold in the Ama seems to have some advantage with their cold adaptation during diving, as Rennie *et al*⁽¹⁰⁾ have already pointed out in connection with their studies on the Korean Ama. We made measurements of the Ama's skin-fold thickness and tentatively correlated it with their reported daily frequency of diving. The correlation coefficient between the thickness and the diving frequency was significantly positive ($r = .435$). The results will be reported elsewhere⁽¹⁶⁾.

Table VII shows the age difference of the ventilatory capacities between the Ama and the farmers. There is a clear decrease in the ventilatory capacity with age in both Ama and farmers⁽¹¹⁾. However, the decrement appears to be

less marked in the Ama, presumably because she has to rely more upon the ventilatory capacity in her daily activities than the farmer. Table VIII shows the effect of age upon various physical characteristics of Japanese women obtained in a national survey.

TABLE VIII

Physical Characteristics, by Age, of Japanese Women Obtained
During the National Nutritional Survey in 1963 (Mean Values).

Age, years	21-25	26-29	30-39	40-49
Height, cm	152.7	151.7	150.9	149.5
Weight, kg	49.2	49.3	50.1	50.5
Chest circum, cm	81.6	82.3	82.0	82.5
Sitting height, cm	84.0	83.8	83.8	83.1
Upper arm circum, cm	24.1	24.4	25.0	25.4

IV. GENERAL COMMENTS

During the past 35 years, several anthropometric studies of the Ama have been done in three places of Japan, viz., in Shima, Abu and Boso. Ogawa⁽⁵⁾ concluded in 1929 that the physique of the Ama was far better than that of the female textile worker (Table I). However, the vital capacity in the Ama was even larger than that of the ordinary inhabitants at that time⁽³⁾. Seven years after this paper appeared, Yamamoto⁽¹⁷⁾ made a similar survey on a large scale in Shima. He only measured the height, body weight, and chest circumference. But all three values were greater in the Ama (Table II). These two studies were done before World War II. After the war, Shibuya and Sukegawa made their study on Ama in Boso in 1951⁽⁸⁾. Then, Oka et al did their studies on both the male and the female Ama in Abu in 1952^(6, 7). In 1956 Tатаi studied the pulmonary functions on the Ama of Shima⁽¹¹⁾. Nukada in his scientific essay on the Ama presented his own observations on the physique of the Ama⁽⁴⁾. Most recently, Tатаi et al^(15, 16) studied the Ama in Boso again in 1964. All these studies are primarily concerned with the anthropometry of Japanese.

The evaluation of results, such as shown in Tables IV and V, which were obtained in 1951 and 1952 must take into consideration the deprivation of the war and post war periods.

Generally speaking, the skin divers have larger vital capacity⁽¹⁾ and of particular interest is the fact that the Funado revealed the largest vital capacity among all kinds of Ama⁽⁴⁾. This larger vital capacity may be considered as one of their occupational adaptations. The Ama makes many dives a day, each time experiencing tremendous change of the ambient pressure and making special respiratory efforts in preparation for breath holding and in the water. This would be the reason why superior respiratory functions were observed among the anthropometric characteristics of the Ama

V. SUMMARY

Several anthropometric studies on the Ama have been done in Japan since 1929. The results of these studies were reviewed in this present manuscript. The Ama, who engages in heavy occupational work, revealed many morphological adaptations to their unique occupational environment. The parameters, such as the height, the body weight, the sitting height, and the chest and the upper arm circumference were found to be best correlated with their profession. However, the most conspicuous feature of the physical characteristics of the Ama was her excellent ventilatory functions. The vital capacity and the maximum breathing capacity were very much larger, presumably due to the greater exercise of the breathing muscles, which play an important part in her professional work.

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OCCUPATIONAL DISEASES OF THE AMA

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Occupational diseases of Amas have not been reported until comparatively recent years in Japan, although Amas started their activities hundreds of years ago. At the first time in the history of occupational health studies of Amas in Japan, G. Teruoka made his investigation of Amas from the viewpoints of respiratory physiology as well as of occupational health including diseases due to their work. He published the first part of his studies in Japanese (1928), in English (1931) and in German (1932), but left the second part unpublished until now. We shall try to supplement our present review of studies on occupational diseases of Amas in Japan with these results by him and Iwasaki, his associate, together with those obtained by us last summer.

Following Teruoka's study of Amas in Shima Peninsula district, Mie Prefecture, which is well known to have various Ama villages along its coast of Ise Gulf but most of them on the shores open to the Pacific Ocean, K. Yamamoto (1936) reported specifically of the ear ailment as one of occupational diseases of Amas in the same district. Later Y. Kataoka (1954) examined the ear and throat conditions of female Amas as well as male ones in Kaibe District, Tokushima Prefecture, where one can find Amas of both sexes. The place is located on the Pacific coast of Shikoku Island. There are a few localities in Japan where both sexes are engaged in breath-hold diving. The most recent study was made by S. Anzai (1960) of the Amas' ecology, physiology and occupational health again in Shima District.

THE REVIEW OF JAPANESE REFERENCES

Before going into the detailed review of studies made by Japanese authors on the occupational diseases of Amas, we may cite from Dr. Teruoka's paper a few important points.

He was concerned about the pressure equalization of the middle ear during diving. It had been previously established in caisson workers that the ear drum could curve inwards during compression and cause congestion and even bleeding but that this was prevented if the pressure increased at a rate of 0.1 atm per 45 seconds

or longer. On the other hand, his own measurements showed that such a change in pressure occurred in 0.7 to 1.0 seconds in one Ama and in 0.69 seconds in another during descent. These observations puzzled him at that time since he did not observe any ear damage. However, they were later noticed by other Japanese workers.

He was also well aware of the fact that the nitrogen in the alveolar gas of Amas dissolved in the blood due to the increased ambient pressure during their dives. But he wrote in his paper that he could not find any confirmed cases of decompression sickness among these Amas. He calculated that Amas stayed at the depth corresponding to about 3.5 atmospheres for about one minute and then they were pulled up to the sea surface at 1 atmosphere within from 13 to 18 seconds. The reason why there was no obvious case of decompression sickness among Amas was, by Dr. Teruoka's consideration, the short duration of the stay at an increased alveolar air pressure and the breath-hold act of the Amas. But he mentioned the necessity of further research for a more satisfactory explanation.

The review of references by Japanese workers published in their mother tongue begins with Yamamoto (1936). He made an examination of the external auditory canal and found in many of the Amas a small tumor, a few to several millimeters in size, on the frontal or posterior wall of the canal. It was described as an elevation of bone covered by the skin on the surface where blood capillaries were seen. It was exostosis and the Amas felt pain when it was pressed. Because of the exostosis in the canal, the ear drum was difficult to observe. The Amas, examined, told the author that they usually dive from 10 to 30 meters and stayed under water for about one minute. They repeated dives of this sort from 60 to 90 times a day. The prevalence of exostosis was almost none in the age group younger than 30, but it was seen in 19 per cent of the age group between 30 and 40, and reached as high as 48 per cent in Amas older than 40 years of age. The author observed that the frequency increased with the age and also with the diving depth (see Table I).

Inward retraction and perforation of the ear drum to different degrees were also observed in some Amas. The author's description was as follows: heavy thickening almost without mobility in the younger group and thin connective fiber tissues sometimes even lacking in superficial epithelium in the older group. The opaque thickening was caused mainly by stimulating effect of high water pressure and it atrophied later. The author believed that these deformities were accelerated by inflammatory processes in the middle ear, because the majority of 120 Amas examined showed partial stricture or stenosis of the Eustachian tube. Regarding hearing loss the author reported that this is apparently greater during the summer months of August and September when they were most actively engaged in their job and that the loss was partially recovered in January and February. The Amas' season of ordinary diving began every year from April and ended in September and they made shallower dives during other months only for a short time per day to collect seaweeds but not any shells. Table I shows the rate of hearing loss in various tone levels during January and February. The rate was understood to be that of the permanent loss of hearing.

In August 1952 the staffs of departments of physiology, ophthalmology and oto-rhino-pharyngo-laryngology, School of Medicine, University of Tokushima,

TABLE I
Per Cent of Permanent Hearing Loss at Various
Frequencies in the Ama vs their Age, from Yamamoto⁽⁷⁾

Age, years	Percentage of Amas who showed hearing loss			
	C	C ^a	C ^b	C ^c
	%	%	%	%
16-20	32	33	27	21
21-30	38	37	28	17
31-40	44	38	33	28
41-50	55	43	42	41
51-60	63	48	45	40
Medium divers (15-25 meters)*	56	43	32	27
Deep divers (up to 35 meters)*	65	55	50	38

*Depth in meters was that which the Ama reported to the author.

made a comprehensive survey of health and activities of Amas in a district of the Prefecture of Tokushima where the medical school is located in the capital. In this district male Amas engaged in breath-hold diving to the greater extent than female Amas, and in one of their reports Y. Oka et al⁽³⁾ indicated that in a village of 1006 inhabitants, 37.5 per cent of the males were engaged in diving and the corresponding percentage for females was 27.3 per cent, the ratios of male to female being 47.5 per cent. to 52.5 per cent.

In order to make an occupational health study here Kataoka⁽²⁾ drew a random sample of male and female divers and examined their ear and throat conditions which were compared with those of the non-divers control group of the population. The results are shown in Table II. There were more abnormal conditions in the ear, nose and throat among male and female Amas than control non-divers. He described these abnormalities to have been caused by irritating effects of sea water itself and sometimes contaminants to these parts of the body. Percentages of examinees with hearing loss are also indicated in Table III with its severity. According to the author the loss resulted from either the opacity and thickening of the drum and otitis media or from the direct effects of high pressure on the internal ear organ. The latter effect had been shown to exist in experiments using guinea pigs, but he could not find any disturbances of the vestibular function among Amas when examined by an appropriate method.

TABLE II
Abnormal Conditions in the Ear, Nose and Throat,
from Kataoka⁽²⁾

Abnormalities	Male and female Amas (79)	Control non-divers (43)
Opacity of ear drum	79 (100%)	22 (50%)
Stenosis of Eustachian tube	27 (34%)	6 (14%)
Otitis media	4 (5%)	1 (2%)
Sinusitis	12 (15%)	1 (2%)
Hyperplastic rhinitis	10 (13%)	2 (5%)
Hyperplastic tonsils	8 (10%)	4 (9%)

TABLE III
Distribution of Severity of Hearing Loss among
Divers and Non-divers, from Kataoka⁽²⁾

Severity	Male and female Amas (74)	Control non-divers (36)
Severe	36 (49%)	10 (28%)
Medium	12 (16%)	5 (14%)
Light or normal	26 (35%)	21 (58%)
Total	74 (100%)	36 (100%)

In a more recent report Anzai⁽¹⁾ took the history of previous ailments and complaints by Amas in villages in the Shima district and tabulated them as shown in Table IV. Among 88 Amas and 86 controls of non-Amas, ear pain, including tinnitus and loss of hearing, were the most frequent complaints by the Amas. There was, however, no significant difference between the two groups in the other items listed.

TABLE IV
Comparison of Previous History of Bodily Ailments
and Complaints between Amas and Non-Amas, from Anzai⁽¹⁾

	Amas (88)		Non-Amas (86)	
		<u>per cent</u>		<u>per cent</u>
Susceptibility to catching cold	15	(6.6)	15	(7.4)
Lung tuberculosis	0		3	(1.5)
Respiratory diseases including asthma, bronchitis, etc.	8	(3.5)	11	(5.4)
Heart diseases	6	(2.6)	7	(3.5)
Rheumatism and neuralgia	35	(15.4)	32	(15.8)
Lumbago	28	(12.3)	25	(12.4)
Otalgia including tinnitus and loss of hearing	45	(19.8)	4	(1.9)
Other ear and throat diseases	13	(5.7)	10	(4.9)
Headache	39	(17.2)	36	(17.8)
Intestinal diseases	22	(9.7)	20	(9.9)
Liver diseases	5	(2.2)	6	(3.0)
Kidney diseases	1	(0.4)	3	(1.5)
Cystitis	0		8	(4.0)
Slight injuries	3	(1.3)	4	(2.0)
Diseases of reproductive organs	0		9	(4.5)
Others	7	(3.1)	9	(4.5)
Total	227	(100.0)	202	(100.0)

Considering all these scientific reports over the past 20 years, occupational diseases of the Ama seem to be restricted to limited body regions, viz., the ear, the nose and the throat; i. e., inflammatory processes and hearing loss. In connection with this fact, it is very interesting to cite from Dr. Teruoka's observations that Amas are peculiarly cautious about their state of health before diving and that they are usually reluctant to work when they have a cold and feel irritation in the throat. This caution must have been gained by their own experiences, and was necessary to prevent further development of slight symptoms into disabling diseases.

As a background for the understanding of the Amas' health conditions Anzai⁽¹⁾ collected the vital statistical data in four Ama villages between 1954-1958 and analyzed them thoroughly. Amas in this report were defined as those who have had a diving experience of more than ten years. From his studies a few important conclusions may be cited here.

Although there was no significant difference in the crude death rate as revealed from Figure 1, between the populations of Ama and non-Ama villages in the same district, it is worth mentioning that the first of the leading causes of death in Ama villages was senility, and the deaths due to the vascular lesions of the central nervous system was the fifth, whereas in non-Ama villages the leading causes of death followed from the vascular lesions of C. N. S. as the first cause exactly in the same way as in the total population of Japan, except that in this district the second cause was senility which is the third leading cause in the total population.

The author believed that the nature of the Amas' work under natural conditions of the sea was the main reason of the low death rate due to the vascular lesions of the C. N. S., although their physical exercise was extreme. However, as he mentioned in his explanations, we have to take into consideration the hereditary factor among Amas who tended to get married to men of the same village.

In connection with the low death rate due to the vascular lesions of C. N. S. in Ama villages the author drew attention to the fact that Ama blood pressure was lower than that of controls and that no Ama was found whose blood pressure exceeded 130 mmHg.

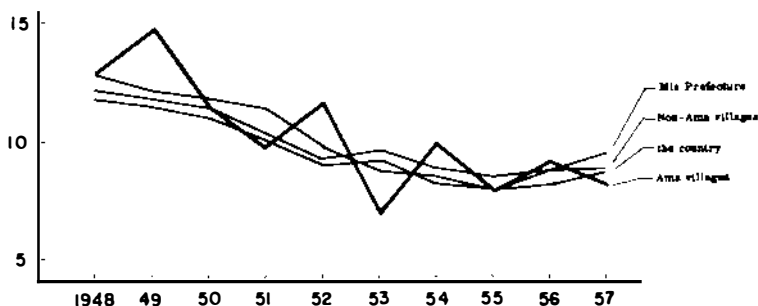


Figure 1. The crude death rate (per 1000) in Ama and non-Ama villages, Mie Prefecture and the country as a whole. From Anzai⁽¹⁾.

He also counted the pulse rate and found an interesting fact in that the distribution of pulse rate suggested two groups of Amas, one group of less than 60 per minute and another of more than 60. This is shown in Figure 2.

Regarding the reproductive function of Amas, the author

reported that 44.6 per cent of them gave premature birth of less than 2.5 kg body weight as compared to 15.8 per cent of non-Ama mothers of the district. The rate of still birth, however was low among Amas.

There was in the Japanese references no definite evidence for Ama cases of paralysis of the respiratory center due to anoxia. It may be difficult now to prove such accidental cases. Furthermore, no Japanese workers have ever reported any symptoms of decompression sickness among Amas.

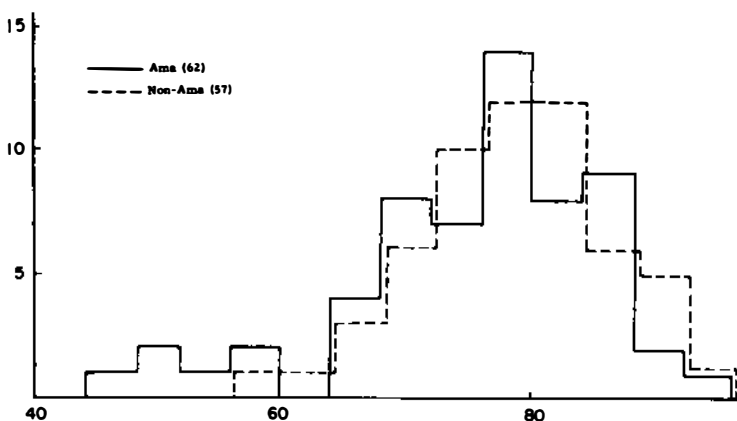


Figure 2. Distribution of pulse rates among Amas and non-Amas. Numbers observed on ordinate, pulse rate in abscissas. From Anzai⁽¹⁾.

OUR SURVEY IN THE SHIMA DISTRICT

Our survey of occupational diseases of Amas was made early in August 1964 at Wagu village where Dr. Teruoka started his study more than 30 years ago and where since then he and one of us (Mrs. Iwasaki) visited repeatedly for continuation of the study. In the present study we took advantage of the fact that Mrs. Iwasaki was well acquainted with the locality, some of the Amas recognized her again and felt familiar with her. The survey consisted of personal interviews with practically all Amas who were available at the village and who were still engaged in deep diving (15-17 m). We added to our own survey some health statistics of the village. These were obtained from the health center of the district.

The number of Amas we interviewed was 22. Ages and years of experience in deep diving ranged from 29 to 59 and from 12 to 43 years respectively. The distribution of both of them is indicated in Table V. Practically all Amas who we interviewed had been engaged as Funados more than ten years. It is interesting that many were borne by mothers who were also Funados.

The main complaints concerning the ear were tinnitus, rupture of ear drums and spontaneous otalgia as shown in Table VI. It is worth while to mention that ear drum ruptures occurred only unilaterally without exception, and that we found in the external ear canal of a few Amas the exostosis which was described first by K. Yamamoto⁽⁷⁾ but was not reported by Y. Kataoka⁽²⁾. The incidence of the exostosis seems to depend on the localities of the Amas. Our survey and Yamamoto's study were done in the same locality of Ise district, whereas Kataoka

TABLE V

Distribution of Ages, Years of Experience and
 Mother's Jobs of Amas Interviewed

A. Ages

Age (years)	No. Amas
29	3
30-39	8
40-49	5
50-59	<u>6</u>
Total	22

B. Years of experience in Ama

Years	Number of Amas		Combined
	Cachido*	Funado**	
1-4	11		
5-9	7	1	
10-14	1	8	1
15-19	0	2	4
20-24	1	2	3
25-29	1	1	4
30-34	0	4	4
35-39	0	2	1
40 and more	0	1	4
not indicated	<u>1</u>	<u>1</u>	<u>1</u>
Total	22	22	22

*Cachido — shallow diver.

**Funado — deep diver.

C. Relationship to mother's job

Mother's job	Number of Amas
Cachido	4
Funado	16
Agriculture	1
Not indicated	<u>1</u>
Total	22

TABLE VI
Ear Complaints of Twenty-one Amas

Items	No. Amas complained	Percentage
Tinnitus	14	38.9
Rupture of ear drum (one side)	12	33.3
Spontaneous pain	6	16.7
Exostosis in external ear canal	<u>4</u>	<u>11.1</u>
Total	36	100.0

investigated Amas in a different locality. The Amas of the latter author were Cachidos while the Shima-amas were Funados. The diving depth or water pressure may have played a role in the difference of results.

Prevalence of otitis media in the previous history of diseases of Amas was high and about one-half of them reported it in our survey. As other authors concluded, we think also that deformities of the ear drum including its rupture and the resulting loss of hearing may have been caused to a greater extent by otitis media than by pressures acting on the ear drum during a dive. About one-half of the Amas we interviewed did not dive when they had a cold or felt something unusual about their throat.

During the interview we learned that there seemed to be some sort of occupational hazard caused by stings of jelly fish, by sea urchins and by bites of other fishes. Some of the Amas reported acute general symptoms of various degrees, most of which were dyspnea due to the swelling of the throat, but also some fainting. This lasted for a few hours when they were rescued and rested on board the boats. Chronic skin eczema was found to have occurred in only three Amas. These skin reactions and diseases seemed to have been caused by external effects on exposed parts of the body. However, in recent years the Ama's body has been fairly well covered by adequate clothing for the protection of body heat loss, leaving only hands and feet bare. Fifteen Amas out of twenty-two complained of stiff shoulders and a previous history of arthritis presumably due to the coldness of the sea water.

We collected at the health center the death certificate returns from the population of the village for two years, 1960 and 1961, and examined 46 and 49 deaths for male and female, respectively. The deaths and their causes are presented in Table VII for ages over twenty, because the earlier deaths were limited in number. The population of over twenty years of age as of 1963 in this village was 1976, 1460 and 3436 for males, females and total respectively. We

TABLE VII
Death Certificate Returns of 1960 and 1961

	71 and over		41-70		20-40		Total	
	M	F	M	F	M	F	M	F
Senility	7	16	0	0	0	0	7	16
Brain hemorrhage	0	7	6	4	0	0	6	11
Heart disease	9	5	4	4	0	0	13	9
Pneumonia and bronchitis	0	1	1	0	0	0	1	1
Neoplasm	2	2	5	2	1	0	8	4
Accident	0	1	1	2	3	0	4	3
Other	<u>2</u>	<u>5</u>	<u>3</u>	<u>0</u>	<u>2</u>	<u>0</u>	<u>7</u>	<u>5</u>
Total	20	37	20	12	6	0	46	49

could not confirm the conclusion of Anzai⁽¹⁾ that Amas are apt to die of senility more frequently than of brain hamorrhage. The discrepancy may be due to the small number of our samples, but the pattern of deaths among the general population, including Amas of the village, was fairly similar in both studies.

During approximately ten years from 1955 to 1963, a death by cardiac arrest under the sea surface and another by misguiding from the boat during diving were recorded. The cause of these accidental deaths were, of course, reported by practicing physicians but we are not able to know their real reason and mechanism.

Regarding maternity care of the Amas, Mrs. Iwasaki obtained the results in Table VIII by her direct interview.

The decline of the number of Amas during recent years in a district of Mie Prefecture is shown in Table IX.

TABLE VIII
Results of Interviews About Maternity Care

	Questions	Answers	No. Amas
I	How long are you absent from your job before parturition?	1 day	6
		none	11
		no comment	<u>4</u>
		Total	21
II	How long are you confined after parturition?	1 week	4
		2 weeks	3
		3 weeks	7
		4 weeks and longer	4
		no comment	<u>3</u>
		Total	21
III	How long do you stay away from household activities after parturition?	2-3 weeks	8
		4-5 weeks	3
		7 weeks and longer	8
		no comment	<u>2</u>
		Total	21
IV	How long do you stay away from your job after parturition?	2 months	3
		3 months	10
		through the season	6
		no comment	<u>2</u>
		Total	21
V	Do you practice birth control?	yes	4
		no	15
		no comment	<u>2</u>
		Total	21
VI	Have you experienced artificial abortion?	yes	5
		no	11
		no comment	<u>5</u>
		Total	21

TABLE IX

Decline of Number of Amas in Recent Successive
Years in a District in Mie Prefecture*

Year	Number of Amas**	
	Cachido	Funado
1954	1, 109	504
1955	1, 143	449
1956	920	448
1957	918	445
1958	757	391
1959	747	341
1960	702	342
1961	710	289
1962	820	288
1963	730	238
1964	754	138

*Figures from a report of Mie Prefectural Marine Biological Research Institute. This district represents one of the Ama localities in Japan, and comprises five Ama villages; Hamashima, Goza, Koshika, Funakoshi and Wagu.

**The numbers refer to those who are registered in the district irrespective of their sex as engaged in both types of diving. One-half of Funado Amas are diving women and the other are men who stay on boats to guide diving women and pull them up from the sea. Consequently, only one-half of the figures for Funado in each year represents the number of real Amas.

SUMMARY

Four of the most important contributions by Japanese workers mainly dealing with occupational diseases of Amas have been reviewed of their contents which were written in the Japanese language. We supplemented them with results of our own survey which was made last year.

Occupational diseases of Amas represent ailments or sufferings in the ear, nose and throat region of the body. The chief type of diseases is chronic otitis media resulting in deformity or often rupture of the ear drum. Consequence of these changes is permanent loss of hearing capacity in various degrees. The initial state of otitis media is caused through the Eustachian tube which is apt to be affected by sea water while diving. We can hardly believe that all of the deformities of the ear drum including rupture are due to high pressures, during diving exercise, on the ear drum, although we do not neglect its possibility in some rare instances.

Occupational diseases may include acute general symptoms such as dyspnea and fainting presumably by venom of jelly-fish sting through the exposed part of the skin. Fortunately the body reaction does not last long and is completely reversible, although it is severe in degree of cardiovascular nature. Regarding these reactions of the body, it may be suggested that some form of symptoms of bends might have also been included. Amas think and indicate that all of these symptoms were caused by external agents in the sea. But the nature of description about the symptoms and their cause demand a further investigation.

We do not have any reports on record concerning Ama cases or deaths obviously due to anoxia. Nor is there any description of definite decompression sickness in Japanese references. There have been, however, in Wagu village, two accidental deaths reported during ten years, the nature of which unfortunately was not medically studied.

In concluding the present paper we would like to draw the reader's attention to the fact that Amas are decreasing in number in recent years. Figures in Table IX indicate this tendency revealed in a district which is one of the representative Ama localities in Japan. The number of Funado Amas has decreased to one-fourth of those who were registered 11 years ago. They need to do their job in the extreme bodily endurance under rough conditions of external environment of the sea. Cachido Amas also decreased to less than two-thirds of the earlier years. They dive in shallower depths than Funado Amas.

It is obvious that Ama jobs are not very popular among women in these districts in this industrialization and mechanization period of Japan. Younger generations of women are attracted to other easier jobs with more favorable income. There are almost no daughters at present who will succeed their mother's traditional job of Ama.

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HAE-NYO, THE DIVING WOMEN OF KOREA

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There are many indirect lines of evidence to indicate that many thousands of Korean women have been actively engaged in daily diving work for centuries along the shore of the southern part of the Korean Peninsula, especially of Cheju Island (Fig. 1). These women (Fig. 2) are called either Hae-Nyo (sea women), Jam-Soo (diving lady) or Jam-Nyo (diving women) in Korea and are engaged in so-called "unassisted, breath-hold dives." Although both men and women are known to engage in this profession in Japan, nowadays women alone are involved in Korea. Moreover, the Korean diving women, as a rule, work throughout the year, in contrast to some Japanese divers who dive mostly during warm seasons.

Inasmuch as these diving women present to physiologists many interesting problems, we have since 1959 made a series of physiological studies on the mechanics of diving as well as various problems associated with respiration, circulation and body temperature regulation (2-6, 10, 16, 19). However, non-physiologic aspects of Korean diving women are very poorly documented and hence one can find only a few brief articles in the literature (1, 11, 14, 19, 21). Therefore, the author will attempt to summarize in the present communication various aspects of Korean diving women, which are not directly related to physiology.

A. Geographic Distribution

Along the shore of the Korean Peninsula are scattered approximately 20,000 diving women, the density increasing toward the southern tip of Korea. Although it is impossible to know if there are at present any diving women in north Korea above the 38th parallel, women divers of Cheju Island

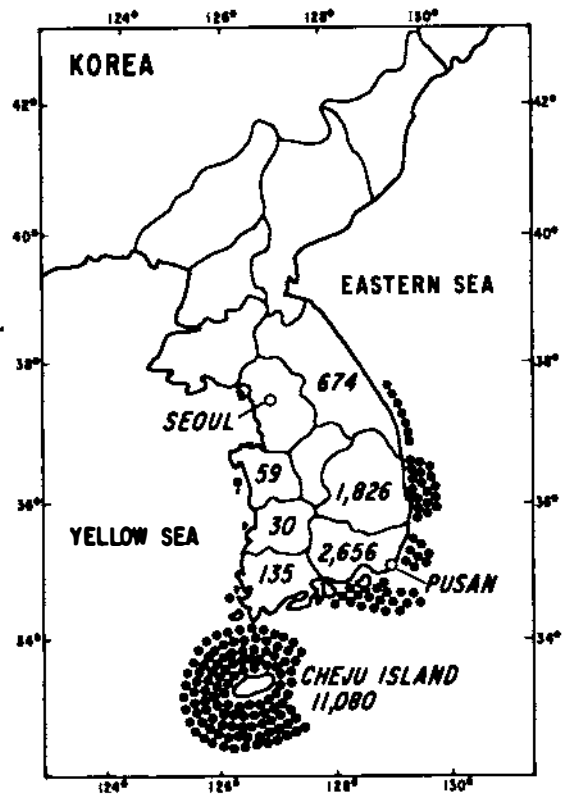


Figure 1. Geographic Distribution of Diving Women of Korea. The figures indicate the actual number of divers in each Province. Each dot represents 100 divers. Note that nearly 70 per cent of divers are found in Cheju Island.



Figure 2. Korean Diving Woman from Cheju Island. Note float and collection net. The broad belt was provided by experimenter for recording depth of dive. Subject holds an underwater alveolar gas sampler in right hand. (From Hong et al⁽³⁾).

illustrated by the fact that, in a particular village on the island where we conducted a field investigation in 1960⁽³⁾, there were nearly 1,200 potential divers out of a female population of 2,400. This means that a majority of young women in that community are engaged in the diving profession on and off. Similar phenomenon was also noted in other villages. It may also be pointed out that some divers migrate to the mainland to settle down permanently while others return to the island during the cold season.

B. History

Although it has been virtually impossible to trace the exact beginning of divers in Korea, it is generally agreed that Cheju Island is the place where this profession was started in Korea. An historical survey⁽⁸⁾ revealed that, as early as in 434 A.D., there were pearls in the Shilla Kingdom (southeastern part of

were known to migrate to north Korea before 1945⁽¹⁹⁾. According to an estimate by the Korean government authority, the total number of active diving women was approximately 27,000 as of 1945 but decreased to 22,000 in 1956 and it is now estimated to be in the order of 16,000. If the number of divers decreases at this rate, one would predict that this profession would die out before the turn of the century (Fig. 3). Why the number of divers decreases in Korea will be discussed later.

The geographic distribution of diving women in Korea is illustrated in Figure 1. Of 16,000 divers, nearly 70 per cent are found in Cheju Island and the rest scattered along the southern part of the mainland. Actually, most of the divers working on the mainland came from Cheju Island. Moreover, women divers of Cheju Island have also been known to migrate as far as Japan and China before 1945^(19, 21). This suggests the importance of Cheju Island as a center of women divers from where they spread not only to the Korean mainland but also to the Far East. This may also be

Korean Peninsula) which had frequent exchanges with Tam-La (ancient name of Cheju Island). Moreover, later references indicate that the Cheju Island became so famous for pearls that a king of China dispatched his officials in the 13th century to this island for the purpose of obtaining pearls⁽¹²⁾. From these facts, it is inferred (11, 14) that the pearls which were already known to exist in Shilla in the 5th century perhaps originated in Cheju Island where they were most probably collected by the divers. Another line of evidence in support of this view is the record that during the 13th century Japanese divers came to Cheju Island in order to harvest pearls, thus stimulating the local diving activity⁽¹¹⁾. It is also

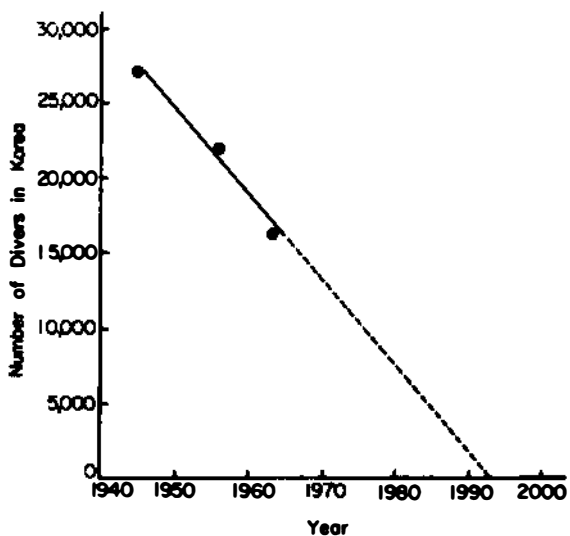


Figure 3. Changes in Number of Divers in Korea by Year.

recorded in history that peoples of Cheju Island already began to migrate during the 15th century to the mainland. It is stated in the "History of Lee Dynasty" that a group of men (not women) from the Cheju Island made their living by processing abalones in the southwestern part of Korea⁽¹³⁾. Although the supply source of these abalones is not clear, it is assumed that these were harvested by women divers who accompanied their husbands to the mainland⁽¹⁴⁾.

However, the term "Jam-Nyo" (diving women) appears for the first time in the literature published during the 17th century. In a monograph entitled "Geography of Cheju Island," there is a description of the diving women as follows: "Nude women engaged in diving work in the spring and the summer to harvest sea-weeds and abalones, but most of their produce are collected by the government officials and they are allowed to sell only a fraction of their harvest for a living. Moreover, these women are working with men without any feeling of disgrace." Recent literature^(7, 21) indicates that diving women of Cheju Island began to migrate massively to the mainland in 1887 and to Japan in 1903. Later on they extended their diving ground to China.

From these historical considerations, one may speculate that the people of Cheju Island began to engage in the diving profession as early as in the 5th century or before for the purpose of harvesting pearls. Moreover, it is clear that both men and women were engaged in diving work at the beginning but somehow men dropped out later. From the physiological point of view, women have not only greater subcutaneous fat but the shivering threshold is also elevated as compared to men^(10, 16), and thus women are distinctly in a better position than men to work in cold water. Undoubtedly, there could be many other reasons. However, these facts would lead us to postulate that men could not compete successfully by virtue of their poor tolerance to cold.

C. Diving Pattern, Seasons and Harvest

1. Age: At the age of 11 to 12, girls start to learn how to dive in shallow water (about one meter in depth). When they become 17 to 18 years old, they develop into full-fledged divers and continue their profession until they get too old to dive. In any divers' community, it is not unusual to see active divers 65 years of age. Although many young women are actively engaged in daily diving work, there is no evidence for alterations of either menstrual cycle, sexual maturity or marital status^(9, 14). It is also to be noted that the menstrual cycle does not interfere with their work. Moreover, at the time of pregnancy, they usually continue to work until the day of delivery, and rest only five to ten days after the delivery^(9, 14). Thus, it is common to observe diving women nursing babies on the shore between shifts.

2. Diving Pattern and Seasons: As indicated earlier, diving women of Korea are solely engaged in unassisted dives in contrast to some Japanese Ama who are engaged in assisted dives. Differences between these two types of dive are illustrated in a previous publication from our laboratories⁽³⁾.

As long as the weather permits, divers spend the whole day without lunch in the sea as well as on the shore where they prepare for daily work and rest between shifts. Although they dive the year around, they take three shifts a day in the summer and two shifts in the spring and autumn. However, they take only one or rarely two, shifts a day in the winter. Not only the number of daily work shifts is different by the season, but the duration of a work shift was found to be closely related to the temperature of the sea water in which they are working. A detailed analysis indicated that the duration of a shift was proportional to the sea water temperature⁽⁵⁾.

Although it varies somewhat with the season, diving women walk to the shore around ten o'clock in the morning after a heavy breakfast. They carry a big bamboo basket on their back, which contains a cotton swimming suit, a hollowed-out gourd float and wood. If the distance of their diving location is far, they often take a boat to get to the shore in the vicinity of the working area. There is no particular assembly house and thus each group settles anywhere on the shore rather randomly in order to prepare for a day's work. Interestingly enough, even when they take a boat, they do not prepare for a day's work aboard.

When they get to the shore they first change to working clothes which consist of a black (occasionally white) swimming trunk and a white cotton jacket. They also put a towel over their head. It may be of interest to note in this connection that Japanese women divers in certain areas do not wear a cotton suit but dive nude. During this period, one of them builds a fire from wood which they carried to the beach. There is not much necessity for a fire in mid-summer, but this is absolutely necessary in other seasons. They sit around the fire warming up about an hour or so before they go into the water. In mid-winter, they warm up for as long as two hours before they take off into the sea.

As they walk into the sea, they put on a face mask which tightly covers the eyes as well as the nose. This face mask was introduced to them about 30 years ago and they were using eye glasses for nearly 50 years before this face mask was

made available. However, even at present, one occasionally finds divers still using old-fashioned eye glasses, especially among very young divers who must be starting their diving profession. It is needless to say that the introduction of either eye glasses or face mask practically revolutionized the art of diving. In some parts of Japan, one finds eye glasses with small rubber bags attached to equalize the pressure within the glass⁽²⁾. However, we have not found this type of eye glasses in Korean divers.

They also carry hollowed-out gourds which are used as floats. The diameter of this gourd is approximately 10 to 12 inches and below this gourd is attached a collecting net which is kept submerged. Supporting their bodies on gourds they swim out to the diving area which is five to ten meters deep and located usually within 200 yards from the shore.

At the time of a dive, they hyperventilate for five to ten seconds, take a deep breath, abandon the float and then dive to the bottom of the sea, returning to the surface in 20 to 40 seconds. Immediately following the return to the surface, they again hyperventilate for five to ten seconds. After approximately 30 seconds of rest the dive is repeated. When they hyperventilate either before or after the dive, they purse their lips and emit loud whistles which can be heard for long distances. Why they practice hyperventilating maneuvers in such a peculiar way is not clear at present but they claim "it protects their lungs." While this question still remains to be answered, we have speculated earlier that this whistling maneuver may be developed to minimize the degree of hyperventilation thereby limiting excessive loss of CO_2 ⁽³⁾. An excessive loss of CO_2 by extensive hyperventilation before the dive may be dangerous in that the time at depth may be postponed to a point where the O_2 pressure is reduced to such values that upon ascent it must fall to levels where the O_2 transfer stops or is actually reversed. Actual analysis of alveolar gas obtained just before the dive indicated that the effective hyperventilation is not very great⁽³⁾.

The lung volume with which the diver descends to the bottom was found to be equivalent to 85 per cent of the vital capacity. However, upon emergence after 30 to 40 seconds they lost approximately 740 ml of gas of which approximately 300 ml can be accounted for by the excess loss of O_2 over CO_2 gained. The remainder can be divided between that which is used to equalize pressure in the face mask and that which is either voluntarily vented or lost from the face mask itself as they move their facial muscles to prevent any initial leak⁽³⁾. Why the lungs are not completely filled initially is difficult to evaluate. It might be either too uncomfortable, since the intrapulmonary pressure under such conditions exceeds 30 cm H_2O , or, on the other hand, it may be that the buoyancy becomes excessive and requires more effort for active submergence. Since Korean divers are not assisted during the dive, they descend and ascend by their own effort and the problem of buoyancy would be important. The rates of descent and ascent were found to be approximately 0.6m/sec. which are considerably slower than those of Japanese assisted divers^(3, 20).

During 1960 and 1961, we have observed the diving activity of several divers all day long in Pusan in the winter, spring and summer. On the basis of these observations, we have calculated the time being spent for various activities in the field and the average data are tabulated in Table I. As stated earlier, the duration

TABLE I
Detailed Breakdown of Diving Works During
Various Seasons (Pusan Area)

Shift	Winter	Spring		Summer			Summer	
	(1/17/1961)	(4/23/1961)	(4/23/1961)	8/21/1961)	8/21/1961)	8/21/1961)	8/28/1960	8/28/1960
	#1	#1	#2	#1	#2	#3	#1	#2
Air temp. (C)	1	19	19	30	31	31	28	29
Water temp. at surface (C)	10	16	16	27	28	29	26	27
Water temp. at bottom (C)	9	15.5	15.5	26.8	26.5	27.5	25.5	26
Total time in water (min)	21	20	28	69	94	44	58	60
Total diving time (min)	11	11	15	34	48	24	29	36
Total rest time (min)	10	9	13	35	46	20	29	24
No. of dives/shift	29	40	40	77	84	49	81	93
Duration of a dive (sec)								
Average	23	16	22.7	26.5	34.1	30	21.6	22.6
Maximal	31	25	44	43	48	39	26	28
Minimal	11	8	9	6	16	11	11	13
Duration of dive (m)	4-6	2-3	5-7	5-7	5-7	5-7	2-3	2-3
Oral temp. at end (C)	33.8	33.9	33.9	34.3	34.5	35.3	-	-
Duration of rest between dives (sec)								
Average	21	13	18	27	33	23	27	15
Maximal	32	34	39	168	105	46	39	26
Minimal	10	8	9	3	8	8	9	9
Harvest								
Sea slugs	13	-	24	-	-	-	-	-
Sea urchins	5	-	-	89	90	50	-	-
Viviparus	-	-	100	2	7	2	-	-
Oysters	-	-	-	1	-	2	1	-
Abalones	-	-	-	1	1	-	-	-
Octopus	-	-	2	1	-	-	-	-
Mussels	4	-	-	3	10	2	-	-
Sponges	-	-	-	5	20	40	-	-
Glacilaria (Agar weed) (dry wt.)	-	-	-	-	-	-	290gm	360gm
Laminaria (Seaweed) (no. of leaves)	3	300	5	10	5	5	-	-
Gigartina (weed for construction material) (dry wt.)	-	-	-	-	-	-	540gm	360gm

of a shift varied with the water temperature from 20 minutes in the winter to as long as 94 minutes in the summer. Moreover, the duration of a shift was different even during the same season and thus it was shorter in the morning and in the late afternoon than in the early afternoon. It may also be seen that while they are working in the sea only one-half of the time is spent in actual diving and the rest at the surface. The actual number of dives also varied with the season, primarily due to differences in the duration of a shift. In the winter, they made only 23 dives on the average per shift while they made as many as 93 dives in the summer. As a whole, there is a linear relationship between the number of dives and the duration of a shift (Fig. 4). On the average, they make one dive per minute. Since the duration of a dive was averaged to be approximately 30 seconds, it follows that they rest for approximately 30 seconds between two dives. It should be noted, however, that this resting period is sometimes very short and, on one occasion, it was as short as only three seconds.

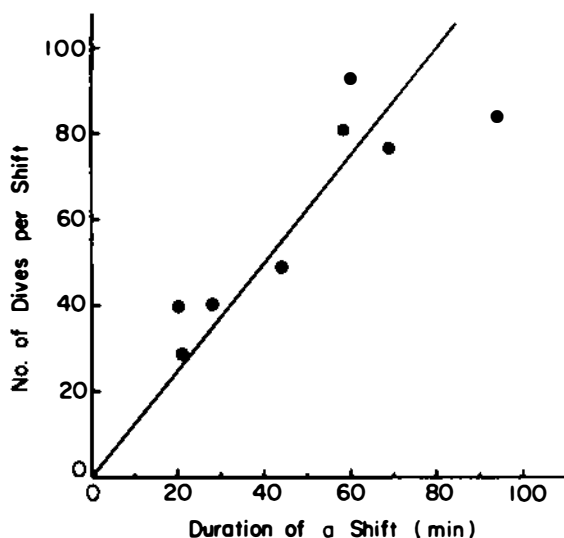


Figure 4. Number of Diver per Shift as a Function of the Duration of a Shift.

passive on descent and ascent which occupies approximately 50 per cent of the total diving time⁽²⁰⁾. Alveolar gas measurements made at the end of an unassisted dive are extremely low in O_2 ⁽³⁾ but do not differ from those for assisted dives⁽²⁰⁾, suggesting that the limit in each case is achieved when a given amount of O_2 has been removed from the lung.

As stated earlier, the Korean divers are mostly engaged in shallow dives, although they are able to dive to a depth of approximately 15 to 20 meters⁽³⁾. Since the unassisted divers of Korea spend a considerable length of time for descent and ascent, they have to increase the depth at the expense of the bottom time for harvesting. In order to compromise these two opposing factors, they have come to prefer shallow dives to deep dives. Interestingly enough, assisted divers of Japan routinely dive to a depth of 15 to 20 meters⁽²⁰⁾ because of faster

The duration of a dive of assisted Ama of Japan was reported to be in the order of one minute⁽²⁰⁾ but that of unassisted Ama of Japan is approximately 30 seconds, in agreement with our findings. Actually, these divers are able to dive much longer. When their maximal diving time was measured in Cheju Island, the longest dive lasted for 82 seconds⁽³⁾. Japanese divers who are engaged in assisted dives are also known to stretch their diving time to as long as 110 seconds⁽²⁰⁾. This large difference in diving times between assisted and unassisted divers is probably due to a difference in metabolic rate. The unassisted diver is continuously active during a dive while the assisted diver remains completely

rates of descent and ascent but the actual working time at the bottom for a given period is about the same as that of unassisted divers of Korea⁽³⁾.

On the basis of these considerations, one may depict the average diving pattern for two types of divers. The unassisted diver of Korea dives for 30 seconds, rests for 30 seconds and thus accomplishes in one hour approximately 60 dives to a depth of five meters. The assisted diver of Japan, on the other hand, dives for one minute, rests for one minute, and accomplishes approximately 30 dives in one hour to a depth of 15 to 20 meters. Thus the total time of submergence is about the same⁽³⁾.

Inasmuch as divers are engaged in their work in the sea water colder than the body temperature, they are bound to lose considerable body heat. Although the heat production is augmented significantly, it contributes little to the maintenance of normal deep body temperature. Even during the mid-summer, one finds divers shivering violently toward the end of a working period. Actual measurements revealed that both the oral and the rectal temperature are lowered progressively during the course of water immersion^(5, 6). In one instance, the oral temperature was lowered to nearly 32°C in the winter⁽⁵⁾. The magnitude of daily heat loss during the diving work was estimated to be approximately 1000 Kcal regardless of the season⁽⁶⁾. However, actual dietary surveys indicated that their caloric intakes are also greater by as much as 1000 Kcal than non-diving women of Korea⁽⁶⁾. This suggests that women divers of Korea are routinely exposed to a cold stress which seems far greater than that recorded for any other human being.

It is evident from these facts that both the respiratory and the thermoregulatory systems of the diving women are subjected to constant strain and, consequently, have developed many adaptive phenomena in these divers^(2, 5, 16, 18). However, it is beyond the scope of this communication to deal with these interesting adaptations.

3. Harvest: As stated earlier in discussing the historical development, the diving women used to dive for pearls in the old days. However, pearls are no longer available and hence they look for other items which are indicated at the bottom of Table I. The most valuable of all objects are abalones, oysters, sea slugs and octopus which are sold at better prices than other items. Although prices are rather cheap, seaweeds are also important items which are supplied by women divers.

Recent statistics compiled by the Korean government indicate that 16,250 women divers of Korea contribute 19,249 metric tons of sea products annually, which are equivalent to approximately \$720,000.00. This means that annual earnings of a diver amounts to roughly \$45.00. If we assume that a diver works, on the average, 300 days a year, a daily earning may be estimated to be only \$.15. Of course, there are definite variations in their daily earnings which is much better in the summer than any other season. As a whole, their living is miserable to say the least. One can, therefore, understand why the number of divers is decreasing fast. Considering the hard life and their small income it is natural that they look for better jobs. This matter will be discussed again later.

D. Socio-Economic Status

Various aspects of the socio-economic status of the diving women of Cheju Island and Pusan have been reported by Kim⁽⁹⁾ and Kang of our laboratories (unpublished data of Kang, B. S.), respectively. The former study is based on 79 divers and the latter on 98. Since the divers of the two communities showed little difference, they will be discussed together.

The educational background of the diving women was practically none in 55 per cent of the cases, and only two per cent of the divers attended secondary school. Although they are quite aggressive in pursuing their profession, they are like other Korean women in that their husbands are selected by the parents. However, 40 per cent of the husbands have no regular job and hence their living is largely dependent on the income of divers. Whether this high incidence of unemployment among husbands of divers is due to a high unemployment rate of Korea as a whole is not clear at present. One might think that the active nature of divers would make their husbands feel inferior and thus make them shy away from social life, but no conclusion could be made at this stage. Of those husbands employed, two-thirds may be classified as fishermen and the rest engaged in agriculture and business.

Approximately one-half of the divers stated that they do both housekeeping and diving work while the rest of the housekeeping is done by other family members such as their daughters, sisters or mothers. Only one diver was able to afford a servant. One interesting finding in this connection was that, in six per cent of the cases, husbands were doing housework. In addition, a majority of the divers in Cheju Island were also engaged in agriculture whenever it was demanded. As for the care of the children, 62 per cent of the divers stated that they bring their children to the shore while the rest had their children staying at home with other family members. In 17 per cent of the cases, husbands attended children at home.

In order to find out whether or not they feel some kind of self-satisfaction in their active life, a question was asked how they compare themselves with other women in the community. To this question, 38 per cent answered that they are satisfied with their life and have no desire to live passively like others. However, the rest of the divers indicated that they would like to live like others but have no choice because of economic demand. To a question whether or not they would let their daughters engage in the diving profession, only 36 per cent answered affirmatively but the rest said emphatically "no." Even those who answered in the affirmative, made it clear that their answers were based on economic necessity. These results clearly indicate that a majority of diving women feel quite inferior to others and discourage their daughters from becoming divers. In addition, not only are their earnings very poor but they become worse every year because of a growing number of divers using underwater diving equipment which was introduced to Korea about 80 years ago⁽⁷⁾. In view of these facts, it is not surprising to see a progressive reduction in the number of divers and it is predicted that they will not be in existence in due course.

As stated earlier, the average daily earning is estimated to be only \$. 15 or so, although there are great seasonal variations. According to our survey on active divers in the Pusan area, the average daily earnings may be approximated

to \$.23, \$.54, and \$.15 and \$.11 in the spring, summer, autumn and winter, respectively. Although divers in Pusan are earning more than the national average, their incomes are still very unimpressive. Naturally, other members of the family also contribute their earnings to maintain the family, but it is interesting to note that divers earned more than the rest of the family members in 70 per cent of the cases. In general, over-all family economy is very poor and only nine per cent of the divers stated that they are living rather comfortably and 60 per cent stated that they are living miserably. While the average family consisted of 4.5 persons, only 16 per cent of the divers own a house and the rest are living in rented rooms.

E. Occupational Diseases

Although there could be dangers of developing "decompression sickness," the Korean divers are completely unaware of any incidence. It is perhaps due to the fact that the depth of diving is not only shallow but the duration of a dive is also short. In addition, the divers take enough rest between the two successive dives and this should help eliminate N_2 from the body. On theoretical grounds, a sufficient amount of N_2 could accumulate during repeated dives if the rest periods between dives are not long enough.

Considering the extremely low values of PO_2 at the time of return to the surface, one would expect the development of anoxia, loss of consciousness or loss of clear thinking ability. However, many divers we interviewed were unaware of such hazards. This again indicates that the basic diving pattern has been evolved to avoid the development of such critical conditions. As discussed earlier in this communication, as well as in an earlier publication⁽³⁾, we postulated that the prevention of excessive hyperventilation before a dive by the whistling maneuver is a trick they learned by experience. What other factors are involved in this matter remains to be solved in the future.

In the course of diving, the Eustachian tubes play a very important role in equalizing the pressure across the tympanic membrane. Therefore, it may be of considerable interest to make otolaryngological examinations on the divers. According to the studies by Pak⁽¹⁵⁾ and Yoon of Yonsei University, women divers displayed various diseases, some of which are not seen in non-diving women living in the same community. The tympanic membrane was opaque in 85 per cent of the divers as compared to only 25 per cent in non-diving women. Strangely enough, the stenosis of Eustachian tubes was noted in 80 per cent of the divers. Since this tubal stenosis would not favor a fast equalization of pressure across the tympanic membrane, the rate of descent or ascent would be limited. How this unfavorable condition is developed in the diver is not evident. Another interesting observation in the diver is the development of exostosis which was seen in 31 per cent of the cases. This is located on the osseous wall of the external auditory meatus, especially in the posterior wall. In several cases, the presence of exostosis made it very difficult even to observe the tympanic membrane. The shape of the exostosis was round or oval and the color was light yellow in most cases. In non-diving women, there was no incidence of exostosis. Audiometry showed that divers have distinct hearing defects in all cases, while only 40 per cent of control subjects showed defects. Although there were various types of defects, the hearing

loss was most frequent at low frequency level. Caloric tests were also performed but there was no difference between divers and the control. What factors are involved in developing various diseases as outlined above is difficult to say at present, although some parts of daily diving work in the sea might contribute in some way to bring about various disorders.

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THE PHYSIOLOGICAL STRESSES OF THE AMA

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The profession of the Ama and other breath-hold divers is unique in that it involves a variety of stresses not commonly found elsewhere. Practically all organ systems are affected in some manner as a result of abrupt changes in pressure, thermal gradients, and the supporting environment. More specifically, we are dealing with very abrupt and repetitive on-and-off changes in absolute pressure during diving, the more subtle changes in transthoracic pressures while afloat, large differences in heat transfer across the body, and the effects of buoyancy which eliminate some of the gravitational stresses, particularly on the circulatory system.

Our concern in this Symposium is to describe for the first time in detail the effects of these stresses on each organ system and eventually to describe their interrelations so that one may obtain a total picture of man's response to this peculiar aquatic environment.

I would like to provide a brief overview of some of the problems which face the Ama and to anticipate the various stresses to which she is subjected. This may provide a general basis for the detailed discussions to follow which will focus upon particular organ or regulatory systems.

Diving Patterns

A number of different diving procedures have evolved to meet various local conditions in the coastal waters of Japan. The two most common, and probably the simplest and most sophisticated, are the approaches represented by the Cachido and the Funado illustrated in Figure 1.

The Cachido must swim actively in order to reach the bottom and return to her float, and her oxygen consumption during each dive is thus relatively large. This limits her time under water and restricts both the depth she can reach and the time she can spend on the bottom. As a result the Cachido is restricted to shallower waters and denied the deeper harvesting areas.

The Funado uses a 12 kg weight and descends passively to depths of about 20 m. She is then pulled back to the surface by her husband. Since the Funado has a lower rate of oxygen consumption during her dives, her time under water can be longer than that of the Cachido. Together with her greater rate of descent and ascent, this permits her to reach greater depth and spend more time on the bottom. The obvious economic advantage of the deeper and larger harvesting area that results is in part offset by the need for a boat and for an extra person to manage the boat and assist the diver.

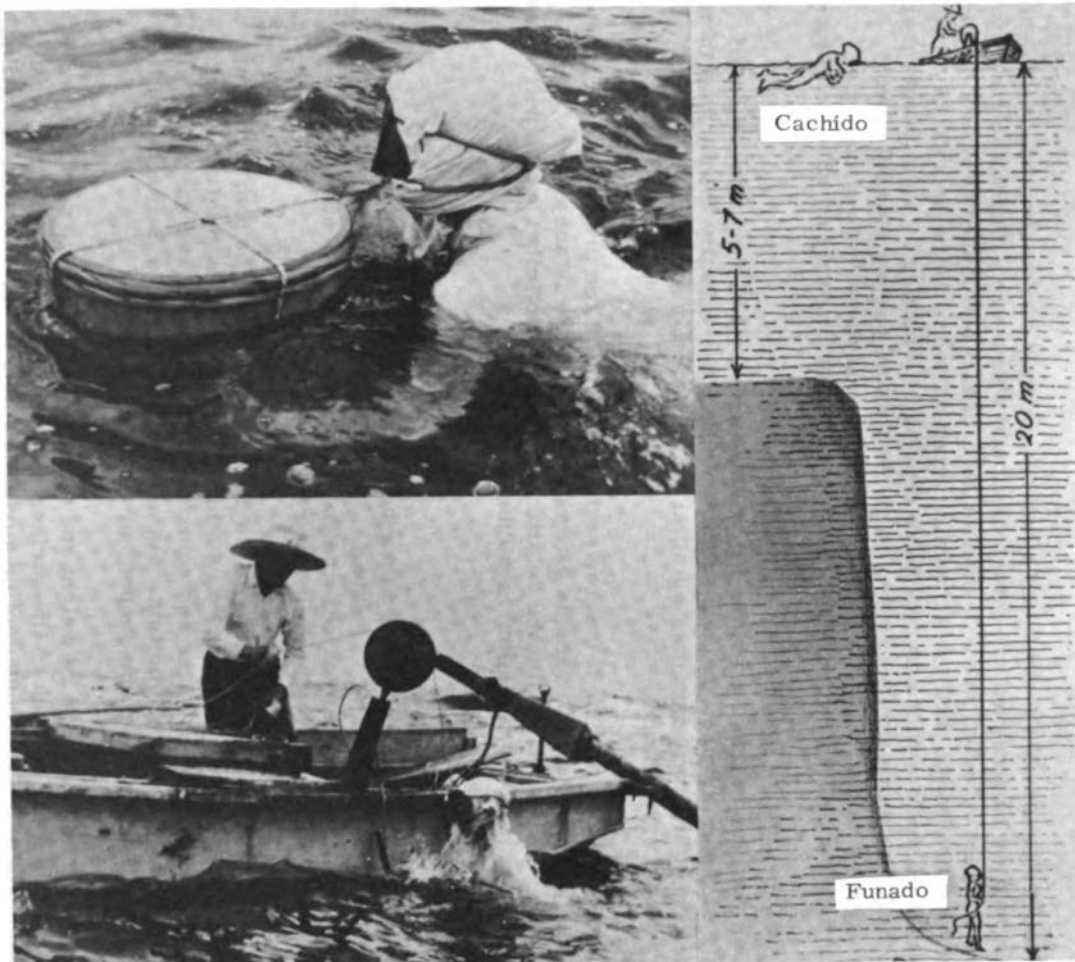


Figure 1. Upper left, a Cachido with float. Lower left, Funado just emerging from dive. Note abalone knife in her right hand. Photos taken by author in Shima Peninsula in 1960. Right hand figure is a schematic representation of typical diving depths.

Both of these patterns of diving consist of a series of repetitive dives made at short intervals over a period of one hour or more. In the summer there may be three one-hour diving periods per day. In any case, the Ama must adjust her pattern in such a way that she can work as efficiently and uninterruptedly as possible for relatively long periods of time.

More detailed analysis and comparison of the patterns require estimation of the actual harvesting time on the bottom, and this depends in large part upon the rates of descent and ascent. In the Cachido these rates are surprisingly uniform at about 0.6 m/sec⁽⁵⁾. In the Funado the rates are two to two and one-half times faster^(15, 8). In the following example we have assumed that the Funado descends and ascends at 1.3 m/sec. Choosing a depth of 5 m for a typical Cachido and 20 m for a typical Funado, we can largely represent the Japanese Ama by describing two characteristic diving patterns. These are illustrated in Figure 2.

According to this analysis, the Cachido performs 60 dives in one hour, while the Funado performs only one-half this number. But the bottom time of the Cachido is only 15 seconds while that of the Funado is twice as long. At these depths and rates both patterns thus yield the same total bottom time.

It is apparent that the Cachido could dive deeper; but doing so repetitively may not yield a worthwhile bottom time, or the extra cost in energy and recovery time might make the undertaking inefficient. It is likely that for sustained repeated diving each of these patterns is optimal time for the divers who use it. The total energy costs for the Cachido are higher than those for the Funado, as will be discussed in detail by Drs. Yokoyama and Iwasaki.

Problems of Underwater Vision

The loss of the air-cornea interface during submersion reduces the visual acuity to such an extent it is remarkable that successful harvesting could be accomplished by the Ama before the introduction of underwater goggles. Figure 3 attempts to illustrate this loss of visual acuity. The photograph on the right represents the subjective impression of the visual image when the objects on the left were viewed through a four-foot column of water.

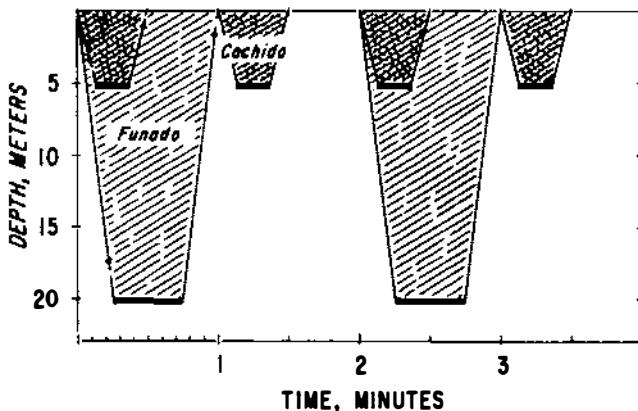


Figure 2. Typical Repetitive Diving Schedule of a Cachido and a Funado. Note the slower descent and ascent rates of Cachido. Her bottom time per dive is about one-half that of the Funado. Overall-bottom time, however, is about the same.

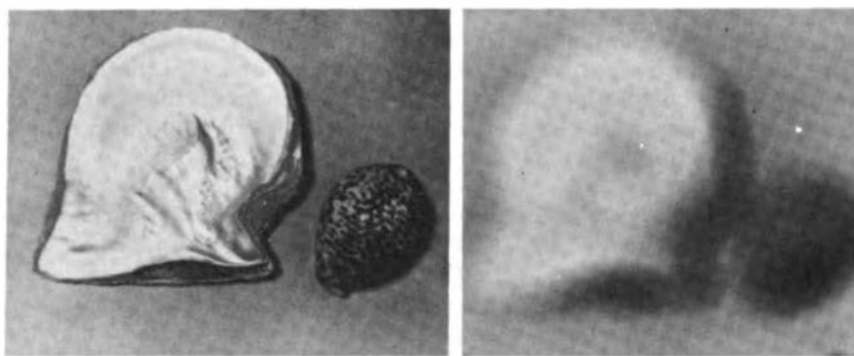


Figure 3. Objects on right are shown out of focus to simulate the subjective visual impression of several members of the laboratory when they viewed these objects through a four-foot column of water.

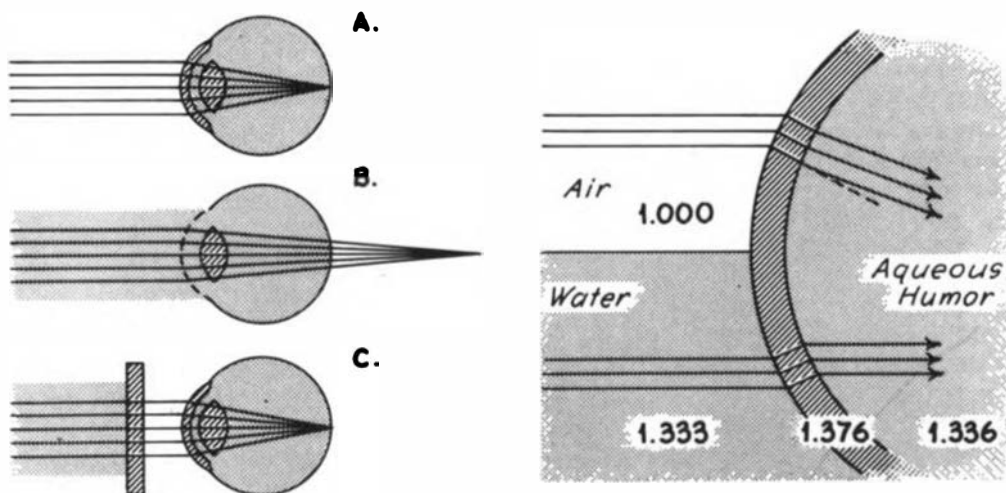


Figure 4. In A is shown the reduced eye where parallel light is refracted at cornea and lens to be focused on the retina. In B the cornea is submerged and parallel light now focuses about 30 mm behind the retina. By restoring the air-corneal interface with a goggle (C), nearly normal vision is returned. On the right-hand side is shown schematically how the light is refracted when an air-cornea and a water-cornea interface are achieved. In the latter case some refraction does occur both at the outer and inner curvature of the cornea but it is essentially equal and opposite so that only the crystalline lens is left for refraction.

In Figure 4A we have a schematic representation of the eye where the air-cornea interface contributes 43 diopters and the lens about 15 diopters to the focusing of parallel rays upon the retina. The power of a lens is proportional to the change in refractive index and inversely proportional to the radius of curvature. Normally it is the difference in refractive index between the air (1.000) and the cornea (1.376) which accounts for the major refraction at the air-cornea interface. When water is substituted for air (1.333) this difference becomes so small that parallel rays are now focused about 30 mm behind the retina. This makes the eye "farsighted" or hypermetropic and distorts the image as shown in Figure 3. Even maximal accommodation of the lens will not help very much. Under these conditions only the lens can still refract parallel rays. This can be appreciated if one calculates the dioptric power of the cornea in air and in water. If $D = (R' - R'')/r$ (where the refractive index, R, in air = 1.000, cornea = 1.376, aqueous humor = 1.336, water = 1.333, and the radius, r, of front surface of cornea = .0077 m and of back surface = .0068 m), then it is equal to 48.8 on the front surface of the cornea in air and -5.88 at the back side. These effects are shown on the right side of Figure 4 by the broken line which represents schematically the refraction of the front surface (48.8 diopters), which in turn is bent back (-5.8 diopters) to enter the aqueous humor (solid line).

A similar line of reasoning shows that when the cornea is submersed in water the differences in refractive index between water, cornea, and aqueous humor are such that the slight convergence of parallel light on the front surface is essentially canceled by the back surface. Thus parallel light in water entering the eye stays parallel until it reaches the crystalline lens. The usefulness of the cornea as the major lens for focusing the light on the retina is eliminated. By simply restoring the air-cornea interface with the use of goggles visual acuity is restored (Fig. 4C). In spite of the high refractive index of glass (1.5) the parallel rays are not refracted since now r on the glass plate is infinite.

Development of Goggles

The discovery and use of goggles must have been revolutionary in the art of diving. According to Teruoka⁽¹⁵⁾ they were introduced about 120 years ago; however, according to Miyamoto (7) it was not until 1890 that simple goggles were imported from Hawaii. In any event, this revolutionary device immediately presented new problems since without proper pressure equalization it limited the depth of diving. This type of goggle is shown in Figures 5-1 and 6-a. Teruoka describes its limit as about 3 m since beyond this point conjunctival bleeding occurs. The next step was the compensating rubber bulbs (Figs. 5-2 and 6-b) which, in turn, was followed by inflatable leather bags made from cat, goat, or deer skin (Figs. 5-3 and 6-c). Modern versions of these devices using rubber are still in use today (such as shown in Fig. 5-4) and have been adopted or developed independently in other parts of the world. In Japan the face mask (Fig. 6-d) came into use in 1920⁽¹⁵⁾. Today it is in wide use in Japan, Korea, and the rest of the world. With this device the lungs instead of the rubber bulb furnish the gas for pressure equalization. However, this type of mask can also be depth limiting as will be discussed below.

Before leaving the problem of goggles and their limiting gas equilibrium problem another unique approach must be mentioned which, as far as I am aware,

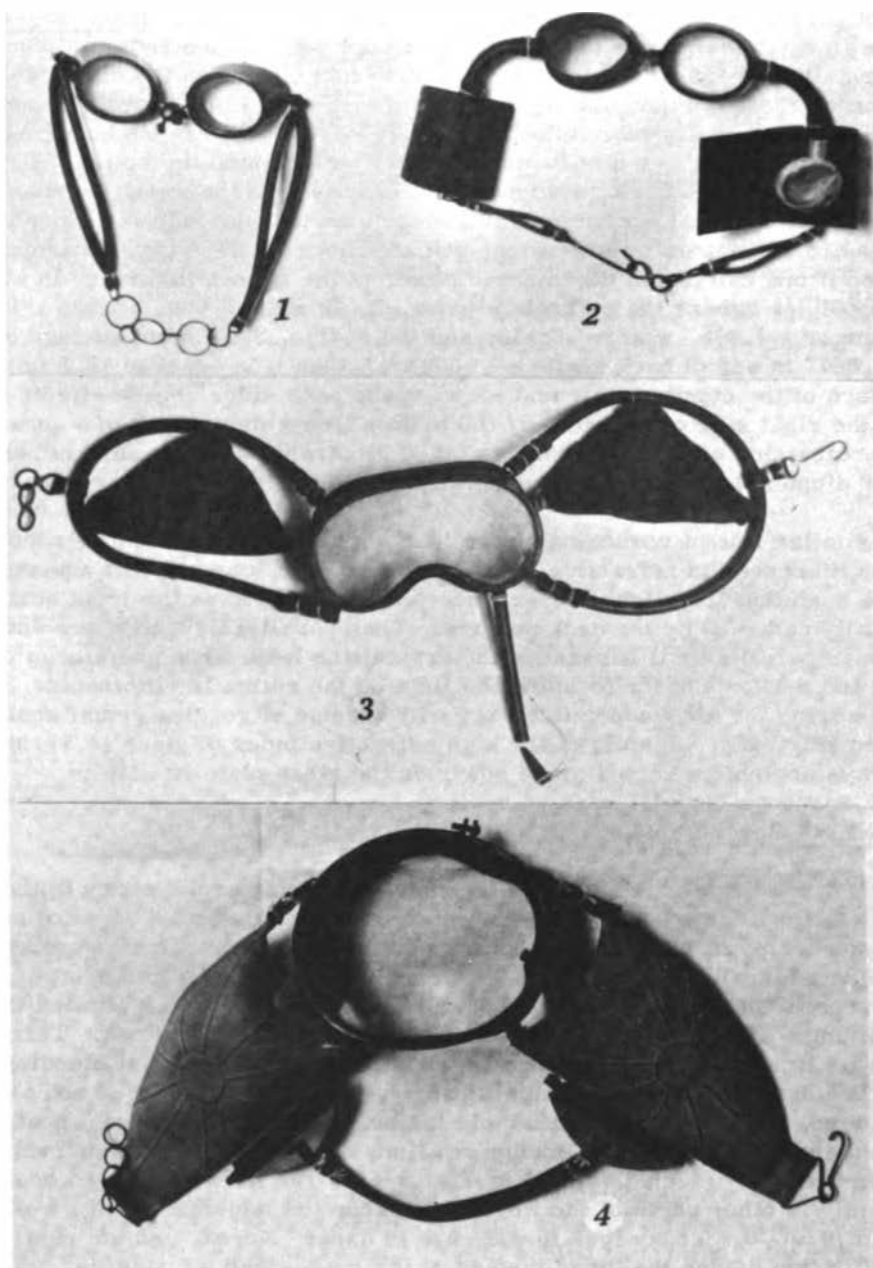


Figure 5. Historical development of compensating devices for the Ama's goggles. The small rubber bags in #2 were protected by a metal housing. Compensating bag in #3 was leather and goggle could also be inflated by mouth with rubber tube. In #4 face mask with large rubber compensating bags. The author is indebted to Dr. Teruoka for permission to reproduce these photographs.

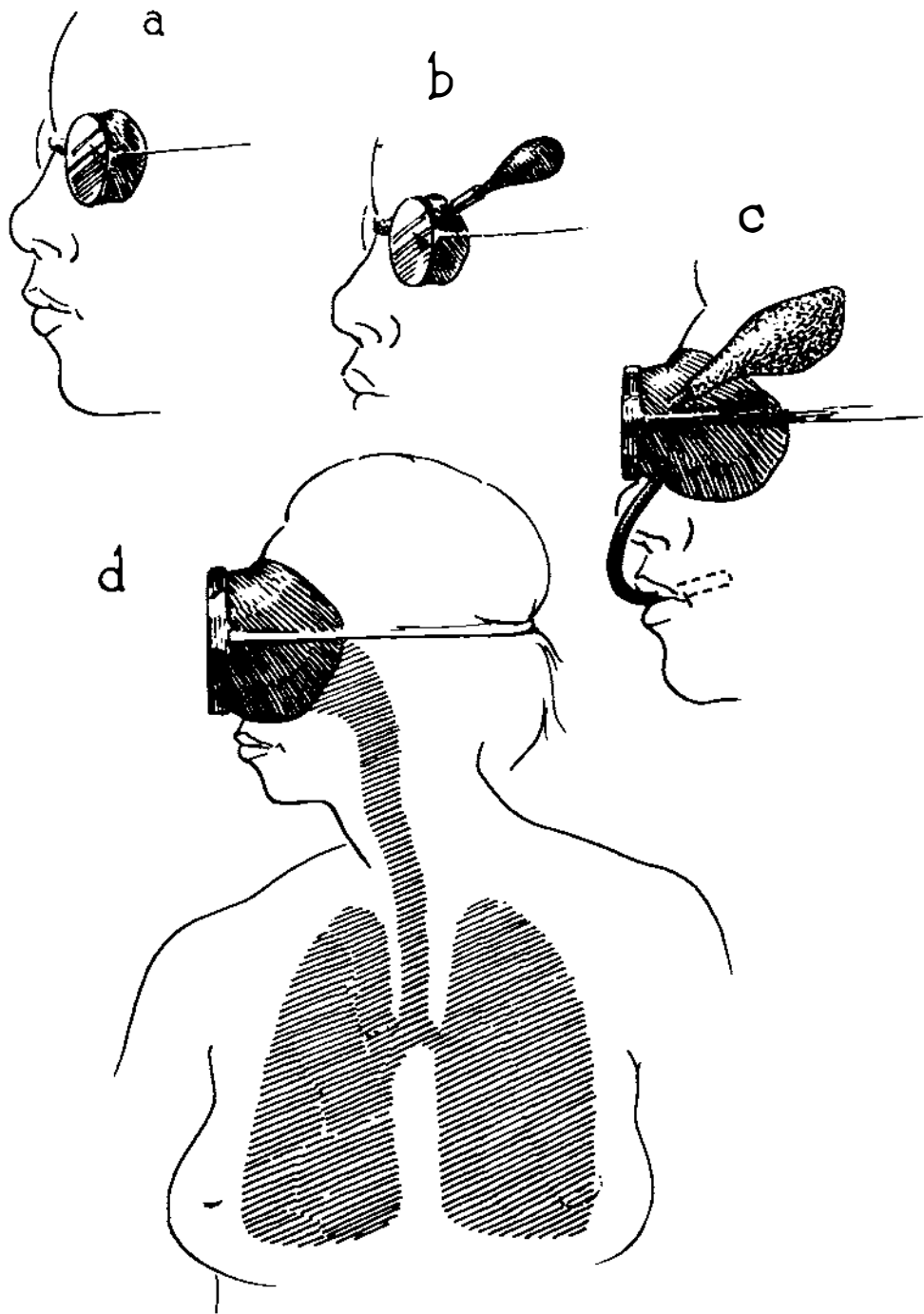


Figure 6. Redrawn from the original article of Dr. Teruoka. Type b is the early compensating goggle. Type c is a later development. Face mask, type d, is now most popular. Here the lungs become the compensating chamber.

has not been previously discussed. As long as an air space exists over the corneal surface, its pressure must be equalized during compression. However, the equalizing medium need not be gas but can be fluid or tissue. This conclusion must be deduced from the reports of Williams⁽¹⁶⁾ on the Tuamotu divers who dive to 40 meters and for some Japanese male divers⁽⁷⁾ who both use very small goggles in very deep dives without external compensating devices. Not only are the goggles smaller than the ordinary type, but their volume is further reduced by limiting the rim with a hard wax as shown in Figure 7. These particular goggles

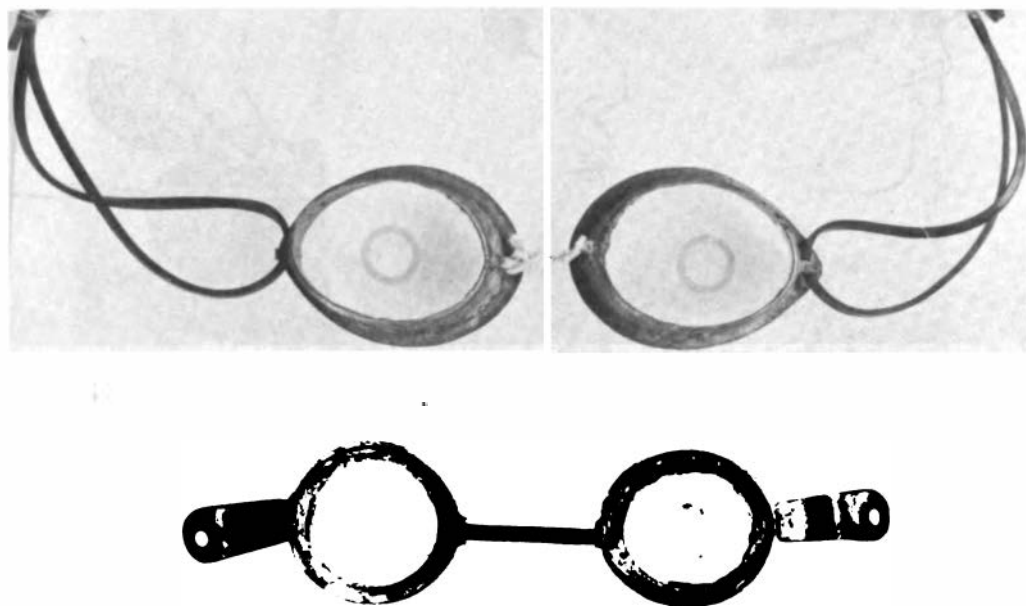


Figure 7. Ordinary glasses without compensation which limit the depth of the diver to about 3 meters (Teruoka). Below is shown glasses worn by male divers of the Tuamotu Archipelago who dive to 40 meters. Note that they have a small goggle volume which is even further reduced by lining the rim with wax. The air space over the eye is 7.2 ml in the former and 3.2 ml in the latter. A similar small type goggle is found among certain male Ama in Japan.

come from the Tuamotu Archipelago. I measured the total gas volume which remains after they were put over my eyes. The ordinary goggles have a gas volume of about 7.5 ml for each eye and these are reported to limit a dive to about three meters before conjunctival congestion or hemorrhage develops. The small glasses have a gas volume of about 3.2 ml over each eye and allow the Tuamotu Islanders to descend to 40 meters. For such a dive, four-fifths, or 2.56 ml of volume, should be displaced by tissue mass but without rupturing any vessels.

Figure 8 indicates how the initial ambient gas volume of 3.2 ml must change during compression from 1 atm to 5 atm or a dive to 40 m. At any depth

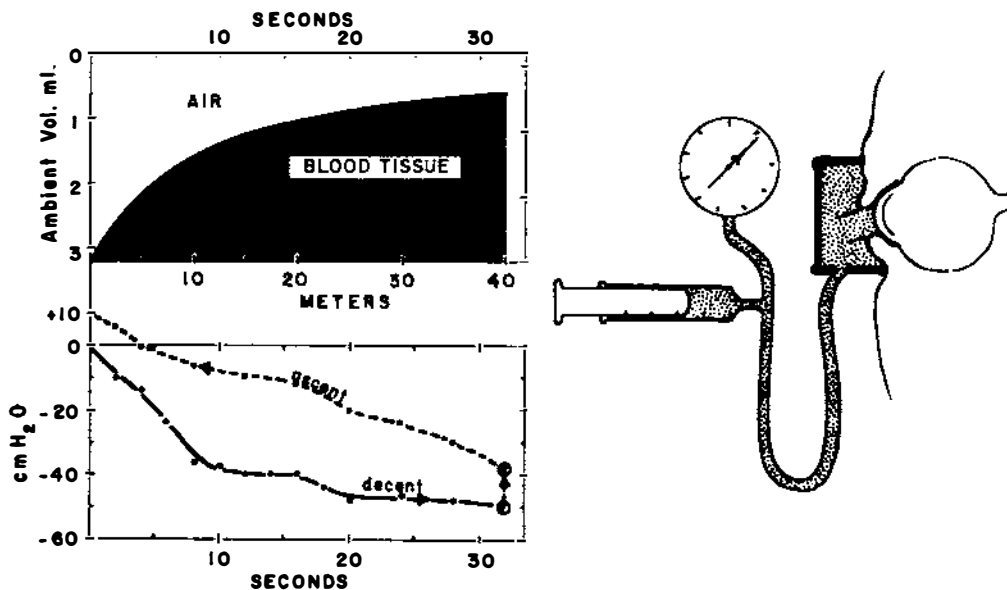


Figure 8. Upper left corner shows how the 3.2 ml gas volume over the eye must decrease with time (upper abscissae) and depth (lower abscissae) if adequate pressure compensation takes place during a dive to 40 meters at a rate of 1.25 m/sec. If compensation is adequate the black area under the curve represents the volume of tissue which must be pushed into the goggle space. To test this hypothesis and the negative pressure which must develop under these circumstances, a fluid-filled goggle system was employed so that fluids could be removed at the desired rate (upper left-hand graph) and the simultaneous extraocular pressure measured. The latter are shown in the lower left-hand graph and are described further in the text.

the resulting difference in volume (shaded regions) must enter the goggle space to compensate or maintain the proper pressure. Presumably this must be the tissues around the eyeball or the eye itself being pushed out into the goggle space by the distention of veins and sinuses.

In order to test this hypothesis of tissue compensation I placed a goggle over my left eye, attached a syringe and pressure transducer to the goggle rim as shown in Figure 8, and filled the whole system with saline solution. Mr. Morin then assisted me by withdrawing fluid at a rate which would simulate the decreasing gas volume in a real dive to 40 meters at a descent rate of 1.25 m/sec. By gradually accumulating in the syringe over a period of 32 seconds the volume marked blood-tissue in Figure 8, he withdrew a total volume of 2.56 ml. During this time the pressure was recorded and is shown in the lower half of Figure 8. During the simulated descent it reached a negative value of 50 cm H₂O in 32 seconds. At this point we waited 30 seconds, simulating the bottom time of the diver.

During this interval the pressure fell to -45. We simulated the ascent by reinjecting the fluid. This was done in the reverse order, reinjecting fluid slowing at first and more rapidly at the end. The upper pressure tracing shows the time course during ascent. Just before returning to the surface the pressure became temporarily positive.

This simple experiment merely illustrated the fact that sufficient tissue could accumulate in the periocular space to compensate for the shrinking gas space and that the necessary negative pressures did not exceed -50 cm H₂O. This experiment was repeated several times. No pain was ever felt and afterwards there was no indication of a conjunctival hyperemia or hemorrhage.

However, there must be a limit to the degree of tissue deformation and when this is exceeded the pressures become sufficiently negative to cause capillary damage. This occurs when the initial gas volume over the eye is too large and presumably a 7.5 ml gas space is of this order. In any event, this is a remarkably simple solution to the goggle compensation problem. It recommends itself particularly for very deep dives where the lung volume changes become the limiting factor. A face mask with a 200 ml dead space would require 800 ml of gas for compensation during a 40-meter dive. This gas must come from the lung and its loss to the mask would not only limit the maximum depth to which the diver may go, but also remove 160 ml of O₂ from the gas exchange.

Pressure Equalization During Diving

The gas cavities of the body must obviously adjust to the large and rapid changes of pressure during a dive. These are well recognized phenomena of diving. What perhaps is unique in the case of the Ama is not only the fast compression and decompression times but also the rapid sequence of these exposures. A 20 m dive of the Funado is accomplished in 13 to 17 seconds. The ascent is accomplished in 11 to 14 seconds and there are about 30 such dives in one hour.

Predicting the maximal depth which a breath-hold diver can reach and still equalize the pressures in his rigid gas cavities is not simply a matter of applying Boyle's law to the total lung volume: residual volume ratio. This ignores the volume of the various rigid chambers of the upper airway, the face mask volume, the unequal gas exchange in the lung during breath-holding, the pressure-volume relationships of the chest, and the correction for water vapor. These will be discussed in the succeeding presentation by Dr. Agostoni.

I would like here to briefly review the whole gas volume system and divide it into the rigid and collapsible chambers, since it is their ratio which becomes the basis for any prediction before additional corrections are applied. I have defined here the rigid chambers as those which cannot collapse and must remain open. Nor can they become unduly negative in relation to the ambient hydrostatic pressure without congestion or bleeding.

Table I lists the best approximation of the rigid and collapsible volumes for an Ama. The residual volume (minus the dead space) is assumed to be the minimal alveolar which can be tolerated, since we have no experimental data to the contrary.

TABLE I
The Rigid and Collapsible Chambers

Rigid Chambers	ml (BTPS)	Reference
Both nasal passages	18	(10)
All paranasal sinuses	50	(10)
Both middle ears and mastoid air cells	20	(10)
Airway (respiratory dead space)	122	(11)
Face mask	200	(5)
Residual volume (minus dead space)	1020	(13)

<u>Total Rigid Chamber Volume</u>	1430	
 <u>Collapsible Chamber</u>		
85 % of the vital capacity	2920	(5)
<u>Total Gas Volume</u>	4350	

Thus the (total lung volume)/(rigid chamber volume) ratio is 4350/1430, or 3.03, before additional corrections are applied, and indicates a maximal compression from 1 to 3 atm or a dive to 20 m. These volume relationships are also shown in Figure 9.

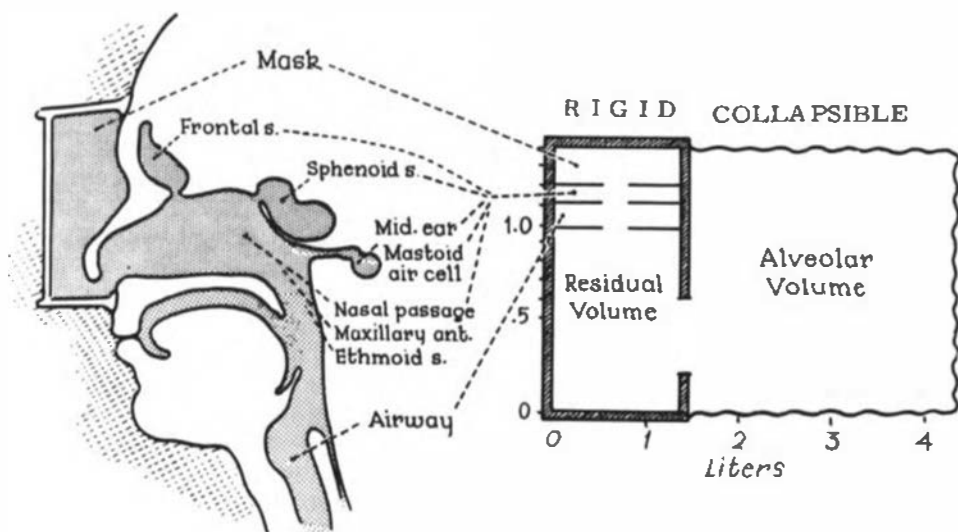


Figure 9. Schematic representation of the various rigid chambers in man which must be properly pressure compensated during a dive. The values for a typical Ama are given on the right and in the accompanying table.

We also do not know to what extent the Japanese Funado fills her lungs before a deep dive. The Korean Cachido fills her lungs only to 85 per cent of her vital capacity.

Ventilation of the Middle Ear

Before leaving the topic of pressure equalization it is of interest to focus for a moment on the middle ear — mastoid air cell chamber. Not only is it one of the smallest rigid cavities, but it also causes frequent trouble during diving. The middle ear chamber has a volume of about 1 ml and is, in turn, connected to the air cell of the mastoid with a volume of about 9 ml. Thus the total gas volume is about 10 ml; and during a dive to 20 m, a gas volume equivalent of 20 ml (measured at 1 atm) must enter the Eustachian tube. For 30 dives an hour to 20 m, therefore, 600 ml will enter and leave this cavity.

Since the typical average rate of descent of the Ama is 1.35 m/sec, this pressure equalization must take place in almost 15 seconds. Thus during this interval, gas must enter the middle ear at a rate of 20 ml/15 sec, or 1.33 ml/sec (when volume is expressed at 1 atm condition). The actual or ambient volume at each succeeding pressure interval, however, is smaller when corrected for the ambient pressure conditions. This is shown in Figure 10 where the ambient volume rate is shown during a dive to 20 m. If this curve is integrated against time, the over-all ambient volume which must enter the middle ear during each compression is only about one-half (10.7 ml).

Ventilatory Preparation before the Dive

The hyperventilation before a dive and the volume of the last breath are obviously important events. A little experience teaches one that the length of the dive will depend to a great extent on the hyperventilation, while the maximal depth which can be reached depends upon the volume of the final inspiration.

The last breath before diving does not appear to be a complete or maximal inspiration. The reason for this is not understood but possibly because it may be uncomfortable since the intrapulmonary relaxation pressure rises between 30 and 40 cm H₂O. It is also possible that the buoyancy becomes excessive, but this would be of little consequence when descent is aided by a weight.

Torres Strait Islanders of Australia when interviewed indicated that they usually take two deep inhalations followed by a normal breath, called the "good breath." They do not take full inspiration on the last "good breath."

In the Tuamotu Archipelago, Williams⁽¹⁶⁾ describes a series of long slow breaths and "finally letting out part of the last breath" before diving. In Korea, Hong⁽⁵⁾ measured the lung volume on the last breath of the Cachido and found that it averaged 85 per cent of the vital capacity.

Whistling: This is the trademark of the Ama both in Japan and Korea. The hyperventilation preceding a dive is accompanied by a loud low whistle which in some individuals increases suddenly in pitch on the last expiration. It is interesting to note that Williams⁽¹⁶⁾ describes a similar maneuver for the pearl divers of the Tuamotu Archipelago, namely, "a series of long, slow breaths, giving off whistles and falsetto notes."

Upon surfacing the Ama also whistles on expiration. I was told by the Japanese Ama that upon surfacing they breathe as slowly as they can since fast breathing is harmful to the lung.

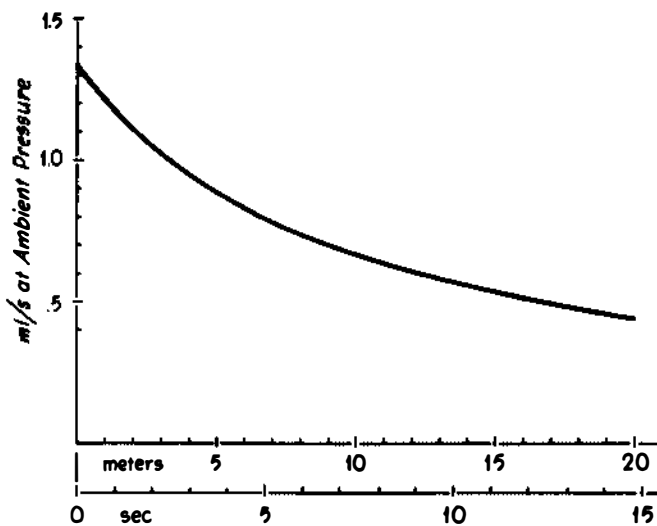


Figure 10. The ambient volume rate changes of compensating gas which must enter through the Eustachian tubes, the middle ear, and the mastoid air cell during a 20-meter dive at a rate of 1.3 m/sec. Since the chamber is about 10 ml for each ear, about 20 ml (STPD) of gas enter and leave the ear with each 20-meter dive. However, the ambient volume flow is less, as indicated in the figure (see text).

The reason for whistling is obscure. The Ama merely state that this maneuver "protects their lungs" and that it "feels better." Hong⁽⁵⁾ proposed that this restrictive maneuver might possibly prevent excessive hyperventilation which Craig⁽³⁾ and others have shown could account for unconsciousness during excessively long dives. Alveolar CO₂ gas concentrations measured just prior to diving were approximately 28 mm Hg in the Korean Ama⁽⁵⁾, which indicates only a moderate reduction in their normal CO₂ levels.

I would like to speculate about another interpretation which was suggested by Dr. Rennie. It is well known that when floating in water the vital capacity is reduced by five to ten per cent. When recently he stood up to his neck in the water and measured his vital capacity before and after whistling, he was able to show on himself and another subject that the vital capacity after whistling was always increased by several hundred ml. The whistling was controlled by blowing through a tube which allowed one to measure simultaneously the intrapulmonary pressure which was about 40 cm H₂O. These preliminary experiments suggest that the intrathoracic blood volume becomes displaced and thus allows for a greater volume of gas to be inspired. It corroborates the previous observations of Bahnson⁽²⁾ who showed an increase in vital capacity after Valsalva maneuvers.

Since the Ama does not appear to fill her lungs maximally prior to a dive, this additional amount of lung gas would seem to be of little consequence. However, raising of the intrapulmonary pressure by whistling may be important if it increases the residual volume, particularly for the Funado who must go to a great depth. Agostoni *et al*⁽¹⁾ noted that during submersion up to the neck the residual volume is normally decreased by over 20 ml presumably due to replacement by an equivalent amount of intrathoracic blood. If during whistling this blood volume is replaced by air, it would provide two advantages. First, 200 ml of extra gas would be available and, secondly, during very deep dives the residual volume could again be reduced by 200 ml as blood replaced the gas. This would increase the total lung volume/residual volume ratio and for the Ama extend the maximal depth of dive from 20 meters to about 25 meters.

Breath-Holding During Descent and Ascent

The changes in lung volume and gas tensions during a dive are quite complex and dramatic. They will form a large part of our discussion. Much of our information on this topic is relatively new but it does corroborate and explain the relatively low O₂ and CO₂ tensions at the end of a dive which Teruoka first described over thirty years ago⁽⁵⁾. Figure 11 indicates in a qualitative manner the direction and changes in gas fluxes which one must expect during a breath-hold dive. They are indeed unique and can only be simulated in the laboratory by breath-holding during rapid compression and decompression in a pressure chamber. As the lung volume decreases during descent, the partial pressures of all gases exceed that of the mixed venous blood and therefore enter the circulation. This continues on the bottom except that the CO₂ flux becomes less and may reverse depending upon the time. During ascent the lung volume expands with a consequential fall in partial pressures. This now induces a rapid efflux of CO₂ from the circulation and reduces the N₂ as well as the O₂ influx. Of particular interest is the fact that the alveolar O₂ tension can fall below that of the mixed venous blood and thus reverse momentarily the O₂ gradient. Judging from Teruoka's

figures it is probably safe to predict that a rather profound arterial unsaturation occurs for a few seconds during a typical ascent of the Funado.

Gas Storage During Repeated Dives

Figure 11 also suggests that unless recovery after each dive is of a sufficient interval to eliminate the CO_2 and N_2 stored during compression, these gases could eventually accumulate when diving is repeated frequently enough. Such phenomena had hitherto been unsuspected. However, evidence will be presented later which indeed suggests that N_2 can be stored under conditions of repeated breath-hold dives to a point where it may actually give rise to bends or possibly taravana, the diving disease of the Tuamotu divers. Similar questions can be asked concerning the accumulation of an O_2 debt and will be discussed by others.

Breath-Holding Time Under Pressure

Is this time extended or reduced under pressure and what advantage or disadvantage does one have over breath holding at the surface? The lung volume is greatly reduced and thus should increase the breaking point stimulus; however, the O_2 tensions are extremely high which would extend breath-holding time. What is the role of the high N_2 tension? Does it in any way influence synaptic or cortical function as far as the breaking point is concerned? We do not know the answers to most of these questions because they were never asked before.

Pulmonary Adaptations

Naturally one asks what structural and functional changes occur in the pulmonary system when this organ is repeatedly stressed in this peculiar fashion. That there are some functions which differ from non-divers is not surprising and these have been reported for Japanese and Korean Ama as well as diving instructors in the United States. But are these all the changes?

Submersion Up to the Neck

When man stands in water up to his neck many subtle changes in pressure distribution are brought about which affect his pulmonary, cardiovascular and

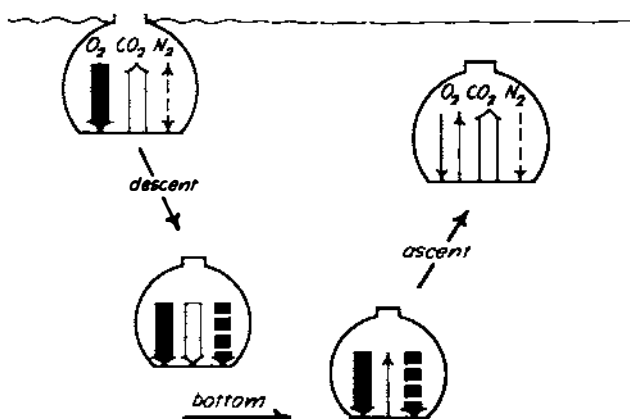


Figure 11. Typical changes in pulmonary gas exchange during descent and ascent. Note that on descent all gases enter the blood. Width of arrow indicates grossly the magnitude of the flux. During ascent partial pressures in alveoli fall and the O_2 tension can fall below that of the mixed venous blood (see text).

renal systems. Relatively little is known about some of these changes although they are experienced daily by many people. It is important first to review the major changes in the pressure distribution. The alveolar surface of the lung can be considered an extension of the air-water interface which is pulled below the general water level, while the hydrostatic pressures of the tissues can be thought of as equal to and continuous with the water phase of their environment except for the tissues inside the thoracic cage. This is shown in a highly schematic fashion in Figure 12 and emphasizes the protection afforded the intrathoracic tissues from the external hydrostatic pressures by being within a semi-rigid, elastic thoracic cage.

Effects on the Pulmonary System: The

major effects are the consequences of a hydrostatic pressure gradient on the thoracic cage. This is shown by the two arrows marked C indicating the increasing compression, while the intrapulmonic pressure remains equal to the barometric. The functional residual volume is thus greatly altered due to changes in both residual and expiratory reserve volume. The average changes for four subjects are shown in Table I. That the pleural surface pressure became less

negative and the rib-cage pressure became more negative is not surprising. However, it is interesting to note that the calculated abdominal pressure below the diaphragm did not increase by an expected 25 cm H₂O (distance between the dome and surface). This indicates that the relaxed abdominal wall offers a resistance of approximately 13 cm H₂O against the hydrostatic pressure.

The changes in residual volume are possibly more than of passing interest. If one looks at the residual volume as a nearly rigid chamber (see Table II) or a chamber with a very low compliance, then its volume changes may represent mostly changes in the intrathoracic blood volume. This would not be surprising in view of the absolute increase of pressures of the extrathoracic vascular system due to submersion while the intrathoracic pressures remained nearly as before. A similar effect is achieved by negative pressure breathing which also results in a decrease of residual volume⁽¹⁾.

One may now speculate that a Valsalva maneuver during submersion would force this accumulation of blood out of the thoracic cavity. This might be achieved by the whistling maneuver prior to diving. This would not only provide 300 additional ml of air, but during the following compression could in turn be replaced

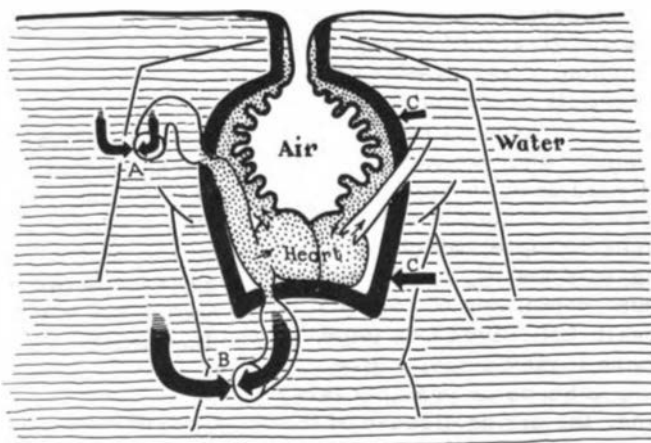


Figure 12. Pressure distribution in the body during emersion up to the neck. For details see text.

TABLE II
Changes in Lung Volumes, Respiratory Mechanics,
and Airway Resistance, Seated in Air and Submersed up to the Neck

	Air	Submersed	Diff.
Expiratory reserve volume l	1.87	0.51	1.36
Residual volume l	1.67	1.39	0.28
Functional residual volume l	3.54	1.90	1.64
Pressure on pleural surface . . . cm H ₂ O	-6	-2	4
Pressure of rib cage cm H ₂ O	-6	-19	13
Abdominal pressure below diaphragm cm H ₂ O	-6	+12	18
Airway resistance: cm H ₂ O			
Pressure required for flow of 1 lit/sec	2.1	3.0	0.9

The average distance between dome of diaphragm and surface of the water was 25 cm. (Averages of four subjects, Agostoni et al⁽¹⁾.)

by blood and thus extend the maximal depth to which a diver goes. At 20 meters this would provide an extra five-meter margin.

The compression of the thoracic cage can be overcome by a sustained voluntary effort of the inspiratory muscles during expiration. This would probably maintain a more normal airway resistance which is appreciably increased during submersion⁽¹⁾. That the inspiratory muscle tone is more developed is possibly suggested by the observations of Song et al⁽¹³⁾ who showed that the Korean Ama can develop a significantly greater maximal inspiratory pressure than the non-diving women, while the maximal expiratory pressures were equal.

Effects on the Cardiovascular System: It is important to bear in mind that the intrathoracic vessels are largely protected from the changes in the absolute pressures to which all the extrathoracic vessels are exposed. The rib cage and the highly collapsible veins provide an efficient barrier to blood and prevent excessive accumulation within the intrathoracic space.

The extrathoracic compartment is not protected and is thus subjected fully to the hydrostatic pressures. Furthermore, these peripheral blood vessels now become supported by a medium with a density similar to that of blood. One may, therefore, purely on physical grounds, expect a redistribution of the peripheral

blood volume, particularly the venous blood. For example, the pressure at the bottom of a 100 cm column of blood is 105.5 cm H₂O when this vessel is supported in air, 5.7 cm H₂O when supported in fresh water, and 2.7 cm H₂O when supported in sea water (see Table III).

TABLE III

Pressure Differences between a Column of
Blood and Supporting Media

Δp in air	=	$k (1.056 - 0.0012)$	= $k 1.055$
Δp in fresh water	=	$k (1.056 - 0.999)$	= $k 0.057$
Δp in sea water	=	$k (1.056 - 1.027)$	= $k 0.029$

(k = height x acceleration and the densities at about 15°C are assumed as follows: air 0.0012, fresh water 0.999, sea water 1.027, and blood 1.056 g/cm³.)

If one neglects the small difference in density between blood and water during emersion, we have a balanced system. As shown in Figure 12 a vein such as A near the surface of the water is subjected to the same transmural force as a vessel such as B far below the surface. This condition simulates the condition of zero gravity. Thus peripheral venous pooling and transmural pressure differences arising from gravitational forces when the body is in air are essentially eliminated during submersion. It is of interest to speculate on the effects of a supporting medium which is denser than blood, such as the Dead Sea or the Great Salt Lake. This should facilitate the return of venous blood from the foot if one were able to stand upright in such a dense salt solution. The intravascular pressure of the bottom of a 100 cm blood column supported by a 25 per cent salt solution is now approximately 16 cm H₂O less than that of the supporting column.

Intrathoracic Vessels: On the other hand, the vessels within the thoracic cage are not supported by water. Thus the gravitational factors operating on the pulmonary vessels are not affected by submersion. A new redistribution of pulmonary blood flow would only be accomplished by altering the pulmonary artery pressure or the transmural pressures across the capillaries.

At first glance one might therefore expect not only a greater increase in venous return but also a congestion of the intrathoracic vessels, neither of which appears to happen except that we had noted a possible increase of 300 ml of the intrathoracic blood volume. The explanation is probably a physical collapse of the large veins as they enter the chest. This is suggested in Figure 12. If we analyze the transthoracic pressure difference we note that the intrapleural pressure in air is -6 cm H₂O during submersion, -2 (Table I) due to the reduction in lung volume. If we assume that the venous pressure as it enters the rib cage

is normally atmospheric, or 0, then we have a pressure difference of 6 cm which drives the blood into the chest. During submersion the absolute pressure in venous blood must increase. If we assume that the vein is 20 cm below the surface as it enters the chest, there is now a (20 to -2) or 22 cm H₂O pressure difference to drive the blood into the chest. However, the thin-walled veins are subjected to the extramural hydrostatic pressure which exceeds that of the intrapleural space and thus collapses the vein at the entrance to the chest. The pressure difference of 22 cm is largely dissipated by the resistance in a manner similar to that of a waterfall, the exact analogy used by Duomarco and Rimini⁽⁴⁾ in analyzing this particular situation, and more recently by Permutt and Riley⁽⁹⁾. In other words, an increase in the pressure drop across the chest during submersion does not exert any influence upon the gross venous inflow. What submersion accomplishes is to increase the height of the "waterfall" across the chest, a situation which must be similar to that of negative pressure breathing or during the Muller maneuver when the intrapleural pressure is reduced by voluntarily creating a large negative intrapulmonary pressure. However, in spite of the collapse of the veins near the thoracic cage and the waterfall effect, there appears to be some distention of the intrathoracic vessels. That these changes in the cardiovascular system play a role in the bradycardia observed during diving is a new and refreshing attack which will be discussed by Dr. Craig. Indirect evidence of intrathoracic blood pooling may also be deduced from the observations of the diuresis which commonly occurs when submersed. This suggests an effect similar to or identical with the Henry-Gauer effect which was first described during negative pressure breathing and is attributed to reflexes arising in the stretched left atrial wall and reduce the ADH secretion. This will be described in more detail by Dr. McCauley.

The bradycardia of breath-hold diving is somehow implicated with the act of submergence, since breath-holding in air or during air compression in a pressure chamber does not elicit the same degree of response. This fact will be stressed by several of our speakers. While during the last few years we have been accumulating rapidly many new observations on the pulmonary, cardiovascular, and renal systems of man while submerged, we are greatly handicapped in our interpretation for lack of an adequate description of the cardiac output and the hemodynamic response when man's body is submersed, with and without breath-holding.

Heat Stresses

Water provides a particular challenge to the thermoregulatory functions of a homeothermic animal. Aquatic mammals have solved this problem by heavy insulation but have sacrificed as a consequence locomotor ability in the air medium. Water not only has a very much higher heat capacity, but also a very much higher heat conductivity. Convective and conductive heat loss thus becomes a formidable stress and probably presents the greatest practical problem which faces the Ama.

The importance of water temperature is well illustrated by Hong and his associates who have observed the Korean Ama throughout the year, where water temperatures vary from 27°C in the summer to 10°C in the winter months. The core temperature drops to 35°C or less during a diving shift. However, in the winter this drop occurs in 20 minutes or less, while in the summer it is prolonged to 60 minutes or more^(6, 14).

The rate of temperature loss is a function of the over-all body insulation and this has been measured during submersion in Korean men and women⁽¹²⁾. It is linearly correlated with subcutaneous fat thickness which becomes, therefore, a highly selective factor for efficient performance of prolonged diving operations. Since women have a thicker layer of subcutaneous fat, this may explain why women and not men began to dominate in this profession.

Adaptations

In addition to subcutaneous fat insulation there are other adjustments which seem to play a role in the diving women. Indirect observations suggest that in winter there is a greater peripheral vasoconstriction. Another adaptation is the shivering threshold which is elevated in the diving women. These are areas of great current interest and will be discussed in more detail.

Heat Production

Exposure to cold water requires great metabolic expenditure which has recently been measured in winter and summer⁽¹⁴⁾. It has been estimated that the daily energy cost of diving is about 1000 Kcal. This appears to be about the same the year around since in the winter they work only one or two short shifts, while in the summer they work three long shifts. The Korean Ama's daily diet contains an average of 3065 Kcal during summer and winter, compared to an over-all Korean average of 2000 Kcal/day⁽⁶⁾.

Of particular interest are the observations of Hong and associates^(6, 14) that the basal metabolic rate increased appreciably during the winter months in Ama but not in non-diving women. No comparable seasonal elevation of BMR is known for air-exposed man. It is highly suggestive that the daily cold water exposure may in some ways be responsible for triggering this reaction, and this will be discussed later.

It is furthermore of great interest to compare the cross-channel swimmers with the Ama. This is another professional group, limited in performance by their ability to regulate body temperature. Dr. Pugh will show that their thermoregulatory behavior differs in some respects, for they manage to maintain relatively normal body temperatures in quite cold waters.

Excessive heat loss and hypothermia must have always been one of the greatest stresses which the Ama faced since they began harvesting the ocean floor. The greater skin adiposity which nature provided the female probably contributed greatly to her selection over the male diver as the one best equipped for this profession. During the long evolution the female Ama has further experimented in various ways to increase her insulation and to restore her heat loss after a prolonged diving shift. Various stages in this evolution are shown in Figure 13, depicting various local habits practiced today in Japan. It is also important to point out that these various degrees of physical insulation are influenced or modified by local traditions, water temperatures, and possible acclimation as well as economic competition.



Figure 13. Different types of body insulation among the Ama of Japan. On the left the Ama of Hekura Island, in the middle Ama from Shima Peninsula in cotton suit, and on the right the recent foam rubber suit of Ama from the Boso Peninsula. (Permission to reproduce these photographs is gratefully acknowledged. Left picture: F. Maraini — The Island of the Fishermen — Harcourt, Brace and World, Inc. Center picture: Y. Nakamura — Ama in Japan — Tokyo Chunichi Press Co. Right picture: Hiroo Tanaka — Mainichi Press Co.)

Restoration of heat loss after prolonged diving shifts is accomplished by warming next to fires. These may be small fires on the boat of the Funado, but more usually are open fires on the shore, and in other cases open fires in specially constructed warming sheds which also afford protection from winds. Data of Hong and associates indicate that oral temperatures of the Korean Ama do not return to normal until at least one hour after emerging from a diving shift. Similar data on Japanese Ama at different times of the year are needed.

Energy Costs of Diving

These are difficult to measure but are of great interest in that they describe the over-all energy costs of such maneuvers. This type of evaluation becomes today even more pressing since we have heard from various speakers that the number of Ama, in Japan as well as in Korea, is rapidly declining.

Of particular interest is to compare the energy cost of the Cachido with that of the Funado. The former dives by herself and is limited to shallow depths; the latter goes passively by weight to great depth and is pulled to the surface by her partner. Therefore, one must also consider the energy cost of the partner, who is shown in action in Figure 14. Not only must he bring the Funado up to the surface, but also the counterweight.

Drs. Yokoyama and Iwasaki have set themselves the difficult task of evaluating the energy costs of the Ama during a particular diving program. What their interesting analysis reveals is, among other things, how little we really know about such elemental facts as the drag resistance of man. It also focuses upon



Figure 14. Partner pulling up the counterweight of a Funado. From the collection of Dr. Teruoka.

the interesting question of what size counterweight is used and how their use and shape evolved over the years. Figure 15 is here reproduced, revealing various types of counterweight and their weight in air.



Figure 15. Different types of counterweight used by the Funado. From the collection of Dr. Teruoka.

The future of the Ama and her profession appear to be uncertain. At what rate her numbers will disappear or whether she will eventually hold her own at a very much re-

duced number is largely an economic question. These considerations depend upon the total metabolic cost of gathering the foodstuffs from the ocean floor vs the metabolic value (or the economic value) of the produce harvested. The metabolic cost of this diving operation is no small matter if it requires a caloric expenditure 50 per cent greater than for the non-diving population(6). In areas where the harvest is poor it is conceivable that the cost becomes greater than the yield.

The obvious complexity of such questions is further emphasized by asking about the probable effects of modern diving equipment. Even foam neoprene suits (Fig. 13) should add significantly to productivity by increasing the diving time that is tolerable from the standpoint of cold, and perhaps reduce the need for additional food. But even such suits must be costly in this economic framework.

The self-contained underwater breathing apparatus (SCUBA) would greatly increase the productivity of a diver. Bottom time is now continuous and harvesting would be much more efficient and systematic. However, the harvest beds would be quickly depleted unless the number of Ama in each village were substantially reduced. One can estimate that for every Ama with diving equipment five to seven Amas would have to retire if the total harvest were to remain the same. Even if such an innovation were economically sound, it would probably not be worth the price in terms of the social upheaval which would necessarily follow in these small villages whose major activities for centuries have developed around a communal diving enterprise.

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LIMITATION TO DEPTHS OF DIVING MECHANICS OF CHEST WALL

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During breath-hold diving the gas containing cavities of the human body are compressed by the increased ambient pressure according to Boyle's Law (pressure x volume = constant) and the compliance of the cavities' walls. As the depth increases the lung volume is accordingly reduced and the chest wall becomes less compliant. When the chest is compressed to a volume smaller than that found at the end of a full expiration, a partial collapse of the lung may take place and the intrathoracic pressure becomes markedly lower than the ambient pressure and therefore the pressure of body tissues and the blood. This situation produces a vascular engorgement of the lung which may lead to pulmonary edema and bleeding of the pulmonary capillary ("thoracic squeeze")⁽¹⁹⁾. Direct data on this condition in man are not available. However, this does not occur in diving mammals (seals, whales); their compliant chest wall is compressed to a complete collapse of the lungs⁽¹⁷⁾.

From the mechanical point of view the maximum depth that can be safely reached by men, during breath-hold diving, depends essentially upon the ratio between the maximum volume of gas that can be contained in the lungs and the volume that is still contained in the lungs after a full expiration, i. e., upon the ratio between total lung capacity (TLC) and residual volume (RV). This, however, is only approximate, because, as mentioned below, the lung volume, during breath-hold diving, is decreased also by other factors and because, generally, the subject inspires deeply, but not fully before a dive.

Lung Volumes: The residual volume in men and women, from 18 to 34 years of age, is about 20 to 25 per cent of the total lung capacity^(2, 13); hence the TLC/RV ratio is four to five, i. e., the maximum compression that the lung may undergo is, roughly, four to five times, which corresponds to a depth of 30 to 40 m.

The average TLC/RV ratio of 20 Korean diving women is four, and not significantly different from that of a control group⁽¹⁸⁾. The value of the TLC/RV ratio decreases with age, mainly because of the change of the RV, which increases about 50 per cent from age 20 to 60⁽²⁾. A similar trend is seen in the Amas⁽¹⁸⁾.

Static Volume-Pressure Curves of the Respiratory System: The static volume-pressure curve of the respiratory system during voluntary relaxation is shown in Figure 1. When the subject relaxes at full expiration his respiratory system tends to expand with a pressure of almost 40 cm H₂O; conversely when the subject relaxes at full inspiration his respiratory system tends to collapse with a pressure of almost 40 cm H₂O. The collapsing pressure at the upper volume limit is given in part by the chest wall and mainly by the lung, the expanding pressure at the lower limit is given by the chest wall (Fig. 1).

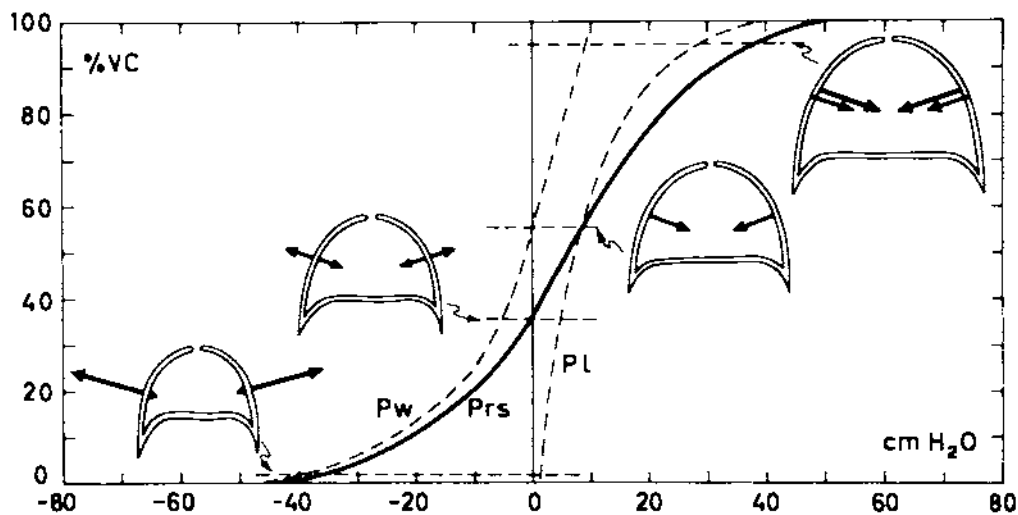


Figure 1. Static volume-pressure curves of the respiratory system (P_{rs}), of the chest wall (P_w) and of the lung (P_l) during relaxation in sitting position. The static forces of the lung and of the chest wall are pictured by the arrows in the side drawings (the dimensions are not in scale); the volume corresponding to each drawing is indicated by the horizontal broken lines. [From Agostoni and Mead⁽²⁾, modified from Knowles et al⁽¹⁴⁾].

When the external force compresses the chest wall below the resting and the residual volume of the respiratory system, the decrease of lung volume occurs mainly through a cranial displacement of the diaphragm, because at these lung volumes the compliance of the rib cage is much lower than that of abdomen-diaphragm^(2,4).

Factors Limiting the Volume Extremes: The upper volume limits, in the majority of subjects, seems to be set by the balance between the passive opposing force, which rises markedly at the largest lung volume, and the force of the inspiratory muscles, which decreases because of mechanical disadvantage and possibly inhibition⁽²⁾.

The lower volume extreme seems set not only by the passive opposing forces, but also by the antagonist contraction of the diaphragm^(2,5,6). The mechanism leading to this contraction is not yet clear. Morphological^(10,11) and functional^(7,8,16) studies indicate that the stretch reflex in the diaphragm should be weak or nil. Furthermore measurements of the transdiaphragmatic pressure in subjects submerged up to the neck showed that the diaphragm at the end of a spontaneous expiration is not active, notwithstanding that it is stretched cranially almost as far as at full expiration⁽³⁾. Even when breathing from a tank in which the pressure is kept 40 cm H_2O below atmospheric and end-expiratory transdiaphragmatic pressure is only slightly higher than that during relaxation

while the end-expiratory lung volume is only three to four per cent VC⁽³⁾. This suggests that also the Hering-Breuer deflation reflex is weak in the conscious subject, in analogy to what has been found for the inflation reflex on several occasions^(1, 21, 22).

It seems therefore that the mechanism leading to the strong contraction of the diaphragm at full expiration, is in some way related to the simultaneous contraction of the abdominal muscles. Hence when the lung volume is reduced by an external force, the antagonist contraction of the diaphragm is negligible down to about RV, and even below RV.

Mechanical Conditions of the Ama's Respiration System During the Dive:

The average depth and period of dive for a Japanese Ama are 16 m and 60 sec; in her diving operation she is assisted and her descent and ascent velocities are 1.5 and 1.9 m/sec, respectively⁽¹²⁾. Higher values of depth and lower values of ascent and descent velocities have been reported by Teruoka⁽²⁰⁾.

Since no data are available on the lung volumes of the Japanese Amas just before a dive, the mechanical conditions of their respiratory system before ascent are analyzed by assuming that their lung volumes are similar to that of the Korean Ama, which however dive only to a depth of 5 m and for a period of 30 sec. The Korean Amas have an average VC of 3.44 liters and a RV of 1.14 liters⁽¹⁸⁾. They inspire to about 85 per cent VC before diving⁽¹²⁾ and therefore the total lung volume is 4.06 liters. Since the volume of the face mask is about 0.2 liters⁽¹²⁾ the total gas volume of the system before diving is 4.26 liters.

The initial lung volume is decreased by compression and by the following factors: (1) excess of O₂ loss over CO₂ gain in the lung during breath-holding, and transfer of CO₂, O₂, and N₂ from alveoli to blood because of the increased pressure of the gas phase^(9, 12, 15); (2) equilibration of pressure in the mask during compression and leaks for the adjustment of the mask⁽¹²⁾.

The decrease of the gas volume due to the compression is indicated by the broken line in Figure 2, which is calculated according to Boyle's Law correcting for the water vapor. The continuous line takes into account also the volume decrease due to the factors mentioned under (1). Because of the lack of information on all the variables involved and the complexity of the phenomenon, the volume decrease produced by factors (1) has been estimated by approximating the experimental data of Lanphier and Rahn⁽¹⁵⁾ to the diving pattern mentioned above. The excess of O₂ loss over CO₂ gain in the lung during 50 sec of breath-holding has been estimated to be 0.3 liters at surface level. The transfer of gas from the lung to the blood because of the increased pressure of the gas phase, has been assumed, for simplicity, to increase linearly with depth; it corresponds to a volume, expressed at 1 atmosphere, of 0.2 liters per 10 m depth. The leakage from the mask has been neglected and the volume of the mask has been considered constant, because the masks used by Amas are rather rigid.

It appears from Figure 2 that the residual volume is reached at a depth of about 16.5 m; since the average immersion depth is 16 m, the Japanese Amas work at the limit of their possibilities. By inspiring to 95, instead of 85 per cent of the VC, before diving, the maximum depth could be increased about 2 m; a similar increase could be obtained by using smaller and more compliant masks.

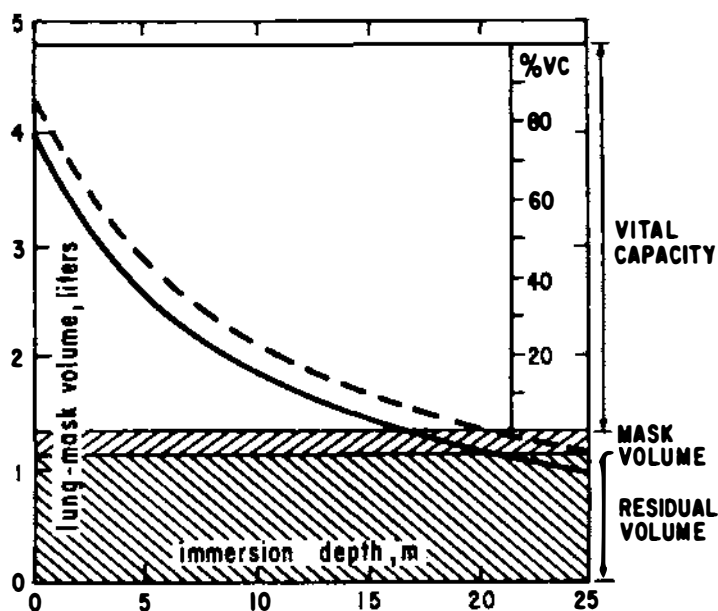


Figure 2. Mechanical limit to compression of the Ama's lung. The volume of the lung plus that of the face mask is plotted against the immersion depth. Since the masks used by the Amas are rather rigid, the volume of the mask has been assumed constant. Before diving the Ama inspires to 85 per cent VC. The broken line is calculated according to Boyle's Law correcting for water vapor. The continuous line takes into account approximately, the excess of O_2 loss over CO_2 gain in the lung during breath-holding and the transfer of gas from the alveoli to the blood because of the increased pressure of the gas phase. These values refer to the moment before ascent (50 sec after immersion) and are estimated from the experimental data of Lanphier and Rahn(15).

Actually, when the lung volume is reduced to RV and the respiratory muscles are relaxed, a pressure of about 30 cm H_2O is sustained by the chest wall; hence at this depth the pressure compressing the gas in the lung is only two per cent less than the average ambient pressure acting on the chest wall.

The pressure exerted by the relaxed respiratory system and chest wall at different depths of submersion is shown in Figure 3. As a result of Boyle's Law and of the mechanical features of the chest wall, the slope of the curve, relating the immersion depth to the pressure of the relaxed chest wall, changes only little in a relatively wide volumes range around RV. Hence, if the diver descends two to three meters below the depth at which his lung volume is reduced to RV, the increase of pressure across the chest wall does not become abruptly critical. This could explain why the Amas may work safely at a depth which compresses their lung close to the residual volume. It is in fact conceivable

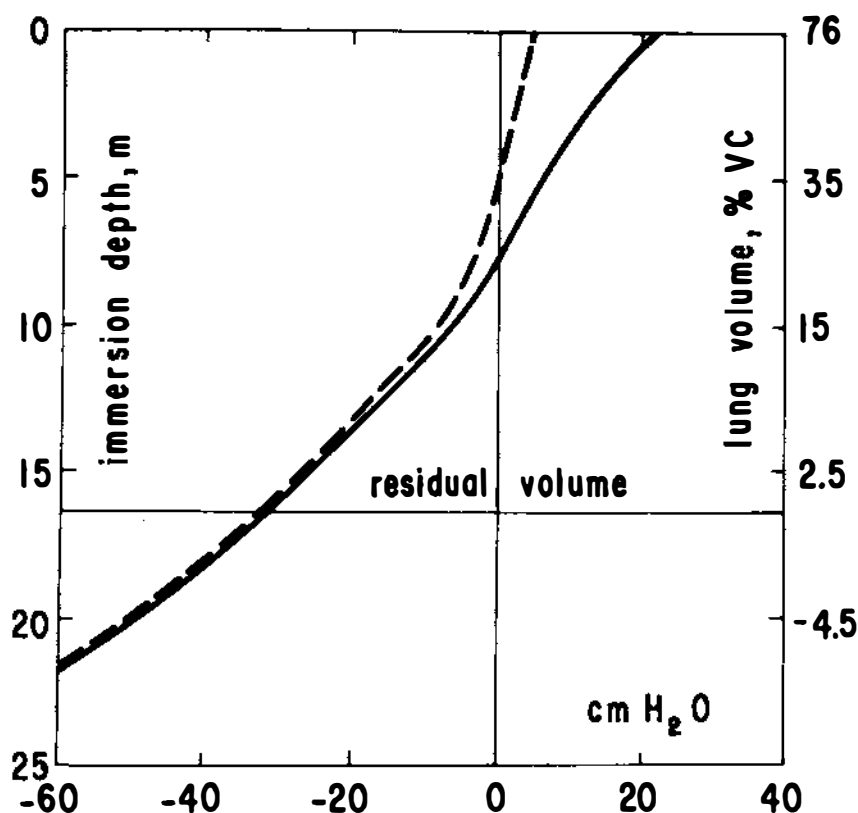


Figure 3. Alveolar pressure (continuous line) and pleural surface pressure (broken line), referred to the average ambient pressure acting on the chest wall of a relaxed subject, at different depths of immersion. The ordinate on the right gives the corresponding values of lung volume, expressed as per cent of the vital capacity. The breath is held at 85 per cent VC: during relaxation the volume is reduced to 82 per cent VC and after 50 sec of breath-holding at the surface it becomes 76 per cent VC. The curves are obtained from the data of Figure 2 and of the volume-pressure curves of the relaxed chest wall and of the lung of supine male subjects, since no such data are available for the Amas; the supine position has been chosen because it is more close to the average condition of the submerged subject.

that, unless warned by painful stimuli from the compressed chest, the Amas may occasionally descend a few meters below the depth at which the RV is attained. Then a partial collapse of the lung may occur through the cranial displacement of the abdomen-diaphragm. The lower resistance to compression at the abdominal boundary of the chest wall along with the probable lack of a strong sustained contraction of the diaphragm could be seen as a useful feature, because, by allowing a partial collapse of the lung and a further compression of the gas, it probably postpones the rupturing of the pulmonary capillaries and tissues, which is the worst alternative.

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ALVEOLAR GAS EXCHANGE DURING BREATH HOLDING AND CONSIDERATION ON THE BREAKING POINT

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It has been revealed that during breath holding the alveolar PO_2 falls continuously but at a diminishing rate, while the PCO_2 rises in an exponential manner^(1, 2, 3). The elevation of arterial CO_2 level has been considered to be an important factor in the onset of breaking point. Despite the detailed analysis by Mithoefer⁽²⁾ and further investigations of Lanphier and Rahn⁽³⁾, the characteristic time course of alveolar and blood PCO_2 changes during breath holding remains not satisfactorily explained.

In this symposium we wish to present a theoretical approach to the interpretation of the pattern of CO_2 retention and distribution in the body that occurs during breath holding and to point out the significance of a time factor in CO_2 stimulation on the respiratory activity when the breaking point occurs. These may provide a physiological basis for practical problems concerning the breath-hold dives.

Theoretical Approach to the Change in CO_2 Level During Breath Holding

In contrast to the differential analysis of Mithoefer⁽²⁾, Lanphier and Rahn⁽³⁾, we have performed an integral analysis⁽⁴⁾. If we assume that the CO_2 level in arterial blood and alveolar air, and that in venous blood and tissue is practically equilibrated, a hydrodynamic analog can be considered as a model (Fig. 1), where: $1/b$ is the CO_2 capacity of circulating venous blood and tissues, and v the PCO_2 level of vessel V , while $1/c$ and l represent similar values, respectively, of the circulating arterial blood and alveolar air in vessel L . Water flow from the faucet B represents the CO_2 production of the body and tube A represents the gas exchange surface.

In this model, during normal respiration, the volume of water, which is pumped out from the vessel L is the same as the volume of water flowing into L from V , which in turn is equal to the water volume pouring in from the faucet, so that the $v-l$ difference is kept unchanged. With an arrest of ventilation the pumping stops and the water level begins to rise. In this condition of respiratory arrest, changes in water level could be described in the following way:

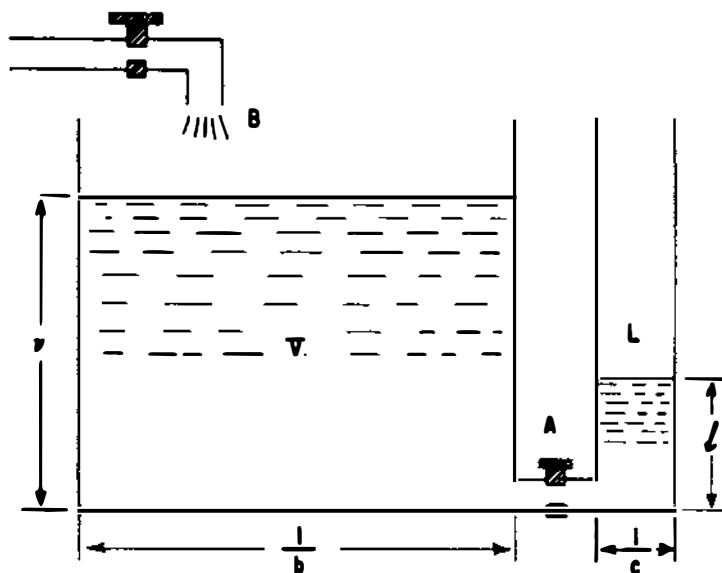


Figure 1. Schema of our CO₂ Model.

The rate of flow through A is given by

$$\frac{dm}{dt} = a(v-l), \quad (1)$$

where \underline{m} = quantity of water flow through A, \underline{a} = flow conductance of A. Considering the rate of CO₂ production in the body (B) to be constant during breath holding,

$$-\frac{dv}{dt} = b \left(\frac{dm}{dt} - B \right) \quad (2)$$

$$\frac{dl}{dt} = c \frac{dm}{dt}. \quad (3)$$

From equations (1) and (2)

$$-\frac{dv}{dt} = ab(v-l) - bB \quad (4)$$

$$-\frac{d^2v}{dt^2} = ab \frac{dv}{dt} - ab \frac{dl}{dt}. \quad (5)$$

From equations (1) and (3)

$$\frac{d^2 l}{dt^2} = ac \frac{dv}{dt} - ac \frac{dl}{dt}. \quad (6)$$

From (2) and (3)

$$\frac{dv}{dt} + \frac{b}{c} \cdot \frac{dl}{dt} - bB = 0. \quad (7)$$

Substituting (7) in (5), we obtain

$$- \frac{d^2 v}{dt^2} - \frac{a(b+c)}{c} \frac{dv}{dt} + \frac{abcB}{c} = 0. \quad (8)$$

Here, if we write \underline{P} instead of $-dv/dt$, \underline{A} instead of $a(b+c)$, B' instead of $\frac{abcB}{c}$, we can now rewrite the equation (8)

$$\frac{dP}{dt} + AP + B' = 0. \quad (8')$$

The general solution is now obtained —

$$P = e^{-At} \left(- \int B' e^{At} dt + C_1 \right) = C_1 e^{-At} - \frac{B'}{A}. \quad (9)$$

Further

$$v = \frac{C_1}{A} e^{-At} + \frac{B'}{A} t + K_1 \quad (10)$$

$$\text{If } \underline{t} = 0, \underline{K}_1 = v_0 - \frac{C_1}{A}.$$

Hence,

$$v = v_0 + \frac{B'}{A} t + \frac{C_1}{A} (1 - e^{-At}). \quad (11)$$

By similar operation we can obtain

$$l = l_0 + \frac{B'}{A} t + \frac{C_2}{A} (1 - e^{-At}). \quad (12)$$

Determinations of the values of C_1 and C_2 are as follows. If $t = 0$, the equation (9) may be written by substitution of (4).

$$C_1 - \frac{bcB}{b+c} = b \{ a (v_0 - l_0) - B \}. \quad (13)$$

$$\text{So, } C_1 = b \left\{ a (v_0 - l_0) - \frac{bB}{b+c} \right\}.$$

$$\text{Similarly, } C_2 = c \left\{ a (v_0 - l_0) - \frac{bB}{b+c} \right\}.$$

The final solutions are, therefore,

$$v = v_0 + \frac{bcB}{b+c} t - b \left(\frac{v_0 - l_0}{b+c} - \frac{bB}{a(b+c)^2} \right) (1 - e^{-a(b+c)t}) \quad (14)$$

$$l = l_0 + \frac{bcB}{b+c} t + c \left(\frac{v_0 - l_0}{b+c} - \frac{bB}{a(b+c)^2} \right) (1 - e^{-a(b+c)t}). \quad (15)$$

Equations (14) and (15) give the time course of changes in CO_2 level in mixed venous blood and in alveolar air or arterial blood, respectively. Graphic illustration of these formulae is shown in Figure 2.

The equations apply to all values of v_0 and l_0 , even when l_0 is higher than v_0 . (Broken line in Fig. 2).

In process of our theoretical consideration several important factors were disregarded, such as Haldane effect in the blood CO_2 dissociation and shrinkage of lung volume(1, 2, 3). Nevertheless, the curve thus obtained agrees well with experimental curves, if appropriate values are given for the constants in the equation (Fig. 3, 4), and it provides a good explanation for the time course of changes in CO_2 level during breath holding (Fig. 2).

In the latter part of breath holding the alveolo-arterial and tissue-venous CO_2 levels rise almost linearly and parallel to each other, keeping a certain difference which is determined by the value of $bB/a(b+c)$. The gradient of the linear rise depends on CO_2 production and CO_2 capacity of the body. The value indicated by " a " is largely dependent on the circulation or cardiac minute volume, and is called here the "transfer coefficient of CO_2 ." The transfer coefficient is concerned in the rate of the initial curvilinear rise or fall of the curve and the level difference between v and l . The curves l and v cross before they become linear and parallel, when the alveolo-arterial CO_2 is higher than tissue-venous CO_2 (Fig. 2).

Values of the constants in the equations (14) and (15) for computations were obtained as follows:

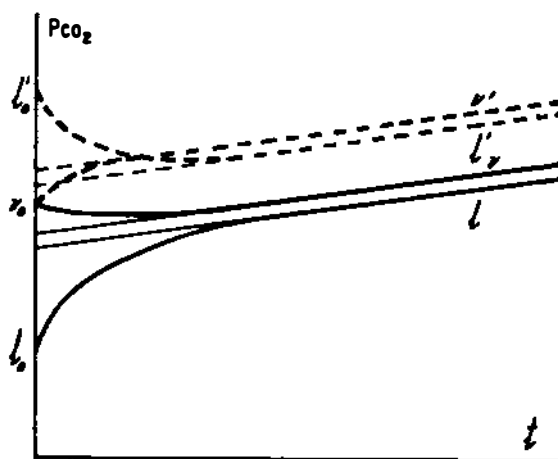


Figure 2. Theoretical curves of CO_2 changes in alveolo-arterial and tissue-venous compartments during breath holding.

Solid lines: Breath holding in normal condition.

Broken lines: Breath holding with a high CO_2 mixture.

Distance of each pair of asymptotes is determined by $aB/a(b+c)$, and the ratio of the distance on ordinate from v_0 to the asymptote concerned to the distance from t_0 or t_0' to the asymptote concerned is as b/c .

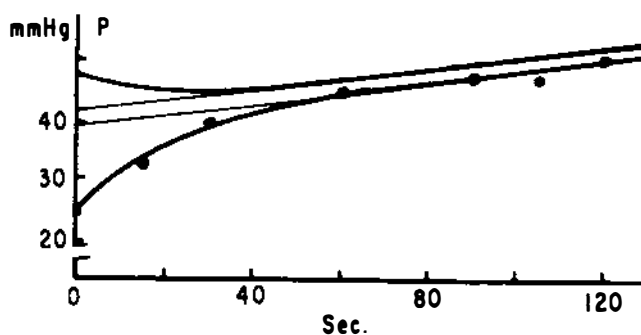


Figure 3. Theoretical curve and measured values (●).
 (Subject H. K., male, 55 kg, breath holding with oxygen.)

t_0 was obtained from analysis of alveolar air immediately after a deep inspiration (for details see below), and v_0 was determined by the CO_2 rebreathing method(5, 6). Though the CO_2 absorption curve of blood is not directly proportional to the CO_2 tension, it could be considered linearly proportional in the range of changes during breath holding. The value of 0.5 ml/mmHg was adopted in the breath holding with oxygen, and 0.8 ml/mmHg

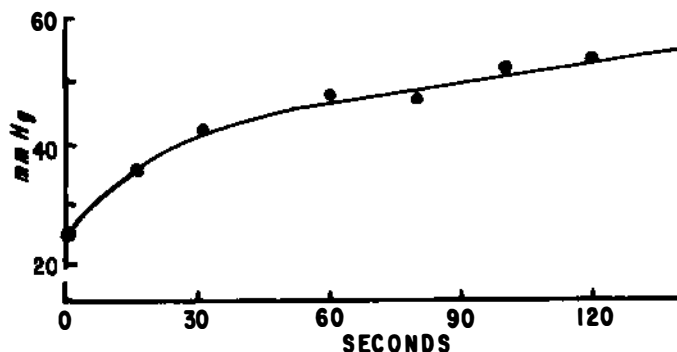


Figure 4. Theoretical curve and measured values (●). (Subject T.N., male, 54 kg, breath holding with air.)

in that with air. For the circulating blood volume the value of 0.06 l/kg body weight was adopted(7). Volume ratio of circulating arterial and venous blood was regarded as 1:3. Thus, $1/c$ could be determined. The CO_2 capacity of body tissues was assumed to be equal to or a little less than that of circulating blood(8). Thus, the value of $1/b$ could be given. The transfer coefficient a was assumed to be 0.37 ml/sec·mmHg. The curve thus obtained showed a fine agreement with the curve experimentally obtained, as seen in Figures 3 and 4.

Experimental curves were obtained as follows: The subject sat in a straight chair breathing room air through a mouthpiece on one arm of a T-way stopcock. After a full expiration, the stopcock was turned to connect the subject to a spirometer containing oxygen or air. He inspired maximally and the volume was read. The breath was then held for a predetermined length of time, at the end of which the subject fully exhaled into an open rubber tube 1 m in length and 2.5 cm in inside diameter. An end-expiratory alveolar gas sample was immediately taken from the tube and volumetrically analyzed. This procedure was repeated for various holding times with 10 to 20 second intervals up to and including the breaking point.

As already stated, our theoretical procedure was performed from an integral viewpoint. The values of alveolo-arterial and tissue-venous CO_2 levels represent the mean of levels in all parts of both compartments at the times concerned. It has been stated by others that the alveolo-arterial PCO_2 exceeds the tissue-venous level in the later stage of breath holding with air due to the Haldane effect and the lung volume shrinkage(2, 3). In our calculated curves, however, the alveolo-arterial PCO_2 is always higher than the tissue-venous PCO_2 even in the later period because of the limitations of our equations. The PCO_2 in our calculation has a composite character and represents therefore the "effective" CO_2 tensions responsible for all the transfers of CO_2 including the Haldane effect or other buffer effects. The decrease of lung volume may result in a rise in alveolar PCO_2 , but it would not be sufficient reason for the steady rise in PCO_2 in the later period.

The prediction of the time course of CO_2 change during breath holding with varied CO_2 concentrations in O_2 are illustrated in Figure 5. It can be seen that

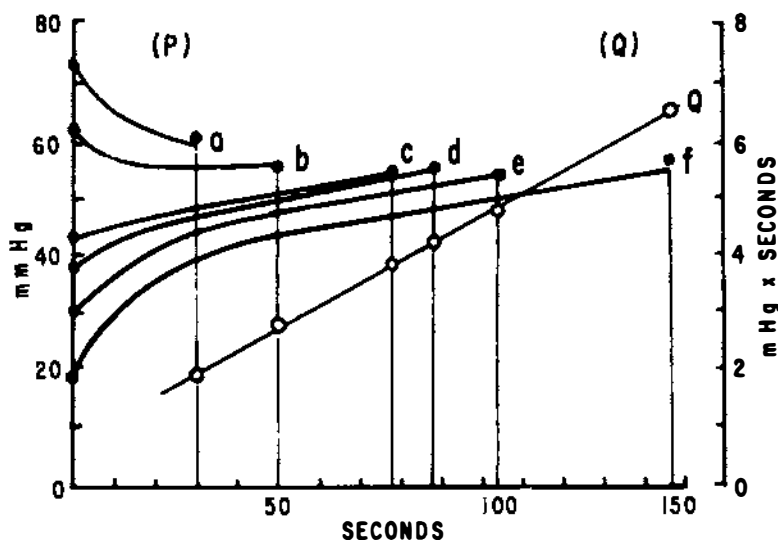


Figure 5. Calculated alveolar PCO_2 changes, measured PCO_2 at breaking points and Q-t curve in breath holding with varied CO_2 concentrations in O_2 .
 CO_2 concentrations in inhaled gas were: a — 16.0%, b — 12.8%, c — 6.7%, d — 5.5%, e — 3.2%, f — 0%.

the calculated curves starting from the measured initial alveolar PCO_2 run through the points actually measured at the breaking point.

It was then attempted to draw a predicted curve during a breath-hold dive of the Funado. For the convenience of calculation, it was assumed that the subject was suddenly brought into and out from the depth of 2 atm pressure, without any circulatory changes. These are shown in Figure 6 and may be compared with the figures of Lanphier and Rahn(9).

Breaking Point and CO_2

A diagram of alveolar O_2 - CO_2 relationship at the breaking point is shown in Figure 7. The diagram indicated by open circles (curve O_2) was obtained from the results of breath holdings with varied O_2 in the inspired gas. A similar curve has been shown by Agostoni(10). This relationship reveals that as a function the CO_2 of the breaking point is lowered by the presence of hypoxia. But, if the breath is held with varied CO_2 concentrations in the air, the breaking point occurs at higher alveolar CO_2 level (curve CO_2 in Figure 7).

Increase of breath-holding time up to a certain limit (commonly about two minutes) with repeated trials or daily training is our common experience. This increase, however, is not accompanied by a correspondingly great change in gas concentrations(11). The black circles in Figure 7 were assembled from values of several subjects during various times of breath holding. In these cases the breath was held with room air. The curve 'air' in Figure 7 follows the time course of the change in alveolar O_2 - CO_2 during breath holding with air and shows that the increase in holding time must be mainly attributed to the increase of will power.

Time Factor in CO_2 Stimulation

These considerations suggest the importance of a time factor in CO_2 stimulation which is concerned in the determination of the breaking point. This we have done by utilizing our theoretical formula. For elimination of anoxic effect, the breath was held with oxygen containing varied CO_2 concentrations. In Figure 5,

an example of these experiments are illustrated. The time course was estimated from the initial alveolar CO_2 level with our formula. Further, the quantity of CO_2 stimulation, which was effective during the breath holding, (tension or content of $\text{CO}_2 \times \text{time}$), could be determined by an integration of equation 15 from the beginning of breath holding up to the breaking point(12).

Relationship between holding time and quantity of CO_2 stimulation (Q) thus estimated was fairly linear (Fig. 5) and suggests the great importance of the time factor in the CO_2 stimulation on central nervous activities related to respiration. A similar Q - t relationship and the significance of the time factor has been reported in ether anesthesia (13). It is interesting that the intensity-duration relationship is similar to that seen in electrical stimulation even though the chemical stimulations act relatively slow.

The Q - t relationship of several subjects are shown in Figure 8. It may be impressive that the slope of Q - t shows only small differences among the subjects. The increase of holding time in the same subject was not accompanied by a slope change of Q - t relation, but only by a parallel upward shift (Fig. 8). This slope may be likened to the rheobase of electrical stimulation and correspond here to a "basic tolerable CO_2 level." It is very interesting that the basic CO_2 level thus estimated was 39.1 mmHg in mean (range: 34.0 - 43.9 mmHg), which coincided with the normal alveolar PCO_2 . In other words, alveolar PCO_2 lies just under the level necessary to cause a dyspneic sensation.

The individual difference in holding time may be mainly dependent upon the difference of will power and the increase in holding time learned by daily repetition.

Summary

With a theoretical consideration, equations indicating the change in PCO_2 in the alveolo-arterial and the tissue-venous systems during breath holding were obtained. The equation is widely applicable to breath holding under various conditions, including underwater diving.

The continuous slow rise of alveolo-arterial and tissue-venous PCO_2 in the later period of breath holding resulted mainly from CO_2 retention in the tissues,

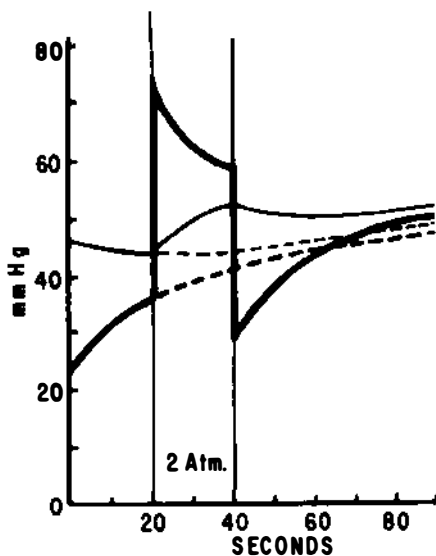


Figure 6. Theoretical changes of alveolo-arterial and tissue-venous PCO_2 during breath holding and sudden dive to the depth of 2 atm pressure for 20 seconds. Thick solid line: alveolo-arterial PCO_2 . Thin solid line: tissue-venous PCO_2 . Broken line: PCO_2 , if the dive did not intervene. (Values of constants adopted for the calculation were those of subject H. K. in the case shown in Figure 3.)

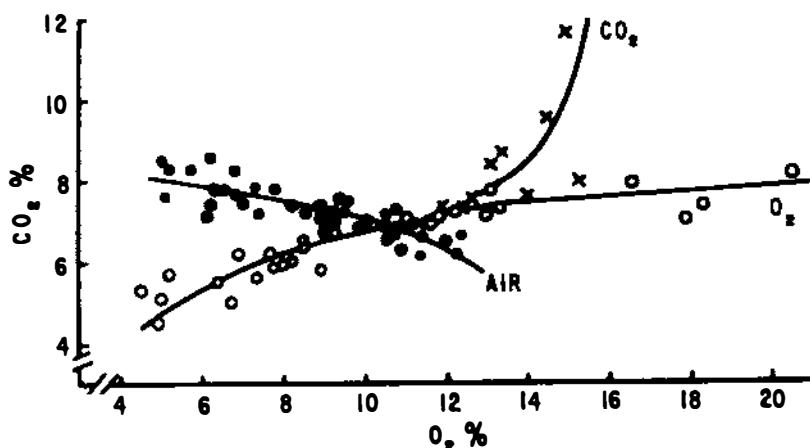


Figure 7. Diagram of Alveolar O_2 - CO_2 relationships at the breaking points in various conditions.

Open circles (line O_2): Breath holding with varied O_2 in N_2 .

Closed circles (line 'air'): Breath holding with air, values were obtained in the way of increasing holding time by daily repetition of holding.

Crosses: Breath holding with varied CO_2 concentrations in air.

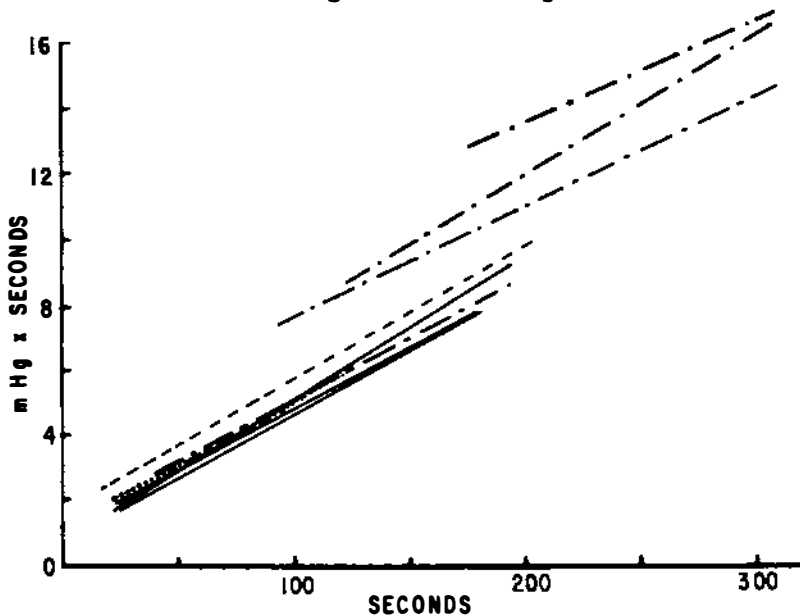


Figure 8. Q-t relationships obtained from several subjects.

Chain lines were obtained from a subject being in the way of holding time increase.

Solid lines: H. H., 27 years, male.

Broken line: K. T., 39 years, male.

Dotted line: S. K., 30 years, male.

Chain lines: K. M., 22 years, female.

and, therefore, its rising rate depends upon the CO_2 capacity and CO_2 production rate of the body.

It becomes evident that the alveolo-arterial PCO_2 of the breaking point is related to an intensity-duration relationship which is similar to that seen in electrical stimulation. This emphasizes the importance of a time factor in the CO_2 stimulation, and probably also in various kinds of other chemical stimulation.

It was found that the basic tolerable CO_2 level, which corresponds to the rheobase in electrical stimulation, was almost the same as the normal alveolar CO_2 level and there was little individual or daily variation.

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*Written in Japanese.

ALVEOLAR GAS EXCHANGE DURING 20-, 30-, AND 40-METER DIVES: THEORY

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The theory for calculating gas exchange during diving with the breath held assumes that the partial pressures of alveolar gases are influenced by two factors; first, being the change due to compression or expansion, accompanying a change in depth, and the second being the change in partial pressure due to exchange of gas between the alveolar air and the blood flowing through the lung capillaries. Because each of these factors may be calculated, if we know the starting conditions and diving conditions, it is possible to calculate the alveolar gas tensions during successive stages of the dive. This calculation is made in a stepwise or cumulative fashion, i. e., one calculates tensions at one meter of depth, then uses these to calculate new tensions at two meters, then at three meters, and so on until completion of the dive(1, 2).

Calculations of alveolar gas tensions have been made for the descending phase of a ten-meter dive and a 20-meter dive, assuming starting conditions and descent rates as close as possible to average conditions measured on diving women and published in recent literature. In these calculations, corrections are made for the effect on alveolar partial pressures due to the shrinkage of gas volume caused by the exchange of O₂, CO₂ and N₂ with the blood flowing through the lungs, and in this respect the calculations are one step more refined than those carried out previously for a dive to 30 meters⁽¹⁾. The metabolic rate is assumed to be greater than in the preceding calculation. This is because the Ama are (a) swimming to stay afloat or to gather food, and (b) exercising or shivering to maintain increased heat production.

The starting and diving conditions were assumed to include a metabolic rate of 1.0 L. (STPD) O₂/min⁽⁵⁾, corresponding cardiac output of 12 L/min⁽⁷⁾, alveolar PCO₂ of 29 mm Hg and PO₂ of 120 mm Hg⁽⁴⁾, mixed venous PCO₂ of 50 mm Hg, and lung volume of 3.7 liters (STPD)⁽⁴⁾. The dive to ten meters was assumed to be made at a descent rate of 0.5 M/sec⁽⁴⁾, and the dive to 20 meters at a descent rate of 1.2 M/sec⁽⁹⁾.

The actual calculation for each dive required progressively filling in a table with ten rows (depth intervals) and 20 columns using simple arithmetic to calculate each entry in the spaces. After completing one row of calculation, the results would be used to start on the next row, and so forth to the end. The columns began with a simple statement of depth, and of time. The alveolar gas tensions from the previous row were multiplied by the pressure ratio to obtain the new tensions. These were then corrected for change in tension due to gas

¹This work was done during the tenure of a Public Health Service Career Investigator Award.

exchange, by calculating the amount of gas volume absorbed by the blood (Fick principle) during the time interval between depths and converting to partial pressure change. These new net partial pressures were further corrected for the shrinkage of lung volume due to gas exchange. Finally, a new lung volume was calculated, based on the compression ratio and the volume of gas exchanged. This completed one row. The next row was calculated the same way, but with ratios altered by the change in depth.

For example, let us calculate the first row (first two meters) of a 20-meter dive at a descent of 1.2 M/sec. The initial PAO_2 is 120, PA_{CO_2} 29.0, and P_{AN_2} 567 mm Hg. The compression ratio is 11.4/9.4 (second depth in meters plus 9.4 M/first depth in meters plus 9.4 M). The number 9.4 is one atmosphere of pressure, in meters of water, minus vapor tension at 37°C, in meters of water. The alveolar tensions due to this compression would be 145, 35.1, and 686 respectively.

To calculate the volume of O_2 , CO_2 and N_2 exchanged between alveolar air and blood, we use the Fick principle. For oxygen, the change in volume, STPD, equals blood flow times A-V content difference times time interval. However, so long as the blood is saturated with oxygen, this calculation is practically the same as calculating volume change due to the mean metabolic rate multiplied by the time interval, or $-17 \text{ cc/sec} \times 1.79 \text{ sec}$, or $-30.4 \text{ ml } O_2 \text{ STPD/sec}$. For CO_2 , we take blood flow (200 cc/sec) times mixed venous (50) minus alveolar tension (35 mm Hg after compression) times the slope of the CO_2 dissociated curve, which is $0.47 \text{ cc STPD/100 cc blood per mm Hg}$ over this range of PCO_2 (3), times the time interval, 1.79 sec. This amounts to $+25.2 \text{ ml } CO_2$. Nitrogen exchange would equal blood flow multiplied by alveolar tension (now 686) minus venous tension (567 throughout the dive) multiplied by the solubility of N_2 in blood ($0.0018 \text{ ml } N_2 \text{ STPD/100 cc bld/mm Hg}$) multiplied by the time interval, again 1.79 sec, a total of $-0.76 \text{ ml } N_2 \text{ STPD}$. The algebraic sum of these volumes for O_2 , CO_2 and N_2 is then -6.0 ml STPD , or $6.0 \times 9.4/11.4 = 5.0 \text{ ml}$ at the new ambient pressure. To convert the small gas volume changes in the lung to their respective partial pressure changes, we multiply them (-30.4 , $+25.2$, -0.76) by $(B-47)/\text{lung volume}$ (ambient pressure, 0°C dry), or $7 \text{ } 13/3.7$, yielding -5.9 , $+4.9$, and -0.1 mm Hg . These small changes in partial pressure are added algebraically to the figures for alveolar gas tension after compression (i.e., 145, 35, 686) to give net partial pressure resulting from compression plus gas exchange (139, 39.9, 686). Next these numbers are corrected for lung volume shrinkage due to gas exchange by using the ratio of lung volume (3,700 ml) to lung volume plus volume change (3,700 ml-5ml). The corrected values for PO_2 , PCO_2 and PN_2 then are 139, 39.9, and 687 mm Hg. Finally, the new lung volume is calculated by using the former lung volume from which gas exchange had been subtracted (i.e., $3,700-5$) and multiplying it by the compression ratio (11.4/9.4 M/M), yielding 3.05 at ambient pressure 0°C, dry). These alveolar gas tensions and this lung volume then are used as the starting values applicable to the next depth (2 M). The next row is calculated, and so forth. During each new depth calculation for CO_2 , a new alveolar CO_2 tension necessitates use of a slightly different dissociation slope, obtained from the reference cited(3).

The results of calculating the alveolar gas tensions for the two dives (10 M, 20 M) under conditions assumed to correspond to those measured for the Korean

and Japanese Ama^(4, 9) are given in Table I and Table II, respectively. In these tables, lung volume has been converted back to BTPS by multiplying the values at 0°C, dry, by the ratio

$$\frac{(10M + \text{depth in M})}{(9.4M + \text{depth in M})} \times \frac{310}{273}$$

Inspection of the two tables allows us to examine several points of interest, because we can compare the theoretical values with those measured on diving women, and we can see whether the various correction factors all are necessary, or whether simple depth ratios would suffice to calculate such things as lung volume, related to the problem of "squeeze," or alveolar nitrogen tension, which is relevant to problems of "bends."

First, by comparison of the alveolar gas tensions calculated at 8 M depth with those measured on Cheju Islanders at 8.2 M depth, July 1960⁽⁴⁾, we see that the theoretical alveolar PO₂, PCO₂ and PN₂ would be 144, 54.3 and 1137 mm Hg, whereas the alveolar gas samples collected from an expired air trap were 149, 42 and 1143, respectively. The agreement between calculated and measured oxygen and nitrogen tensions is very close, whereas the measured PCO₂ is far less than that which is predicted theoretically. There are two alternative possible explanations for this difference, one being that the mixed venous PCO₂ of the diving women was about 40 mm Hg instead of 50 mm Hg, and the other that CO₂ may have been lost from the gas sample due to diffusion into water or rubber prior to analysis of the gas sample. Inclusion of dead space air in the alveolar sample is a third possibility.

The trend of gas tension during diving may be compared with that obtained by analysis of alveolar samples obtained in a compression chamber⁽⁶⁾, or underwater^(4, 8). In the theoretical calculation, a greater metabolic rate has been assumed, corresponding to values measured on women diving to five meters, and averaging summer and winter values⁽⁵⁾. Since accurate data on women diving to greater depths were not available, the rate of oxygen consumption was assumed to be equal to that of women diving to five meters. Due to assistance in diving from the person in the boat, this may be an overestimation of metabolic rate.

The alveolar nitrogen tensions calculated using the corrections for O₂, CO₂ and N₂ exchange with blood were 1300 at 10 M and 1920 at 20 M, compared with alveolar nitrogens due to compression done amounting to 1170 and 1775, representing potential errors of 11 per cent and 8 per cent, respectively, if simple depth ratio alone were used to calculate N₂ tension. For practical purposes, i. e., bends, this error would be negligible, and therefore the more elaborate calculations of gas exchange are not needed in estimating bends hazard.

The lung volumes at depths of 10 at 20 M due to simple compression would have been 2.09 and 1.37 L (BTPS) contrasted to values of 1.87 and 1.22 L (BTPS) calculated by taking gas exchange into account. Thus, 220 ml and 150 ml shrinkage occurred due to gas exchange. For purposes of calculating the effect on alveolar partial pressures and on minimal lung volume at depth (squeeze), these volume differences would introduce errors of 12 per cent and 12 per cent respectively, and this is not a great error for most practical purposes.

To complete the picture, it is intended to calculate alveolar gas changes during the period on the bottom and during ascent, using the same general method of calculation. Changes in mixed venous CO₂ and O₂ tension probably will be taken into account. Calculation on dives to greater depth (30 and 40 M) also should be made, time permitting.

TABLE I

Dive to 10 Meters Depth at 0.5 M/sec
(Oxygen consumption 1.0 L/min, cardiac output 12 L/min)

DEPTH (M)	TIME (sec)	LUNG VOLUME (L, BTPS)	Alveolar Gas Tensions		
			P _A O ₂ (mm Hg)	P _A CO ₂ (mm Hg)	P _A N ₂ (mm Hg)
0	0	4.50	120	29.0	567
1	2	4.01	126	39.9	630
2	4	3.61	132	47.8	692
3	6	3.27	137	51.7	759
4	8	2.97	141	54.1	829
5	10	2.73	143	55.0	899
6	12	2.51	145	55.3	981
7	14	2.32	145	54.9	1057
8	16	2.15	144	54.3	1137
9	18	2.01	141	53.5	1217
10	20	1.87	137	52.9	1300

TABLE II

Dive to 20 Meters Depth at 1.2 M/sec
(Oxygen consumption 1.0 L/min, cardiac output 12 L/min)

DEPTH (M)	TIME (sec)	LUNG VOLUME (L, BTPS)	Alveolar Gas Tensions		
			P _A O ₂ (mm Hg)	P _A CO ₂ (mm Hg)	P _A N ₂ (mm Hg)
0	0.0	4.50	120	29.0	567
2	1.8	3.65	139	39.9	687
4	3.6	3.05	158	48.5	816
6	5.4	2.58	177	54.3	953
8	7.1	2.26	192	56.7	1090
10	8.9	2.00	205	56.8	1206
12	10.7	1.79	215	55.7	1342
14	12.5	1.61	223	54.2	1478
16	14.3	1.46	230	53.1	1629
18	16.1	1.32	234	51.9	1778
20	17.9	1.22	234	51.3	1920

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BREATH HOLDING UNDER HIGH PRESSURE

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Physiological studies on breath holding under hyperbaric conditions may conveniently be divided into two main groups, viz., (1) those dealing with conditions of changing ambient pressure, and (2) those performed at a constant elevated pressure. While in the past several investigations pertaining to the first group have been reported(5, 10, 20, 24, 35, 36), only a few reports are available on voluntary apnea at constant raised pressures(2, 15, 37). The present communication is restricted to investigations on man at rest under constant ambient pressures. It includes recent and hitherto unpublished observations from our laboratory, and deals mainly with the alveolar gas exchange and related functions in breath-holding experiments with closed airways and with raised alveolar O_2 and N_2 tensions.

Breath-Holding Times

Within the pressure range studied so far (0.5 - 4.0 atm abs) the maximum breath-holding time after breathing air increases with the ambient pressure(2, 12, 15, 16). Under hyperbaric conditions (Table I) the relation of the maximum breath-holding time in seconds (y) to the ambient pressure in atm abs (x) is a very close approximation to the logarithmic expression $y = a \log_{10} x + b$, where a and b are constants which vary between individuals(16). The mean values of a and b in eight subjects were 166 and 54, respectively(16). At subatmospheric pressures, on the other hand, the maximum breath-holding time has been found to vary in direct proportion to the change in ambient pressure(12).

As pointed out recently by Agostoni(1) the period of breath holding may be divided into two parts, the first being characterized by voluntary inhibition of respiratory muscle activity, the second by involuntary respiratory efforts. Under hyperbaric conditions the duration of the first period, i. e., the time of apnea up to the onset of diaphragm activity increases with the ambient pressure but relatively less than the maximum breath-holding time (Table I).

Time Courses of Changes in Alveolar Gas Tensions

During the first 15 to 20 seconds of breath holding at high arterial PO_2 levels, the alveolar (arterial) PCO_2 rises exponentially to approach that of the oxygenated mixed venous blood(9, 11). From this it can be inferred that when voluntary apnea is initiated at normal resting lung volume, the alveolar (arterial) PCO_2 will surpass the true mixed venous PCO_2 after some 10 to 15 seconds. Beyond this point the rise in $P_A CO_2$ proceeds at a slower rate as illustrated by the curve in Figure 1. The solid part of the curve was constructed from data obtained in eight subjects in breath-holding experiments performed with oxygen or air at such ambient pressures that $P_A O_2$ at the breaking point exceeded 100 mm Hg. The resting metabolic O_2 consumption averaged 230 ml O_2 per minute STPD, and the

TABLE I

Breath-Holding Time at Breaking Point and at Onset of Diaphragm Activity After Breathing Air at Different Ambient Pressures

		Ambient pressure, atm. abs.						Apnea initiated at:	Subjects	Reference
		1.0	1.3	2.0	3.0	4.0	6.0			
A. Time of apnea at breaking point, sec.	Mean	91					217	Full inspiration	Experienced divers n = 25	Shilling et al(37)
	Range	52-167					76-617			
	% of control*	100					230+16			
	Mean	69		120	145	186†		End of normal expiration	Instructors at Escape Training Tank n = 3	
	Range	53-90		94-152	117-200	142-229				
	% of control*	100		176+4	210+11	241				
	Mean	54	74	103	135	154		Normal resting lung volume	Professional and amateur divers n = 8	
	Range	41-71	56-102	70-142	85-253	97-309				
	% of control*	100	139+7	189+6	245+21	276+29				
B. Time of apnea at onset of diaphragm activity, sec.	Mean	28	39	45	54	60		Normal resting lung volume	Professional and amateur divers n = 8	Hesser et al(16)
	Range	17-35	25-53	21-65	26-86	31-99				
	% of control*	100	142+5	159+13	190+16	214+21				

*Values are means + SE. Control values refer to data obtained at sea level pressure (1.0 atm. abs.).

†Mean of two subjects.

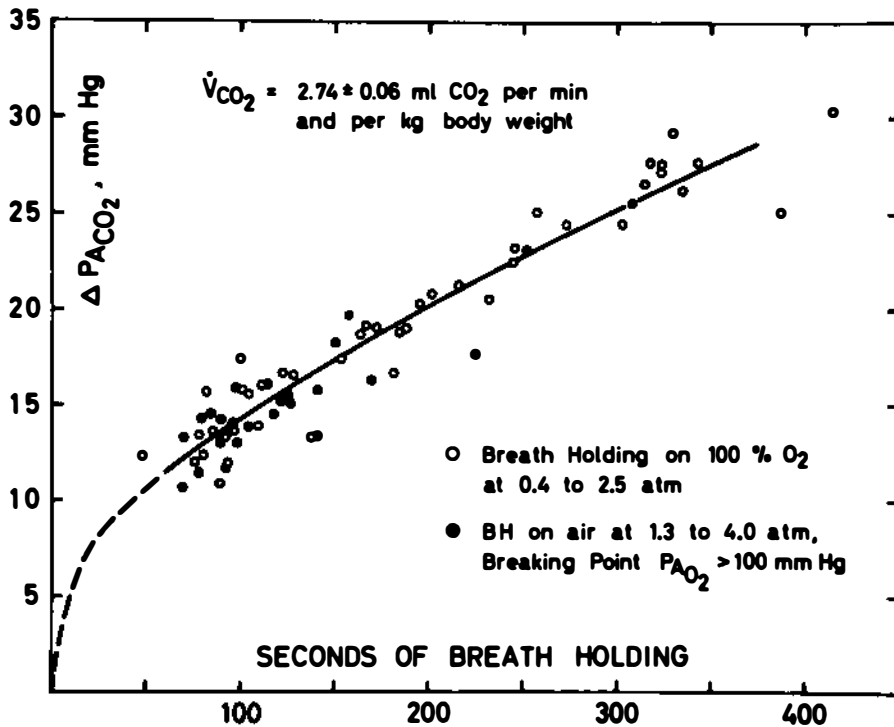


Figure 1. Increase in Alveolar PCO_2 Plotted Against Time of Breath Holding.

Individual data from eight subjects. Solid part of the curve was constructed by the aid of advancing means. First 20 seconds of broken part based on data from DuBois, Britt and Fenn⁽¹¹⁾ and Fenn and Dejours⁽¹³⁾. Data refer to experiments where the alveolar PO_2 at the breaking point exceeded 100 mm Hg and hence the arterial O_2 saturation remained at a high level. [Hesser, Beskow and Holmgren⁽¹⁶⁾.]

lung volume at the start of breath holding about 3.0 liters BTPS (Table II). The increments in P_ACO_2 at equal breath-holding times showed a tendency to be higher with oxygen than with air. The difference between the oxygen and air data was very slight, however, and both sets of data were therefore used for the construction of the curve.

The slope of the curve in Figure 1, i. e., the rate of increase in P_ACO_2 diminished as the breath-holding time was prolonged. Thus, after one minute and five minutes the speed at which P_ACO_2 rose amounted to about 5 mm Hg and 3 mm Hg per minute, respectively. It can be shown by calculation that whereas the alveolar (arterial) PCO_2 increased by approximately 25 mm Hg during five minutes of breath holding (Fig. 1), the simultaneous rise in mixed venous PCO_2 was only about 15 mm Hg.

The predominating factors governing the rate of fall in alveolar PO_2 during voluntary apnea are (a) the fraction of O_2 in the inspired gas, (b) the lung volume at start of apnea, (c) the ambient pressure, and (d) the rate of O_2 uptake from the lungs. When the breath is held with air under hyperbaric conditions at normal

TABLE II

Alveolar O₂ Tensions and Other Related Data at Start and at
 Breaking Point (BP) of Breath Holding (BH)
 on Air Under Normal and Hyperbaric Conditions

Variable	Symbol	Ambient pressure, atm. abs.				
		1.0	1.3	2.0	3.0	4.0
Breath-holding time, minutes	t	0.90	1.23	1.72	2.25	2.56
Alveolar PO ₂ before BH, mm Hg	P ^o O ₂	102	146	254	409	563
Alveolar PO ₂ at BP, mm Hg	P ^t O ₂	59	86	161	288	425
Alveolar PN ₂ before BH	P ^o N ₂ /P ^t N ₂	.944	.938	.936	.944	.951
Alveolar PN ₂ at BP						
Expiratory reserve volume at BP, liters BTPS	-	1.15	1.24	1.21	1.28	1.34
Lung volume at BP*, liters BTPS	V ^t	2.73	2.82	2.79	2.86	2.92
Lung volume at start of BH†, liters BTPS	V ^o	2.89	3.01	2.98	3.03	3.07
Average O ₂ uptake from lungs during BH‡, ml/min STPD	$\dot{V}_A O_2$	172	186	207	214	221
Average fall per min in P _A O ₂ during BH, mm Hg	-	48	49	54	54	54
Average decrement per min in lung volume during BH, % of V ^o	-	6.2	5.0	3.7	2.5	1.9

Mean values for eight subjects (two determinations in each subject).

Subjects: Age 22-38 years; weight 58-89 kg; height 164-188 cm; metabolic O₂ consumption ($\dot{V}O_2$) before breath holding 230 ± 10 ml O₂ per min STPD (mean ± SE); vital capacity 4.75 ± 0.23 liters BTPS.

*Calculated as expiratory reserve volume plus residual volume. Residual volume estimated to constitute 25 per cent of total lung capacity.

†Calculated from the relationship $V^t = V^o P^o N_2 / P^t N_2$, assuming the N₂ content in the lungs to remain constant during breath holding (see text).

‡Calculated as $\dot{V}_A O_2 = (P^o O_2 V^o - P^t O_2 V^t) / 0.863 t$.

[Hesser, Beskow and Holmgren(16).]

resting lung volume, $P_A O_2$ decreases at an approximately constant rate of about 1 mm Hg per second as long as no hypoxia ensues(16). Beyond this point, the rate of fall in $P_A O_2$ decreases (cf Table II).

Dynamics of Changes in Alveolar Gas Stores and Lung Volume

During breath holding on air at ground level with the airways closed, the lung volume decreases progressively because the rate of O_2 uptake through the alveolar membranes is then always higher than the rate of CO_2 output(34, 38). In this special case the net exchange of N_2 in the lungs is negligible, so that any change in the total lung volume is a quantitative reflection of the extent to which the sum of alveolar O_2 and CO_2 stores have changed. By contrast, whenever the P_{N_2} of the alveoli differs appreciably from that of the body tissues, the alveolar N_2 store will also change and add to the total effect.

In the following we shall consider the alterations occurring in the alveolar N_2 , O_2 and CO_2 stores, and thus in the total lung volume, during breath holding at high ambient pressures. These alterations depend on the rates of exchange of the three gases in the lungs; in the case of N_2 , alterations are greatest at the beginning of an exposure to a new pressure level. It follows that whenever short-lasting exposures are used for studies of this kind — as one may be tempted to in order to avoid time-consuming decompression — any alterations in the total lung volume with time may be significantly influenced by the N_2 exchange. We shall therefore first look into the effects of N_2 exchange on the alveolar N_2 store and total lung volume, assuming for the sake of simplicity that the ambient pressure is raised abruptly in a step-change fashion prior to the breath-holding tests.

Alveolar N_2 Store: From published data on the dynamics of N_2 washout during oxygen breathing(27, 28) we have calculated the rate of uptake of nitrogen, $\dot{V}N_2(t)$, by the body tissues of a 70-kg man during the first 60 minutes following an abruptly induced 1.000 mm Hg increment in $P_A N_2$. Results of these calculations are given in Figure 2, Curve I. As can be seen $\dot{V}N_2$ decreases rapidly as the time of exposure to the raised $P_A N_2$ is prolonged, and becomes less than 20 ml N_2 per minute beyond the fifteenth minute. When the breath is held with closed airways, the alveolar N_2 store must decrease at the same rate as the peripheral N_2 stores increase, because the total amount of N_2 stored in the body then remains constant. It follows that Curve I also shows the speed at which the alveolar N_2 store decreases in this situation, provided that cardiac output does not change significantly.

Curve II (Fig. 2) shows the rate at which the peripheral and alveolar N_2 stores, $\dot{V}N_2(t)$, are changed when the breath is held on air following a sudden rise in ambient pressure from 1.0 to 4.0 atm. The rate of the resulting reduction in lung volume ($\dot{V}L$), expressed in percentage of the initial lung volume (V_L^0) can be read from Curve II using the right hand scale. Since $\dot{V}N_2(t)$ is proportional to the initial increment in $P_A N_2$, the speed at which the alveolar N_2 store (STPD) diminishes during breath holding is increased in almost direct proportion to the rise in ambient pressure. However, this is not the case with the resulting reduction in lung volume (BTPS), which is only slightly influenced by the ambient pressure. Thus, a sudden increment in ambient pressure from e. g., 1.0 to 7.0 atm will result in a 100 per cent increase of the $\dot{V}N_2(t)$ values of Curve II, but only in a 14 per cent increase of the $\dot{V}L/V_L^0$ values.

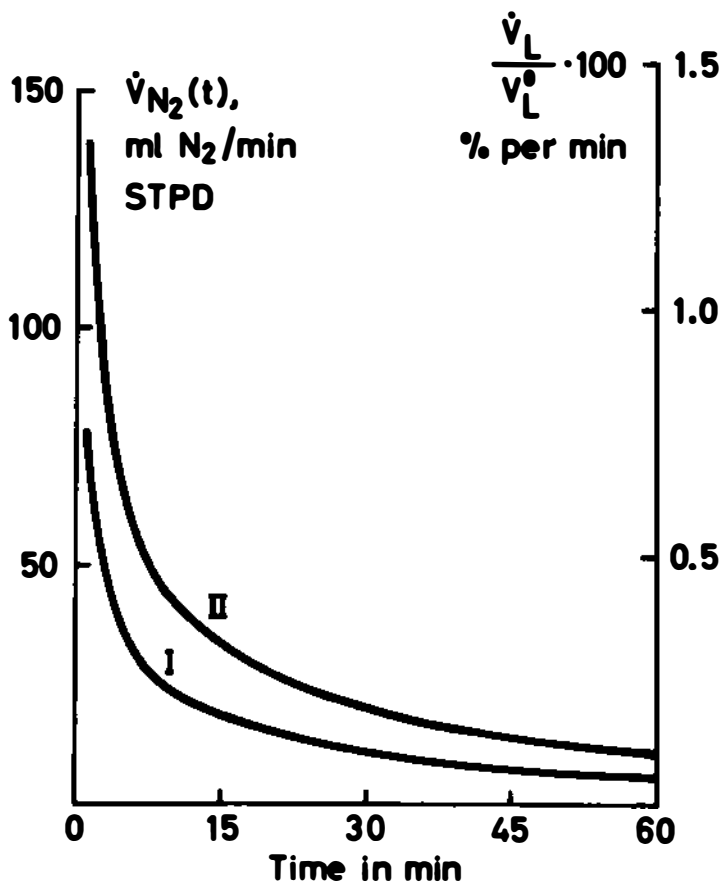


Figure 2. Rate of N₂ Uptake in the Body Tissues of a 70-kg Man Following a Step-Function Increment in Alveolar PN₂:

Curve I: when P_AN₂ is abruptly increased by 1.000 mm Hg;

Curve II: when the ambient pressure is suddenly raised from 1.0 to 4.0 atm during air breathing.

Also indicated by the curves are the rates at which the alveolar N₂ store decreases during breath holding with closed airways initiated anywhere along the time axis. In the case of Curve II, the associated reduction in lung volume (\dot{V}_L) may be read from the right hand scale in per cent per minute of the initial lung volume (\dot{V}_L^0), here assumed to be 3.0 liters BTPS.

The curves were constructed from data on N₂ elimination during O₂ breathing^(27, 28), with body fat content assumed to be 20 per cent of the body weight.

Alveolar O_2 Store: Evidence has been presented that when the breath is held with high alveolar O_2 tensions at ground level, the rate of O_2 uptake from the lungs ($\dot{V}_A O_2$) is approximately the same as the rate of metabolic O_2 consumption ($\dot{V}O_2$) prior to the apnea^(34, 38). This may indicate that the average metabolic rate does not change appreciably in man during apnea. When, on the other hand, breath holding is initiated at a normal or lowered $P_A O_2$ at ground level and the breath is held until the breaking point, $\dot{V}_A O_2$ becomes less than $\dot{V}O_2$ ⁽²⁵⁾. Under these conditions therefore, part of the metabolic O_2 need is probably covered by oxygen from O_2 stores other than the alveolar⁽³⁴⁾.

Support for the view that the average $\dot{V}O_2$ does not change significantly during voluntary apnea has been found in breath-holding experiments under hyperbaric conditions⁽¹⁶⁾. Results of these experiments (Table II) also indicate that during breath holding on air at raised pressures, the metabolic O_2 requirement is almost entirely supplied from the alveolar O_2 store, provided that $P_A O_2$ at the breaking point exceeds about 150 mm Hg. This follows from the following observations. The average $\dot{V}O_2$ of the eight subjects was 230 ml O_2 per minute before breath holding. During the periods of apnea the calculated average O_2 uptake from the lungs was about 210 ml per minute in experiments where $P_A O_2$ was higher than 150 mm Hg (ambient pressure 2.0 atm or higher), and fell to 186 and 172 ml per minute in experiments at 1.3 and 1.0 atm, in which $P_A O_2$ at the breaking points averaged 86 and 59 mm Hg, respectively (Table II). In these calculations the volume of N_2 in the lungs was assumed to remain constant during the periods of breath holding, which seems permissible since (a) at least 15 minutes were allowed to pass after each change in ambient pressure before apnea was initiated, and (b) the data on alveolar gas tensions were obtained from two different series of experiments, the first one with successive, stepwise increments, and the other with successive, stepwise decrements in ambient pressure. In this way any errors introduced in the calculations of lung volumes due to N_2 gas exchange should tend to be cancelled.

Thus, when the breath was held on air at 2.0 atm or higher ambient pressures, only about 20 ml O_2 per minute were drawn from body O_2 stores other than the alveolar. This O_2 portion, which evidently was drawn from the blood and tissue O_2 stores, increased when $P_A O_2$ fell below the 150 mm Hg level, amounting to some 45 ml/min in the experiments at 1.3 atm, and to 60 ml/min at 1.0 atm. Because of the shorter duration of apnea at 1.0 atm, the total amount of O_2 supplied from the blood and tissue O_2 stores was approximately the same (about 55 ml) in the two breath-holding periods. The lower rates of O_2 uptake from the lungs at 1.0 and 1.3 atm resulted in lower rates of fall in $P_A O_2$ (48 and 49 mm Hg per minute, respectively) than at the higher pressures, where $P_A O_2$ fell by an average of 54 mm Hg per minute (Table II).

From the above calculation that approximately 20 ml O_2 per minute were drawn from the blood and tissue O_2 stores, certain conclusions can be reached concerning the behavior of the a-v O_2 content difference during the course of breath holding at high pressure. Thus, with the same fall in arterial PO_2 as in the alveolar PO_2 , i. e., 54 mm Hg/min, each liter of arterial blood will give off 1.7 ml O_2 per minute from the oxygen stored in physical solution ($\alpha = 0.024$). For the case that all regional a-v O_2 differences throughout the body should remain constant during breath holding, the O_2 content in each liter of venous blood

should also decrease at a rate of 1.7 ml/min. Assuming a total blood volume of 5.3 liters, the arterial and venous blood O_2 stores would thus deliver 9 ml O_2 per minute. On the other hand, an increment of e.g. 1 vol per cent in all regional a-v O_2 differences signifies that the venous blood O_2 stores have diminished by about 40 ml O_2 (venous blood assumed to constitute 75 per cent of the total blood volume).

By analogy then, an increment as small as 0.28 vol per cent per minute in the regional a-v O_2 differences would be enough to account for the O_2 portion (11 ml O_2 per minute), that was not drawn from the total blood O_2 stores by virtue of the fall in arterial PO_2 . It may be inferred therefore, that in man the a- \bar{v} O_2 content difference does not change appreciably during breath holding on air at high pressures. The same holds for the cardiac output, because also the O_2 uptake from the lungs remained approximately constant. These conclusions do not exclude the possibility that in man, as in certain diving mammals, there is a redistribution of peripheral blood flow during apnea. It is also possible that due to the Bohr effect the O_2 tension increased in some tissues and, hence, that the O_2 stores of these tissues increased during the periods of apnea.

From the above discussion and experimental observations it may be inferred that during breath holding on air under high pressure the alveolar O_2 store decreases at a rate that is slightly less than the metabolic O_2 consumption as long as P_{AO_2} exceeds about 150 mm Hg. When P_{AO_2} falls below this level, the rate diminishes because an increasing fraction of the metabolic O_2 need is then covered by oxygen from other O_2 stores.

Alveolar CO_2 Store: The rate and magnitude of changes in the alveolar CO_2 store ($V_A CO_2$) during breath holding are dependent not only on the initial lung volume, cardiac output and $\dot{V}CO_2$, but also on the ambient pressure and the composition of the inspired gas prior to the apnea. This is illustrated in Figure 3, which shows the calculated changes in $V_A CO_2$ when breath holding is initiated at normal resting lung volume after breathing air at 2.0 and 4.0 atm, and O_2 at 1.0 atm. There is a striking difference in the dynamics of the $V_A CO_2$ changes when the breath is held on O_2 at 1.0 atm and when held on air at 4.0 atm, although P_{AO_2} remains at a high level in both conditions. In the former case $V_A CO_2$ reaches a maximum after about one minute and then decreases, whereas at 4.0 atm there is a continuous increment in $V_A CO_2$, the rate of which decreases as the time of apnea is prolonged. Also at 2.0 atm $V_A CO_2$ increases steadily, but at a somewhat lower rate, as long as the breath can be held without causing hypoxia.

The different magnitude and rate of changes in $V_A CO_2$ in the above situations are readily explained as follows. During the first 15 - 20 seconds of breath holding the CO_2 content of the pulmonary mixed venous blood remains approximately constant, whereas the CO_2 content of the arterial blood rapidly increases to approach that of the mixed venous blood. Therefore the a- \bar{v} CO_2 content difference and, if a constant cardiac output is assumed, the rate of CO_2 output to the lungs rapidly decrease. Because of the higher and approximately constant rate of O_2 uptake the lung volume decreases, which in turn will cause the alveolar CO_2 concentration and hence the alveolar (arterial) CO_2 tension to rise at a higher speed than would be the case with a constant lung volume. Therefore, the greater the rate of decrement in lung volume, the sooner will the alveolar PCO_2 attain and eventually surpass the oxygenated

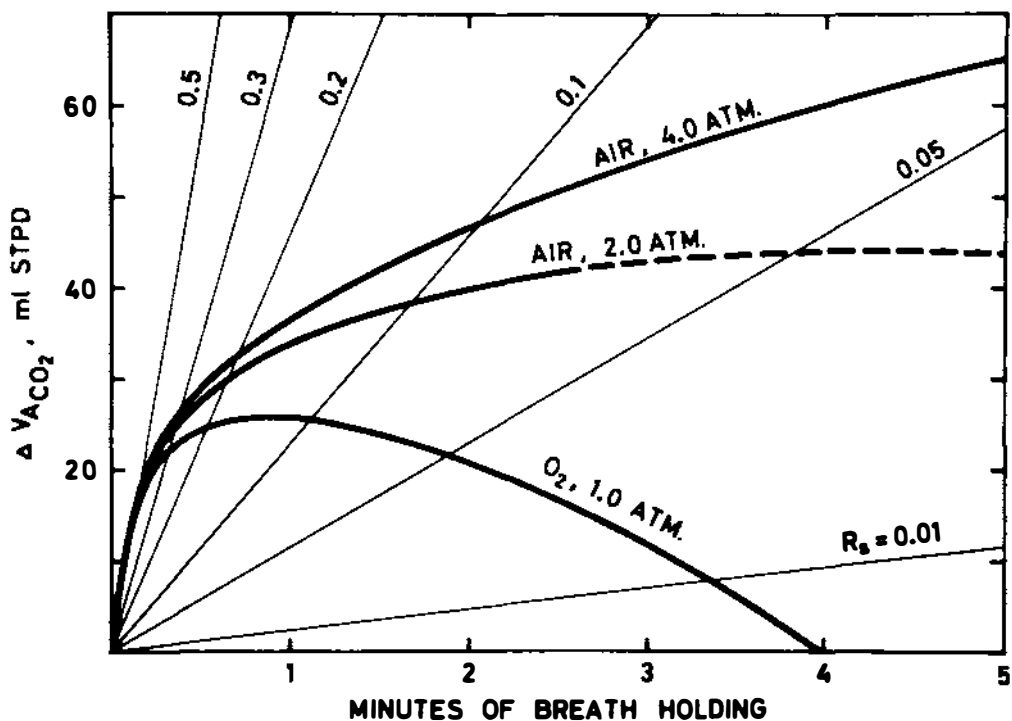


Figure 3. Changes in Alveolar CO₂ Store ($\Delta V_A \text{CO}_2$) During Breath Holding on Air at 4.0 Atm and 2.0 Atm, and on O₂ at 1.0 Atm, Plotted Against Time of Apnea. The respiratory gas exchange ratio (R_G) of the alveolar gas stores at any point of the curves can be read by referring the slope of the curves to the R_G -value obtained from the fan of R_G -lines.

$\Delta V_A \text{CO}_2$ (ml CO₂ STPD) at time t was calculated

$$\text{as } (P^t \text{CO}_2 V^t - P^0 \text{CO}_2 V^0) / 0.863$$

where V^0 and V^t are lung volumes in liters BTPS at start and at time t of breath holding, $P^0 \text{CO}_2$ and $P^t \text{CO}_2$ alveolar CO₂ tensions in mm Hg at corresponding times. V^0 and $P^0 \text{CO}_2$ assumed to be 3.0 liters and 38 mm Hg, respectively. $P^t \text{CO}_2$ obtained as $P^0 \text{CO}_2 + \Delta P_A \text{CO}_2$ at time t , the latter value being read from the curve in Figure 1. V^t calculated as $[V^0 (B - 47 - P^0 \text{CO}_2) - 0.863 t \dot{V}_A \text{O}_2] / (B - 47 - P^t \text{CO}_2)$ where B = ambient pressure in mm Hg, t = time of apnea in minutes, and $\dot{V}_A \text{O}_2$ = average O₂ uptake (ml/min STPD) from the lungs during breath holding (obtained from Table II).

mixed venous PCO_2 . From now on a reversal of the normal CO_2 transfer in the lungs will occur, i. e., CO_2 is driven from the alveolar spaces into the blood perfusing the lungs. When the breath is held on oxygen at ground level and at normal resting lung volume, the lung volume decreases at such a high rate (cf Fig. 4) that already after about one minute $P_A CO_2$ surpasses the arterialized $P_{\bar{v}} CO_2$ and, as a consequence, the alveolar CO_2 store starts to decrease (cf ref 30). At 4.0 atm on air the rate of decrement in lung volume is slow, and $P_A CO_2$ remains lower than the oxygenated $P_{\bar{v}} CO_2$; in this situation, therefore, there is a continuous increase in $V_A CO_2$ during the entire period of apnea as shown in Figure 3.

Respiratory Gas Exchange Ratio: From the above it follows that there is a continuous decrease in the respiratory gas exchange ratio (R_g) of the alveolar gas stores during the course of breath holding. This is illustrated in Figure 3, where the R_g -lines were constructed by assuming a constant rate of O_2 uptake

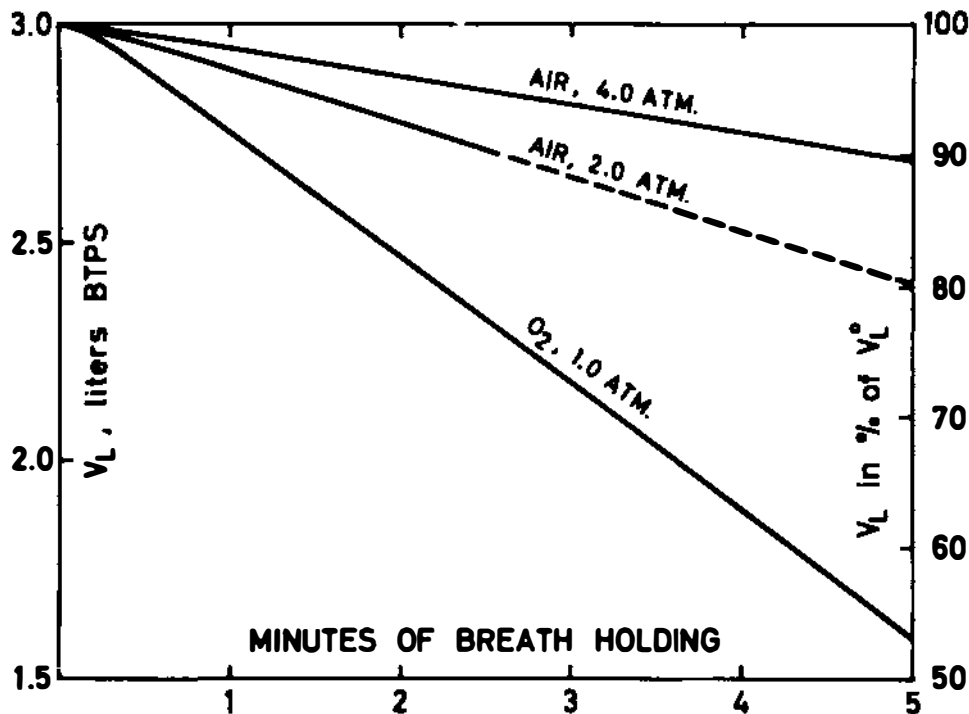


Figure 4. Lung Volume (V_L) as a Function of Breath-Holding Time When the Breath is Held on Air at 4.0 Atm and 2.0 Atm, and on O_2 at 1.0 Atm. On the right hand scale V_L is expressed in per cent of the lung volume (V_L^0) at start of breath holding. Broken line represents the hypothetical time course of changes in V_L at 2.0 atm if the breath could be held longer than two and one-half minutes and no hypoxia would ensue.

Lung volumes were calculated in same way as described for V^t in the text to Figure 3. In both figures it was assumed that the peripheral N_2 stores of the body have become readjusted before apnea is initiated.

from the lungs of 230 ml/min. As can be seen, R_g became less than 0.05 already after about one minute when the breath was held with air at high pressures, and even negative with O_2 at ground level.

Changes in Lung Volume: When R_g is less than unity, the lung volume will decrease during breath holding. Because of the approximately constant rate of O_2 uptake from the lungs in combination with a decreasing R_g , the rate of lung shrinkage will increase with the time of apnea when the breath is held with oxygen or with air at raised pressures (Fig. 4). With a given initial lung volume the rate of lung shrinkage is approximately inversely proportional to the ambient pressure (cf Table II). When the breath is held on air shortly after a sudden rise in ambient pressure, the lung volume will diminish also in consequence of the decreasing alveolar N_2 store. As already shown the reduction in the alveolar N_2 store proceeds at a rather slow speed, however, and has no appreciable influence on the rate of lung shrinkage when apnea is initiated more than 15-20 minutes after an abruptly induced change in alveolar PN_2 .

Alveolar Gas Tensions at Breaking Point and at Onset of Diaphragm Activity

In 1951 Alvis⁽²⁾ reported that within a pressure range of 1.0 - 4.0 atm abs his subjects were able to hold their breath after breathing air to higher alveolar PCO_2 levels as ambient pressure was increased. Alvis also found that $P_A CO_2$ at the breaking point appears to have a linear relationship to $\log_{10} P_A O_2$. This has later been confirmed to be valid when the breath is held on air at raised pressures and $P_A O_2$ at the breaking point ranges from about 60 to 300 mm Hg⁽¹⁵⁾. Above the 300 mm PO_2 level the rise in breaking point $P_A CO_2$ seems to flatten out (cf Fig. 5), but data at hand do not include the critical pressures that are needed to settle this question.

As shown in Figure 5 the alveolar PCO_2 at the onset of diaphragm activity also seems to have a linear relationship to $\log_{10} P_A O_2$ when the breath is held on air at high pressures and $P_A O_2$ ranges from about 100 to 300 mm Hg. The rise in $P_A CO_2$ with increasing $P_A O_2$ is less, however, than for the breaking point $P_A CO_2$. The $P_A CO_2$ values in the lower set of data in Figure 5 were obtained by subtracting from the observed breaking point $P_A CO_2$ the increment in $P_A CO_2$ that occurred from the onset of diaphragm activity up to the breaking point as read from the curve in Figure 1. The corresponding $P_A O_2$ values were obtained by adding to the observed breaking point $P_A O_2$ the decrement in $P_A O_2$ that would occur in the same time period if there is a linear fall in $P_A O_2$ during apnea.

Factors Influencing the Breath-Holding Ability

Available data^(6, 14, 29, 31) suggest that under normal resting conditions the breaking point of breath holding is determined by the interaction of chemical (low O_2 and high CO_2) and neurogenic factors. High nitrogen pressures are known to exert an intoxicating or narcotic effect on man^(3, 4, 7) which is characterized by slowed mental activity, motor incoordination, and other symptoms indicating the occurrence of fundamental changes in the central nervous system⁽⁴⁾. The influence of high nitrogen pressure on the breath-holding ability at raised

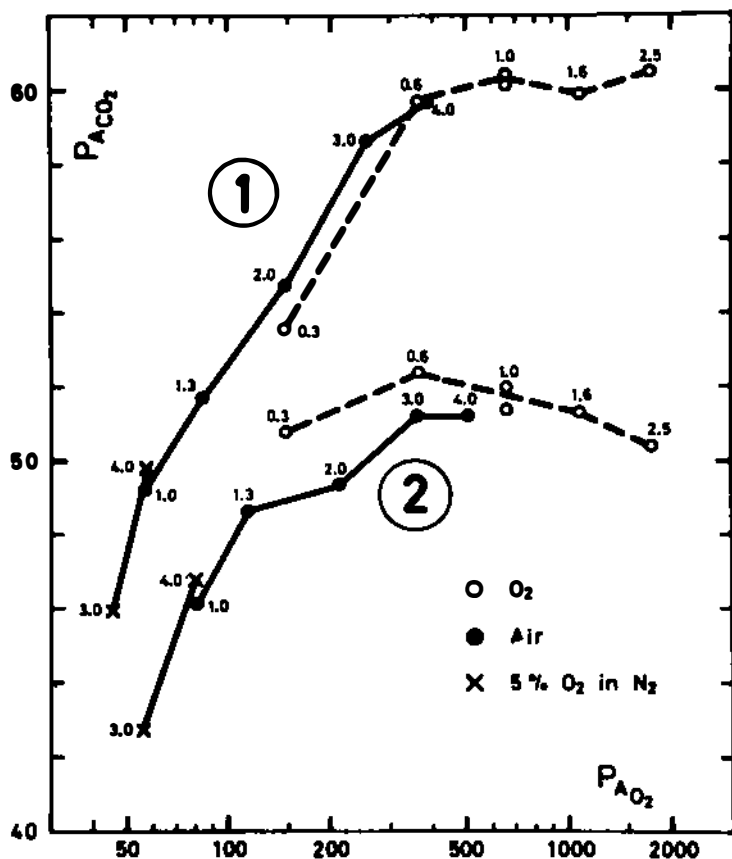


Figure 5. Semi-log Representation of Alveolar CO₂ and O₂ Tensions (mm Hg) Obtained:

1. at the breaking point (upper set of data);
2. at the onset of diaphragm activity (lower set of data) in breath-holding tests on oxygen, air and five per cent O₂ in N₂ to various ambient pressures (ambient pressure in atm abs indicated at each point by small numbers). Mean values for four subjects. [Hesser, Beskow and Holmgren⁽¹⁶⁾.]

ambient pressures should therefore also be considered⁽¹⁵⁾. A discussion of the relative importance and interaction of neurogenic and chemical factors in the voluntary control of respiration under hyperbaric conditions will follow.

Neurogenic Factors: It is well known that under normal resting conditions there is a direct relationship between the degree of lung inflation (lung volume) and the maximum breath-holding time^(32, 33, 40). This is in part explained by the observation that tolerance to hypercapnia^(8, 29, 33) and hypoxia⁽²⁹⁾ becomes higher with increased lung volume. Since the tolerance to these stimuli is higher during rebreathing than during sustained breath holding^(6, 14, 19), and is also increased

when rebreathing is performed at large lung volumes⁽³¹⁾, it appears that afferent impulses related to lung volume and respiratory movements interact with chemical stimuli in setting the breaking points of breath holding and rebreathing. The onset of diaphragm activity during breath holding, on the other hand, seems to be due mainly to chemical stimuli, and not to neurogenic factors as those mentioned⁽¹⁾.

The large lung volumes at start of breath holding in the experiments of Shilling et al⁽³⁷⁾ (Table I) may thus explain why the average breath-holding time at ground level was significantly longer than in the two other series of experiments shown in the table. Whether high N_2 pressures have a modifying effect on the influence of the afferent impulses related to lung volume and respiratory movements cannot be settled with the data on hand.

Chemical Factors: The roles of hypoxia, hypercapnia and high PN_2 for setting the breaking point and triggering diaphragm activity during breath holding in normal subjects may be judged from the data contained in Figure 5, which were obtained on the same four subjects in twelve different experimental conditions. The lung volume at start of breath holding was adjusted for each subject in such a way that approximately the same lung volume (about 2.8 liters BTPS) existed at the breaking point, regardless of the time of apnea. It therefore seems justified to assume that the influence of neurogenic factors related to lung volume and respiratory movements was about the same in the different conditions.

The upper set of data in Figure 5 shows the relationship between $P_A CO_2$ and $P_A O_2$ at the breaking point of breath holding after breathing oxygen, air, or five per cent O_2 in N_2 at various ambient pressures. The relation between the two variables at the onset of diaphragm activity under the same experimental conditions is shown by the lower set of data. Perhaps the most important features of the two sets of data are (a) the progressive rise in $P_A CO_2$ with increasing $P_A O_2$ also beyond the PO_2 level (100-150 mm Hg) where the stimulation of the carotid and aortic bodies by low PO_2 is considered to cease, (b) the indication that the rise in $P_A CO_2$ levels off at O_2 tensions above 300 mm Hg, and (c) the close coincidence of the O_2 and air data in the high PO_2 range on one hand, and the air and five per cent O_2 data in the low PO_2 range on the other.

From the observations under (c) it appears that nitrogen at high pressure (up to 3.8 atmospheres) has no significant influence on the breath-holding ability under resting conditions (cf ref 15). It may then also be inferred that such N_2 pressures exert little, if any, depressant action on the respiratory centers. This confirms earlier observations from this laboratory⁽¹⁷⁾ concerning the effects of raised ambient pressure on respiration in man. Thus evidence was presented that the respiratory changes found at elevated pressures were caused by the combined effects of increased O_2 tension and of increased breathing resistance due to increased gas density, whereas the role of high PN_2 was negligible.

The observation that $P_A CO_2$ at the breaking point of breath holding may reach a plateau at O_2 tensions above a certain high level is in line with the hypothesis of Otis, Rahn and Fenn⁽³⁴⁾ that the breaking point occurs when the total stimulus to breathe becomes equal in value to a constant maximum voluntary inhibition. On this assumption, and provided there exists a PO_2 threshold above which changes in PO_2 cause no change in ventilation, the breaking point should

always occur at the same PCO_2 when the O_2 tension exceeds the PO_2 threshold. Our data (Fig. 5) suggest that the breaking point $PACO_2$ approaches a constant level at alveolar O_2 tensions in excess of about 350 mm Hg. Similar observations were made by Stroud⁽³⁹⁾ in breath-holding tests performed at ground level after breathing various O_2 - N_2 gas mixtures.

In view of the general consensus that the chemoreceptors of the carotid and aortic bodies are stimulated by oxygen only at arterial O_2 tensions below 100-120 mm Hg, it seems rather surprising that the breaking point $PACO_2$ did not attain a final maximum value until the alveolar O_2 tension exceeded 350 mm Hg. However, oxygen at high pressure may exert at least three different effects in the chemical control of respiration, viz., (1) a depressant effect caused by reduced chemoreceptor activity due to removal of the "tonic hypoxic drive" (cf ref. 18) and supposedly also due to a suppression by oxygen of chemoreflex stimulation by carbon dioxide (cf ref. 21), (2) a stimulating effect due to central CO_2 accumulation⁽²³⁾, and (3) a depressant effect on the ventilatory response to CO_2 (21, 22, 26). The progressive rise in breaking point $PACO_2$ observed in the 100-350 mm PO_2 range (Fig. 5) may then be explained on the basis of a changing balance between (2) and (3). It would be of special interest to examine whether the tendency for the diaphragm activity to become triggered at lower CO_2 values when the O_2 tensions exceeded 350 mm Hg (Fig. 5) can be verified by direct sampling and analysis of arterial and internal jugular venous blood.

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HAZARDS OF HYPOXIA DURING DIVING

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Aside from pathology, the word "hypoxia" evokes high altitude environment. However, there is one other circumstance during which hypoxia may become very severe, and that is breath holding. While severe hypoxia produced by prolonged breath holding in air environment is without consequences because the resumption of respiration reoxygenates the subject quickly, it may be catastrophic for obvious reasons during skin diving.

It is worthwhile recalling some fundamentals concerning:

1. the hypoxic danger level,
2. the sequence of events during breath holding,
3. the factors which control these events,
4. the mechanism of the breath-hold breaking point.

1. The hypoxic tolerance levels have been frequently studied because of their implication for aviation physiology. Unacclimatized normocapnic subjects have some psychomotor troubles when $P_{A}O_2$ falls below 60 mm Hg. Mental performance is not severely impaired until $P_{A}O_2$ falls below 40 mm Hg, although individual differences in susceptibility are quite marked(19). But when combined with hypocapnia or hypercapnia, a milder hypoxia is capable of inducing mental troubles(19).

2. Every breath holder has experienced the two successive phases of breath holding: the easy-going phase and the struggle phase. The struggle phase (which can also be called "the urge to breathe" phase) starts rather abruptly with involuntary gasping contractions of respiratory muscles; these become stronger and more frequent until suddenly and involuntarily the subject can no longer hold his breath. Thus, one may summarize the sequence of events during breath holding: easy-going phase; gasping point; struggle phase; and breaking point. Accordingly there exists a gasping appearance time and an over-all breath-holding time. The difference between the two times measures the duration of the struggle phase.

A discussion about the gasping appearance time and the struggle phase duration is relevant to the subject of diving because a diver must ascend and surface before the end of this phase. It may be noted immediately that it is not safe to wait until the manifestation of the "urge to breathe phase" before deciding to ascend.

3. Several factors are involved in the mechanism of breath-hold events:

- a. The Composition of Alveolar Gas at the Start of Breath Holding: It is well known that hypocapnia or hyperoxia prolong the breath hold. In a certain measure a higher PCO_2 may be compensated by a higher PO_2 . When hypocapnia and hyperoxia are combined the

breath-holding time may exceed in some subjects 14 minutes⁽¹³⁾. On the PCO_2 - PO_2 diagram it must be possible to draw isotime breath-holding lines. But it would probably be more rewarding to predict breath-holding time on the actual O_2 and CO_2 stores or changes of stores, instead of on P_ACO_2 and PAO_2 prevailing at the start of breath holding, because, I have observed, breath-holding time starting from a low P_ACO_2 obtained by a voluntary hyperventilation during one minute is shorter than breath-holding time starting from the same hypocapnia resulting from a less intense, but much prolonged (ten minute) voluntary hyperventilation. The difference between these two breath-holding times is particularly great if an eventual hypoxic drive has been eliminated by previous breathing of pure O_2 . The depletion of the CO_2 stores is relatively small after a short hyperventilation, but relatively important after prolonged hyperventilation. During the subsequent breath hold, a critical value of alveolar CO_2 tension is reached faster in the first than in the second condition.

- b. The Initial Lung Volume: Obviously when the breath is held with the lungs filled, the time courses of PCO_2 increase and PO_2 decrease are slower than with smaller lung volume.

The lung volume has another action on the time of the breaking point. The hypercapnia or the combined hypercapnia and hypoxia to be observed at the end of the apnea with small lung volume are lower than those with large volumes⁽¹⁷⁾. The breaking point thus appears to depend in part on some nervous factors related to lung volume. It has been ascribed to reflexes of the Hering-Breuer type⁽¹⁷⁾, although Hering-Breuer reflexes, as they are understood from experiments on animals, do not seem to play an important role in man^(6, 9).

- c. The Gas Exchange Rates: During exercise the rate of change of alveolar gas composition is higher than at rest, and the breath-holding time is shorter. At the breaking point, a more advanced alveolar asphyxia is observed in exercise than at rest^(1, 4, 18). According to Craig and Babcock⁽⁴⁾, this observation need not mean that at the break of breath holding in exercise the ventilatory drives are greater than at rest because, the rate of change of the alveolar gas composition in exercise being very rapid, PO_2 and PCO_2 of the sample of alveolar gas at the breaking point are more asphyxic than the central PO_2 and PCO_2 .

4. What mechanism accounts for the break of a breath hold? Two explanations may exist: (1) The will to breath hold is overcome by the urge to breathe. (2) The breath hold stops as consciousness dims. For ordinary breath holding at sea level the first explanation is probably right. However, the second one (loss of consciousness) is certainly valid in some cases if the breath-holding subject has been rendered hypoxic and hypocapnic by hyperventilating a hypoxic mixture or even air⁽³⁾.

In my experience, after nine minutes of hyperventilation of 8.8 per cent O_2 in N_2 , during which P_{ACO_2} and P_{AO_2} fell to 17 and 49 mm Hg, when I then started to hold the breath, the struggle phase was not well defined, the consciousness dimmed, and at 47 seconds suddenly my conscious effort of the voluntary apnea disappeared. At that time I was close to fainting and P_{ACO_2} and P_{AO_2} were 30 mm Hg and 33 mm Hg. One explanation is that toward the end of the breath holding the CO_2 drive is not strong because of the foregoing hyperventilation, yet the arterial PO_2 was very low because I started breath holding at an already low P_{AO_2} .

Relevant to the mechanism of the breaking point are the changes in cerebral circulation. It is known that hypocapnia is a powerful factor in decreasing cerebral blood flow, which induces a brain hypoxia⁽¹⁴⁾. On the other hand, very severe hypoxia is a factor of increase of cerebral circulation. The action of different combined levels of arterial PO_2 and PCO_2 have been studied⁽¹⁴⁾, but how cerebral blood flow changes during the continuous drifts of arterial PCO_2 and PO_2 observed during breath holding is unknown. Consequently how O_2 and CO_2 tensions in brain influence cessation of apnea and more particularly the eventual loss of consciousness are difficult to evaluate.

During breath-hold diving the sequence of changes of volumes and pressures of gases in lungs, blood and tissues is considerably modified by the compression of air in the chest during descent and constant depth, and by the decompression during ascent. In the following discussion the respiratory muscles are assumed to be relaxed so that the total pressure of lung gas is essentially the same as the surrounding hydrostatic pressure.

First of all it must be pointed out that a subject about to dive starts with the same over-all stores of O_2 and CO_2 as a subject starting a breath hold in air environment. As will be discussed later, the volumes of O_2 and CO_2 in the lungs are lower after a dive than the corresponding volumes at the end of a breath hold in air of the same duration. Assuming the same O_2 and CO_2 metabolic gas exchanges in both cases, the difference in alveolar gas composition at the end of the two conditions of breath holding is due to some changes in the distribution of gas volumes in the body.

Lanphier and Rahn⁽¹⁵⁾ have studied alveolar gas changes during an artificial dive of 80 seconds; 20 seconds for descent, 40 seconds at constant depth of 10 m, and 20 seconds for ascent.

During the 20 second period of diving descent, gas was compressed in the chest and alveolar PO_2 and PCO_2 increased (Figs. 1 & 2). If the compression had been instantaneous, P_{AO_2} would have risen to 260 mm Hg. But during the 20 seconds of the descent the increase was partly checked by the O_2 uptake, so that the observed value of P_{AO_2} at 20 seconds was 175 mm Hg. During the period at constant depth, P_{AO_2} decreased progressively, but for the first 20 seconds remained high enough to maintain an almost normal O_2 uptake. Then between 40 and 60 seconds, P_{AO_2} decreased enough to diminish considerably the arterial blood O_2 saturation: the O_2 uptake then decreased. At the same time, by the Bohr effect, the high value of P_{ACO_2} opposed the fixation of O_2 by blood.

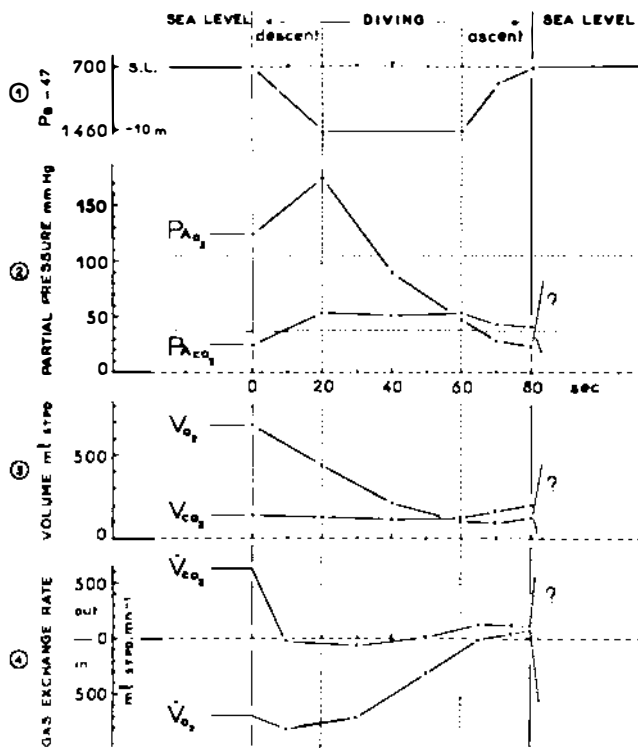


Figure 1. Respiratory Effects of a Simulated Dive in a Pressure Chamber. (adapted from Lanphier and Rahn(15)).

The subject was doing a mild exercise on a bicycle ergometer ($\dot{V}O_2 = 700$ ml STPD \cdot min $^{-1}$), in order to stimulate the increase of metabolism observed during an actual dive.

Upper curves 1

At time 0, start of the diving
 0-20 sec, descent to an equivalent depth of 10 m (2 atm)
 20-60 sec, constant depth of 2 atm
 60-80 sec, ascent
 at 80 sec, surfacing.

Curves 2: Time courses of alveolar PO_2 and PCO_2 . At sea level P_{AO_2} and P_{ACO_2} are respectively 124 and 25 mm Hg; this is due to the fact that the subject hyperventilated for one minute, then took a near maximum inspiration before the dive. The dotted lines indicate P_{AO_2} and P_{ACO_2} of normal breathing of the pre-dive period.

Curves 3: Volumes of O_2 and CO_2 in the lungs at different stages of diving. Allowance is made for diffusion of N_2 from alveolar spaces into the lungs at a rate of 1.2 ml \cdot sec $^{-1}$ at 2 atm.

Curves 4: Rates of O_2 and CO_2 exchanges during diving. Above the 0 line: gases diffuse out of the blood into alveolar spaces. Below the 0 line: gases diffuse from the alveolar spaces into the blood.

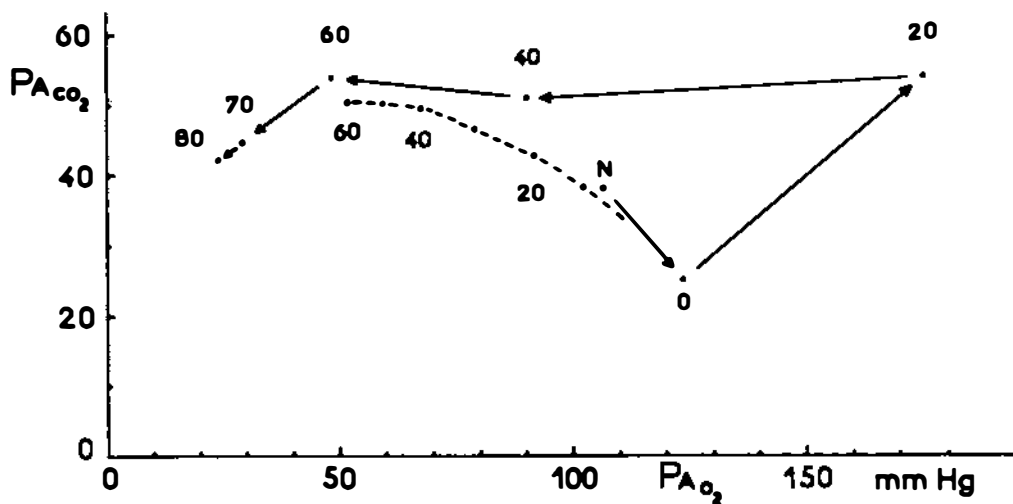


Figure 2. Alveolar Gas Composition Changes During a Simulated Dive in a Pressure Chamber(15).

Subject worked on a bicycle ergometer ($\dot{V}O_2 = 700 \text{ ml STPD} \cdot \text{min}^{-1}$).

N: alveolar gas in normal breathing.

O: start of the breath holding after one minute of hyperventilation followed by a near maximal inspiration.

Numbers refer to the time of breath holding.

From 0 to 20 sec: descent; from 20 to 60: constant depth; from 60 to 80: ascent.

The same $P_A\text{CO}_2$ and $P_A\text{O}_2$ have been plotted vs time in Figure 1.

The dotted line concerns the pattern of alveolar gas composition in air environment⁽¹⁶⁾, during breath holding after a single forced expiration followed by a near maximal inspiration ($\dot{V}O_2 = 600 \text{ ml} \cdot \text{min}^{-1}$ approximately).

Because breath holding in diving and breath holding in air environment do not start with the same state of gas stores in the body, and the intensities of exercise are not exactly the same, they are not absolutely comparable.

During descent there also occurs an increase of $P_A\text{CO}_2$, a reversal of the normal pressure head between venous blood and alveolar PCO_2 and consequently an uptake of CO_2 by blood, and this limits considerably the increase of $P_A\text{CO}_2$. This phenomenon may explain why $P_A\text{CO}_2$, which has reached 54 mm Hg at the end of a 20 second descent, decreases to 51 mm Hg between the 20 to 40 second period at constant depth. Later $P_{\bar{V}}\text{CO}_2$ itself increases so that a small CO_2 -output reappears. Because of this small output, but above all because of the decrease of lung volume due to the O_2 uptake, $P_A\text{CO}_2$ rose from 51 to 54 mm Hg.

At 60 seconds of diving, O_2 and CO_2 volumes in the lungs are respectively 110 and 123 ml STPD, while at the end of a breath holding in an air environment the corresponding values would have been of the order of 300 ml STPD. Indeed, although the pressures of O_2 and CO_2 are of the same order of magnitude in both types of breath holding, the fractions of O_2 and CO_2 in alveolar gas and the total lung volumes are smaller during compression than at normal barometric pressure.

If tissues CO_2 production is assumed to be the same in both types of breath holding, these results show that the CO_2 store in the tissue is greater in breath holding under compression than in breath holding at normal pressure. As for O_2 , if the tissues consume the same amount of O_2 in both cases, the O_2 debt of the whole body is the same in both cases, but it is more a pulmonary O_2 debt at 60 seconds of breath holding under compression than at 60 seconds of breath holding in air environment.

During ascent, the fall of the total pressure in the lungs provoked a large decrease in both $P_A\text{O}_2$ and $P_A\text{CO}_2$. Carbon dioxide output from blood to lungs increased. The fall of $P_A\text{O}_2$ is such that, from 60 to 70 seconds, the O_2 exchange between blood and alveolar air is almost nil, and from 70 to 80 seconds $P_A\text{O}_2$ becomes lower than $P_{\bar{V}}\text{O}_2$ and a reversal of O_2 exchange a transfer of O_2 from blood to alveolar gas actually occurs. One will note the extremely low value of O_2 at 80 seconds (24 mm Hg). This value did not stop the breath holding, presumably because $P_A\text{CO}_2$ was brought back during decompression toward its normal range and because by itself the expansion of the chest decreases the urge to breathe⁽¹⁷⁾. Anyway the subject has a feeling of relief while ascending.

The foregoing general review of O_2 and CO_2 variations during breath holding in air and during diving suggests how a dangerous hypoxia may occur in these circumstances. However the problem of hazards of hypoxia in diving is more complex for the following reasons:

1. O_2 Requirement. In the examples of breath holding given above the O_2 consumptions were raised to 600 and 700 ml STPD $\cdot \text{min}^{-1}$ by exercise on a bicycle ergometer. But, in real diving, O_2 consumption may well be above these values. Kang et al⁽¹²⁾ observed that O_2 consumption was tripled in the Ama during the first five minutes of their immersion in cold water (10-13°C). During the resting periods between dives, still higher values were measured ($\dot{V}\text{O}_2$ from 1090 to 1690 ml STPD $\cdot \text{min}^{-1}$). Obviously during an actual dive this relatively large increase of metabolism affects the time courses of $P_A\text{O}_2$ and $P_A\text{CO}_2$ changes, of O_2 and CO_2 exchanges between alveolar gas and blood, and modifies the distribution of O_2 and CO_2 stores throughout the body.

2. Cardio-Vascular Reactions. Divers, such as Ama^(10, 26) or pearl divers in the Tuamotu Islands in the South Pacific^(5, 27) and many skin divers throughout the world hyperventilate before diving. As mentioned above, the hypocapnia resulting from hyperventilation may lead to some decrease of cerebral circulation and may be a factor of cerebral hypoxia and one cause of loss of consciousness during or simply swimming under the surface⁽⁷⁾.

Immersion in cold water may be a relevant factor not only because it increases the O₂ requirements but also because it provokes a skin vasoconstriction. The changes of distribution of blood throughout the body while horizontal, head up or head down during immersion are certainly different from those occurring with the same changes in posture in air environment.

3. Intrathoracic pressure. It has been assumed in prior sections that the respiratory muscles of the subject were relaxed. However, if the subject with a closed glottis exerts a negative or a positive intrathoracic pressure (Müller or Valsalva maneuvers), there may occur some interference in the pulmonary circulation which could result in cerebral ischemia.

4. The very detailed analysis by Lanphier and Rahn⁽¹⁵⁾ discussed above concerns moderately deep dives. While unassisted Ama dive to five to ten meters of depth⁽¹⁰⁾, the assisted Ama reached depths of 25 m^(10, 26). Schaefer and Carey⁽²³⁾ have studied the U. S. Navy escape training instructors who dive to 27 m. The general pattern of change of their alveolar gas composition are similar to those described by Lanphier and Rahn⁽¹⁵⁾. In particular their alveolar PO₂ at the end of the dive may be at 30 mm Hg. One of the subjects studied by Schaefer and Carey⁽²³⁾ was unconscious when surfacing.

Williams⁽²⁷⁾ and Cross⁽⁵⁾ have observed the pearl divers of the Tuamotu Islands who go down to 40 m. Their diving time may reach two minutes, and they repeat such dives six to fourteen times an hour. Before diving they hyperventilate intensely. Many incidents or accidents called Taravana by the natives have been recorded in these divers such as defect of vision, dizziness, vertigo, nausea, paralysis of one limb, hemiplegia, unconsciousness. These accidents seem to occur when the diver is ascending or surfacing. On one particular day of the diving season on one island dozens of accidents of Taravana including two deaths have been recorded⁽⁵⁾. The physiology of these amazing divers has not been studied. To judge from what is already known, their pattern of diving would suggest the development of a severe hypoxia, since they hyperventilate before diving, dive very deep, very long and repeatedly.

5. No mention has been made yet of decompression sickness, due to formation of bubbles of nitrogen during ascent and after surfacing. The possibility of its occurrence has been pointed out recently by Paulev⁽²⁰⁾ who reported an observation on himself of decompression sickness after repeated skin dives at great depths.

Accidents during diving of the type described above would not occur if the diving duration was short enough to avoid severe hypoxia. Often the subjects of diving accidents are found to have hyperventilated before diving^(2, 3, 7, 8, 26). Such a practice increases quite significantly the breath-holding time in retarding the

attainment of the hypercapnic level which initiates a strong respiratory drive, but it permits the development of a severe hypoxia. Consequently, it should be forbidden to hyperventilate before diving, as well as to prolong unduly a dive for the sake of amusement or competition. Unfortunately, professional divers, as pearl divers, who depend on this activity to make their living could not dive efficiently if they did not hyperventilate intensely beforehand.

Breathing pure oxygen before diving and above all hyperventilating pure oxygen would, if correctly used, permit longer dives without hazards of hypoxia. However, other dangers such as CO₂ narcosis and eventually O₂ poisoning from deep dives, could be encountered. If this procedure has not been used up to now on a large scale, it is probably because the professional skin diver groups cannot afford such an elaborate technique. Possibly the same practical reason explains why Ama divers wearing ordinary swimming dress and not the protective wet suit which would so improve their comfort and efficiency, particularly in winter.

It must be pointed out that not all drownings which occur in dives after hyperventilation fit the scheme of the simulated dive of Lanphier and Rahn⁽¹⁵⁾ and of the actual dives of Schaefer and Carey⁽²³⁾, and Hong⁽¹⁰⁾. In some cases of drowning^(3, 7, 8), there is no indication that a deep dive has been made; this peculiarity is evident for drownings in ordinary shallow swimming pools. Possibly the other factors of hypoxia or cerebral ischemia which have been mentioned could be involved in these cases as well as in accidents of deep diving.

A Final Speculation: Why is man such a poor diver compared to air breathing mammalian divers⁽²¹⁾? The problem is far from solved. Seals dive for 20 minutes and whales for one to two hours, while two minutes of free diving seem to be a maximum for man. Diving mammals differ from man in several aspects (see References 11 and 24):

1. **O₂ Stores.** The blood O₂ stores in diving mammals are generally greater because of a relatively large blood volume and high O₂ capacity. As a rule the myoglobin concentration of skeletal muscles are greater in divers than in non-divers. But the lung volume per unit of body weight is not different.
2. **O₂ requirements during diving** are decreased in diving mammals because the decrease of temperature and intensity of metabolism in some peripheral tissues and the shift to anaerobic metabolism. Lactic acid accumulates in muscles, and a rise of the lactic concentration in blood does not appear until the end of the dive.
3. **Oxygen in lungs and blood** seems to be made available only to certain organs such as heart and brain. This is made possible by the decrease of blood flow through other organs such as muscles; cardiac output and heart frequency are decreased while systemic blood pressure remains normal. This pattern of circulatory changes may exist to some degree in humans who exhibit a marked bradycardia during diving⁽²⁴⁾.

4. **Diving mammals can tolerate more severe hypoxia and hypercapnia than man. This property implies not only a special resistance of the tissues to asphyxia, but also a greater ability to withstand strong ventilatory drives. In this respect, it has been shown that many diving mammals are almost or wholly insensitive to CO₂ breathing, while for man(22, 25) a decrease of the ventilatory sensitivity to CO₂ divers compared to non-divers is small if it exists at all.**

Rahn⁽²¹⁾ has speculated whether a man, who normally can hold his breath for one minute when he starts breath holding at the end of normal inspiration without prior hyperventilation, could develop the apnea time of a seal. The conclusion is that, if the man had the seal's physiological mechanisms: greater O₂ store, preferential distribution of blood to brain, lungs, and heart, and eventually a lower O₂ requirement of his brain, he could, indeed, hold his breath for 20 minutes. Normal man, of course, remains very different from the seal. Professional divers, however, may be somewhat intermediate, since they exhibit a more marked bradycardia during diving than does terrestrial man⁽¹¹⁾. Nothing is known about the relative blood volume of professional divers.

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THE BREAKING POINT OF BREATH HOLDING

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Breath holding is a mechanism by which the respiratory system can be shut off from its external environment. It provides man with a natural means by which to forsake his normal gaseous surroundings and enter the aquatic world. How long he can visit this strange environment, and still reenter his own, is determined by his breath-holding ability. The limit of breath holding is termed the breaking point and has been defined as the termination of breath holding in response to the development of a net ventilatory stimulus too strong to be further resisted by voluntary effort⁽²¹⁾. This definition implies the response to a stimulus which in reported studies has varied from sensations of mild unpleasantness to agony. The breaking point is usually measured in terms of breath-holding time or alveolar gas composition and as such has been studied under a variety of atmospheric conditions, for the most part by physiologists interested in the regulation of respiration. Certain deductions can be made from these studies which are applicable to the subject of diving, although the breaking point of breath holding has in fact never been measured under these conditions.

Breath-Holding Time

The breath can be held for varying periods of time depending upon the interaction of many factors including the lung volume, inspired gas concentrations, ambient pressure, metabolic rate and psychological elements. Figure 1 brings together published results on breath-holding time under a variety of conditions when the breath is held at an initial lung volume at or near vital capacity. The shortest times of 30 seconds are for breath holding with air during moderate exercise. These values obtained in the laboratory⁽²⁴⁾ are comparable to the reported average diving time of the unassisted Ama⁽¹³⁾. As inspired oxygen tension increases or initial carbon dioxide tension is lowered by hyperventilation, breath-holding time becomes progressively prolonged up to the astonishing length of 20 minutes and 5 seconds after 7 minutes of hyperventilation with air followed by several deep breaths of oxygen⁽¹⁰⁾. This feat is said to have been accomplished at Wesleyan University by a student named E. Frechette, a cross-country runner who was in peak physical training at the time of the breath hold; he is said to have had an unusually large vital capacity in relation to his body size⁽¹⁰⁾. The longest published record in the scientific literature, 15 minutes and 13 seconds, was also set by a student at Wesleyan University where, for many years breath holding was a regular laboratory exercise in the Department of Biology⁽²⁵⁾.

Figure 1 gives a general picture of the effect of the initial inspired gas tensions, metabolic rate and hyperventilation on breath-holding time. The factors which determine the wide variation in the time required to reach the breaking point may now be examined in detail.

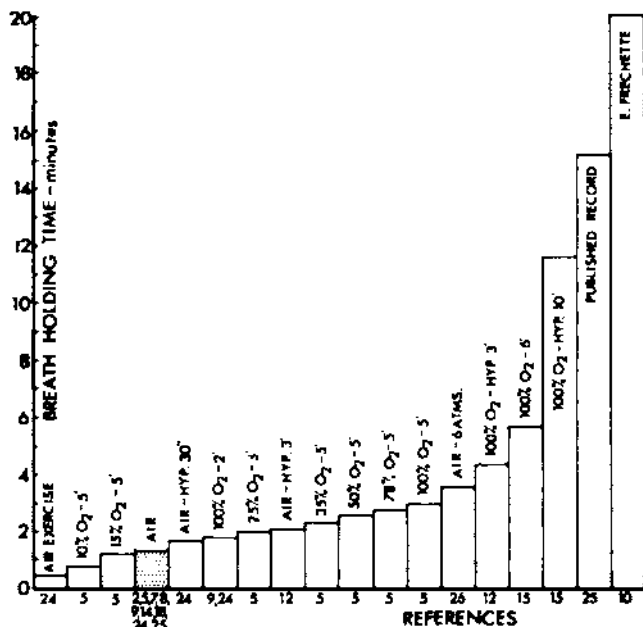


Figure 1. Breath-Holding Times under Various Conditions when Initial Lung Volume was at or Near Vital Capacity. The sources of the data are given by numbers along the abscissa which refer to the bibliography.

Determinants of the Breaking Point

The breaking point is brought on by the interaction of a number of independent variables. These may be divided into three general groups: Psychological factors, lung volume and gas tensions.

1. Psychological Factors: Psychological factors may prolong breath holding to extraordinary limits. In 1908 Hill and Flack observed that "one of the most important factors seems to be that of pluck or resolution to withstand discomfort and this, in the same individual, varies according to the state of his nervous system⁽¹¹⁾." Under atmospheric conditions outside the laboratory, this psychological motivation can be most commonly seen in the breath-holding spells of infants where apnea may be prolonged to the

point of cyanosis, unconsciousness and convulsions. Such attacks, though distressing to watch, are usually self-limited⁽¹⁾. Thus, under atmospheric conditions the consequences of "pluck and resolution" are followed at the breaking point by a happy sensation of relief which is provided by the environment. This is not true under water where an asphyxial environment surrounds the diver and may greet the breaking point with lethal aspiration rather than recovery. The psychological prolongation of a breath-holding dive is hence of great importance⁽³⁾ and is discussed in detail in another chapter of this book (Dejours, P., page 183).

2. Lung Volume:

a. The Effect of Lung Volume in Determining the Breaking Point of Breath Holding under Atmospheric Conditions

Other conditions being the same, the breaking point as measured either by breath-holding time or alveolar gas tensions is directly related to both the initial and final lung volume⁽¹⁹⁾. This is because a restriction in lung volume is an independent ventilatory stimulus which presumably acts through the Hering-Breuer reflexes⁽²²⁾. It interacts with the stimuli from hypoxia and hypercapnia in determining

the breaking point of breath holding⁽¹⁹⁾ and rebreathing⁽²²⁾. This is illustrated in Figure 2¹ which compiles data from the literature on breath-holding time with air. When the initial lung volume was at vital capacity, the mean breath-holding time was 78 seconds as determined from 278 observations from nine different sources^(2, 5, 7, 8, 9, 14, 18, 24, 25). The value at normal inspiratory volume is from 26 observations from one source⁽¹¹⁾ and at FRC the mean of 22 observations from three reports^(8, 23, 28). At normal inspiratory volume the breath can only be held about 55 per cent as long as it can at vital capacity, and at FRC the time is shortened to 40

per cent, and at residual volume to 24 per cent (unpublished observations). The broken line is an extrapolation to zero lung volume at a breath-holding time of about eight seconds, which is approximately the normal circulation time from lung to brain.

During breath holding, the volume of gas in lung shrinks as the result of a disproportion between oxygen removal and CO₂ delivery^(19, 20, 23, 27). This results in a progressively strong reflex stimulus which ends in a breaking point determined in part by the final volume of the lung⁽¹⁹⁾. This is shown in Figure 3 which relates final lung volume to P_ACO₂ at the breaking point of breath holding with oxygen. Volume at the breaking point is shown as per cent vital capacity, P_ACO₂ as per cent of the maximum P_ACO₂ tolerated by each subject. P_AO₂ was always above normal since the breath was held with oxygen. The interaction between final lung volume and P_ACO₂ can be seen as a diminished tolerance for hypercapnia as the strength of the stimulus from volume restriction increases. An interaction between the stimulus from hypoxia and volume restriction has also been demonstrated during breath holding with air⁽¹⁹⁾.

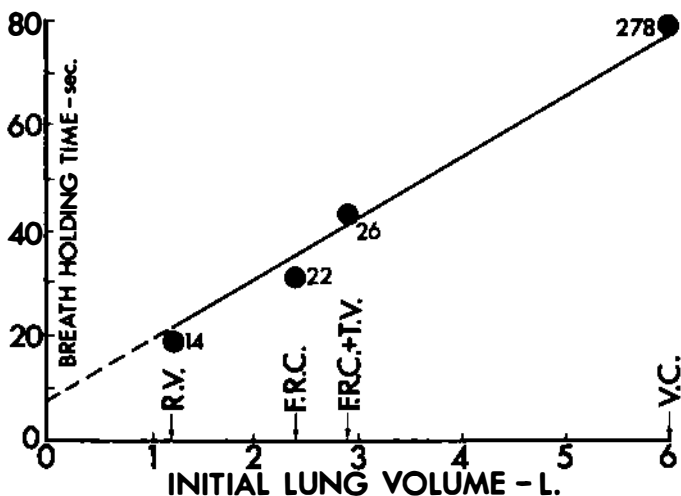


Figure 2. Compiled Data from Literature Showing Relationship between Initial Lung Volume Breath-Holding Time when Inspired Gas is Air. Number of observations indicated at each point; see text for sources.

¹Figures 2, 3, 4, and 5 were previously published⁽²¹⁾ and are reproduced with the permission of the American Physiological Society.

When breath holding is preceded by hyperventilation with oxygen for ten minutes, it is the shrinkage of lung volume alone which limits breath holding. Under these conditions breath holding can go on until oxygen is depleted from the lung to the level of residual volume⁽¹⁵⁾. At this breaking point there is no hypoxia and $P_{A}CO_2$ does not rise to intolerable levels. Therefore, under these conditions breath holding time can be predicted as follows⁽¹⁵⁾:

$$\text{Breath holding time (minutes)} = \frac{\text{Vital Capacity (STPD)}}{\dot{V}O_2 \text{ (STPD)}}$$

The relation between the stimuli from volume restriction and PCO_2 is maintained when the breath is held with oxygen following hyperventilation, a procedure which lowers the initial PCO_2 and prolongs breath-holding time. As a result, lung volume at the breaking point is smaller, following hyperventilation, than it is after initially normal breathing and so the PCO_2 which can be tolerated is less^(19, 15). The increased stimulus from volume restriction imposed by hyperventilation accounts for the observation first recorded in 1909⁽²⁹⁾ that PCO_2 at the breaking point is lower when breath holding is preceded by hyperventilation than when it is not.

The interaction of the stimuli from volume restriction with the chemical stimuli explains a number of interesting observations. One is the old observation that the $P_{A}CO_2$ at the breaking point of breath holding is never as high as at the breaking point of rebreathing when volume is unrestricted⁽¹¹⁾. This difference was originally thought to be due to mechanical impedance of the circulation during breath holding but it is more likely the result of the volume restriction which

develops during breath holding. Another example of this interaction is the fact that by reinflating the lungs at the breaking point with gas which does not change the alveolar tensions, breath holding can be prolonged to progressively higher levels of CO_2 ⁽⁸⁾.

b. The Effect of Lung Volume in Determining the Breaking Point During Diving

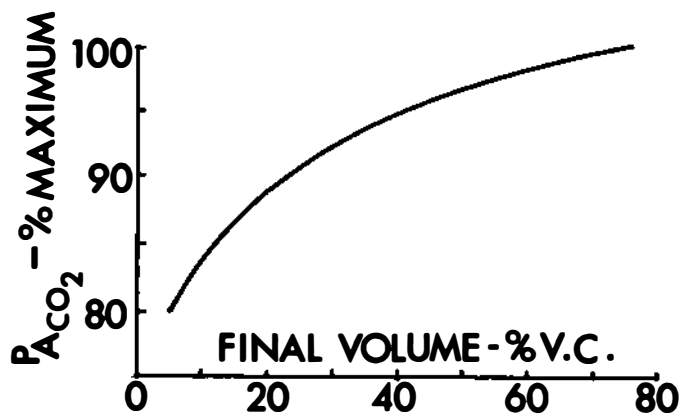


Figure 3. Effect of Lung Volume (expressed as per cent vital capacity) at Breaking Point of Breath Holding with Oxygen on Tolerance for CO_2 , Expressing $P_{A}CO_2$ at Breaking Point as Per Cent of Maximum PCO_2 Tolerated when Initial Volume was at Vital Capacity.

Since a decrease in lung volume acts as an independent ventilatory stimulus which determines the breaking point, one might expect that during a dive the decrease in gas volume which results

from compression would have the same effect. This would mean that, other conditions being equal, for any inspired volume breath-holding time would be longer on the surface than when submerged. As shown in Figure 2, under atmospheric conditions, the breath-holding time at an initial lung volume of six liters is 80 seconds whereas at an inspired volume of three liters it is 45 seconds. From this one might expect that if a diver inspired to vital capacity then quickly descended to 33 feet his breath-holding time would be reduced to one-half. The experiment has not been performed and it is impossible to predict its outcome with certainty for many reasons, among them:

1. The comparative effect of the two forms of volume reduction on oxygenation is complex. Volume reduction by compression increases alveolar oxygen tensions whereas reduction in inspired volume reduces it. An increase in oxygen tension by compression would tend to increase breath-holding ability. On the other hand, the higher $P_{A}O_2$ from the breath-holding dive would allow more rapid transfer of oxygen from lung to blood and hence might shorten breath-holding time by an initial rapid depletion of oxygen supply.
2. With sudden compression of lung gas during a breath-holding dive, $P_{A}CO_2$ rises to a level the magnitude of which is dependent upon the depth of dive and rate of descent. It then falls, as the gradient is reversed, and CO_2 moves from lung to blood(17). There is thus a sudden increase in ventilatory stimulus from CO_2 which, together with the volume reduction, might bring on the breaking point. This surge in PCO_2 is, however, short-lived and the strength of the stimulus wanes as CO_2 is removed from the lung and $P_{A}CO_2$ falls. This rapid decrease in stimulus from CO_2 might well act to overcome the associated stimulus from volume reduction and allow breath holding to continue.

Because of the complexities imposed by compression upon the interactions of lung volume and gas tensions, it is impossible to predict the effect of submergence on breath-holding ability. The experiment should be performed and this important question answered.

3. Gas Tensions: The third category of stimuli which may determine the breaking point is that of PO_2 and PCO_2 . These variables interact with lung volume and their strength as stimuli is determined largely by three conditions: (1) the inspired gas composition and tension, (2) metabolic rate, and (3) the buffering capacity for CO_2 at the onset of breath holding, and the level of CO_2 stores.

a. The Effect of Gas Tensions in Determining the Breaking Point Under Atmospheric Conditions

The effect of these three conditions in determining the breaking point is shown in Figure 1 where, at equal inspired volumes, breath-holding time increases with increasing inspired oxygen concentrations or pressure, where it decreases as metabolic rate is increased by exercise and where it is increased by diminishing initial carbon dioxide stores by hyperventilation.

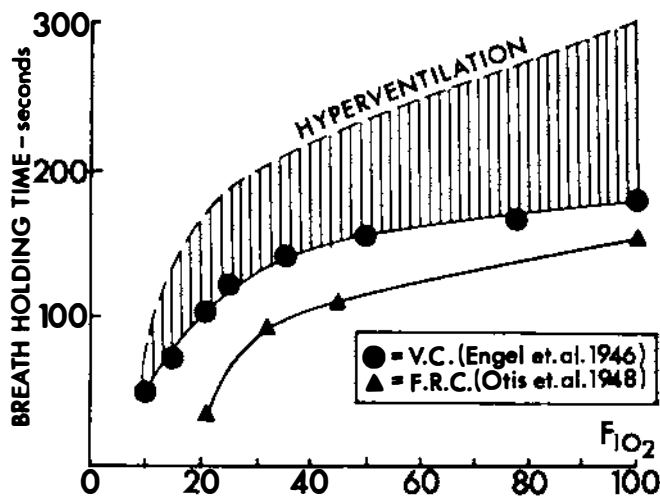


Figure 4. Effect of Inspired Oxygen Concentration ($F_{I}O_{2}$) on Breath-Holding Time at Two Levels of Inspired Volume, VC and FRC. Broken line indicates predicted elevation of VC curve that would be produced by two minutes of hyperventilation.

data of Figure 1 a theoretical curve has been constructed in Figure 4 (broken line) which shows the prolongation of breath-holding time which is to be expected by two minutes of hyperventilation at various inspired oxygen concentrations when initial lung volume is at vital capacity. It is interesting to note that, at high inspired oxygen concentrations, the effect of hyperventilation is much greater than at lower oxygen tensions. This is because, in the absence of hypoxia, the breaking point is brought on primarily by the interaction of PCO_{2} and lung volume restriction whereas, at lower oxygen concentrations, even though CO_{2} tension is diminished by hyperventilation, hypoxia quickly develops to terminate breath holding.

The effect of interaction of gas tensions in producing the breaking point may also be considered in terms of the level of PCO_{2} which can be tolerated for a given PO_{2} . During breath holding, the tolerance for CO_{2} increases as alveolar oxygen tension increases, a relationship which was first described in 1908 by Hill and Flack⁽¹¹⁾. The next year, this relationship was studied in more detail by Douglas and Haldane⁽⁴⁾ and their results are shown in Figure 5 (solid circles) together with those from two more recent publications. These studies indicate a positive interaction between PCO_{2} and PO_{2} in determining the breaking point. The data of Ferris, *et al*⁽⁶⁾ lie above those of Otis, *et al*⁽²³⁾ primarily because, in the former study, the initial lung volume was at vital capacity while, in the latter, it was at functional residual capacity.

The shrinkage in lung volume which occurs during breath holding has a direct effect on gas tensions. As lung volume is decreased as a result of oxygen

A more detailed analysis of the effect of inspired oxygen concentration on breath-holding time can be seen in Figure 4 which depicts the results of two systematic studies. One was done with the breath held at vital capacity⁽⁵⁾ and the other at functional residual capacity⁽²³⁾. Breath-holding time was 70 per cent greater with oxygen than with air when the breath was held at vital capacity. At functional residual capacity the effect of oxygen is proportionately greater, producing a three-fold increase in breath-holding time.

There are no systematic studies on the interaction of hyperventilation and inspired oxygen concentration. However, from the

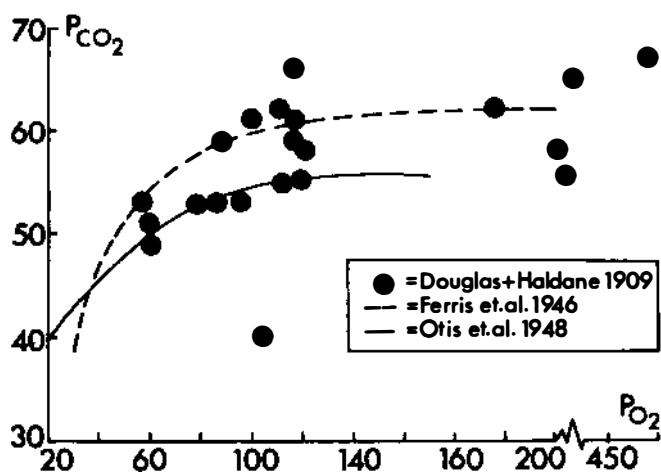


Figure 5. Relationship Between Alveolar or Arterial PCO₂ and PO₂ at Breaking Point of Breath Holding from Three Sources in the Literature.

uptake, CO₂ is concentrated in the lung and its partial pressure rises. This diminishes the CO₂ gradient from mixed venous blood to alveolar gas and, hence, the amount of CO₂ delivered to the lung decreases. This sets up a self-perpetuating cycle in which the falling alveolar exchange ratio, in the face of sustained oxygen uptake, accelerates the rate of lung volume shrinkage and, therefore, the rate of rise of alveolar and arterial PCO₂. This cycle in the lung is promoted by the effect of oxygenation of hemoglobin (C-D-H effect) which also tends to raise P_ACO₂ (16, 20, 21). By this mechanism, anything that increases

oxygen uptake, for example exercise, will decrease breath-holding time by increasing P_ACO₂ through the mechanism of volume shrinkage as well as by depleting oxygen supply and increasing metabolic CO₂ production. This limitation, which is imposed on breath holding by the indirect effect of volume shrinkage on PCO₂, is of great practical importance to the diver.

b. The Interaction of PO₂ and PCO₂ in Determining the Breaking Point During Diving

The compression of gas in the lungs which accompanies a breath-holding dive results in certain changes in alveolar gas tensions which may affect the time of onset of the breaking point. With descent, P_AO₂ rises as a result of gas compression, then falls as oxygen is taken up from the lung. With ascent, lung volume increases and P_AO₂ falls still farther. P_ACO₂ also increases with the compression of descent, then falls as the normal PCO₂ gradient from mixed venous blood to alveolar gas is reversed and CO₂ moves from lung to blood. With ascent, P_ACO₂ falls still farther as a result of expansion of lung volume (17). These interactions have never been studied with regard to the breaking point of a breath-holding dive but some inferences may be drawn from available data.

Changes in PO₂ and PCO₂ have been measured while breath holding with air at vital capacity during simulated 33 foot dives, in a high pressure chamber, during which oxygen consumption was doubled by exercise to simulate the work of diving (17). The results are shown in Figure 6 drawn from the data of Lanphier and Rahn (17). These changes are compared with those which occur during breath holding under normal atmospheric conditions at the same work load (17) and with the alveolar gas tensions that were measured during diving in Korean Amas (13). None of these subjects held his breath to the breaking point but, for comparison, a

breath-holding breaking point curve, obtained under atmospheric conditions at an initial lung volume near vital capacity, has been drawn from the data of Ferris *et al* (6).

During the 60 second breath hold with work at the surface, the alveolar pathway moves up and to the left with progressively diminishing slope, indicating a falling alveolar exchange ratio. The final point lies almost on the breaking point curve and it is interesting to note that the authors state: "Most of the subjects found that the 60 second work experiments taxed their breath-holding ability whether at the surface or during dives." (17)

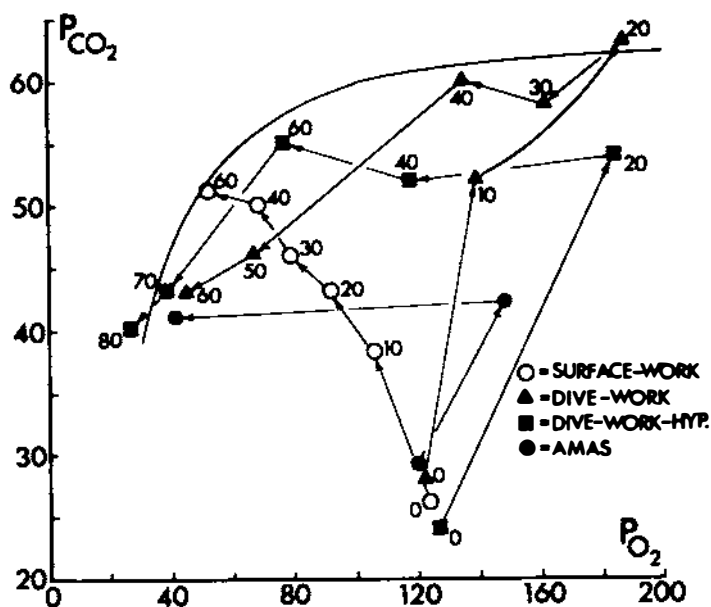


Figure 6. Alveolar Gas Tensions at the Breaking Point of Breath Holding During Exercise Under Atmospheric Conditions (0) and During Diving (\blacktriangle , \blacksquare , \bullet). Also shown is a breaking point curve obtained under atmospheric conditions. See text for sources.

During descent (0-20 seconds) in the 60 second dive-work experiments, $P_{A}CO_2$ rose above the breaking point curve, as shown, and the authors comment: "A brief period of marked desire to resume breathing was commonly noted shortly after reaching maximum pressure." As pressure was sustained, $P_{A}CO_2$ fell to below the breaking point curve and only approached it at the end of the period of compression, which extended from 20-40 seconds. It then fell considerably below during ascent (40-60 seconds). Referring to these intervals, the authors state: "Most subjects were then relatively comfortable until shortly before ascent and ascent itself afforded considerable relief."

In the dive-work experiments following hyperventilation, $P_{A}CO_2$ did not rise as high during descent (0-20 seconds) and did not reach the breaking point curve. The values remained below the curve during the dive (20-60 seconds) but, during ascent, they rapidly approached it at an hypoxic level (70 seconds) and surpassed it on surfacing (80 seconds). The authors comment: "With hyperventilation the 80 second dives were not markedly more taxing than the 60 second dives without hyperventilation. The transient distress noted early in the latter was not reported. The major difference was that the relief noted upon ascent was rapidly replaced by confusion and loss of control."

This analysis compares the data obtained during simulated dives with an atmospheric breaking point curve and the authors' observations on subjective

sensations. The comparison suggests that the breaking point curve during diving is similar to that of breath holding at the same initial lung volume under atmospheric conditions since, whenever the gas tensions came close to the breaking point curve, there were unpleasant subjective sensations. However, since the breaking point curve shown in Figure 6 is not that of the subjects of the diving experiments, it is impossible to say whether or not volume reduction by gas compression acts as an added ventilatory stimulus which limits the breath-holding dive. The analysis is presented as a summary of our present knowledge of this aspect of the subject and to indicate the need for further experimentation.

The alveolar gas tensions measured in the Amas were obtained immediately before, upon descent, and on surfacing from 30 second dives to 8.2 meters(13). The initial values were below normal as a result of slight hyperventilation. Because of this, but more importantly, because they exhale during the dive, $P_A\text{CO}_2$ did not rise much above normal during descent. At the completion of the dive their alveolar gas tensions did not reach the breaking point curve, a finding consistent with their apparent lack of respiratory distress.

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TARAVANA DIVING SYNDROME IN THE TUAMOTU DIVER

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PREFACE

The underwater exploits of the pearl divers of the Tuamotu Archipelago are equaled by no other group of breath-holding divers in the world. True, a few individuals have exceeded depths and/or duration of dives made by the Paumotan pearl-ers. But none equals the rigorous daily diving of this group during the peak of the pearling season.

As might be expected such great compressions and decompressions of the body, coupled with repeated stints of near maximum breath holding, cause syndromes of several diving ailments to manifest themselves. The most feared disease of this group of divers is called taravana by all the people of the Polynesian Islands.

This report will detail observations of this group of divers, most of whom were active in the Tuamotus in 1958 at the time of observations. Other divers, either retired, disabled, or more gainfully employed, were located in Tahiti, Raiatea, and in Honolulu, who had been stricken to some extent by taravana. In addition, information found in two unpublished reports will be covered. One deals with the frequency of taravana in a three week period of diving at Takapoto Lagoon; the other is the detailed observations of these divers by Dr. Truc, a Frenchman. Also presented are historical references to similar syndromes experienced by ancient sponge divers, pearl divers of other areas, and very early reference to the disease of the Tuamotu pearl diver.

INTRODUCTION

Skin diving, by breath holding, pre-dates recorded history. The earliest mention of a diver appears to be in the Iliad, where the fall of Hector's charioteer is compared to the action of a diver diving for oysters. In 460 B.C., Herodotus writes of a Greek diver employed to recover treasure from sunken ships. Naval divers were trained and employed as part of the offensive armies as early as 333 B.C.

References to the problems, diseases, and deaths in early skin divers, date nearly as far back in recorded history. Indications are that there were numerous accidents and deaths in this group of divers, just as there are today. The earliest such reference is in the Rhodian Sea Law which dates to about 400 B.C. Obviously each era and each area of diving would have different names for the diving maladies.

TABLE I
 List of Male Divers Working at Takapoto Lagoon in 1957(8)

Name of Diver	Age	Greatest Depth Reached (in Brasses)*	Began Diving In (Year)	Diving Accident Suffered	Remarks
ARII, Teihoae	43	20	1930	none	
AROIAU, Andre**	19	15	1955	none	
BELLAIS, Tavita**	45	6	1953	none	worked reefs only
FATUARAI, Narama	38	22	1949	none	
GATATA, Temoana**	36	22	1945	taravana	died, Hikueru 1958
HARRIS, Pori	46	14	1935	none	
HUATEKI, Tetohu	43	17	1940	none	
HUNTER, Alfred	34	8	1954	none	English diver
KAMEHAMEHA, Marere	27	20	1952	none	
MAHOTU, Alfred Roo	44	16	1937	vertigo	
MAHOTU, Theodore	20	23	1957	vertigo	
MARONUI, Joane	34	24	1949	vertigo	
MARUHI, Kipiriano	28	18	1957	none	
MATAI, Ernest	32	15	1947	none	
MATAIHAU, Terii**	60	18	1918	vertigo	
OPUU, Arona	19	15	1957	vertigo	
PARAPARE, Puhakuaruru	25	22	1952	none	
REHU, Manukura	25	17	1949	none	
REHU, Moana	41	17	1949	none	
REHU, Pepe	62	20	1911	vertigo	
SNOW, Edouard	57	14	1935	none	
SNOW, Hugo	35	23	1937	none	
TAHIRI, Matahuira	37	17	1948	vertigo	
TAHUA, Totoarii**	48	25	1948	vertigo	reached greatest depth
TAIKI, Moo	39	13	1950	none	
TANE, Maeva	24	23	1950	vertigo	
TAPI, Tuhiragi	37	18	1952	none	
TEAHI, Faaina	26	4	1954	none	worked reefs only
TETUHI, Teahi	59	9	1942	none	worked reefs only
TEUFI, Petero	48	17	1950	none	
TIMI, Taputira	32	24	1944	vertigo	
TIMI, Taroa	35	20	1943	none	
TIMI, Tihoni	37	24	1943	none	
TOTI, Tuiata	47	4	1946	none	worked reefs only
TUHOE, Tauita	45	25	1924	vertigo	reached greatest depth

TABLE I (A)

List of Female Divers Working at Takapoto Lagoon in 1957(8)

Name of Diver	Age	Greatest Depth Reached (in Brasses)*	Began Diving In (Year)	Diving Accident Suffered	Remarks
HAPAI, Roo	47	5	1948	none	worked reefs only
HARRIS, Mariane	42	11	1946	vertigo	
SNOW, Moeata	33	5	1949	none	worked reefs only
TAHIRI, Teuru	59	4	1935	none	worked reefs only
TEHOTUA, Miria	35	10	1950	none	
TEPA TEPA**	22	24	1951	none	
TTUEINA, Mokouri**	35	24	1953	none	best woman diver
VAHINETUA, Tetua	48	12	1954	none	

*A brasses is equal to approximately one fathom. It is the distance the diver can reach with outstretched arms and varies with the diver.

**Indicates divers who are known to have worked Hikueru Lagoon.

In addition to the divers listed in Tables I and I (A), there were 27 other divers who resided in Papeete but had come to Takapoto to work as divers during the pearling season.

The divers of the Tuamotus have Paumotan names for some of their diving maladies and French names for others. The most feared of the diseases is tara-vana (tara, to fall; vana, crazily). Topatari means to die in the water, without distinction as to cause. Paremo means to drown as a result of falling into the water from shore or from a boat. Nou-nou is their word for insane greed. Parau means pearl shell. Nou-nou parau is their term for pearl shell insanity.

The people of the Tuamotu Archipelago are basically of Polynesian stock. Not as tall as the populations of the mountainous islands such as Tahiti or the Australs, they are of medium height and are very heavily built. They usually have a tremendous muscular development but have a tendency toward becoming overweight, sometimes at an early age. Most of the pearl divers are of this muscular, well developed, Polynesian stock.

The actual number of divers employed in the pearl industry is difficult to estimate because they drift from one atoll to another with the season as the shell becomes fished out in each of the pearling lagoons. Probably no more than 1000 divers work in all the lagoons during any one season. This includes the major divers, who are all experienced men, with the exception of a few women who are capable of diving to depths in excess of 60 feet. Most of the women, and many children, work the shallow areas of the lagoons. When the pearling season opens in Hikueru Lagoon, for several years the richest of all pearling areas, as many divers as possible will be on hand. In 1958 there were an estimated 235 major divers working the lagoon, several from the Island of Takapoto. Clark⁽⁶⁾ reported in 1951 that the normal population of Hikueru was 150, but for the pearling season some 800 were there, including 200 divers.

DIVING HABITS

The diving season in Tuamotus also corresponds to the season of strongest trade winds and lowest air temperatures. The divers leave the villages at about 7:00 am, are usually at the diving grounds by 8:00 am and most have started diving by 8:30 am. Extremely heavy surge coming into the lagoon over the reef results in little if any diving because of the reduced visibility. Other reasons given by the divers for not diving were the frequent colds suffered by the divers. Berg⁽⁴⁾ mentions this as well as indigestion as a reason for not diving.

The temperature of the water at Hikueru in 1958 was 82°F at the surface on the lee side of the lagoon. On the seaward side, where the ocean water was being driven into the lagoon across the reef by the trade winds, a minimum water temperature of 79°F was found. Temperature varied but one degree to a depth of 20 fathoms. Domard⁽⁸⁾ reported that a maximum water temperature at Takapoto of 83°F with a minimum of 79°F and no change in temperature to a depth of 100 feet (30 m). Air temperature ranged between 73°F and 83°F. All divers observed at Hikueru seemed to suffer from being cold, both while in the water and on the surface. Periodically they climb into their canoe for 10 to 15 minutes for rest and rewarming.

DIVING EQUIPMENT

The equipment of these divers is very simple. In addition to the canoe, most of which are large outriggers with outboard motors, the diver uses a descending line with an 8 to 12 pound lead weight, and either diving goggles or the modern diving mask or face plate. Most observers have reported divers in this area using wooden or metal goggles. When metal, they are usually of copper. A perfect fit is achieved by forming the edges with a mastic material. In 1958 at Hikueru an estimated 50 per cent of the divers used face masks. The diver also wears a strong glove on his right hand, made of light canvas. This is used for tearing the pearl shell from the bottom of the lagoon.

In addition to these aids, the diver has a helper, or "tete" who assists the diver with the canoe's anchor rope, the shell basket, and the rope by which this is lowered and raised. However, the main function of the "tete," and no diver will work without one, is to rescue the diver should taravana strike. Berg⁽⁴⁾, Clark⁽⁶⁾ and Truc⁽¹²⁾ all remark on the importance of the tete in saving the diver from drowning.

DIVING TECHNIQUES

Prior to the first dive of the day, or after a rest period in the canoe, the divers at Hikueru hyperventilate for periods ranging from three to ten minutes. Their hyperventilation is in the form of deep inhalations followed, after only one or two seconds, by a deep expiration accompanied by a long drawn "whooooo" sound. Truc⁽¹²⁾ reported hyperventilation of from two to six minutes. As the diver hyperventilates he puts the glove on his right hand and gets the descending line ready. When he is ready to dive he goes over the side of the canoe and continues to hyperventilate. Just before the descent he increases the rate of hyperventilation, then raises himself out of the water to the waist, takes a deep breath, and descends feet first. See Figures 1 and 2.

During descent the diver holds the lead weight between his feet and holds the rope with his right hand. With his left hand he grasps his nose to assist with equalizing. See Figure 3.

Experience and physical condition seem more important in his ability to reach great depths than does age. However, divers in the 40 to 50 age group were observed working in excess of 100 feet more often than younger divers. However, Domard⁽⁸⁾ reported that 15 out of 35 divers were capable of reaching depths in excess of 20 brasses (about 110 to 120 feet). Their ages ranged from 20 to 62 years with ten divers in the 24 to 38 year bracket.

When making dives to 100 and 130 feet, the descent is made in from 30 to 50 seconds. Truc⁽¹²⁾ reported descents to 30 m in 30 to 40 seconds. The rate of descent probably depends on their ability to clear their ears since divers were observed slowing down or stopping momentarily while grasping their nose to assist in this maneuver. As this ability varies with each diver on different descents, so does the rate of descent.



Figure 1. All divers hyperventilate prior to descent. Inhalation and exhalation were forceful and deep. Exhalation was accompanied by a shrill "whooooo" made through pursed lips.



Figure 2. After a period of hyperventilation, the diver, while still hyperventilating, placed the lead weight between his feet, grasped the descent line with his gloved right hand, and entered the water. After a few more moments of hyperventilation, at a more rapid cadence, the diver took a deep breath and started his descent.

soon as he is on the surface the diver immediately begins a period of hyperventilation lasting from three to ten minutes.

The maximum duration of a dive, from surface to surface, observed on Hikueru was 2 minutes and 35 seconds. This was accomplished by a diver who was posing for pictures, and not during a working dive. Most of the divers remained

As soon as he is on the bottom the diver drops the lead weight and swims and crawls over the bottom searching for shell which he pulls loose and places in the rope basket. See Figure 4.

Four divers working together in a bed of shell were observed and timed while on the bottom in 110 feet of water. Their time on the bottom ranged from as little as 30 seconds to as much as 60 seconds. There was no correlation between an individual on his bottom time and the need to ascend seemed to depend more on how far he had to swim for shell than on how long it took to descend.

The ascent is always rapid and sometimes, after a particularly long dive, the diver appears to be near panic. The ascent is made by pulling himself to the surface on the basket rope. Ascent time is usually no more than 20 seconds from depths of 100 to 130 feet. The divers usually begin some exhalation when very near the surface (as in Fig. 5) but the greatest volume of air is exhaled noisily as he pulls himself up beside the canoe. As

under water no more than one minute and 50 seconds and the average was one minute 30 seconds for a series of timed dives. Berg⁽⁴⁾ reported a maximum time for these divers of three minutes and says the time under water for a particular diver was the same whether he was working in 40 feet or 100 feet of water. Truc⁽¹²⁾ also reported that depth had little relation to duration of the dive.

A brief summary of taravana cases that developed in Hikueru in 1958 and those occurring at Takapoto during a three-week period will serve to point out the frequency and severity of the symptoms of this disease.

In Hikueru Lagoon there were an estimated 235 divers working on a typical day of trade wind weather. Wind, estimated at 15 knots, sunny, with scattered cumulus clouds, air temperature 79°F, water temperature 83°F. The water was clear and only moderately choppy.

At the end of the six-hour day of diving a total of 47 divers had been affected by various taravana symptoms.

Thirty-four suffered vertigo, nausea, and mental anguish.

Six had partial or complete paralysis.

Three suffered temporary unconsciousness with no other symptoms.

Two were mentally affected.

Two died.

At Takapoto Lagoon, in 1957, 43 divers (35 male, 8 female) were working the lagoon. In a three-week period Domard⁽⁸⁾ reported 13 cases of taravana. Twelve were in male divers, one in a female diver.

Twelve cases of vertigo and nausea, one of which was in the female diver.

One serious case involving paralysis.



Figure 3. Nearly on the bottom the diver completed equalization of his ears by holding his nose and forcefully exhaling. This method of equalizing pressure in the ear is wasteful of air. Whenever the diver had to resort to this method of equalizing his time on the bottom was decreased.



Figure 4. The diver swam or semi-crawled over the bottom while searching for shells. He made from one to three trips to the rope basket with shell before he was forced to ascend.

Paralysis was nearly always accompanied by vertigo, nausea, and a general feeling of anguish. However, these symptoms occur frequently without paralysis.

Of the two deaths, one was observed. The other occurred later in the day. The observed death followed a series of dives to a depth of 130 feet. By comparing the amount of shell in the canoe with that brought up in the basket from the last dive it appeared that the diver had made 18 to 20 dives in less than two hours. There was no apparent sign of life when the diver was brought to the surface and hauled into the canoe, nor during the trip to the village.

The second victim was rescued by the *tete* and also pulled into the canoe. I was told he was semi-conscious for nearly two hours but died later in the village.

At Hikueru all divers agreed on the suddenness of the onset of the various symptoms. Seldom was there any warning except divers frequently referred to what translated as "sparkling their eyes." This is undoubtedly what Dr. Truc⁽¹²⁾ referred to as "Scotome Scintillant de la Migraine Ophtalmique (visions d'etoiles filantes, de scintillements lumineux, etc. " The divers also agreed that these symptoms were always too late to be a real warning of other more serious symptoms. Some few seconds after these symptoms the diver may suffer paralysis or unconsciousness.



Figure 5. When no longer able to hold his breath the diver pulled himself rapidly to the surface via the shell basket rope. The rope leads to the side of his canoe. Attached to the smaller rope is the lead weight which pulled him to the bottom. Both ropes were pulled to the surface by the *tete* after the diver was on the surface.

Deaths in skin divers under conditions that would indicate the possibility of symptoms similar to taravana have been reported by many observers. Apple-garth⁽¹⁾ and Byers⁽⁵⁾ reported deaths in skin divers. Berg⁽⁴⁾ reports of the Tuamotu pearl divers, "The young skin diver's greatest danger is overstaying under water. Frequently, as a result he collapses as he nears the surface. More than once I have seen a man come up right beside the canoe — and suddenly — just before he broke water, his limbs relaxed, his body looked as if it had a paralytic stroke, all the remaining air rushed out of his lungs; he began to sink slowly." And on page 325 he states, "Go ashore at a place like the Bahrein Island, and the greatest population in sight seems to be the burying place of dead skin divers."

Clark⁽⁶⁾ reported one death at Hikueru in 1951 and two deaths in 1950. Mericourt⁽⁹⁾ reported that sponge divers frequently dived to depths of 45 to 55 meters and remained submerged from two to four minutes, and that naked divers were frequently paralyzed and died as a result of the dives.

Smith⁽¹¹⁾ in writing of the ancient Greek sponge divers states, on page 9, ". . . if the depth be considerable, the pressure of the water on the breast and the organs is so great that it occasions the eyes to become bloodshot, and produces spitting of blood; and if the practice is persisted in, it will most likely prove fatal, and this has too frequently been the case."

Truc⁽¹²⁾ reported two deaths in divers at Hikueru in 1955 and indicated there were additional deaths in other pearling areas ("Two in the space of three months during the 1955 season in Hikueru alone. ").

The extent and degree that taravana has affected the mental health of the divers in the Tuamotus is tragic. All who have visited these islands, observed the divers, and visited with their families, have remarked on these "people of simple spirit," as they are called.

Of the two taravana cases that were mentally affected during the 1958 season, one was unable to recognize his family or home. He was restless, irritable, and lacking in understanding of his surroundings. The other was unable to speak coherently even though he seemed normal otherwise.

The duration of the taravana symptoms varies greatly. Sometimes they last for a few hours, other divers have been afflicted for life. Tahauri Hutihuti, male Paumotan diver, age 71 (in 1958) claimed he had never had taravana. However, he was mentally slow and often missed what he was reaching for. He was still physically able and dove to a limited extent that year. Clark⁽⁶⁾ refers to these divers as being "punch drunk."

Dr. Truc⁽¹²⁾ approached their problems and conditions more scientifically and devoted a page in his report to this form of taravana, the translation of some of which is quoted as follows:

"The psychopathologic forms of taravana are less frequent than the paralysis but they are not less important because their cure is often less complete. The old divers who suffered the effects all their

lives are numerous and the consequences remain considerably lessened in the intellectual level.

"Certain of these individuals remain prostrated entire hours and days, incapable of adapting themselves to the most elementary physiological needs, in a state of the most complete lack of physical control imaginable. All the forms of agnosia and apraxia can be observed, and the accounts of the divers are abundant in precise descriptions and full of accounts on this subject. Signs of agnosia seem particularly frequent with these sick people and bring forth blunders and silly mistakes. "

Paralysis is a frequent form of taravana. However, a great majority of the cases (Truc⁽¹²⁾ believes 95 per cent to 98 per cent) are temporary and the diver will completely recover in a matter of hours or, occasionally, days.

During my 1958 visit, one case of complete paralysis was rescued. On the way to the village he regained full use of all limbs except his left arm. Two other divers had single limbs affected. The other three divers had one or the other side partially or completely paralyzed.

Applegarth⁽¹⁾ reported two near deaths in separate swimming pool accidents during instruction in underwater swimming while breath holding. "The swimmer was pulled out unconscious. His muscles were rigid." The second case was almost identical.

Barbe⁽³⁾ reported spasmodic paraplegia in sponge divers characterized by anesthesia and hyperesthesia of the limbs, muscle spasms, or convulsions. He felt the cause of the distress of these divers was due to the release of excess gases dissolved in the blood.

Berg⁽⁴⁾ indicated (page 310) that paralysis was a rather common occurrence in the divers of the Tuamotus, ". . . paralysis ever waits to seize the reckless. "

Mericourt⁽⁹⁾ mentions paralysis as one of the hazards of the pearl diver. Oliver⁽¹⁰⁾ stated, "Dangers from attack by sharks, giant eels, rays, and other marine terrors were all very real; and lung collapse or paralysis were the usual prices paid for too long or too deep immersion. "

Truc⁽¹²⁾ discussed the various forms of paralysis to some extent in his report, the important points being quoted below.

"Monoplegia and hemiplegia occur in approximately the same frequency in the case of paralysis studied. Hemiplegia of the right side was constantly accompanied by aphasia.

"The description of the divers agree strikingly on the general character of the paralysis. They appear suddenly and severely and present all the character of central paralysis. All the divers insist that the suddenness of the occurrence of the paralysis is alone responsible for preventing them from being warned by the migraine

ophtalmique already mentioned. The paralysis strikes in one blow all affected areas.

"It is indeed some seconds after the onset during the dive that the paralysis strikes the diver. The paralysis manifests itself mostly at the end of the dive, at the moment the diver is climbing along the rope or at the moment he is trying to hoist himself into the canoe. At that moment he becomes suddenly conscious that a member or one side of his body becomes inert, refusing all movements."

Turoa Hutihuti, male, age 48 in 1958, worked with me in obtaining underwater pictures of the divers equipment and techniques. He had been diving since he was 17 years old. He regularly made dives to 140 feet for periods as long as two minutes, although slightly less as an average. He had taravana several times, once paralysis of his right side; vertigo and nausea several times. The paralysis lasted three months. He also has a slight vision defect. This is possibly from taravana.

A Paumotan diver, now residing in Honolulu, suffered a severe case of paralysis but recovered completely after one year.

By far the most common symptoms of taravana experienced by the pearl divers are vertigo, nausea, and less frequently, mental anguish. Occasionally vertigo alone was the only symptom. Usually, the divers reported acute nausea and were observed lying in the canoe with eyes closed and head grasped in their arms as they rocked back and forth. A total of 34 divers reported various degrees of vertigo in one day at Hikueru. Depths reached by these divers ranged from 40 to 130 feet.

Truc⁽¹²⁾ reported similar observations and says, "The diver has the impression that he sees the canoe turning over rapidly." Truc also reported that vertigo and nausea, while not constant, occurred in 60 per cent to 70 per cent of all cases of taravana.

Vertigo was also reported by Domard⁽⁸⁾ in Takapoto Lagoon where 12 divers out of 43 suffered such symptoms in a three-week period. They had been working at depths ranging from 60 to 150 feet.

In Papeete a pearl diver who had been working the Tuamotu pearl beds was visited in the local hospital. He was of Swedish descent but had lived in the Islands for many years. During the previous pearling season he had been stricken by taravana — temporary unconsciousness, hemiplegia (left side), and had nearly drowned. He recovered in a "few days" except for anesthesia of his left forearm and lower leg. He did not continue diving but returned to Papeete on the next schooner and consulted medical authorities. The condition persisted and slowly grew worse. The first outward sign was a rash and scaly appearance of the affected parts. After several months the rash developed into small open sores that continued to spread over most of the affected areas. When I visited him in the hospital the rash had developed into two large open sores, one on the sole of his left foot, the other on his left hand, surrounded by the flaky, scaly, skin. Except for the open sores the

skin had the appearance of an acute case of shingles. He was also emaciated, weak, and nervous.

Topatari means to die in the water. In Hikueru in 1958, three divers surfaced unconscious. If they had not been rescued they would have drowned and been victims of topatari. These three divers were given the Paumotan equivalent of artificial respiration and recovered with no ill effects and reported no other symptoms. Dr. Truc⁽¹²⁾ reported, "These accidents are still very frequent and are probably due to a bulbar syncope which is comprehensible among people who work or labor in the extreme limits of anoxia."

In addition to the various syndromes of taravana these divers are also subject to more conventional accidents of skin divers in other parts of the world. Most divers observed frequently surfaced with bleeding from the nose and mouth. They do not consider this serious and accept it as part of the day's work. This condition seems to produce no lung or other respiratory pains.

Dr. Truc⁽¹²⁾, in writing of physical examinations he had given said, "Two divers, each over sixty years of age, with thirty years diving for pearls, were examined and their heart and respiratory systems were found in perfect condition. He also stated that ruptured ear drums, and other ear trouble, were extremely rare among the divers of the Tuamotus.

According to Truc⁽¹²⁾ and Mikele (in a personal communication) the divers of Mangareva never experience taravana. Truc states that the only difference between the technique of the Paumotan diver and that of the Mangareva diver is the spacing of each of their dives. The Mangareva divers make a descent about every 12 to 15 minutes instead of every four to ten minutes for the Paumotan diver. Truc also stated that the Mangareva divers use a less forceful but longer period of hyperventilation.

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DECOMPRESSION SICKNESS FOLLOWING REPEATED BREATH-HOLD DIVES

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In *Submarine Medicine Practice* page 259(1), it is stated that: "Decompression sickness is virtually impossible for the skin diver because he can not submerge deep enough or remain long enough to take up a troublesome amount of nitrogen — unless he has access to a supply of air at depth." In the following, the reliability of this statement is questioned by a report of a case of decompression sickness after repeated skin dives to great depths. The case reported concerns a Danish medical officer, an educated diver in the Danish Navy. The author has an intimate knowledge of the event, because the medical officer happened to be himself.

Method

The diving took place in a "free escape" tank, adjacent to the Diving School of the Norwegian Naval Base in Haakonsvaern at Bergen. The tank has a depth of 66 feet (20 m). The equipment and circumstances were the best possible for exercise in "free escape" and skin diving. (By skin diving is meant diving without any breathing apparatus.)

The applied technique for the skin dives was that of a so-called "bottom drop" ("feet-first surface dive"). Provided with a nose clip and a mask, the diver at the surface takes a deep breath, shoves off with his arms from the border of the tank and descends with head up - feet down, without making any movements of his extremities. After the first six to ten feet (two to three M), he will "drop to the bottom" with increasing speed.

On the day of the accident all my dives were skin dives, and no supply of air at depth was used. No oxygen-breathing took place between the dives. Before entering the water I had been in a recompression chamber for about eight minutes to 66 feet (20 M), as attendant during a pressure test. Immediately after that I went to the tank and performed the "bottom drop" technique, in connection with my duties as medical supervisor for Danish submarine crews. The following diving pattern was used in nearly all the dives. It took about 20 to 25 seconds to reach the bottom, where I was sitting or walking slowly about, until the urge to breathe became imperative, usually after about two minutes, which is my maximum breath-holding time during a "quiet dive" to that depth. By making a few powerful pulls on a rope attached above the tank, it was possible to ascend very fast (10 to 15 seconds). The "surface intervals" varied between a few seconds and one to two minutes. The total number of dives were about 60.

Result

The total time in the water was about five hours. During the last two hours I had progressive symptoms of nausea, dizziness and eructations but nothing else. Within one-half an hour after the end of the diving I got pains in the left hip joint, but only very slight at the beginning. They were not accentuated by movements. Later the pain became more intense and also affected the right knee joint. Besides dizziness, nausea and eructation, the right leg felt tired and my right arm was so weak that it was of little use. Two hours after the end of the diving, severe chest pains began. They were not influenced by expiration or change of position, and were accompanied by a feeling of inspiratory distress and a sense of imminent collapse. The paresthesia developed in the right hand together with blurring of vision.

Three hours after the diving a colleague found me markedly pale and exhausted as in impending shock. He made a short examination and substantiated visual disturbances and a partial paresis of the right arm. As the symptoms were in progress, accompanied by abdominal pains and anesthesia of the ulnar region of the right hand, I was placed in the recompression chamber. At six atmospheres absolute (at. abs.) pressure I felt an immediate relief with respect to the dizziness and nausea. In a few minutes the bends and the partial paresis had disappeared. After 25 minutes at 6 at. abs. the paresthesia and anesthesia disappeared, and only a slight prickly sensation in the right hand remained. The medical officer of the Diving School, after a careful examination, treated me after "Table 3" of the treatment table⁽²⁾. The treatment was successful with immediate relief of all symptoms and signs.

Discussion

The neurologic signs and the response to recompression make it certain that bubbles were in the vascular bed. Air embolism after lung rupture can not be ruled out just by the fact that no "free escape" or respiration in compressed air occurred in the water. A common case of acute lung rupture is, of course, excluded. Another possibility is a bronchial constriction or obstruction with a valve effect causing air to be trapped in a lung segment. Ruptures in the lung tissues and vascular walls might then cause air to enter the circulation and the peribronchial and mediastinal tissues, even though no bleeding occurred. A normal chest x-ray and no respiratory symptoms and signs during frequent and extensive diving in a year before and after the event can not totally rule out this explanation.

Let us consider the possibility of accumulation of nitrogen. During a breath-hold dive to 18.5 meters of depth we have in agreement with others determined the mean N_2 content of the alveolar air to about 87-93 per cent⁽⁸⁾ at the bottom dependent upon the time of exposure. Provided that the time function table is applicable in this connection it is possible from this percentage to calculate the PN_2 's in tissues with different half-times, after repeated breath-hold dives of the type here described (Figs. 1 and 2). In five minute tissues a PN_2 of 1565 mm of mercury is reached after 13 skin dives to 61 feet and a PN_2 of 2134 mm after the same number of dives to 100 feet. The curves show three interesting

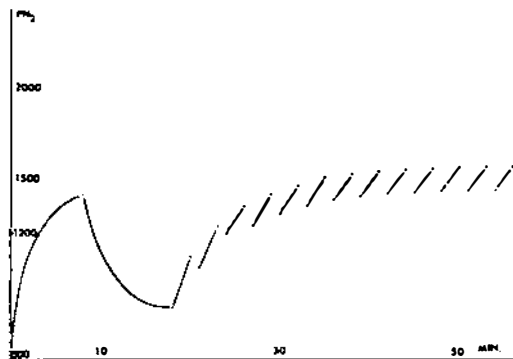


Figure 1. Nitrogen Tensions in Five-Minute Tissues During Repeated Dives. After eight minutes in a pressure chamber at 3 at. abs. followed by a ten minute surface interval which is then followed by 13 breath-hold dives to 61 feet. Each dive lasted two minutes with one minute surface time between each dive.

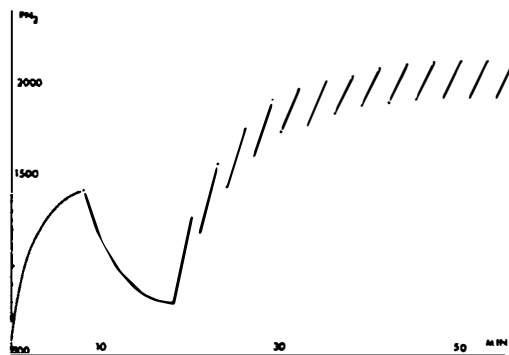


Figure 2. Nitrogen Tensions in Five-Minute Tissues by Repeated Diving. The same diving pattern as in Figure 1, except for the depth of breath-hold dives, which is here 100 feet.

phenomena: (1) the tissue nitrogen tensions increases to a considerable magnitude by repeated breath-hold dives; (2) after a number of dives a certain equilibrium level is reached and then the tissue PN_2 seems to be constant by a continuation of the diving pattern; and (3) this equilibrium level is below the maximum allowable tissue tensions by conventional diving.

In tissues with half-times of 10 to 120 minutes preliminary calculations have shown PN_2 's of about the same level as that of Figures 1 and 2, but after a greater number of dives. This needs further examination. Calculations by the most appreciated help of a computer are in accordance with the conclusions made here(9). Since the rate of ascent was very fast (1.5 to 1.8 meters per sec.) and involved exercise as compared to the passive, conventional ascent (.3 meters per sec), item 3 above, is perhaps not relevant for this type of diving. The rapid rate of ascent would also involve that blood nitrogenated in the lungs at the bottom would still be circulating peripherally when the surface was reached. Some bubble formation on this basis alone could be expected even in the first such dive, although it is not likely that such bubbles would become consequential except in reaching tissues already having a PN_2 sufficiently high to cause nascent bubbles to grow. The final PN_2 's in Figures 1 and 2 are perhaps high enough for this mechanism in the slower half-time tissues.

The N_2 accumulation in combination with the CO_2 retention is perhaps the detail explanation of the bubble formation. A carbon dioxide influence on bubble formation is possible and experimental evidence of CO_2 retention in addition to the N_2 accumulation is present(8). According to our determinations during real breath-hold dives in Norway of the differences in the gas content of the lungs before

and after a bottom drop of 40-60 seconds duration, the CO₂ retention is identical with the CO₂ production during a dive minus about 50 ccs. From Lanphier's and Rahn's data the same amount during a simulated breath-hold dive can be calculated. The amount of N₂ disappearing into the tissues during a seven dive series was on the order of 500 to 800 ccs in our three subjects. Now to the question of the speed with which this enormous amount of CO₂ in N₂ is eliminated after the ascent. With regard to the N₂ this is difficult to evaluate. With regard to the CO₂, Schaefer's findings⁽⁷⁾ and ours⁽⁸⁾ are in accordance. The absorbed CO₂ is not released in great amounts within the first two minutes of the surface intervals. This makes it likely that a gradual accumulation of N₂ and CO₂ will occur during repetitive breath-hold dives to great depths.

The character of the neurological symptoms and signs, their progressive development after the diving, the above theoretical considerations as well as the prompt relief upon recompression makes it reasonable to assume that the case here reported was decompression sickness, as was concluded in a report to the Norwegian Naval Authorities⁽³⁾.

It thus appears that even during relatively short breath-hold dives here described it is possible to produce decompression sickness, which so far has been described only in relation to conventional diving of longer duration.

Three cases of decompression sickness in Norwegian tank instructors were treated by O. Haavelsrud⁽⁴⁾, within one year before the case here reported. All have now totally recovered and are participating in diving experiments. One was a very tall diver with an enormous lung capacity for breath-hold diving. He experienced two episodes of severe decompression sickness. The dives took place in the same "free escape" tank and the same diving pattern was used as described above. These instructors performed a variable number of "bottom drops" before the sickness developed and in each case there was immediate relief by recompression. It is of interest to note that the three Norwegian tank instructors and the case here reported all had a certain degree of N₂ loading by breathing compressed air at 20 meters of depth, before the repeated breath-hold dives took place, and all were cases with severe neurological symptoms and signs. None of these cases displayed any signs of lung rupture.

Cross⁽⁵⁾, has reported a syndrome called "Taravana," of the skin diving pearl divers of the Tuamotu Archipelago in the South Pacific. These divers make 40 to 60 dives per day to depths of 100 feet (30 m) or more, spend an average of two minutes per dive under water, and three to four minutes at the surface. Mild cases of "Taravana" show no more than extreme dizziness or visual disturbances. In severe cases he observed unconsciousness, partial or complete paralysis of one or more extremities (permanent or temporary), and occasionally death. Cross explained his observations in terms of anoxia, and this, of course, is a very likely possibility in cases where only unconsciousness or death is registered. However, the diving pattern (repeated dives to great depths, with long "bottom times" and short "surface intervals") and the neurological character of the injuries reported, is similar to the diving pattern and signs in the case here described. Therefore it is reasonable to assume that "Taravana" is identical with decompression sickness.

On one of the islands, Mangareva, this "skin diving disease" ("Taravana") is not known. The only difference in the diving pattern is that the Mangareva-divers, obeying an old tradition, use "surface intervals" of at least ten minutes, during which time they practice mild hyperventilation. This coincidence of longer "surface intervals" and absence of "Taravana" is in accordance with the explanation of "Taravana" as decompression sickness. Longer "surface intervals" will not only permit a better nitrogen elimination, but also tend to reduce the number of dives per day.

In general, skin diving is performed as "exercise dives"⁽⁶⁾ ("head-first surface dives") in which the demand for oxygen limits the depth, the "bottom times" as well as the number of repeated dives and thereby the nitrogenation. This may explain why decompression sickness is so seldom met in skin diving. However, it should be borne in mind that under certain circumstances repeated skin dives can result in decompression sickness, in which case immediate recompression must be the adequate treatment.

Summary

A report is given of a case of decompression sickness after repeated skin dives to 50 to 66 feet (15 to 20 m). Three similar cases in Norwegian tank instructors are mentioned. All four cases were relieved promptly upon recompression.

A parallel is drawn between the Scandinavian cases of "skin diving disease" and the "pearl diver disease" (Taravana), found on the Tuamotu Archipelago in the South Pacific.

All observed symptoms and signs in these cases of "skin diving disease" may be explained as decompression sickness.

It is emphasized that in such cases immediate recompression is the treatment of choice.

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APPLICATION OF DECOMPRESSION TABLES TO REPEATED BREATH-HOLD DIVES¹

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Decompression sickness is a familiar consequence of exposure to high pressure in caisson or tunnel work and in air-supplied dives, but until recently there was little reason to believe that it was likely to result from breath-hold diving. Schaefer⁽¹²⁾ discussed probable formation of bubbles in the circulation on ascent from deep breath-hold dives and was able to attribute this largely to excess nitrogen, but he could cite no clinical concomitant. The usual view, as expressed by Lanphier writing in *Submarine Medicine Practice*⁽¹⁴⁾, was that enough nitrogen to cause symptomatic bubble formation was most unlikely to be taken up in this form of exposure. Such opinions did not, however, take into account the extremes of depth, frequency, and repetition to which breath-hold diving can be carried.

In 1961 and 1962 Cross^(3, 4) described diving patterns among the pearl divers of the Tuamotu Archipelago and provided a graphic account of "the dread disease" of these divers: "taravana." In Cross' words⁽⁴⁾: "Many of the divers who fall crazily back into the lagoon as they emerge from a dive are rescued by their tete or helper only to die later in the village. Those who survive may be paralyzed or mentally incompetent for days, weeks, and sometimes for the rest of their lives." Cross considered the possibility that taravana was a form of decompression sickness but regarded anoxia as a much more likely explanation. Craig⁽¹⁾ and Lanphier and Rahn⁽⁸⁾ have emphasized the danger of hypoxia in this form of diving but suggested no consequences other than loss of consciousness and resultant drowning. Craig⁽²⁾ seriously questioned anoxia as the explanation of taravana and suggested other possibilities including air embolism and decompression sickness.

Recently Paulev⁽¹¹⁾ has described four cases of severe illness following large numbers of breath-hold dives. The signs, symptoms, and course of events were compatible with the diagnosis of decompression sickness^(9, 15) and were very difficult to explain on any other basis. In addition, all four cases responded dramatically to therapeutic recompression. Paulev⁽¹¹⁾ emphasized points of similarity between these episodes and taravana, both in diving patterns and in some of the symptomatology. The response of taravana to reasonably prompt recompression has apparently not been investigated.

Theoretical considerations are not likely to have the force of proof in this field, but it would be useful to have some method of evaluating the likelihood of decompression sickness in terms of probable tissue nitrogen tensions in this form of diving. Most existing information concerning the relationship between exposure

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to depth, nitrogen uptake, and the corresponding incidence of decompression sickness is embodied in divers' decompression tables such as those used by the U.S. Navy⁽¹⁵⁾. Since these refer to continuous air-supplied dives, they are not directly applicable to breath-hold diving. However, it appears possible to equate, in terms of probable tissue nitrogen levels, a given series of breath-hold dives to a specific air-supplied dive for which a decompression schedule or exposure limit can be specified.

This paper describes such an approach and the tentative conclusions that can be reached from it. These are in agreement with existing information and support the belief that breath-hold diving can, when carried beyond certain limits, result in decompression sickness.

METHOD

Figure 1 presents the relationships seen when the nitrogen level in a hypothetical tissue is computed for repeated breath-hold dives of different consistent patterns. As in computation of U.S. Navy decompression tables^(5, 6, 16) it was

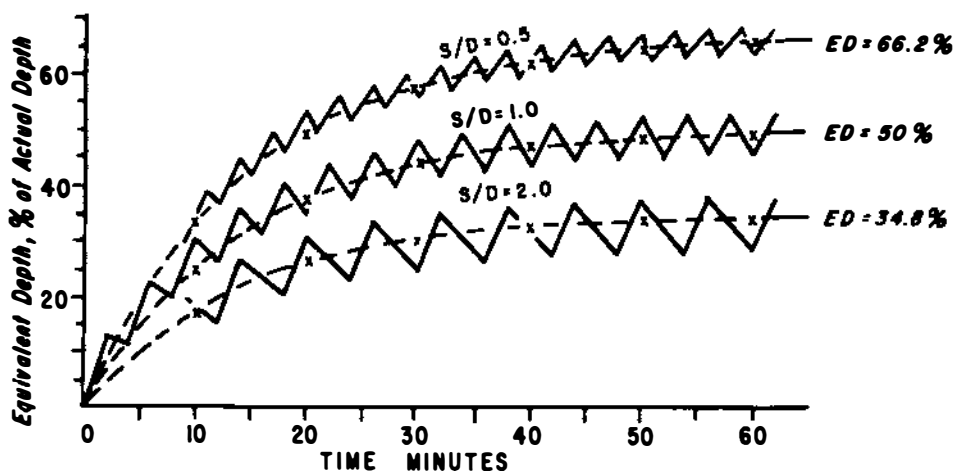


Figure 1. Computed Nitrogen Pressure vs Time in a Hypothetical Tissue of 10-min Half-time During Repetitive Breath-Hold Diving. Horizontal scale: total elapsed time during series of dives. Vertical scale: tissue nitrogen pressure as a percentage of the maximum value with indefinite exposure to air at actual depth (equilibration with air at surface = zero). Solid saw-tooth lines: tissue nitrogen pressure showing fluctuation with each period at depth or surface. Dashed lines: exponential rise of tissue PN_2 during steady exposure to air at equivalent depth (see text). Upper curves: times at surface/time at depth (S/D) = 0.5. Middle curves: S/D = 1.0. Lower curves: S/D = 2.0. (Time at depth = 2 min in all cases; time at surface varied according to specified S/D.) Selection of the "10-min tissue" for use in these examples was largely arbitrary.

assumed that the body can be represented, from the standpoint of nitrogen uptake and elimination, by a collection of tissues each gaining or losing nitrogen exponentially with its own half-time of saturation and desaturation. Calculations were simplified by assuming that descent and ascent were instantaneous and that the alveolar nitrogen concentration remained the same in breath holding as in air breathing at depth.

The scale of nitrogen pressures is most conveniently based upon the PN_2 of air at the actual diving depth, calling this 100 and letting the PN_2 of air at surface be zero. On this scale, the "inward gradient" for uptake of nitrogen at depth is the difference between 100 and the existing nitrogen level in the tissue being considered. The "outward gradient" for loss of nitrogen at the surface between dives is represented by the tissue value directly. Every point on the scale is equivalent to the PN_2 of air at some specific depth. For example, if the actual depth is 100 feet, "50" represents the PN_2 of air at 50 feet.

Equivalent Depth

In calculations like those illustrated in Figure 1, it is evident that the tissue will eventually reach a state of effective equilibrium in which the gain of nitrogen during periods at depth is offset by the loss during periods at surface. The computed tissue nitrogen tension will then oscillate about a steady mean value. This value will be equal to that which the tissue would reach in complete equilibration with air during a continuous air-supplied dive to a specific depth. This depth can be called the equivalent depth (ED) and expressed in per cent of actual depth as on the nitrogen scale.

In approaching ED, the mean nitrogen tension of a tissue follows essentially the same time course during a series of breath-hold dives as it would during continuous exposure to air at ED (dashed curves in Fig. 1). This being the case, the mean nitrogen tensions of all tissues must be much the same at any given point of elapsed time in breath-hold diving as after the same period of time in exposure to air at ED. Once a value of ED has been established for a given series of breath-hold dives, it should thus be possible for present purposes to consider the series entirely equivalent to a single air-supplied dive to that depth.

Figure 1 also indicates that the main determinant of ED is the ratio of time at surface to time at depth (S/D time ratio). The simplest situation exists when times at surface and depth are equal (S/D = 1.0). With equal times, the exponential change must represent the same fraction of the inward gradient and of the outward gradient. With loss equal to gain, the equilibrium level is thus defined as the point at which these gradients are equal. Here, the mean tissue nitrogen tension can only have a value of 50: ED must be 50 per cent of the actual depth. Where the periods at surface and depth are not equal, equal loss and gain of gas requires that the gradient for the shorter period must be greater: where S/D is less than 1.0, ED must be greater than 50 per cent of actual depth, and vice versa. The relationships are not linear because of the exponential gain and loss of gas: except where S/D = 1.0, the computed value of ED depends somewhat upon the absolute times and tissue half-times employed. However, calculation on the basis of two-minute periods at depth and a ten-minute tissue half-time appears to yield a satisfactory compromise. This is the basis of the solid curve of Figure 2, which gives ED (in per cent of actual depth) as a function of S/D.

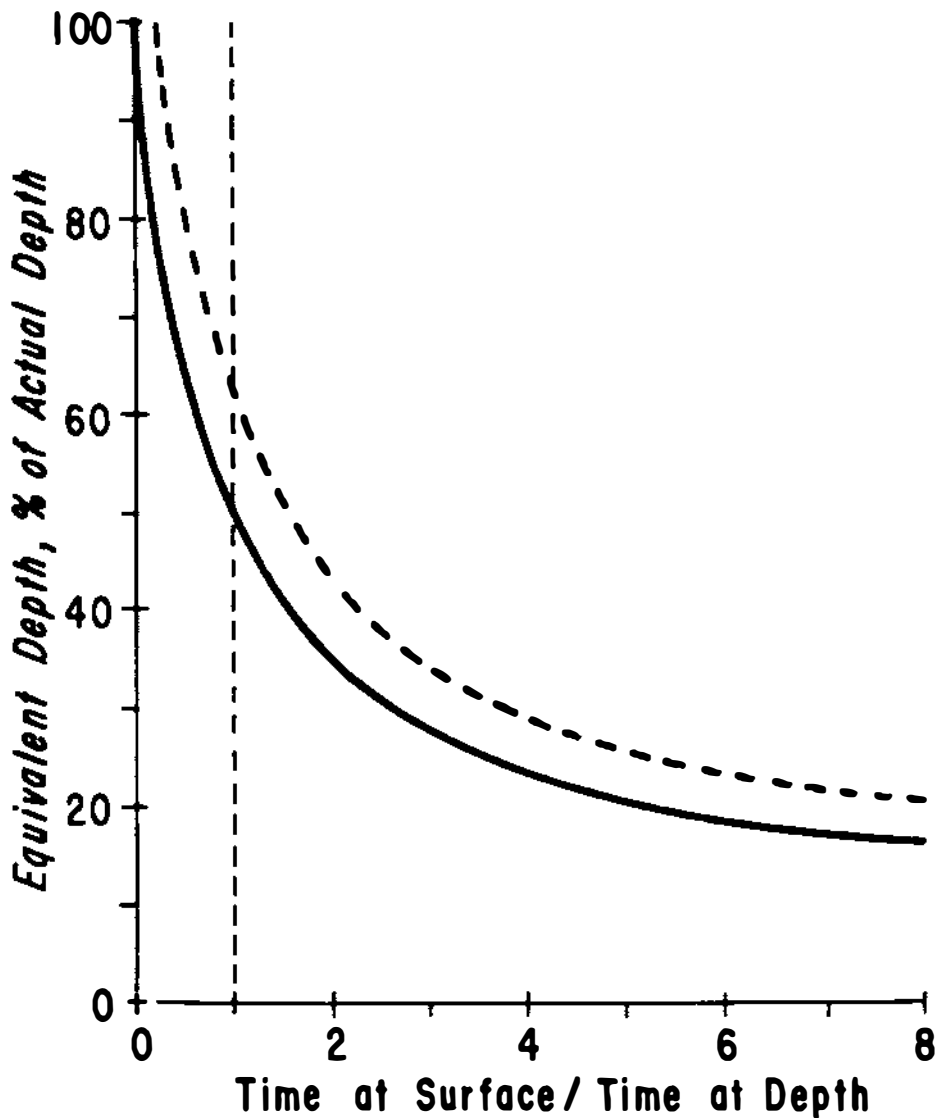


Figure 2. Equivalent Depth (ED, in per cent of actual depth) as a Function of Time at Surface/Time at Depth (S/D) in Repetitive Breath-Hold Diving. The solid line represents ED as computed for two-minute periods at depth and ten-minute tissue half-time according to the formula

$$\text{ED (per cent actual depth)} = \frac{\text{per cent change at depth}}{\text{per cent change at depth} + \text{per cent change at surface}}$$

Dashed line: 125 per cent of ED (see text).

One of the simplifying assumptions was that all of the time at "depth" was spent at maximum depth, ascent and descent being instantaneous. In actual breath-hold diving, time spent in transit would have the effect of reducing ED to a value below that indicated by Figure 2. However, the assumption of constant alveolar PN_2 has an opposite effect. In actuality, the alveolar nitrogen concentration rises during breath-hold dives (7, 8, 12). It does so to an extent largely dependent upon the amount of oxygen consumed. The effect will be to elevate the PN_2 at depth to a value above that with air breathing at the same depth, thus increasing ED. Under most circumstances these two factors can be expected nearly to cancel each other, and in the remainder of the discussion it will be assumed that this is the case. However, diving with unusually rapid descent and ascent and with maximum extension of breath-holding ability may result in values of ED significantly higher than those given by the solid line of Figure 2. The probable maximum of such increase is about 25 per cent, giving values indicated by the dashed curve of Figure 2.

No-Decompression Limits

If the depth and duration of an air-supplied dive do not exceed certain limits, direct ascent to the surface without decompression stops is considered safe. These limits are indicated by the decompression tables and are the portion of the tables of greatest interest in breath-hold diving. The shaded area of Figure 3 indicates the "no-decompression limits" as given in the current U. S. Navy air tables (15). The U. S. Navy tables are based upon a rate of ascent of 60 feet (18 m) per minute, considerably slower than in most breath-hold diving. For this reason, the limits were recalculated using the same basic factors but assuming no loss of gas during ascent. Where the resulting times were shorter, new points were plotted. The solid line of Figure 3 is a curve faired to remain on, or on the "safe" side of, presumably valid points.

In applying these no-decompression limits to a series of breath-hold dives, one must first estimate the S/D time ratio, then find ED in per cent of actual depth from Figure 2, next convert ED to units of depth, and finally find ED on the vertical scale of Figure 3. If the total elapsed time of the series of dives did not exceed the time given by Figure 3 at that depth, it can be assumed that decompression sickness is unlikely.

Another possible application of decompression tables is in estimating the relative likelihood of decompression sickness if the no-decompression limits are exceeded. The total decompression times specified by the tables for dives beyond these limits may provide an index for rough quantitation of the risk and for comparing risks at various levels of ED and duration.

An aspect of the U. S. Navy tables that is particularly valuable in air-supplied diving is the provision of tables for determining proper decompression, or suitable limits, for successive dives. These tables might prove useful in considering the implications of interposing a significant period at the surface between two sessions of repetitive breath-hold diving.

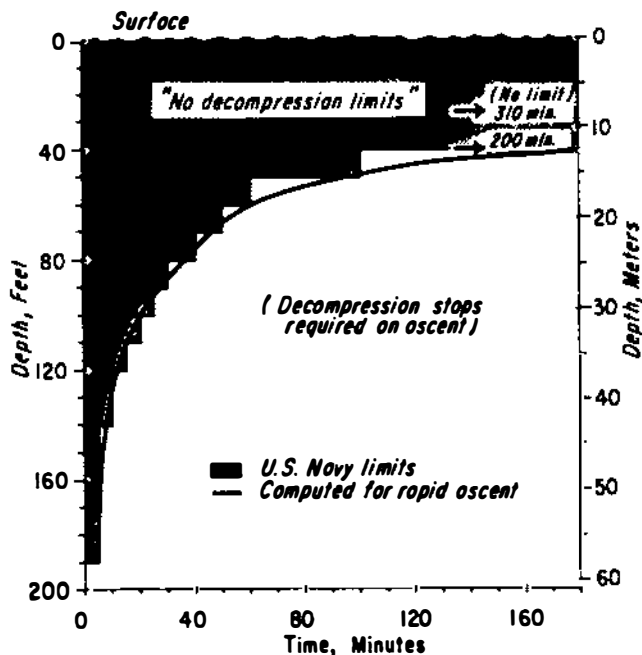


Figure 3. No-Decompression Limits from U.S. Navy Air Decompression Tables (shaded area) and as Recomputed for Rapid Ascent (faired curve). Horizontal scale: "bottom time" of dive or total elapsed time in series of repetitive breath-hold dives. Vertical scales: actual depth or equivalent depth (ED) in feet (left) or meters (right).

S/D Ratio and Limits

Some of the steps in the procedure described above can be eliminated by a graph like Figure 4 in which the horizontal axis represents elapsed time, the vertical scale is in units of S/D ratio, and where no-decompression limits are shown as curves for specific depths. Any depth or pattern of dives is relatively easy to evaluate in such terms. Consider, for example, the curve for dives to 3 atm abs (66 ft or 20 m): This indicates that no limit of total time needs to be imposed if time at surface is at least equal to time at depth (S/D = 1.0). However, the risk of decompression sickness may arise in less than three hours of diving if time at surface is one-half the time at depth (S/D = 0.5).

APPLICATIONS

If the form of analysis described is valid, the risk of decompression sickness becomes a reality beyond readily-defined values of S/D ratio and depth, and exceeding these values is well within the physical capability of many breath-hold divers. It is appropriate to consider some specific situations in these terms.

Amas. The "unassisted" Ama, confining herself to relatively shallow depths (7), should be able to dive indefinitely without fear of decompression sickness. An "assisted" Ama, going to pressures not beyond 3 atm abs, should be safe indefinitely provided that her time at surface is equal to her time under water as normally appears to be the case (7). Unprotected divers in cold water must also derive a safety factor from the necessity of going ashore to warm themselves periodically. It would be of interest to know whether changes in diving equipment, such as provision of rubber suits, will somewhere change diving patterns in such a way as to introduce the possibility of decompression sickness.

Submarine Escape Instructors. In the U.S. Navy submarine escape training tanks instructors do extensive breath-hold diving; but they characteristically obtain air from bells or chambers at depth. For this reason their exposures are monitored

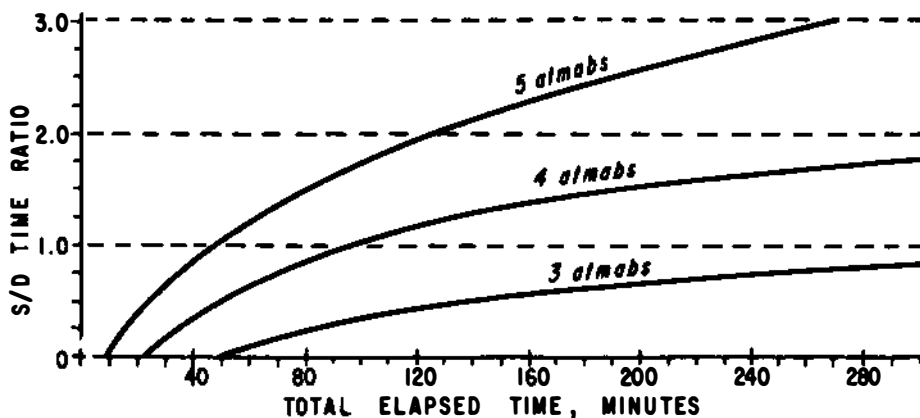


Figure 4. No-Decompression Time Limits for Repetitive Breath-hold Dives. Horizontal axis: total elapsed time in series of dives. Vertical axis: time at surface/time at depth (S/D). Lower curve: no-decompression time limit for dives to 3 atm abs (66 ft or 20 m). Middle curve: limit for dives to 4 atm abs (99 ft or 30 m). Upper curve: limit for dives to 5 atm abs (132 ft or 40 m). Diving to 2 atm abs is assumed to require no limitation regardless of value of S/D.

and controlled as air-supplied dives in accordance with the tables. According to Paulev's description⁽¹¹⁾, instructors in the Norwegian Navy training tank operate from the surface by breath-holding, making very numerous dives in the course of a training session. Paulev's own illness arose during about five hours of diving to depths between 50 feet (15 m) and 66 feet (20 m). He estimated that his periods under water were about two minutes in length, while periods at surface ranged from a few seconds to one or two minutes. He first became aware of symptoms after about three hours of diving. According to Figure 4, decompression sickness was distinctly possible within that period even assuming that the average S/D was about 0.5. Diving to 66 feet (20 m) repeatedly for five hours would require maintaining an S/D time ratio of not less than 0.8 in order to remain "safe."

Tuamotu Divers. Cross⁽⁴⁾ indicated that some of these men go as deep as 140 feet (43 m or 5.2 atm abs) and that periods under water average about 100 seconds but occasionally exceed 120 seconds. Paumotan divers, among whom taravana is common, normally space their dives four to eight minutes apart in contrast to the traditional practice in Mangareva, where the surface period is 10 or 15 minutes and taravana is unknown.

Normal Paumotan practice appears to yield S/D ratios from about 2.0 to 4.8. S/D = 2.0 would provide indefinite safety for dives to 4 atm abs but only about two hours of safety in diving to 5 atm. If S/D were kept at 4.8, ED would be 21 per cent of actual depth, and an indefinite series of dives to nearly 6 atm abs would theoretically be safe. Surface periods of ten minutes or more, as in Mangareva,

would appear to eliminate the likelihood of decompression sickness in any breath-hold dives man is believed capable of making.

Even "normal" diving among the Paumotans seems likely at least to verge upon the risk of decompression sickness. Cross' account⁽⁴⁾ indicates that taravana is most frequent toward the end of a day of diving or when ". . . divers working in a rich lagoon under ideal conditions go crazy with greed and dive until the shell is gone or taravana strikes." Under this spell a diver may double his number of dives, remaining on the surface only long enough for his helper to raise, empty, and lower the shell basket. The implications are clear.

It would be surprising if decompression sickness did not account for many cases of taravana; but Cross' reluctance to explain taravana on this basis was not unfounded. For example, according to Cross' information, accidents classed as taravana apparently occur in depths where decompression sickness is quite unlikely. In addition, taravana is not clearly related in frequency either to depth or to length of time spent under water, and it often strikes when the diver is still at considerable depth. If decompression sickness and taravana are identical, it is also strange that typical "bends" pain, present in Paulev's own case⁽¹¹⁾, is not mentioned even as an occasional symptom. That delayed onset is not mentioned is also surprising.

Hypoxia, as discussed by Craig⁽¹⁾ and Lanphier and Rahn⁽⁸⁾, could account for some of the accidents not readily explained as decompression sickness, but not for all. Air embolism is not a very probable explanation^(10, 11). Taravana is thus likely to retain aspects of mystery at least until it can be given further study on the scene. The response of its victims to prompt recompression would be of particular interest.

CONCLUSIONS

The form of analysis described here permits a series of breath-hold dives to be equated to a single air-supplied dive for which a decompression schedule or no-decompression limit can be specified. This approach yields information that is at least compatible with existing knowledge, seeming to explain why some groups of divers experience apparent decompression sickness while others do not. Cases reported by Paulev⁽¹¹⁾ are adequately explained as decompression sickness both in these terms and on the basis of symptomatology. Not all cases of taravana as described by Cross⁽⁴⁾ are similarly accounted for. Related questions that also deserve further study include the possible implications of circulatory changes during breath-hold dives⁽¹³⁾ and the possible phenomenon of "silent bubbles"⁽¹²⁾. The role of carbon dioxide in production of decompression sickness is probably significant⁽¹²⁾ but remains to be elucidated. Progressive elevation of CO₂ levels in the body during repeated breath-hold diving may be subject to a form of analysis comparable to that applied here for nitrogen.

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ADAPTATION TO BREATH-HOLD DIVING

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During the training of submarine crews in submarine escape procedures, such as "free or buoyant ascent," instructors at the escape training tank frequently hold their breath under water and perform "skin" dives to depths as great as 90 feet. The ascent is carried out by climbing up a line. These diving maneuvers are similar to those practiced by sponge and pearl divers. The escape training tank at the New London Submarine Base (Fig. 1) afforded us an opportunity to study the pulmonary gas exchange during this type of diving(8), and to follow up physiological changes in the tank instructors during their tour of duty.

Since the adaptive processes in breath-hold diving observed under these conditions are related to the particular stress of diving imposed on tank instructors, data on alveolar PCO_2 and PO_2 obtained at the end of dives are presented in Table I to serve as a frame of reference. A reversed CO_2 gradient was established during descent(8). At a 90-foot depth, about 50 per cent of the pre-dive CO_2 content of the lungs had disappeared and was taken up by the blood and tissues.

During ascent the CO_2 gradient is again normal. The influx of carbon dioxide into the lungs can be regulated by the speed of ascent, as shown in Table I. If the ascent was fast, the alveolar CO_2 tension attained on reaching the surface was low, while considerably higher CO_2 tensions were found following slow ascents. It is important to note that extremely low end dive alveolar PO_2 levels (25-30 mm Hg PO_2) are not uncommon, indicating the existing danger of hypoxia in breath-hold dives.

The processes involved in pulmonary gas exchange during the dive, (1) transfer of CO_2 from the lungs, (2) oxygen utilization, and (3) nitrogen transfer into the blood, act in the same direction as the mechanical compression of the thorax during the descent of the diver and cause a progressive shrinking of the total chest volume during the descent. The maximal depth a diver can reach is dependent upon his lung volumes, in particular upon the ratio of total lung volume. In the following data are presented which indicate that under the conditions at an escape training tank, involving multiple daily breath-hold dives, adaptive changes develop into lung volumes and in the responses to high CO_2 and to low O_2 .

Adaptive Changes in Lung Volumes

During their first breath-hold dives, new personnel assigned to the escape training tank usually experience a pressure and stress on their chest at a depth of 60 to 70 feet which prevents them from venturing deeper. After several months they report that they can inspire more air, are able to control their breathing more regularly and are more relaxed. Most of them can eventually reach a depth of 90 feet during breath-hold dives without experiencing any difficulties.

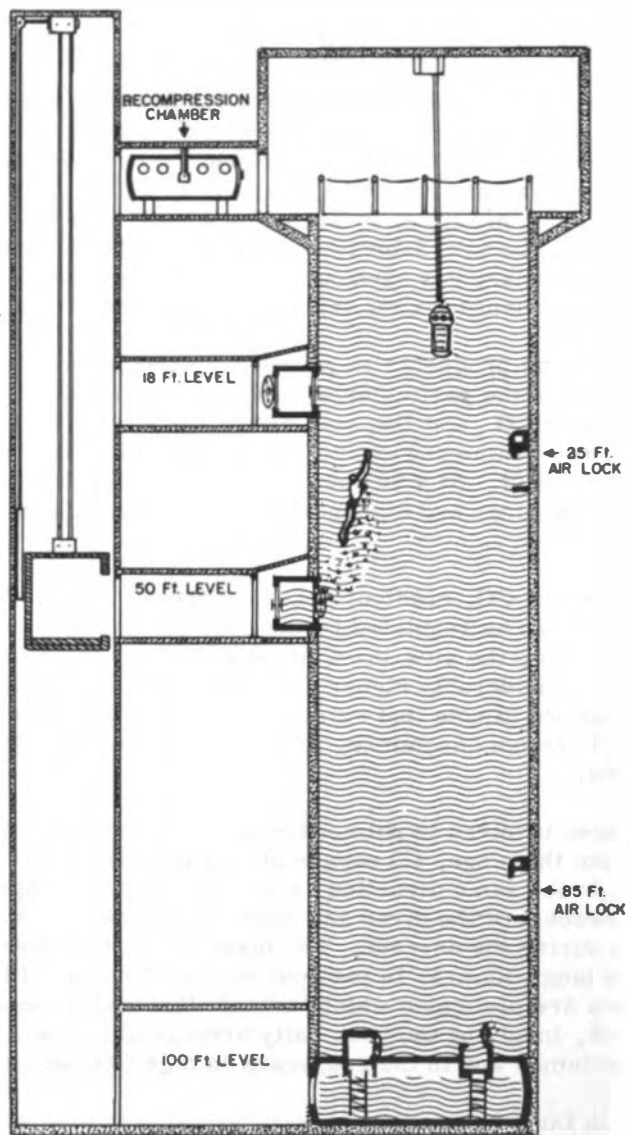


Figure 1. Schematic Diagram of Submarine Escape Training Tower.

TABLE I
End-Dive Alveolar PCO₂ and PO₂ Values Following
Descent to 90 Feet and Ascent with Different Speeds

A. <u>Dives to 90 feet</u> <u>Speed of ascent</u>	<u>Alveolar Gas Tensions</u>	
	<u>PCO₂ mm Hg</u>	<u>PO₂ mm Hg</u>
1.9 ft/sec	45.7 + 4.1 (12)	34.8 + 5.7 (12)
2.3 ft/sec	37.3 + 1.2 (3)	34.7 + 4.2 (3)
3.5 ft/sec	31.5 + 1.3 (3)	27.3 + 3.1 (3)
B. <u>Breath-holding</u> <u>at surface</u>	52.4 + 2.4 (12)	64.8 + 13.4 (12)

() Number of dives.

Breath-holding at the surface was carried out by the same subjects who performed the dives to 90 feet and ascended at an average speed of 1.9 ft/sec. Breath-holding time of 1.5 minutes corresponded with the average time of breath-hold dives.

These subjective experiences suggested an adaptation of lung volumes, which was established in subsequent studies⁽²⁾. A comparison of lung volumes measured in 16 tank instructors and 16 laboratory personnel showed a significantly larger vital capacity in tank instructors, which was 20 per cent higher than could be predicted by their own height, weight, and age, using the West formula⁽²⁾. Furthermore, total lung capacity, tidal volume, and inspiratory reserve volume were markedly increased in the tank-instructor group as compared with the laboratory personnel. In a longitudinal study, lung volumes were measured in tank instructors at the beginning of their tour of duty and after one year. Inspiratory reserve, tidal volume, vital capacity and total lung capacity showed a significant increase in 20 tank instructors, while residual volume decreased. In a second group of eight tank instructors, similar studies were carried out and the ratio of total lung capacity to residual volume plus the volume of the airways was determined (Table II). The volume of the airways (anatomical deadspace) was estimated, using Radford's nomogram⁽⁶⁾. The observed change in this ratio results in a 20- to 30-foot extension in the maximum safe depth to which the instructors could dive after one year of duty.

TABLE II

Effect of Prolonged Diving Training (1 Year) on Maximal Attainable Depth Based on Ratio of Total Lung Capacity to Residual Volume and Volume of Airways (8 Divers)

	Beginning	After 1 Year of Duty
	Volume	in ML (BTPS)
Residual Volume	1918 <u>+510</u>	1621 <u>+287</u>
Anatomical dead space (based on Radford's nomogram)	172 <u>+8</u>	169 <u>+9</u>
Total lung capacity	7373 <u>+961</u>	7643 888
Ratio total lung capacity / residual volume and anatomical dead space	3.65 <u>+ .57</u>	4.38 <u>+ .97</u>
Maximal attainable depth (feet)	87	112

Adaptation to Increased CO₂ in Divers

CO₂ tolerance curves were obtained by exposing subjects for 15 minutes to 3.3, 5.4 and 7.5 per cent CO₂. Alveolar ventilation and alveolar gas tensions were determined at the end of each exposure period. In the case of tank instructors, the CO₂ tolerance curves showed a shift to the right and a decrease slope when compared with those of the laboratory personnel⁽⁹⁾. The high tolerance to CO₂ is developed during the diving period and lost after a three-month lay-off period, as shown in CO₂ sensitivity tests of eight tank instructors (Fig. 2). The ventilatory response to 5 per cent CO₂ is significantly larger at the end of the three-month lay-off period. The changes in lung volumes, consisting of an increase in total lung capacity, vital capacity and tidal volume, and decrease in residual volume, might contribute to the reduced sensitivity to CO₂ because of the relationship found between large tidal volume, low respiratory rate and low response to CO₂⁽¹⁰⁾.

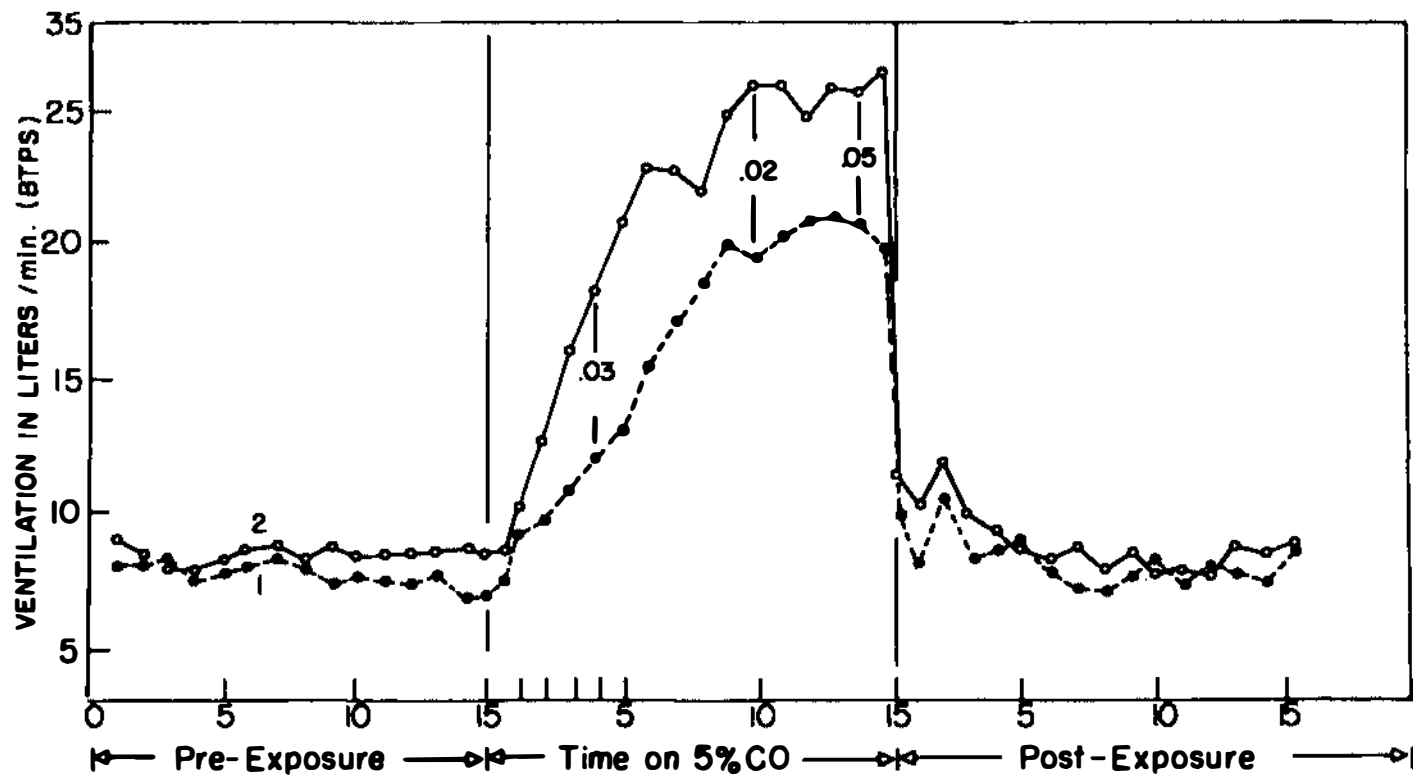


Figure 2. Respiratory Response to 5 per cent CO₂ in Tank Instructors (7 subjects).
(1) During a period of intensive water work.
(2) After a 3-month lay-off period.

Other parameters of adaptation to CO_2 have been previously established in human subjects during prolonged exposure to 1.5 per cent CO_2 (11). They consisted, besides changes in acid base equilibria, in an increase in red cell sodium and a decrease in red cell potassium. Tables III and IV show the distribution of CO_2 in plasma and cells and the distribution of electrolytes in plasma and red cells of 11 tank instructors after a period of heavy water work and a period without water work. It can be seen that after a period of intensive diving, the pH is decreased, PCO_2 and bicarbonate levels are increased, and the sodium and potassium concentrations in red cells exhibit the typical changes observed in prolonged exposure to CO_2 . These data provide further evidence of an adaptation to CO_2 during breath-hold diving. Evidence of an increase in CO_2 stores, as a result of diving, was recently obtained in instructors, following a two-year period of water work when compared with data found after a three-month lay-off period(3). During constant hyperventilation, lasting for one hour, more CO_2 was eliminated and the end tidal CO_2 tension was significantly elevated under the first condition.

Adaptation to Low Oxygen

A group of tank instructors and a group of laboratory personnel were exposed to 10.5 per cent O_2 in nitrogen for a period of 33 minutes.¹ The subjects reported in the morning under basal conditions (14 hours without food) and rested in bed for 45 minutes before the experiment began. They were in supine position and breathed from an open spirometer system through a mouthpiece and exhaled into Douglas bags for an initial period of 33 minutes on room air, followed by 33 minutes on 10.5 per cent O_2 in N_2 , and finally a recovery period of 33 minutes on room air. End tidal oxygen and carbon dioxide samples were obtained with a Rahn sampler. Both end tidal gas samples and expired gas samples were analyzed with a Haldane apparatus. Two tests of this type were conducted on the same subjects at an interval of several months.

Table V shows the average data of alveolar oxygen and carbon dioxide pressures, the ventilatory response and the arterial oxygen saturation and pulse rate obtained during the periods of 23 to 33 minutes while breathing room air, 10.5 per cent O_2 in N_2 , and again room air in two tests. The ventilatory response of the tank instructors to low oxygen is consistently lower than that of the laboratory personnel while alveolar oxygen and carbon dioxide tensions, as well as the arterial oxygen saturation and pulse rate, do not exhibit marked differences between the two groups.

The lower ventilatory response to low oxygen breathing in the divers was found to be associated with the formation of a larger oxygen debt during exposure. Table VI summarizes the data on oxygen debt, oxygen balance and the end of exposure, compensatory oxygen uptake during the recovery period, final oxygen

¹The study of low oxygen breathing had originally been carried out on 11 subjects (8). For the purpose of comparison of the low oxygen effects in skin divers and laboratory personnel, three subjects were excluded. One subject had emphysema, another was a hard-hat diver without training in skin diving and a third subject was assigned to the Escape Training Tank and performed, mainly, desk work probably because of maladjustment to skin diving.

TABLE III

**Effect of Daily Breath-Hold Dives During a Six-month Period on
 Distribution of CO₂ in Plasma and Red Cells (venous blood) of 11 Tank Instructors**

Plasma				Red Cells	
HCO ₃ mmoles/liter	H ₂ CO ₃ mmoles/liter	pH	PCO ₂ mm Hg	HCO ₃ mmoles/liter	H ₂ CO ₃ mmoles/liter
After a five-month period without water work (control)					
25.1 ± 1.5	1.34 ± .09	7.38 ± .01	44.7 ± 2.96	16.76 ± .87	1.12 ± .07
After a six-month period with heavy water work					
28.3* ± 1.38	1.58* ± .18	7.35* ± .05	52.7* ± 6.1	18.60* ± .67	1.32 ± .15

*Differences from controls statistically significant at the 5 per cent level.

TABLE IV

Effect of Daily Breath-Hold Dives for a Period of Six Months on Red Cell and Plasma Electrolytes (venous blood) (11 subjects)

Measured Values					Calculated Values							
Whole Blood					Plasma				Red Cells			
H ₂ O, g/l	Na, mEq/l	K, mEq/l	Cl, mEq/l	Hema- tocrit	H ₂ O g/l	Na, mEq/l	K, mEq/l	Cl, mEq/l	H ₂ O, g/l	Na, mEq/l	K, mEq/l	Cl, mEq/l
After a five-month period without water work (control)												
824	86.8	43.9	84.5	43.0	924	142	4.78	103.5	692	13.7	95.8	59.2
+12.8	+5.0	+2.3	+2.3	+1.9	+7.3	+3.5	+0.62	+3.0	+27	+3.8	+15.4	+6.6
After a six-month period with heavy water work												
811*	86.8	34.6*	83.5	44.8	915**	133*	4.09**	103.5	679	30.4**	72.1*	59.4
+5	+2.9	+2.4	+2.4	+2.3	+9.3	+4.4	+0.39	+1.6	20	+17.3	+5.4	+6.9

*Differences from controls statistically significant at the one per cent level and better.

**Differences from controls statistically significant at the five per cent level.

TABLE V

Average Data of Alveolar Oxygen and Carbon Dioxide Pressures, Ventilatory Response, Pulse Rate and Arterial Oxygen Saturation During the Period of 23-33 Min on Air, 10.5 Per Cent O₂ in N₂ and Air (Recovery)

Laboratory Personnel (4 Subjects)				Divers (4 Subjects)		
Alveolar mmHgPCO ₂	Air Control	10.5% O ₂ in N ₂	Air Recovery	Air Control	10.5% O ₂ in N ₂	Air Recovery
1. Test	38.0 ±2.0	32.4 ±5.5	37.3 ±2.6	38.5 ±3.5	32.6 ±4.2	37.9 ±3.0
2. Test	38.2 ±3.6	31.8 ±5.0	35.8 ±3.3	37.6 ±3.3	33.3 ±3.2	35.4 ±4.4
Alveolar mmHgPO₂						
1. Test	107.5 ±4.3	42.5 ±5.3	109.0 ±10.5	104.9 4.9	49.1 ±17.2	101.5 ±5.9
2. Test	107.9 ±4.6	43.9 ±6.0	107.9 ±6.8	105.4 ±4.6	43.5 ±7.5	106.3 ±7.0
VE						
L/min	5.66	9.03	5.82	6.20	7.67	6.00
1. Test	±0.74	±2.11	±1.04	±0.67	±0.66	±0.66
2. Test	5.72 ±0.49	8.71 ±2.0	6.51 ±1.81	5.98 ±0.93	7.53 ±1.22	5.96 ±1.20
VE, %						
1. Test	100	161 ±13	105 ±4	100	123 ±10	96 ±5
2. Test	100	152 ±26	100 6	100	123 ±7	98 ±3
Pulse rate						
1. Test	64 ±9	79 ±8	61 ±10	56 ±5	74 ±2	58 ±11
2. Test	67 ±8	79 ±12	66 ±13	59 ±11	69 14	53 ±13
Pulse rate %						
1. Test	100	124 ±8	96 ±3	100	132 ±29	99 ±4
2. Test	100	117 ±7	96 ±5	100	129 ±16	98 ±4
Arterial O₂ Saturation						
1. Test	96 ±2	74 ±3	96 ±6	95 ±1	64 ±5	96 ±1
2. Test	96 ±1	74 ±10	97 ±1	95 ±2	74 ±2	97 ±1

TABLE VI

Oxygen Debt and Excess O₂ Uptake, Resulting from 33 Minutes Exposure to 10.5 Per Cent O₂ In N₂, Related Changes in Arterial O₂ Saturation and Oxygen Removal from Inspired Gas, Slope of Oxygen Dissociation Curves in Divers and Non-Divers

	O ₂ debt	O ₂ balance at 33 min exposure	Excess O ₂ uptake above basic values	Final O ₂ balance (33 min recovery)	Arterial O ₂ saturation (23-33 min exposure)	O ₂ removal from inspired gas during 23-33 min exposure to 10.5%O ₂	Slope of steepest part of O ₂ dissociation curve
	(ml)	(ml)	(ml)	(ml)	(%HbO ₂)	(in % O ₂)	
<u>Group A</u>							
Laboratory personnel	-347.8	56.3	1204.8	1261	73.8	3.72	.295
4 subjects	±110.6	±338	±851	±838	±11.1	±.66	±.047
<u>Group B</u>							
Divers	-1033.8	-966.5	868.5	-98	74.0	4.26	.388
4 Subjects	±499	±522.7	±536	±823	±2.2	±.211	±.022

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balance at the end of the recovery period, oxygen removal from inspired air and the slope of the steepest part of the oxygen dissociation curve. The smaller oxygen debt, incurred by the laboratory personnel during the first 11 minutes of exposure to low oxygen, can be explained by the reduction in O_2 uptake due to the fall in arterial oxygen saturation. Following a suggestion of Dr. H. Rahn, we calculated the reduction in oxygen uptake from the difference in arterial oxygen content while breathing air and 10.5 per cent O_2 and assuming that the A-V difference is unaltered on breathing 10.5 per cent O_2 . We further assumed a total circulating blood volume of seven liters. Substituting our value of 22 per cent drop in HbO_2 , and converting it to ml/liter — we then have $(200-156) \times 7 = 308$ ml. In addition, there must be a reduction in dissolved oxygen in tissue fluids. Using the mean capillary O_2 as an index of mean tissue PO_2 tension, this value would not change more than 20 to 30 mm Hg upon going to 10.5 per cent O_2 from air. Therefore, assuming a 20 mm Hg drop in this factor with a solubility factor of 0.02 for O_2 in all tissues, this would yield an additional 70 ml of O_2 , by which the oxygen uptake would be reduced (calculated for a 70 kg man). These are at best only approximations, but they come close to the average values of the oxygen debt obtained in laboratory personnel (378 ml calculated, 348 ml observed). This oxygen deficit can be met by the oxygen reserves of the organism which can be estimated to be in the order of 1300 ml (including the oxygen content of myoglobin).

It is interesting to note that a 22 per cent drop in arterial oxygen saturation is quantitatively compensated by a 50-60 per cent increase in ventilation and a 20 per cent increase in pulse rate, providing the necessary increase in oxygen supply to the alveoli and increased transportation of blood to overcome the reduction in oxygen uptake. The larger oxygen debt incurred by the divers, over the entire exposure period to 10.5 per cent O_2 cannot be explained by the reduction in oxygen uptake due to the fall in arterial oxygen saturation, although the divers show a slightly better utilization of available oxygen as indicated in the larger differences between inspired and expired oxygen concentrations and a slightly larger slope in the steepest part of the oxygen dissociation curves. The oxygen stores of the organism (1300 ml) which cannot be utilized to the full extent will not be sufficient to meet these larger oxygen debts of the divers which, in one case, was 1562 ml. The divers reach a stable level of ventilatory and circulatory response after the 11th minute of exposure, but continue to accumulate an oxygen debt as exposure to low oxygen proceeds. They do not compensate for the reduced oxygen uptake by an adequate increase in ventilation and pulse rate. We, therefore, must assume that a reduction in tissue oxidation has occurred in the divers.

As indicated above, the oxygen debt in one diver was 1562 ml at the end of the 33 minutes of exposure to 10.5 per cent O_2 and still over 1000 ml at the end of a 33 minute recovery period on air. This same subject showed similar trends in a separate experiment, breathing 15 per cent O_2 in N_2 for 33 minutes during which period he accepted an oxygen debt of 930 ml, and at the end of the 33 minute period of recovery on air it was 430 ml. This finding seems to indicate that the reduction in oxidation is still effective in the recovery period on air following exposure to low oxygen or that a shift to anaerobic energy yielding processes might have occurred.

Damping Effect on the Autonomic Nervous System

It had been previously reported that a high tolerance to inhalation of increased CO_2 concentrations (low ventilatory response) was associated with a reduced autonomic response as indicated in smaller elevations of pulse rate and blood sugar⁽¹⁰⁾. Most of the subjects belonging to the group showing a high tolerance to CO_2 in the earlier studies⁽¹⁰⁾ were divers. They also did not exhibit marked symptoms during and after CO_2 inhalation in contrast to subjects with a high ventilatory response to CO_2 .

Since carbon dioxide exposure is known to produce an increased sympathico-adrenal discharge in men, as seen by a rise of epinephrine, norepinephrine and 17-hydroxy cortico steroids⁽¹⁸⁾, a high tolerance to CO_2 , as developed by the divers, appears to be associated with a reduced adrenergic and stress response to CO_2 . The question arose, whether adaptation to diving involves a general damping of the autonomic nervous system activity, including the cholinergic system. We measured the blood pressure response to an injection of a cholinergic drug, Mecholyl, in a group of 13 divers and 19 laboratory personnel. Mecholyl (10 mg per ml) was given intramuscularly and the systolic blood pressure was followed every minute for 6 minutes and then at 10, 15, 20 and 25 minutes. The results expressed in per cent change of baseline values are presented in Figure 3. The divers exhibited a significantly smaller fall in blood pressure than the group of laboratory personnel and practically no overshoot above control levels in the period between 15 and 25 minutes following injection. These findings suggest that adaptation to diving also produces a damping effect on the cholinergic system.

Discussion and Conclusion

Comparison of lung volumes in divers and control groups demonstrated a larger vital capacity in the native diving women in Japan⁽²⁰⁾ and in Korea⁽¹⁹⁾ due to an increased inspiratory reserve volume⁽¹⁹⁾. Similar observations were made in divers at the escape training tank⁽²⁾. These findings suggested an adaptation of lung volumes in breath-hold diving, the existence of which was proven in a longitudinal study in the same divers tested at the beginning and at the end of a long tour of duty at the escape training tank⁽²⁾.

A lower response to CO_2 in divers, as compared with a native group, has also been reported in the Amas⁽¹⁹⁾ and in tank instructors⁽⁹⁾. Evidence for the development of adaptation to CO_2 during a period of regular daily breath-hold dives has been presented in this report. It appears likely that the adaptive change in lung volumes is related to the decreased respiratory response to CO_2 because of the reported correlations of larger lung volumes and low ventilatory response to CO_2 ⁽¹⁰⁾.

Experiments with breathing low O_2 mixtures demonstrated that divers are apparently able to utilize oxygen better than non-divers, as indicated in a larger oxygen extraction from inspired gas, and a steeper slope of the oxygen dissociation curve. This may be an effect of adaptation to diving and could offer an explanation for the lower ventilatory response to low O_2 breathing in dives, if it were not associated with a significantly larger oxygen debt. The oxygen debt of the control group could be predicted on the basis of the reduction in O_2 uptake, due to the fall

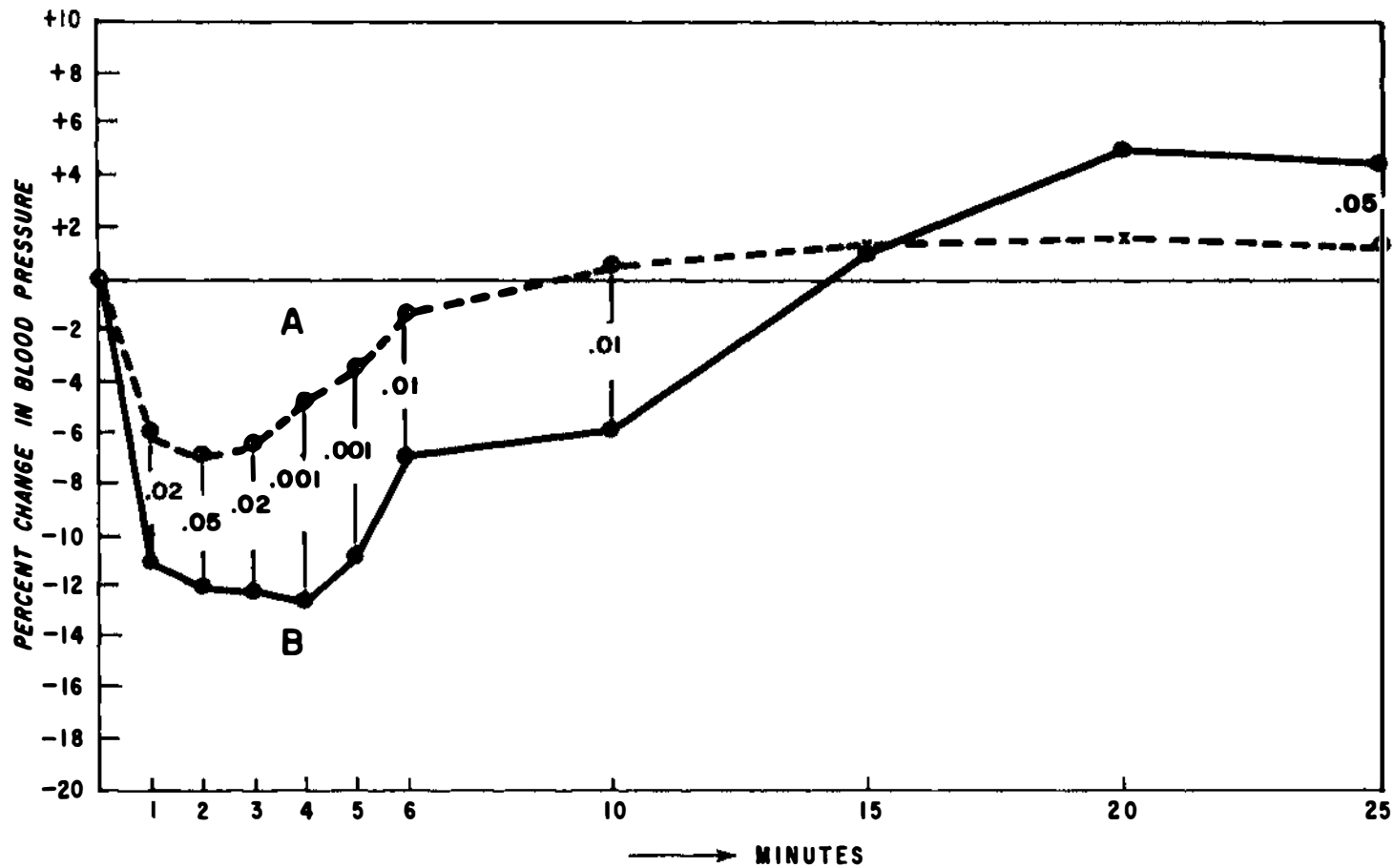


Figure 3. Blood Pressure Response to Mecholyl Injection in 13 Divers (A) and 19 Laboratory Personnel (B)

in HbO_2 , on going from air to low O_2 breathing. However, the three-fold larger oxygen debt of the divers, which cannot be met by the oxygen reserves of the organism, requires the assumption of a decreased tissue oxidation. A reduction in energy metabolism has been demonstrated during dives of ducks⁽¹⁾ and seals⁽¹⁵⁾. The excess oxygen intake of these animals, during the recovery after a dive, covers only a part of the oxygen debt which would have been incurred had the energy metabolism remained at the pre-dive level. They also show a steady temperature loss during breath-hold dives even though they are submerged in thermoneutral water (1, 15).

Since the blood flow through the periphery is reduced during the dive, providing protection against heat loss, it was concluded that the fall of temperature during the dives must have been caused by a decrease in heat production^(1, 15, 16). Scholander⁽¹⁶⁾ also pointed out that the anaerobic energy metabolism during the dive, as measured in the lactic acid production, is too small to compensate for the oxygen deficit under these conditions. However, this does exclude the possibility that other anaerobic energy yielding processes may play a role in diving.

The lowered ventilatory response to low O_2 breathing, found in four experienced and efficient divers, should be confirmed in a larger group of subjects in a longitudinal study, particularly since similar tests in Korean diving women did not show an altered sensitivity to low O_2 ⁽¹⁹⁾. The Amas, however, dive to shallower depths than the tank instructors, which might be one of the reasons for the difference observed.

Under the conditions of diving, man is subjected to hypercapnia and hypoxia, and the acclimatization processes are different from those observed during exposure to high altitude, which produces a chronic hypocapnia and chronic hypoxia⁽⁴⁾. At high altitude, the sensitivity to CO_2 is increased, while the sensitivity of O_2 is unaltered^(7, 5).

The reduced autonomic responsiveness found in divers is probably a consequence of their adaptation to increased carbon dioxide. The two phases of uncompensated and compensated respiratory acidosis, observed in chronic CO_2 exposure, are associated with a period of excitation followed by a period of depression of the central nervous system⁽¹³⁾. During acute exposure to CO_2 stimulating effects on the hypothalamic cortical system are exerted commensurate with depressing effects on the cerebral cortex. After adaptation to carbon dioxide, which is accomplished with the compensation of the respiratory acidosis, the stimulatory effects of CO_2 on the autonomic system subside and the cortical depressive effects become more dominant. Moreover, the stress effect of CO_2 (increased blood corticoid levels) was found to be restricted to the period of uncompensated respiratory acidosis⁽¹⁴⁾.

The stress resistance found in divers is in line with their subjective observations of increased "relaxation" in the course of prolonged diving training as instructors at the escape training tank.

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BODY FLUID VOLUMES AND THE RENAL RESPONSE TO IMMERSION

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INTRODUCTION

Many simple organisms possess no mechanisms for regulating their osmotic pressure and remain isosmotic with their environment, the sea. When our phylogenetic ancestors climbed on land, taking a bit of the primeval ocean as their extracellular fluid, it became necessary to preserve not only the composition but the volume of these fluids. The excretion of water and solute by the kidney is the fundamental mechanism for preserving the constancy of the mammalian extracellular fluid. The mechanisms by which the kidney is notified to retain or excrete water and solute in response to changes in the environment have been defined in considerable detail in recent years. The response of the kidney to water immersion of human subjects, as measured by water and solute excretion, provides a fascinating model for the study of body fluid volume regulation. The Ama divers of Japan and Korea represent specific problems of body fluid volume regulation during immersion as dictated by the depth, duration, temperature and respiratory mechanics of their particular immersion pattern. This paper will present: (1) a description of the renal responses to neutral or indifferent temperature immersion; (2) a brief review of the physiological mechanisms of body fluid volume regulation as we now understand them; (3) a consideration of the role of pulmonary mechanics and water temperature in renal response to immersion; (4) a summary of the possible mechanisms of the immersion diuresis; and (5) speculations about the renal response to Ama diving.

THE IMMERSION DIURESIS

Water immersion of human subjects, whether it be breath-hold diving, head out flotation or "hard hat" or self contained underwater breathing apparatus (SCUBA) diving, produces striking changes in body fluid composition and volume distribution. Because such changes produce no sensation or gross impairment of function they have gone largely unnoticed and unstudied in the long history of diving physiology. Indeed, the most striking manifestation of altered renal function during immersion, the increase in the rate of urine flow or diuresis, is well known to divers, but did not stimulate the curiosity of physiologists until quite recently.

The diuretic response to immersion has been well known to balneologists and hydrotherapists for hundreds of years and was felt to represent the major "therapeutic" effect of warm and neutral temperature baths. Henry Hartshorne, a Philadelphia physician, described this effect and perhaps appreciated the role of blood volume distribution in the mechanism of the diuresis when he wrote in 1847:

" . . . if the blood be thus driven (by the bath) from both the external and internal parts, what becomes of the blood? The heart and great vessels, it would seem, must be burdened. Such is to a degree the case; and it is perhaps the stimulus of this fullness and distention or its action on the elasticity of those vessels and the heart that constitutes the reaction (which leads forth the urine in abundant effusion). Such overloading of the heart and great organs would be dangerous in every case if the volume of blood remained the same(25)."

Bazett in 1924 described a diuresis occurring during warm baths and felt that it was related to changes in renal hemodynamics(6, 7). In 1938, Behnke studied excessive urination in "hard hat" Navy divers during deep experimental dives but there is no published record of this work(9). Von Diringshofen, in 1948, gave a detailed, theoretical analysis of the effects of hydrostatic pressure on capillary exchange and related the immersion diuresis to fluid loss from tissue(41). Bond and Schaefer mentioned a diuresis, dehydration of red cells, and a "large" rise in blood urea in U.S. Navy diving tank instructors immediately after 90 foot breath-hold dives(11).

Graveline et al, in 1959 at the U.S. Air Force School of Aerospace Medicine, utilized water immersion in the design of an experiment in which the buoyant effects of water upon the body were used to create a hypodynamic situation in simulation of weightlessness during space flight(20). The senior author was immersed in water up to neck level for a period of seven days. He was permitted to emerge from the tank briefly for one period each day for the purpose of body hygiene. The subject reclined on a supporting couch and wore a standard "dry" divers suit. The temperature of the bath was controlled at 33.5°C (92.3°F). Progressively increasing asthenia during the daily period of emersion ultimately necessitated termination of the experiment after seven days. Water balance studies showed an immediate doubling of the normal urinary output each 24 hours during the first three days of the tests, which was associated with similarly increased urinary nitrogen excretion (Fig. 1). This striking diuresis during a period of constant intake produced a marked diabetes insipidus-like picture with thirst, hemoconcentration, and weight loss. Subsequent studies by Beckman et al(8) and by Graybiel and Clark(23) have demonstrated similar effects of head out immersion including the marked diuresis, on larger groups of subjects for periods of 12 to 23 hours. Recent studies by Gauer of three subjects during 48 hours of heat-out immersion confirm the persistent diuresis and diabetes insipidus-like picture(16).

Further studies by Graveline investigated the mechanisms of the diuretic response to complete neutral temperature immersion with unrestricted activity. Eupneic or subjectively neutral respiratory pressures were used in a modified partial pressure helmet with a continuous flow regulator to compensate for ambient water pressure. In one series of experiments, the effects of weight bearing and of the administration of pitressin on the diuresis of water immersion were studied in ten subjects immersed for one hour(21). In the free-floating (non-weight bearing) immersion situation, a four-fold increase in urine flow is seen in Figure 2 with a two-fold increase in urea and a six-fold increase in sodium excretion. Solute concentration as reflected in the urine specific gravity is markedly reduced. The administration of pitressin returns urine flow and solute excretion to the control

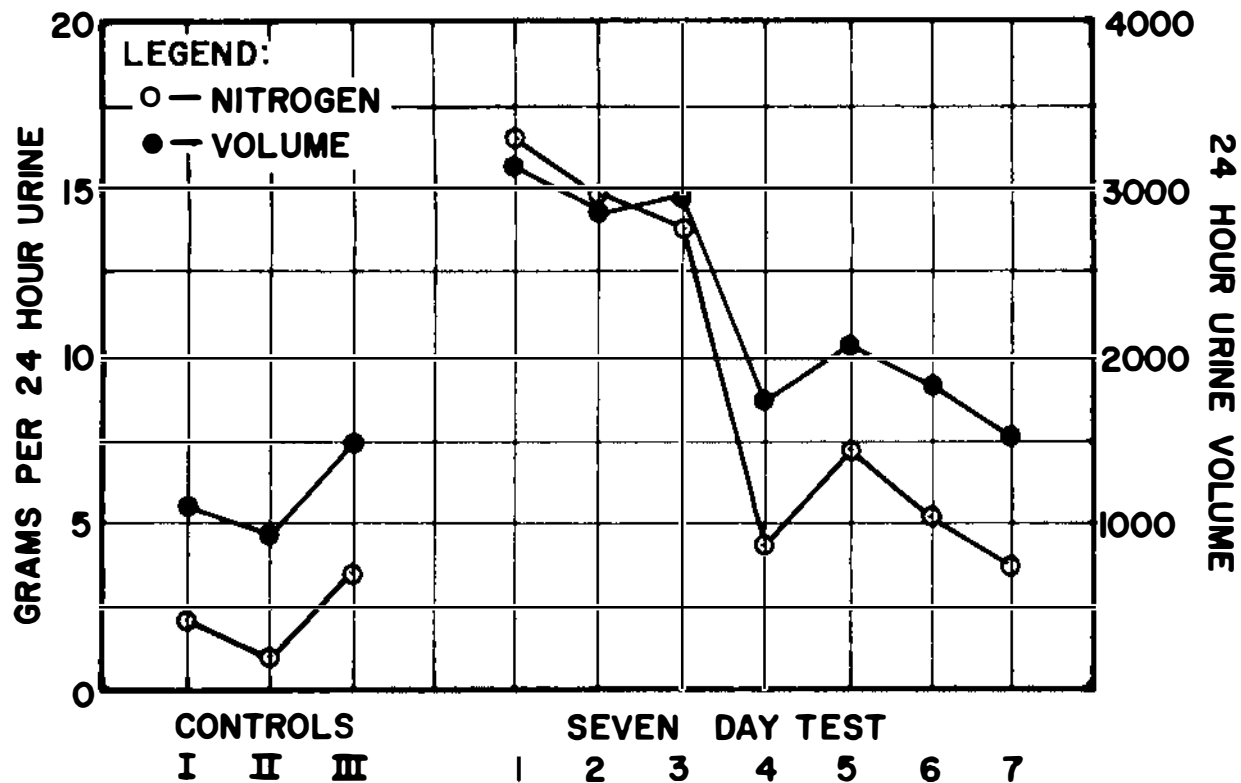


Figure 1. Twenty-four hour urine volumes and urea excretion for a single subject during seven days of head out immersion in a neutral temperature bath, demonstrating a marked diuresis during the first three days.

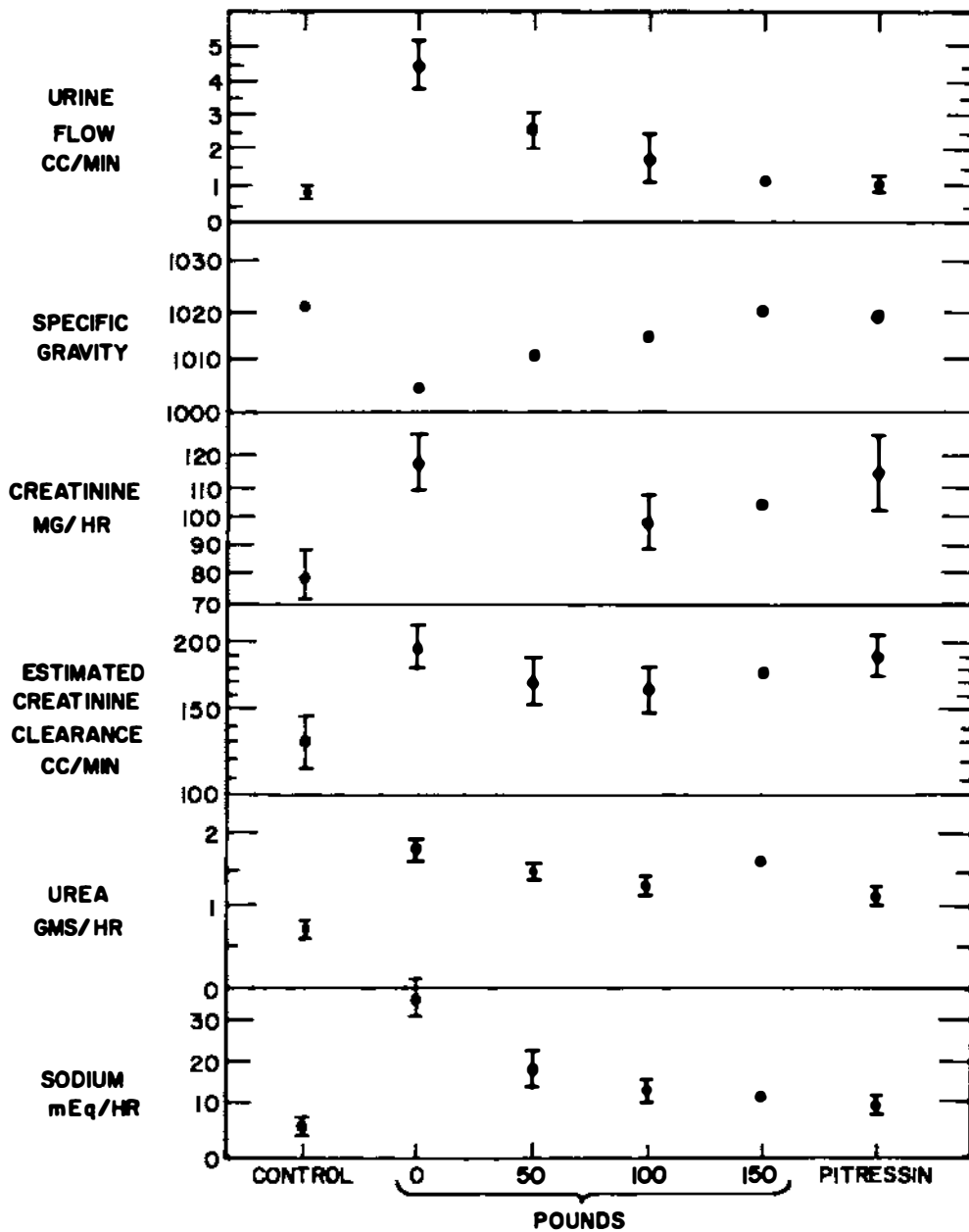


Figure 2. Effect of weight bearing and pitressin administration on urine flow, urine solute concentration and estimated creatinine clearance during one hour of water immersion. The mean and range of values (standard error) of ten subjects are shown. Only two subjects were given the 150-pound weighted test.

range. This suggests that the increased urine flow during immersion is the result, in part, of the inhibition of ADH release with a resulting water diuresis as ADH has little effect on a solute diuresis. Simple weight bearing with a camper's back pack during immersion with weight added in fifty pound increments produces a corresponding decrease in urine flow. Exercise is known to cause a variable inconsistent anti-diuresis, but the effect of weight bearing during immersion on cardiovascular and renal function is unknown.

In five subjects the effects of a six-hour period of complete water immersion with eupneic respiratory pressures on urine flow, solute excretion, hematocrit, serum solutes and renal function were studied⁽²²⁾. The urine volumes excreted during the six hour test periods were substantially increased over those excreted during the control periods. Urine osmolarity decreased in all subjects from a control average of 898 mOs/liter to the immersion test average of 289 mOs/liter. The osmolar clearance was increased during the immersion test and the free water clearance became positive reflecting anti-diuretic hormone (ADH) suppression.

At normal levels of creatinine in the plasma, its clearance may be measured to obtain an estimate of the glomerular filtration rate (GFR). Although in Gravelin's study plasma creatinine determinations were not made, normally it has a very narrow range and if one assumes a value of 1.0mg/100 ml, a rough but reliable estimate of creatinine clearance and GFR may be obtained. Averaging the percentage increase in GFR of each of the five subjects, it may be calculated that approximately a 75 per cent increase in GFR occurred during the immersion test. This varies from no apparent change in one subject to nearly a threefold increase in another.

Urea clearances increased substantially in all subjects, showing an apparent correlation with urine volumes. The subject who had the highest six-hour urine volume also showed the greatest urea clearance. Control urea clearances ranged from 27 to 72 ml/min, compared with the test results of 105-279 ml/min. During immersion the urea clearance actually exceeded the creatinine clearance in three of five subjects.

BODY FLUID VOLUME REGULATION

The regulation of body fluid volume distribution has been thoroughly studied in many laboratories in the past ten years and a number of clear cut regulatory reflexes have been defined. The reader is referred, for further details and supporting evidence, to a number of excellent and authoritative review articles on the subject^(13, 15, 17, 36, 37).

In 1946 Verney described the mechanisms by which the osmotic pressure of the blood is maintained by a balance between water and solute ingested and urine lost and water evaporated⁽⁴⁰⁾. In the case of dehydration the rise in osmotic pressure of the plasma leads to a rise in output of the anti-diuretic hormone (ADH) and a consequent decrease in urinary water excretion. Thus, water is conserved and body fluid volumes are maintained. However, it has subsequently become apparent that there are many instances when, in isotonic volume depletion

such as blood loss, volume information must be sensed by the body as well as osmotic pressure.

In the search for the ubiquitous "volume receptor" many authors examined the effects of various maneuvers which influence the rate of urine flow by changing the distribution of body fluid volumes. There is now ample evidence that any procedure associated with increased filling of the intrathoracic circulation produces an increase in urine flow or diuresis. Figure 3 summarizes the available evidence and shows that measures leading to an expansion of the central or intrathoracic blood volume are accompanied by a diuresis and that reduction in the volume of this critical area produces oliguria.¹ Figure 3 also indicates that if volume changes are moderate there is no correlation between renal venous pressure and urine flow. It has been suggested that the urinary changes following such procedures are due to alterations in systemic arterial hemodynamics, plasma flow or glomerular filtration rate. However, a considerable body of evidence demonstrates that relatively small changes in intrathoracic or total blood volume not associated with appropriate alterations in renal or systemic hemodynamics may reflexly alter the release of the anti-diuretic hormone from the posterior pituitary(17).

Figure 4 presents in schematic form the known mechanisms of extracellular fluid volume regulation. In an elegant series of experiments, Henry and Gauer and their co-workers were able to demonstrate the existence of stretch receptors in the left atrium and pericardial portion of the pulmonary veins whose activity, recorded from single vagal fibers, is decreased by an increase in central or intrathoracic blood volume(17). Distention of the left atrium, by small balloons or by negative pressure breathing, results in a prompt free water diuresis mediated by the inhibition of ADH secretion. Recording from single vagal fibers, Paintal has described a type A atrial receptor that fires during atrial systole and a type B, whose discharge coincides with the v wave of the time of maximum stretch of the atrium at mid-diastole(17). The diuretic response to atrial distention is abolished by cooling the vagus to 8°C which temperature also blocks B type impulses from atrial receptors. The integration of this afferent information in the central nervous system remains to be worked out in detail.

The efferent limb of the reflex from the left atrium is through the hypothalamus-pituitary and the regulation of the release of ADH. Serum ADH assay during balloon distention of the atrium demonstrates reduced anti-diuretic titre during the period of distention and conversely there is an increased serum ADH during hemorrhage(17).

A similar set of volume receptor mechanisms has recently been elaborated for the regulation of the secretion of aldosterone, the potent salt retaining steroid of the adrenal. Anderson et al have demonstrated that distention of the right cardiac atrium inhibits the adrenal secretion of aldosterone(2, 15). It would then be

¹"Central" blood volume is the filling reservoir of the left ventricle consisting of the pulmonary circulation and the left heart during diastole. The "intrathoracic" blood volume is usually determined as a "catheter tip to catheter tip" volume by indicator dilution techniques and comprises the central volume, the right heart and adjacent great veins and an additional ill-defined arterial volume that varies with changes in arterial hemodynamics.

Procedure	Urine flow	Filling of intrathoracic circulation	Filling of extrathoracic circulation	Pressure in renal veins
Hemorrhage	↓	↓	↓	↓
Pos. pressure breathing man, anesth. dog	↓	↓	↑	↑
Balloon in inf. v. cava above renal veins	↓	↓	↑	↑
Balloon in inf. v. cava below renal veins	↓	↓	↑	↓
Orthostasis	↓	↓	↑	↑
Sequestering of blood by cuffs	↓	↓	↑	↓
Sequestering of blood by cuffs plus infusion of 1500 cc. of blood	normal	normal?	↑	normal?
Blood transfusion	↑	↑	↑	↑
Neg. pressure breathing man, anesth. dog	↑	↑	↓	↓
Head down tilt	↑	↑	↓	↓
Immersion of trunk in warm bath	↑	↑	↓	↑
Exposure to cold	↑	↑	↓	↑

Figure 3. Procedures that change the rate of urine flow. (From Gauer et al(18).

VOLUME REGULATION

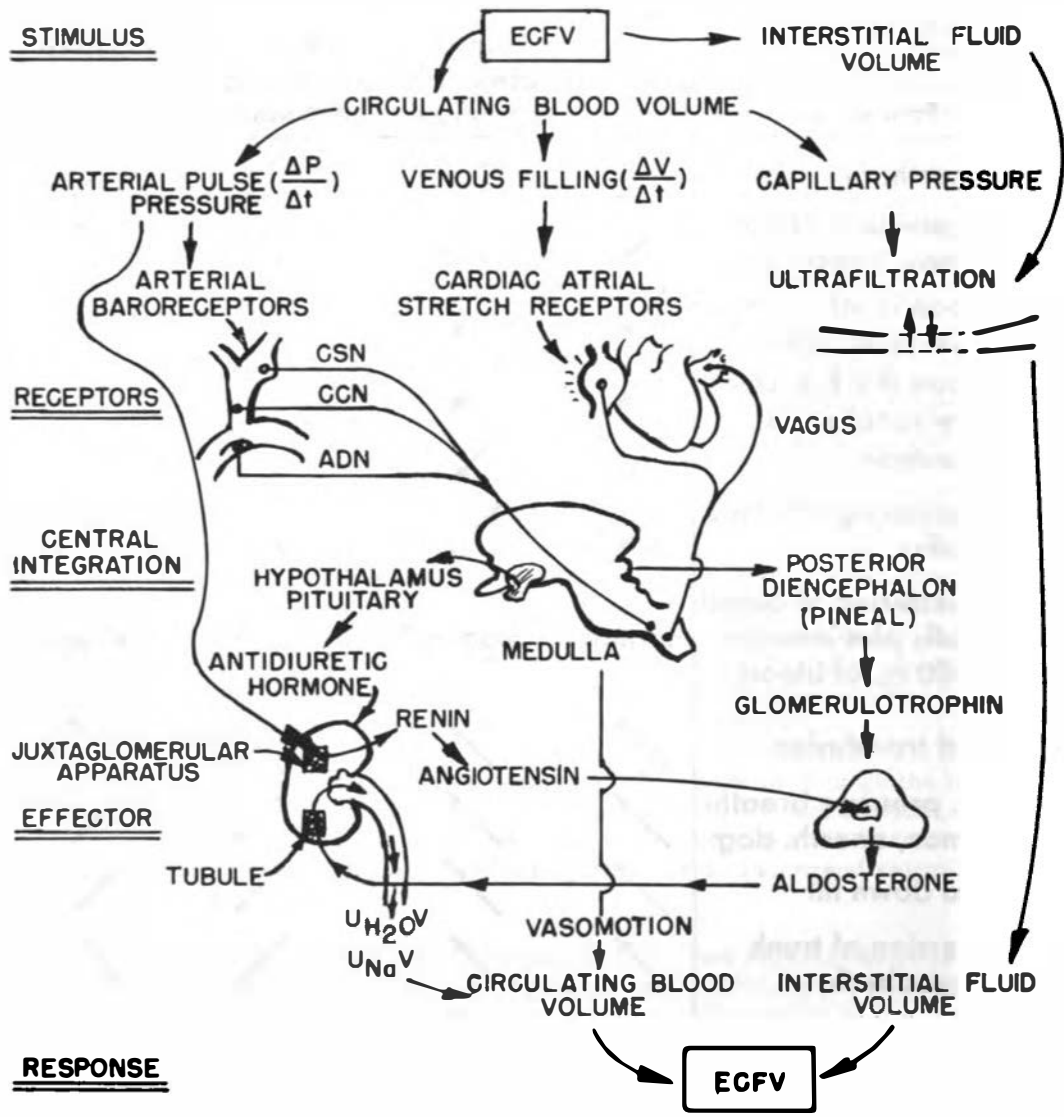


Figure 4. A schematic diagram of the mechanisms of body fluid volume regulation. The stimulus in this case is a change in the volume of the extracellular fluid and the response is an appropriate correction.

expected that all procedures associated with an increased filling of the intrathoracic circulation would lower aldosterone secretion and result in an increased renal sodium excretion or naturesis. This response is not as consistent as the ADH response to increased intrathoracic blood volume⁽²²⁾. Bartter and his associates have demonstrated that the carotid baroreceptors also regulate the rate of aldosterone secretion in response to changes in arterial hemodynamics^(5, 13). Farrell and collaborators have suggested that the pineal gland or some anatomically closely associated structure secretes an aldosterone-stimulating hormone. This material has recently been isolated and tentatively identified as a carboline and acts directly on the zona glomerulosa of the adrenal to increase the secretion of aldosterone⁽¹⁵⁾. Aldosterone in turn acts on the renal tubule to promote sodium transport and thereby sodium retention by the kidney.

More recently, a third reflex arc for the regulation of aldosterone secretion has been identified⁽¹³⁾. In this case, the kidney is both the receptor and the effector organ. In response to changes in the arterial pressure in the efferent glomerular arteriole, the juxtaglomerular apparatus of the renal cortex releases renin into the circulation. Renin enzymatically releases angiotensin II from its bound form in plasma and angiotensin then acts directly on the adrenal to stimulate the secretion of aldosterone. According to this view the renal efferent arterioles constitute the receptor mechanism. It now appears well established that the body does indeed, as Peters suggested in 1935,⁽³⁴⁾ sense the "fullness of the blood stream" with stretch receptors located in the cardiac atria, carotid arteries and renal arterioles, and that this information is integrated in the central nervous system to provide appropriate alterations in salt and water balance and peripheral vasomotion to maintain volume homeostasis.

IMMERSION AND PULMONARY MECHANICS

An analysis of the physical properties of immersion in water up to neck level discloses that the subject has his body in a hydrostatic pressure system which is depth-dependent, so that he must breathe against a hydrostatic pressure at the costal margin of about 36 cms of water in addition to the atmospheric air pressure of 988 cms of water. However, the air pressure surrounding the subject's neck and head is only one atmosphere and this pressure is exerted through the airway into the alveolar spaces of the lung. The pressure differential between the air in the lungs and on the exterior of the chest creates a negative pressure breathing situation.

The thesis that is put forward in this paper is that the renal response to immersion is determined in part by the volume of the intrathoracic circulation which in turn is a reflection of the volume rate of venous return from the lower extremities and abdomen into the chest cage. This distribution of venous blood volume between the intrathoracic and extrathoracic capacitance vessels is determined by the pressure gradient across the diaphragm, assuming that the abdominal contents behave as a fluid and transmit pressure equally and that the rib cage is semi-rigid⁽¹⁾. Many workers have attempted to establish an "equivalent" intrapulmonic pressure for subjects seated or standing in water^(8, 12, 26, 28, 33). Beckman et al determined that approximately 10 cms of water positive breathing pressure was required to reestablish normal lung volume compartmentation

in seated subjects immersed to the neck(8). Hong and his co-workers found that the relaxation pressure-volume curve of the whole chest was shifted approximately 6 cms of water to the right during supine immersion and have stated that "lying in a bathtub just completely submerged is equivalent to continuous negative pressure breathing of -6 cms of water as far as the mean transthoracic pressure gradients are concerned(26)." Carey, Schaefer and Alvis have estimated that the equivalent negative pressure while standing to the neck in water in -26 cms of water, in their studies of 16 diving instructors in the Escape Training Tank of the U.S. Naval Submarine Base(12). However, it is apparent that the respiratory mechanics of air and immersion cannot be made equivalent simply by restoring pulmonary pressures or volumes of the immersed subject to ambient levels by the addition of increased breathing pressure. In the first place, the immersed chest is in a gradient pressure system and to use a mean or lump unit such as equivalent transthoracic pressure to describe a distributed parameter such as gradient pressure is in this case perhaps, more confusing than enlightening. The immersed chest is physically not the same system as the unimmersed chest. It is not even the same shape. Secondly, such analysis of pressure-volume relations between environments must be based on absolute or total lung volumes, rather than the compartments included in the vital capacity, as immersion markedly reduces the expiratory volumes of the lung(8, 24, 26, 33, 39). Thirdly, the so-called equivalent mean transthoracic pressure necessary to restore normal lung volumes is obviously less than the greatest depth or pressure outside of the chest. In Rahn's analysis the ambient pressure-volume curve was displaced 6 cms to the right, i. e., it took 6 cms more water pressure during supine immersion to fill the chest to a given volume than in air. Considering that the average chest diameter in the subjects was 22 cms the 6 cms value was considerably "shallower" than the pressure at the back.

Considering the average lateral chest length from the pulmonary apex to the margin of the tenth rib to be 36 cms, the 26 cms estimate of Carey et al for the equivalent mean transthoracic pressure is again shallower than the costal margin. Therefore, even if a mean or equivalent transthoracic pressure gradient is restored to the immersed subject, a negative pressure breathing situation still exists in terms of a pressure gradient at the lower rib margin, possibly favoring an increased volume of venous return. Such an analysis remains to be confirmed by the direct measurement of central venous volume in response to the hydrostatic pressure gradients produced by immersion.

It has been noted by many workers that the "point of comfort" or "eupneic" point for a pressure regulator supplying air to a person under water is at neck level rather than chest level; that is, in a considerably shallower position than the chest(28, 33, 39). Even when swimming horizontally with the regulator above the back, most SCUBA divers deny any sensation of negative pressure breathing. Paton and Sands, in 1947, found that the "eupneic" point of resting, standing divers was five to ten cms below the external auditory meatus, increasing to 10 to 15 cms with hyperpnea from any cause(33). In all other positions the eupneic pressure was attained by positioning the regulator at the suprasternal notch. This data has been confirmed by Thomason and McCally who also found that the eupneic point as selected by seated divers was two to eight cms above the sternal notch and obviously well above the center of mass or volume of the lung(39).

The magnitude of over-pressure on the chest wall and abdomen during head-out immersion is comparable to the intrapulmonic under-pressure used in typical negative pressure breathing studies. The cardiopulmonary alterations which accompany negative pressure breathing in the range of 12 to 16 cms of water have been well studied and recently reviewed(3, 31). Inasmuch as water immersion under the conditions of most reported experiments, including those using demand and continuous flow regulators, exposes the subject to some degree of a negative transthoracic pressure gradient, cardiovascular, pulmonary and renal function changes similar to those produced by negative pressure breathing may be expected during immersion.

TEMPERATURE

The effect of temperature on the observed immersion diuresis is essentially unknown. The cold diuresis of unimmersed subjects appears to be a good case for the relationship between intrathoracic blood volume and urine flow. Taking a man from a hot sweating state to a cold shivering state produces a decrease in peripheral blood flow, and increase in central venous pressure and a free water diuresis apparently mediated by a decrease in ADH concentration in the blood(4). The diuresis can be turned on or off by change of exposure from cold to comfortable or from lying to standing(4, 17). The effect of temperature on the water immersion diuresis is not clear cut. Bazett reported that, "the diuresis seen in a bath is independent of temperature," in the range 30-40°C(6). DeForest and Beckman, however, have shown that the urine flow rate is considerably greater during head-out immersion at 25°C than at 35°(14). Further work is needed to clarify the role of temperature.

MECHANISMS OF THE IMMERSION DIURESIS

The normal distribution of body fluid volumes is determined in large part by hydrostatic pressure gradients due to gravity. In the normal gravitational field the hydrostatic pressure of the body fluids, especially the vascular compartment, exerts considerable effect on body fluid volume distribution during positional changes. On assuming the recumbent position, the plasma volume initially increases(38, 42) is redistributed cephalad(36) with an increase in the filling of the intrathoracic circulation. Similarly, there is good indirect evidence that during immersion there is an increase in intrathoracic blood volume due to the combination of the relatively increased tissue pressure of the extremities by the hydrostatic pressure of the immersion fluid, the relatively negative transthoracic pressure gradient as discussed above and unopposed venomotor tone. Body section radiography during head-out immersion demonstrates a relative increase in thoracic blood volume(10). Guyatt *et al* have demonstrated a 47 per cent increase in pulmonary capillary blood volume during immersion to the mid thorax(24). McCally has recently shown that the plasma volume increases up to ten per cent during the first 30 minutes of complete immersion and then decreases progressively(32), as seen in Figure 5. It has been adequately demonstrated that immersion produced an increase in free water clearance suggesting the inhibition of ADH. Gauer *et al* have recently confirmed a diminished level of ADH in the serum of subjects during immersion(16). Further, the immersion diuresis is inhibited by

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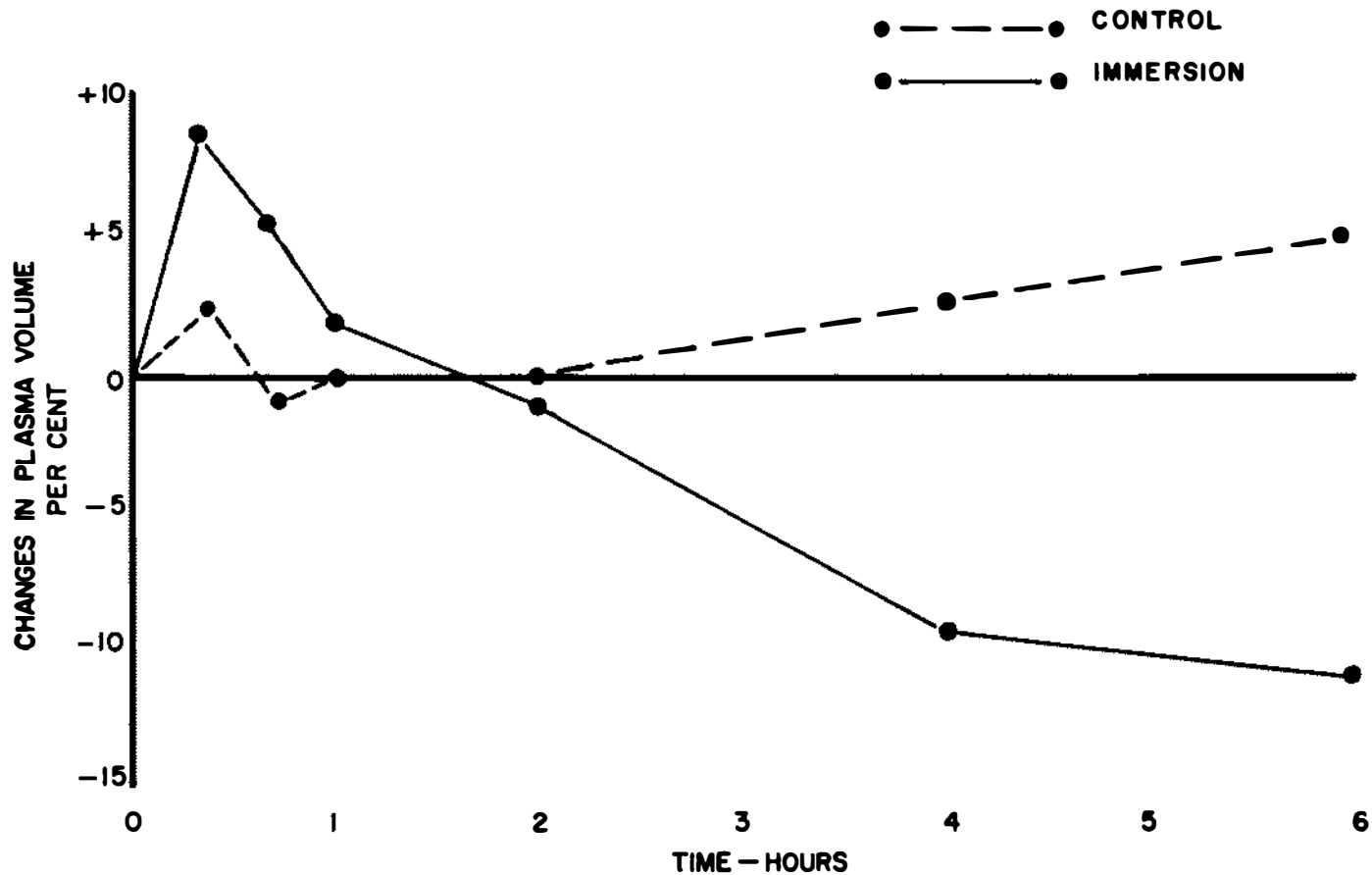


Figure 5. Per cent change in plasma volume estimated from changes in hematocrit hemoglobin concentration for five subjects during six hours of complete water immersion and during an office activity control.

the administration of pitressin⁽²¹⁾. In summary, there is good suggestive evidence that the immersion diuresis is due in part to the inhibition of release of ADH due to distention of cardiac atrial stretch receptors by an associated increase in intrathoracic blood volume produced by the hydrostatic pressure of the immersion medium and a negative transthoracic pressure gradient.

Secondly, the immersion diuresis is, in certain immersion environments, in part an osmotic diuresis. The increase in urinary nitrogen excretion during immersion, as noted by Bazett *et al*⁽⁷⁾, Graveline *et al*⁽²⁰⁾, and Graveline and Jackson⁽²²⁾ cannot be adequately explained at this time. The "exaltation" of urea excretion during an increased rate of urine flow, that is, a rise in urea clearance higher than the expected from the increase in urine flow and exceeding the glomerular filtration rate, is seen on the rising limb of a water diuresis⁽³⁵⁾ and was demonstrated by Graveline and Jackson during the immersion diuresis⁽²²⁾. Schmidt-Nielsen has suggested that active tubular secretion of urea occurs in at least one group of animals (frogs) but this has not yet been proved to occur in mammals. He also suggests the "exaltation" of urea excretion may be due to the washing out of urea from its high concentrations in the renal papilla and surrounding tissue⁽³⁵⁾. This, however, would not seem to explain the three-day elevation of urinary nitrogen observed during Graveline's seven days of immersion⁽²⁰⁾. Whether the urea originates from muscle tissue under the relative disuse conditions of immersion or whether it was "flushed out" of other sources by the increased rate of urine flow remains to be determined.

In studies of Graveline and Jackson, a significant naturesis or increase in sodium excretion accompanied the immersion diuresis⁽²²⁾. Gowenlock and colleagues have reported that, although sodium excretion decreased considerably while standing in air after recumbency, there was no change in sodium excretion while standing in water. Aldosterone excretion decreased during recumbency and while standing in water, but increased within three hours when standing in air⁽¹⁹⁾. No other data is available on rates of aldosterone secretion or excretion during immersion. It remains to be demonstrated that the immersion naturesis is a consistent finding and whether such a naturesis is mediated by cardiac atrial or renal volume receptor mechanisms or simply by simultaneous changes in renal hemodynamics.

The diuresis of immersion may also involve what are as yet poorly understood or unknown mechanisms of body fluid volume regulation. Kaiser *et al* have recently demonstrated the presence of a diuretic factor in the plasma of subjects during an immersion diuresis⁽³⁰⁾.

THE AMA

As far as I am aware there are no data in the literature concerning renal function of the Ama during immersion. Obviously, then, there is little factual to be said at the present time about renal function and Ama diving. However, if we look briefly at the physical characteristics of the Ama's pattern of immersion we can on the basis of the data we have just reviewed make some reasonable speculations and hypotheses to be tested in experiment.

In Figure 6 is sketched a rough approximation of the depth and duration of the dives of unassisted and assisted Ama of Japan and Korea as described by Teruoka and Hong *et al*⁽²⁷⁾. In both patterns of diving approximately one-half of

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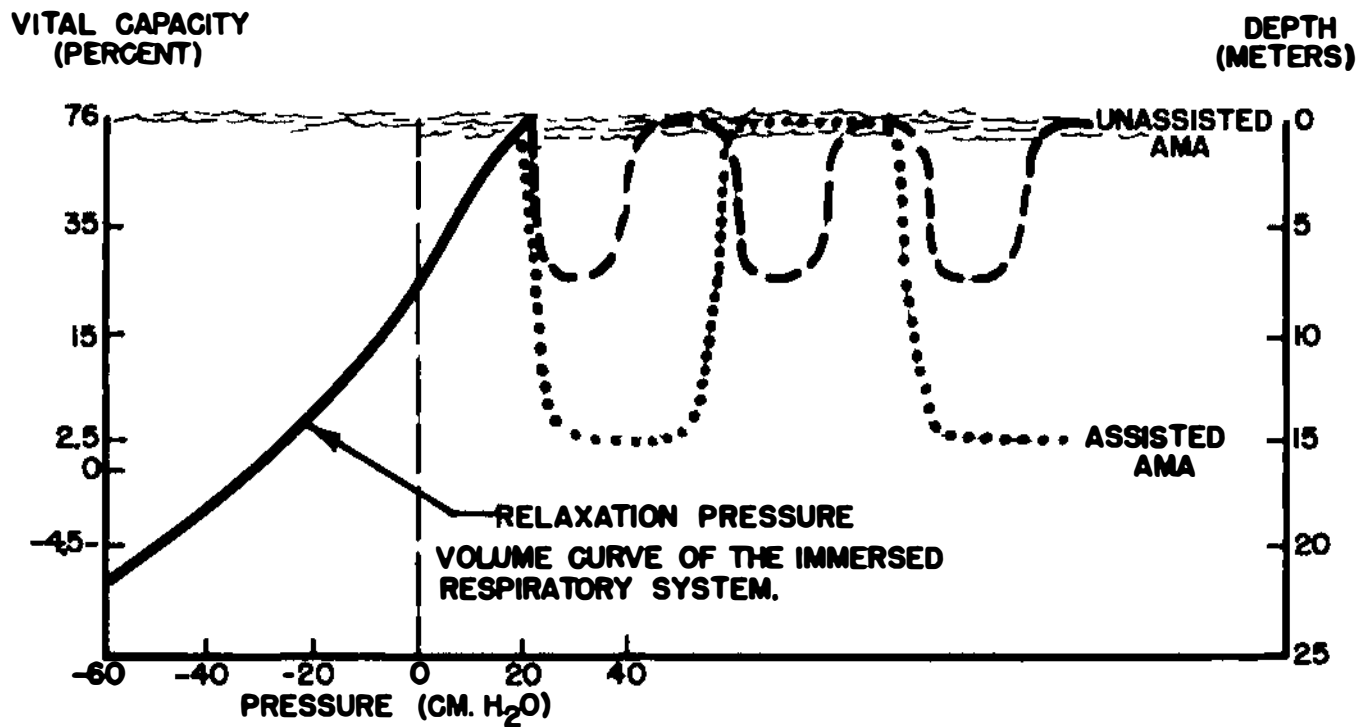


Figure 6. A diagram of the diving pattern of assisted and unassisted Ama in relation to a typical relaxation pressure-volume curve of the immersed respiratory system. (Pressure-volume curve modified from unpublished data of E. Agonstoni.)

the time immersed is spent in simple head-out flotation. Neglecting for the moment considerations of prehydration, ambient temperature and metabolic rate we should expect to see in the head-out periods all of the physiological effects of head-out immersion previously reported including: (1) a transient increase followed by a decrease in total plasma volume, (2) an increase in central or intrathoracic blood volume, (3) an increase in pulmonary capillary blood volume, (4) a decrease in the expiratory volumes of the lung including expiratory reserve volume and functional residual capacity, (5) a free water diuresis, (6) a variable naturesis, (7) a variable increase in blood urine urea concentration, and (8) an increase in glomerular filtration rate and renal plasma flow.

What is the effect of the breath-hold dive which occupies the other half of the Amas' one to three hour immersion shift? Again information available in the literature is sparse but suggests: (1) a decrease in peripheral (muscle) blood flow, and (2) increase in peripheral vasoconstriction, both favoring an increase in intrathoracic blood volume, although no direct measurements have been made. This picture is complicated by the pattern of intrathoracic pressuring during the breath-hold dive. Just before diving the Ama hyperventilate briefly and inspire to 75 per cent to 95 per cent⁽²⁷⁾ of vital capacity, and intrathoracic pressure is well on the positive side of the pressure-volume diagram of the chest as seen in Figure 6. As the diver descends the lung volume is reduced by the increased ambient pressure according to Boyle's Law. However, it is apparent that for dives up to the range of five to eight meters, the transthoracic pressure gradient probably remains on the positive side of the curve tending to reduce or oppose the filling of the intrathoracic circulation. As the diving depth increased toward 15 to 20 meters, the lung volume is further reduced and the chest wall becomes stiffer (less compliant), resisting compression and the transthoracic vasculature, undoubtedly stimulating cardiac atrial volume receptors. Compared to the total hydrostatic pressure on the body at a given depth the differences in pressure or hydrostatic imbalance necessary to cause an increase or decrease in the filling of the intrathoracic circulation are small, only a few centimeters of water. The state of filling of the intrathoracic circulation may be altered by small changes in depth or position on the pressure-volume diagram of the chest. A definitive statement about the operation of a volume receptor reflex obviously demands the direct measurement of the stimulus volume, in this case the "central" blood volume. The Ama experience both head-out flotation and breath-hold diving each with its own particular characteristics of applied hydrostatic pressure and pressure-volume relationships of both the chest and the venous capacitance system. The relation of these hydrostatic pressure gradients to the, as yet, undescribed Ama diuresis awaits further study. In the only available literature reference, Bond and Schaefer have mentioned a diuresis and an increase in blood urea in U.S. Navy diving tank instructors during 90-foot breath-hold dives but no data is available to support their statements⁽¹¹⁾.

In order to directly implicate volume receptor mechanisms in the diuresis of immersion it will be necessary to determine simultaneously during immersion: (1) pulmonary compartmentation including functional residual capacity and the absolute pressure-volume relationships of the chest and diaphragm, (2) central or intrathoracic blood volume and pressure, (3) urine flow, free water and osmolar clearance and glomerular filtration rate, (4) sodium and urea excretion and filtration fraction, and (5) levels of ADH and aldosterone and serum and urine. The answer is in the experiment.

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THE ELECTROCARDIOGRAM PATTERN OF THE DIVING AMA

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It has been known for a long time that slowing of the heart beat takes place during diving in various animals. Irving *et al* (19) report that even in human beings bradycardia takes place during apneic underwater diving, though the details are not available from this paper. Wyss (37, 38), Scholander *et al* (34), Irving (21) report the changes in EKG during apneic diving. Olsen *et al* (29, 30) and Craig (9) experimentally show the effects of the apneic diving upon the EKG. According to these workers, decrease in heart rate and occasionally various kinds of arrhythmias appear during apneic diving.

Irving performed his experiment on professional show divers and Scholander *et al* on pearl divers in the Thursday Island area. Recently, Hong *et al* (17) have begun to study the cardiac rhythm during the diving of the Korean Ama. Since no work on EKG of the Japanese Ama has been reported, we have taken EKG patterns on the Japanese Ama off the coast of Ijika, Toba City, Mie Prefecture in July, and of Shirahama, Chiba Prefecture in August 1964 (Fig. 1).

Methods for Recording EKG Patterns During Diving

The underwater EKG is usually recorded by fixing the electrodes on the chest of the diver and connecting them to the electrocardiograph on board using long cables. Nothing has been discussed on the EKG patterns obtained by this method. Four problems should be taken into consideration.

1. Electrodes should be placed where influence of electromyogram and displacement of the electrodes due to muscular movements are minimum. Furthermore, the EKG recorded from these places should be good enough to evaluate.

Similar discussions have been made regarding this problem while taking EKG patterns during exercise. Actually, in exercise, some combinations of bipolar leads such as between the top and bottom of the sternum, the middle part of the sternum and C4-6, top of the sternum and C5, C5, and C5R etc. are conventionally used.

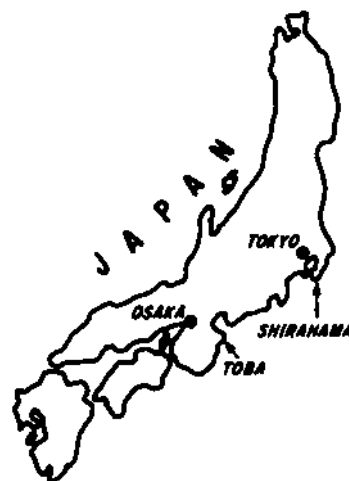


Figure 1.

The limit of the evaluation of the EKG patterns taken by such bipolar lead has never been completely discussed. So far as analysis of cardiac arrhythmias is concerned, the above mentioned bipolar leads are applicable to recording of EKG during diving, while there still remains some questions in evaluating the ST-T changes in the sea. Olsen *et al*⁽²⁹⁾ and Scholander *et al*⁽³⁴⁾ report the ST-T change during diving without any particular evaluation of the patterns.

Olsen *et al* placed the electrodes on the top of the sternum and C4. Their EKG patterns are similar to the standard II lead. Craig⁽⁹⁾ and Hong *et al*⁽¹⁷⁾ placed the electrodes on the top and bottom of the sternum. Their patterns are thought to be similar to the V_1 of the chest lead. Irving placed the electrodes on the forehead and the sternum. Our work was performed by using Olsen's method.

2. In order to exclude sea water penetrating into the site of the electrodes, various kinds of water proof devices were made. In our experiments, the rubber cup which covers the electrode is attached to the skin by contact cement. Vacuum grease is applied to the surroundings of the electrode. A 10 x 10cm rubber sheet is placed over the cup.

3. It is possible that the distribution of the electric potential of the body surface might be altered in sea water. Evaluation of changes in QRS and ST-T patterns become impossible, unless potential distribution of the body surface remains constant in sea water.

According to our results, two cases out of eleven Amas show a ten per cent decrease in amplitude of QRS in sea water in comparison with QRS taken in air (Fig. 2).

4. Effect of long cable on EKG patterns is mainly determined by the electric capacitance in the cable itself. Electric resistance of the cable is usually negligibly smaller than input impedance of the EKG and skin impedance. Unless the cable is over 100 meters in length, its electric capacitance does not deform the EKG pattern.

The foregoing problems suggest that there is little difficulty in making analyses of cardiac arrhythmias during diving, while many problems should be taken into consideration in evaluating QRS and ST-T patterns taken in the sea.

Electrocardiogram During Diving of Japanese Ama

In our experiments, recording of EKG of the Ama was performed during diving 10 m beneath the sea surface. The experiment was performed on Funado who dive directly with the aid of weight of approximately 15 kg and Cachido who dive by their own power. The water temperature was 20°C at the bottom of the sea. Ama with the weight reached the bottom of the sea in about ten seconds. This diving pattern is almost similar to that of the Korean Ama reported by Hong *et al*⁽¹⁷⁾.

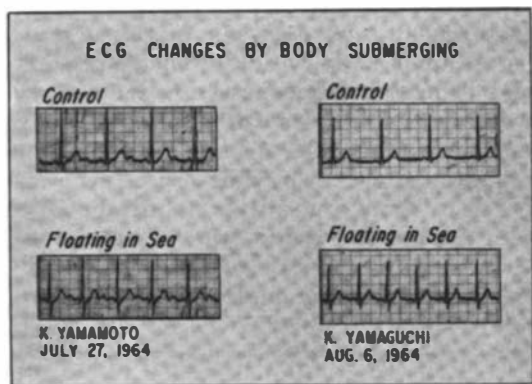


Figure 2.

The heart rate decreases rapidly in 20 seconds. Arrhythmias appears comparatively late during a dive. In one case, idioventricular rhythm occurred early in a dive. See Figure 5.

Reduction of Heart Rate (Bradycardia)

Effect of Exercise

It is reported that bradycardia during apneic underwater diving cannot be prevented by exercise(19, 38). Olsen *et al*(29) reported the EKG in diving persons with and without exercise and showed little change in bradycardia between the two groups. Irving(21) showed that there is little difference in heart rate during vigorous swimming and standing in water. According to Hong's report(17), similar results were obtained in the Korean Ama.

On the contrary, Craig studied heart rate response to exercise with normal respiration in water and to exercise during apneic diving. According to his data, apneic diving with exercise increased heart rate to the same rate as exercise in water with normal respiration, although the recovery of the former is much shorter.

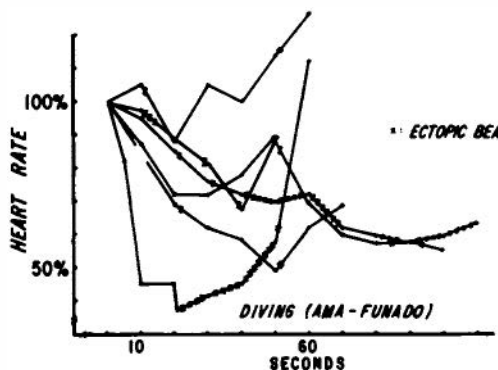


Figure 3.

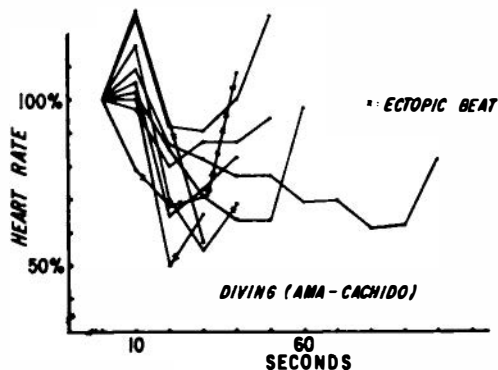


Figure 4.

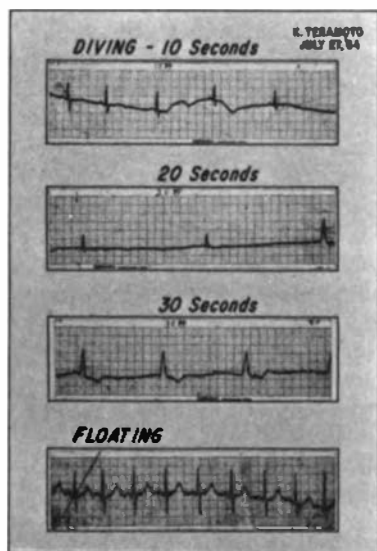


Figure 5.

He considered that this phenomenon might be mostly due to the vagal inhibition, which is not, however, strong enough to prevent increase in heart rate during exercise. Similar results were obtained in our experiments (Fig. 4). As seen in the Cachido, who dives to the sea bottom by her own effort, initial increase in heart rate might be attributed to this exercise, while the Funado, who descends to the sea bottom with the aid of a weight, shows immediate bradycardia with no such transit increase phase (Fig. 3).

Effect of Breath Holding

Slowing of cardiac rate caused by breath holding may be due to the carotid sinus reflex. The bradycardia in apneic diving is more evident than that of simple breath holding. This result was seen by Olsen *et al*(29), Irving(21), Craig and Hong *et al*(17). In our results on the Ama, bradycardia in simple breath holding is not so marked as in

diving (Fig. 6), except one. This exceptional case shows arrest with idioventricular rhythm in apneic diving. While holding one's breath, it is considered that intrathoracic pressure exceeds the extent of relaxation pressure of the lungs and thorax (32), and furthermore, this intrathoracic pressure may become higher in diving. This pressure can not be considered to be the same pressure caused by the Valsalva maneuver(13). Craig(9) observed the relationship between the intrathoracic pressure and heart beat in air and water, but no relationship was shown.

The effect of pressure difference between the environmental pressure and intrathoracic pressure on bradycardia has not been studied. Craig simulated apneic diving in a compression chamber but he observed no bradycardia.

Effect of Asphyxia

Bradycardia appears rapidly during diving. It is, therefore, difficult to consider that systemic asphyxia plays an important role in producing bradycardia. Olsen *et al*(29) and Wyss(37) show that there is no relationship between the degree of bradycardia and duration of apnea. The fact that bradycardia appears less frequently in simple breath holding than in diving indicates that bradycardia during diving can not be attributed to asphyxia alone. It is generally said that increase in heart rate takes place in systemic hypoxia(14).

In experiments on Ama in our laboratory, tachycardia is noticed in acutely

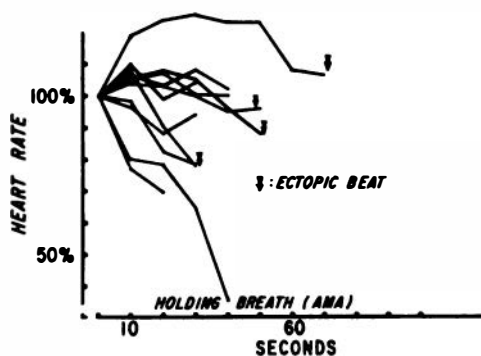


Figure 6.

induced hypoxia by ten per cent oxygen inhalation test. Although Downing *et al*⁽¹¹⁾ say that hypoxic stimulation of carotid body alone causes bradycardia, it is still obscure whether such local hypoxic conditions might persist during diving.

Sensory Reflex

Appearance of bradycardia during submersion of the face with breath holding is recognized by Scholander⁽³⁵⁾, Irving⁽²¹⁾ and Craig⁽⁹⁾. The efferent pathway of reflex bradycardia is considered to be vagal impulse. The disappearance of bradycardia by use of atropine is recognized in experiments using ducks⁽²⁵⁾, rabbits⁽¹²⁾, seal⁽²⁸⁾ and man⁽²⁶⁾. As to the afferent pathway, change in intrathoracic pressure is observed. It is assumed that vasoconstriction plays a small role in slowing of the heart beat in simple breath holding and diving^(12, 31).

In the Japanese Ama bradycardia readily appears when the face is submerged in sea water (Fig. 7). When entering the sea, the Ama's heart rate increases slightly, and bradycardia does not occur until their faces are submersed. Although the occurrence of bradycardia is attributed to sensory reflex, the reflex arch from the nose as seen in duck⁽¹⁾ can not apply to the Ama because her mask covers the eyes and nose. Bradycardia is noticed only by submersing the face into the water.

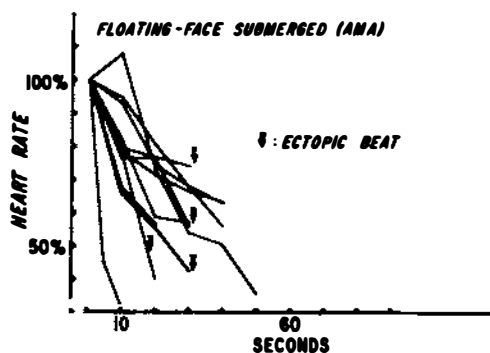


Figure 7.

In our experiments on healthy subjects (non-divers), there is no difference in the degree of bradycardia when the face is submersed with and without an underwater mask (Figs. 8 and 9). In this experiment, exercise performed by kicking the lower extremities can not prevent decrease in the heart rate (Fig. 10). However, slowing of the heart beat in exercise is more gradual than in simple face submersing without exercise. This phenomenon is considered to be analogous to the difference of bradycardia between the Funado and the Cachido.

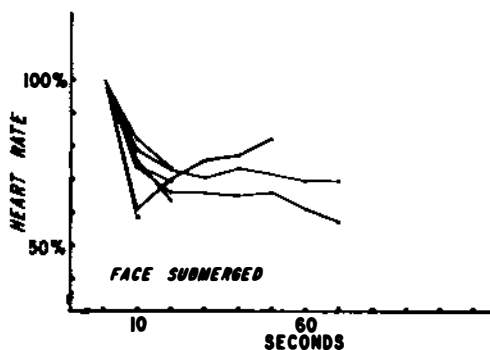


Figure 8.

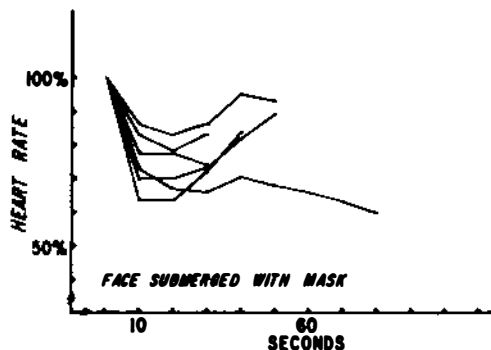


Figure 9.

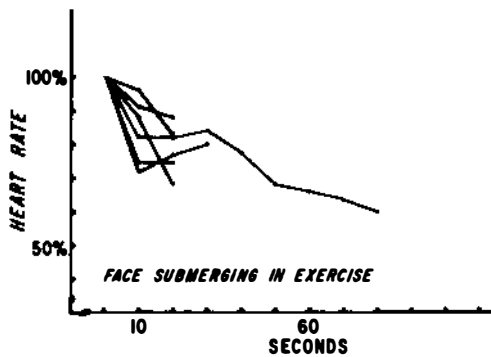


Figure 10.

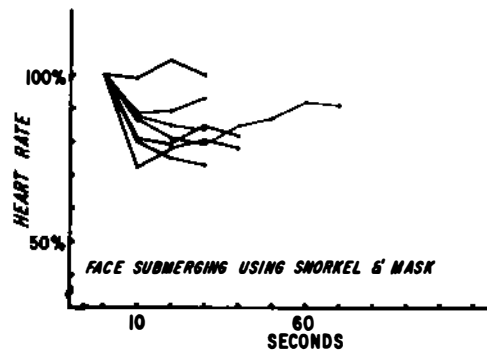


Figure 11.

Contrary to the fact stated before, bradycardia is evidently not recognized when the snorkel is used (Fig. 11). This implies that sensory reflex from the face cannot explain all of the mechanisms of bradycardia during diving.

Effect of Temperature

Craig and Olsen *et al*(29) recognize that bradycardia appears more evident in cold water than in warm water, and many other experimental results(4, 5, 8, 15, 18, 23) reported a change in the heart rate in the hypothermic state. Thus, it seems that hypothermia becomes one of the causes of producing bradycardia, but according to our data, bradycardia has already disappeared after diving, when the Ama's body temperature is still relatively low (approximately 35°C). Immediately after entering the sea, increase in the heart beat is recognized in the Korean Ama(17). These facts show that low temperature alone can not explain bradycardia during diving.

Effect of Training

Bradycardia during diving is seen in every diving animal, but it is said that bradycardia seen in non-diving animals is mild(20). Some report that bradycardia appears more obvious in the well trained diver than in the untrained diver (21), while others report no such differences(9).

Irregularity of Heart Rate (Arrhythmia)

Arrhythmias during apneic underwater diving have never been completely analyzed in the previous reports(17, 29, 34). The fact that change in the P wave appears with sinus bradycardia and sinus arrhythmia, and the fact that the ectopic beat appears after inhibition of action of the pacemaker, (for example, nodal and ventricular escape followed by sinus arrest), are considered to be passive ectopic beats, the cause of which is similar to the cause of bradycardia itself.

A-V block is rarely reported. Arrhythmias appears more frequently in diving than in simple breath holding. Because sinus rhythm before and after

arrhythmias in diving is irregular, the analysis of the focus of the ectopic beat is difficult. Ventricular premature beats appear more frequently than supraventricular premature beats(34). The cause of increase in irritability of the heart muscle which causes the active ectopic beat is considered to be asphyxia. However, asphyxia only cannot explain the discontinuity of arrhythmias. Though excitability of the heart muscle decreases in hypothermia, arrhythmias appear(2, 5). After diving, arrhythmias in the Ama disappear though body temperature is still comparatively low.

Various kinds of respiratory maneuvers(26) cause arrhythmias similar to that during diving. Such causes as the effect of vasoconstriction, should be taken into consideration when one refers to the pathogenesis of arrhythmias during diving.

ST-T Change in EKG Pattern

As stated before, technical difficulties prevent the analysis of ST-T change. Wyss(37) and Olsen et al(29) report the appearance of a tented T during diving. However, tented T appears even in simple breath holding. Usually tented T appears after bradycardia during diving. Tall peaked T waves have also been recorded in various animals during vagal stimulation. This fact is convenient to explain the mechanism of tented T and bradycardia during diving.

In the diving snake, tented T is reported to have relationship with the CO₂ level(22). Tented T and CO₂ might also be considered to have a relation with each other in the experiment of the perfused heart(36). The fact that tented T appears in hyperkalemia is well known(24). Hyperkalemia produced by asphyxia has been observed(7, 10). Acidosis due to exercise gives a deformity in the T wave(3). The relationship between the T wave and the temperature has been studied by many investigators(6, 33).

The appearance of a negative T wave during diving has been reported(34). Asphyxia(27) and low temperature are considered as the pathogenesis of T wave inversion. T wave inversion in the diving Ama is not found in our experiments except in the ectopic beat. The cause of changes in the T wave obtained in human divers still remains to be answered.

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CIRCULATORY ADAPTATIONS TO DIVING IN ANIMALS AND MAN

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It has been known for almost a century that the circulation plays a vital role in the special adaptations of diving animals and birds. The early experiments of Bert⁽¹⁾ and Richet⁽¹¹⁾ showed that ducks experience a profound slowing of heart rate during simple breath-holding dives. Atropine or vagotomy abolished the diving bradycardia. A similar response occurs in other animals, including man, suggesting that it is part of a general circulatory response to asphyxia. Scholander⁽¹²⁾ demonstrated that seals which normally have a heart rate of about 100 beats per minute experience a bradycardia of ten beats a minute or less when forcibly dived. It was later shown that the arterial blood pressure was well maintained throughout the dive due to a very slow pressure drop during diastole⁽⁶⁾. Figure 1 shows such a record of arterial pressure obtained recently by us on an elephant seal.

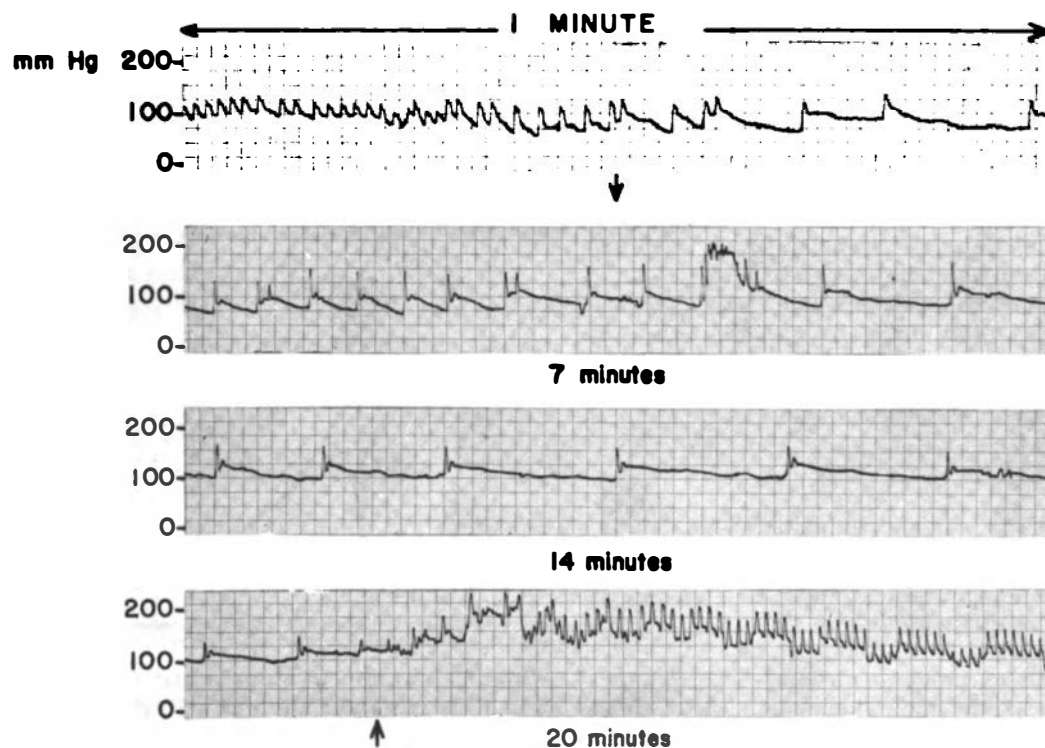


Figure 1. Blood Pressure in the Abdominal Aorta of an Elephant Seal Mirounga Angustirostris at Intervals During a 20 Minute Dive.

Irving(7) used a heated wire flowmeter to show qualitatively that blood flow was decreased in muscle and maintained in the brain during asphyxia in the muskrat, beaver, cat and rabbit. On this basis he hypothesized a redistribution of blood flow in response to asphyxia. Scholander demonstrated the lack of communication between muscle cells and central circulating blood by observing the failure of lactate to appear in high concentration in the blood until after the dive despite its accumulation in muscle tissue(12) (Fig. 2). Furthermore, muscle oxygen of a diving seal decreased at a more rapid rate than did arterial blood oxygen, falling nearly to zero while arterial saturation was still high(13) (Fig. 3). Direct observation of ischemia in seal mesenteries during dives provided additional support for the hypothesis(6).

On the strength of these lines of evidence, therefore, it seemed clear that a widespread and selective vasoconstriction occurred during diving, thus providing for continued oxygenation of vital organs such as brain and heart at the expense of organs of greater anaerobic capacity, such as muscle and gut. The quantitative relationships of cardiac output and blood flow distribution remained to be elucidated.

The development of modern electronic blood flow measuring devices which can be surgically implanted for long-term chronic use has provided the means for obtaining dynamic and quantitative measurements of blood flow in individual blood vessels. The Franklin pulsed ultrasonic flowmeter (5) was used in studies in this laboratory. Surgery was performed aseptically, and the animals were allowed sufficient time to recover from the procedure to the extent that they were to all outward appearances normal, intact animals. Such recovery usually required one week, although some measurements were obtained as early as one day after surgery.

Cardiac Output:

The intense bradycardia with maintained arterial pressure suggests a decreased cardiac output as well as peripheral vasoconstriction. This was tested in our laboratory on a California sea lion trained to immerse its

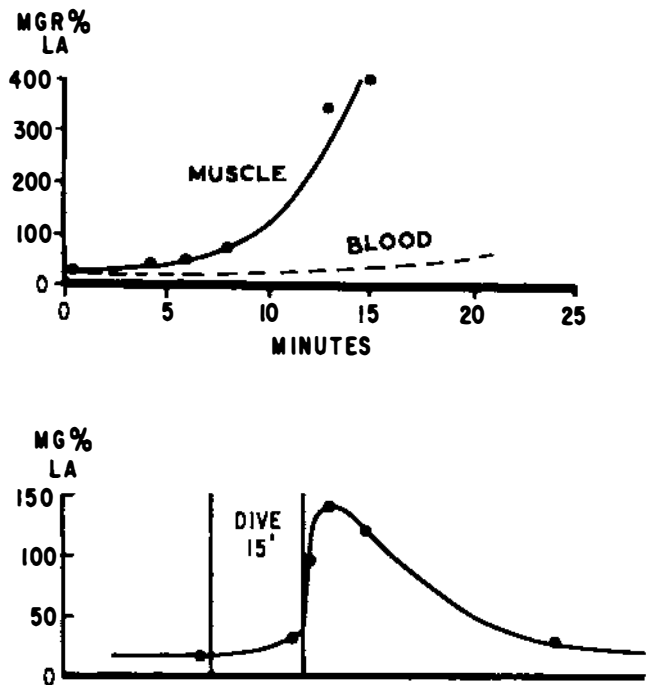


Figure 2. Upper: Lactate in Muscle and Arterial Blood in an Experimental Dive of a Harbor Seal *Phoco Vitulina*(13). Lower: Lactate in Arterial Blood of a Diving Seal *Halichoerus Grypus*(12).

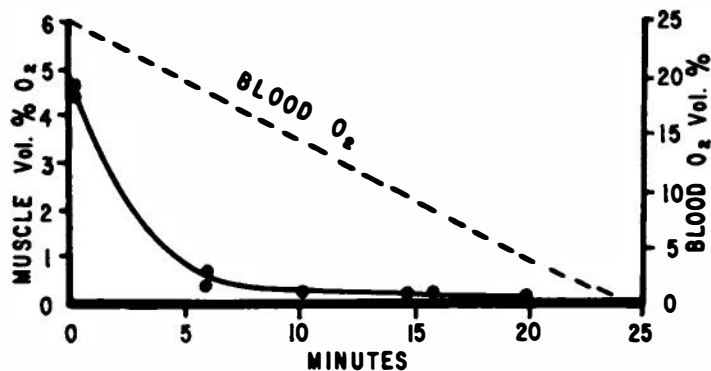


Figure 3. Oxygen Content in Muscle and Arterial Blood of a Harbor Seal *Phoca Vitulina* During an Experimental Dive(13).

when they are forcibly dived than when they have been trained to dive on command either with head immersions alone or with whole body dives. It will be noted in the figures that the stroke volume, represented by the area under the blood flow curves, remained essentially unchanged during immersion. Cardiac output, therefore, varied according to rate. This pattern was observed in many experimental dives in the sea lion and dogs.

head upon command(2). Additional experiments were performed on dogs, usually of Labrador retriever breed, to test the response in animals not generally regarded as aquatic. Sample records are shown in Figure 4 and 5. Cardiac output in the sea lion was obtained by measurement of blood flow in the pulmonary artery, while that in the dog was measured in the ascending aorta.

The diving bradycardia is evident, although it is not as intense as in the harbor seal. We later found that both sea lions and harbor seals have much more profound heart slowing

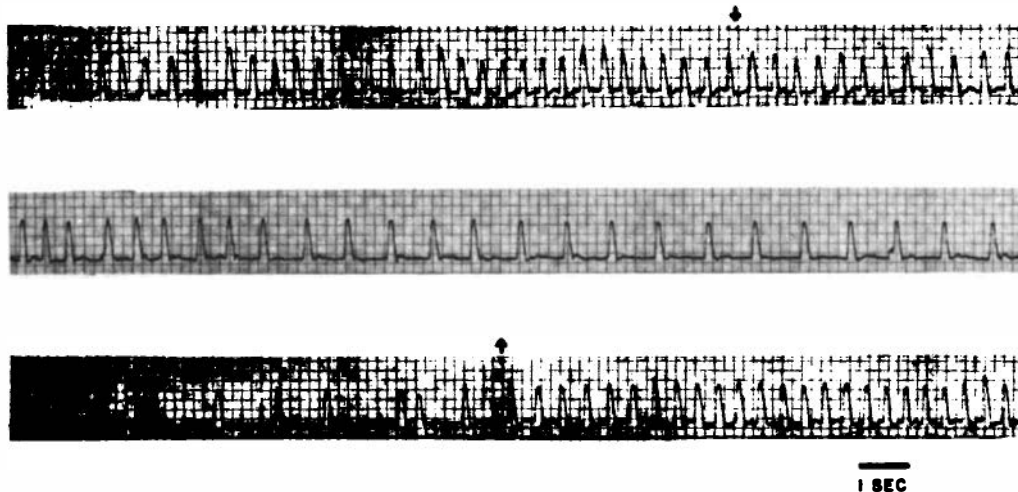


Figure 4. Pulmonary Artery Blood Flow During a Dive of 35 Seconds (indicated by arrows) in an Unrestrained Sea Lion *Zalophus Californianus*(2).

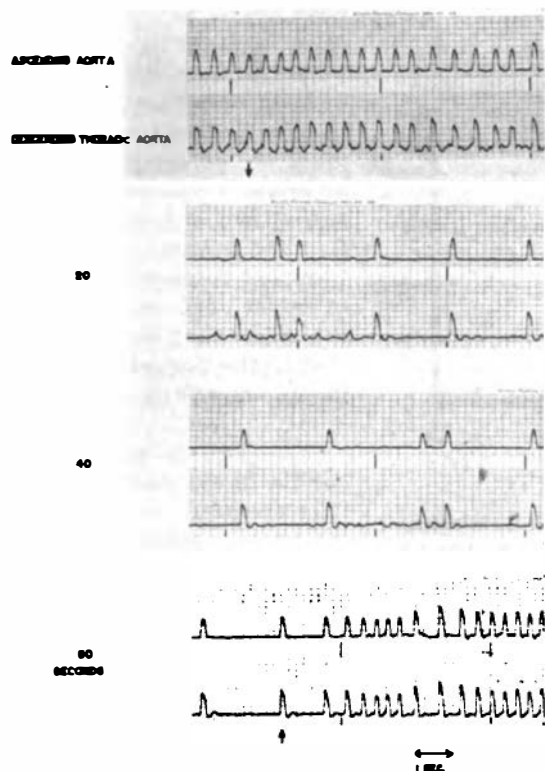


Figure 5. Blood Flow in the Ascending and Descending Thoracic Aorta During an Experimental Dive of One Minute in a Dog(3).

the dive was later determined to indicate zero blood flow. Approximately 50 such dives extending in time to a maximum of 15 minutes were performed in the two seals always with similar profound blood flow changes.

Figure 7 illustrates another record of blood flow obtained in the abdominal aorta and renal artery showing both instantaneous and mean blood flow. The flow records from a tape recorder were directed to a simple analogue computer to obtain mean blood flow information. The animal was first dived for a period of four minutes. It was then brought to the surface for a period of ten seconds and then dived again for an additional two minutes. The prompt and profound bradycardia can be observed as before. Also, the striking decrease in blood flow to virtually zero in these two arteries can be seen. Upon interrupting the dive for ten seconds, the immediate increase in blood flow with its equally prompt decrease at the end of the period can be seen. At the end of the completed dive a slight overshoot in blood flow occurred in both circuits.

Blood Flow Distribution:

Blood flow was measured in harbor seals in the renal artery, terminal abdominal aorta, and the common carotid artery. Measurements were obtained in dogs in the superior mesenteric artery, renal artery and the terminal abdominal aorta. One measurement was obtained in the left circumflex coronary artery of a greyhound dog during a brief immersion. Two young adult harbor seals weighing 30 and 35 kilograms and four full grown adult dogs which ranged in weight from 15 to 25 kilograms were used. In one experiment atropine in the dosage of 0.1 milligram per kilogram was administered to a dog which was subsequently dived(3).

The general features of blood flow changes in the abdominal aorta and renal artery of the harbor seal during a dive are shown in Figure 6. This was a forced dive of eight minutes, and the beginning and end of that dive are shown in the figure, time marks being at one second intervals. The striking bradycardia with a change from 100 to 4 beats per minute is clearly seen. The steady base line of blood flow during

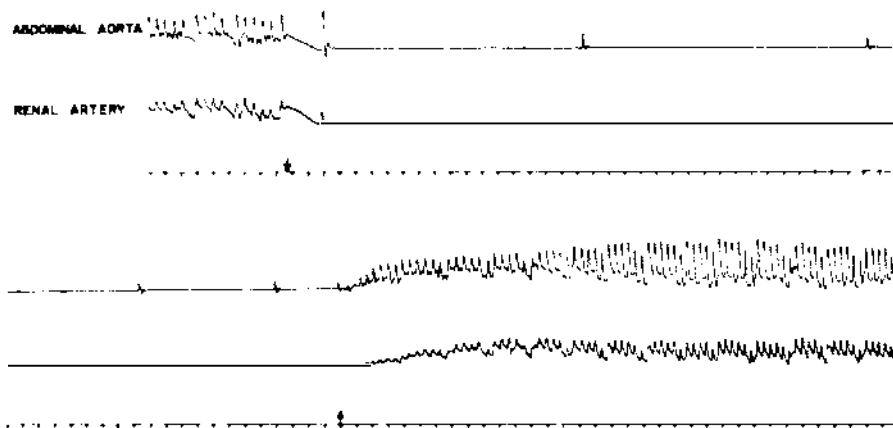


Figure 6. Blood Flow in the Abdominal Aorta and Renal Artery of a Harbor Seal *Phoca Vitulina* at the Beginning and End of an Eight Minute Dive (indicated by arrows)(3).

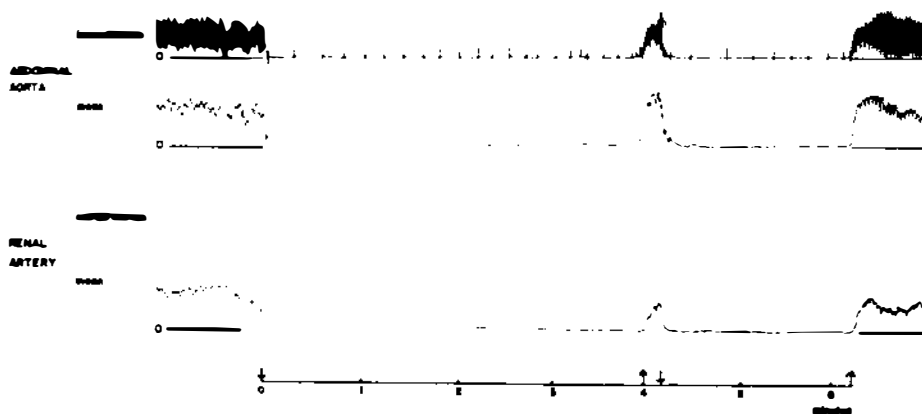


Figure 7. Instantaneous and Mean Blood Flow in the Abdominal Aorta and Renal Artery of a Harbor Seal *Phoca Vitulina* During an Experimental Dive of Six Minutes. A ten second interruption of the dive occurred at four minutes(3).

In Figure 8 blood flow records from a dog are presented. The dive, which lasted one minute, produced a fall to zero in blood flow in the superior mesenteric and renal artery and a considerable decrease in flow in the terminal abdominal aorta. Prompt and complete recovery followed the period of head immersion.

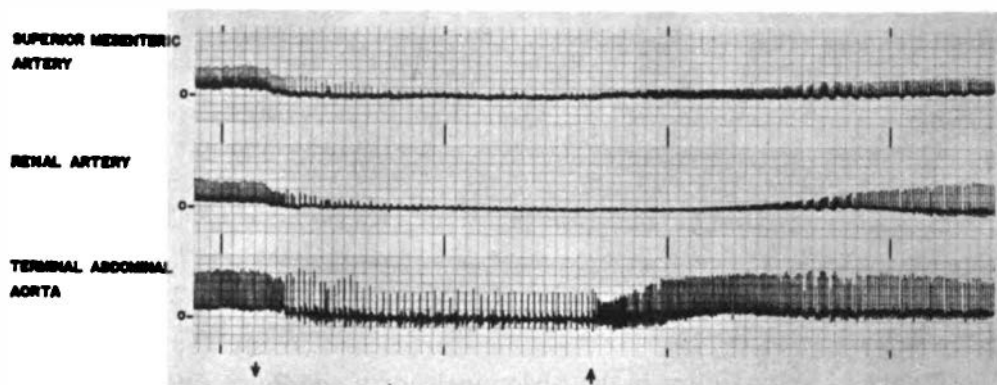


Figure 8. Blood Flow in the Superior Mesenteric and Renal Arteries and the Abdominal Aorta of a Dog in a Dive of One Minute⁽³⁾.

That the intense peripheral vasoconstriction of diving is selective in nature is suggested by the record of common carotid artery flow in the harbor seal shown in Figure 9. In this dive of eight minutes showing some vasoconstriction it is clear that blood flow was sustained at a higher level than in other arteries measured in the seal. It cannot be stated with certainty that the sustained flow in the common carotid is related to the maintenance of cerebral blood flow in this animal, though it is strongly suggested. Figure 10 shows a record of aortic pressure and blood flow in the left circumflex coronary artery of a greyhound dog during a dive of 30 seconds. It can be seen that the blood flow in the coronary circuit was steadily maintained throughout the dive.

Two harbor seals were trained to dive by immersing the head in a pan of water on command. A whistle indicated the termination of the "dive," and the animal was promptly rewarded with a piece of mackerel. A few weeks training produced dives of seven and one-half minutes duration. Bradycardia was of more gradual onset and less profound than that observed in forced dives. One animal with a chronically implanted blood flow transducer mounted on its terminal abdominal aorta was trained to dive in this manner. Several command dives of approximately one minute duration with simultaneous measurement of blood flow were obtained in this animal. A typical recording is shown in Figure 11. It can be seen that the heart rate during the dive is considerably higher than with forced dives. This same animal when submerged with restraint routinely experienced a bradycardia

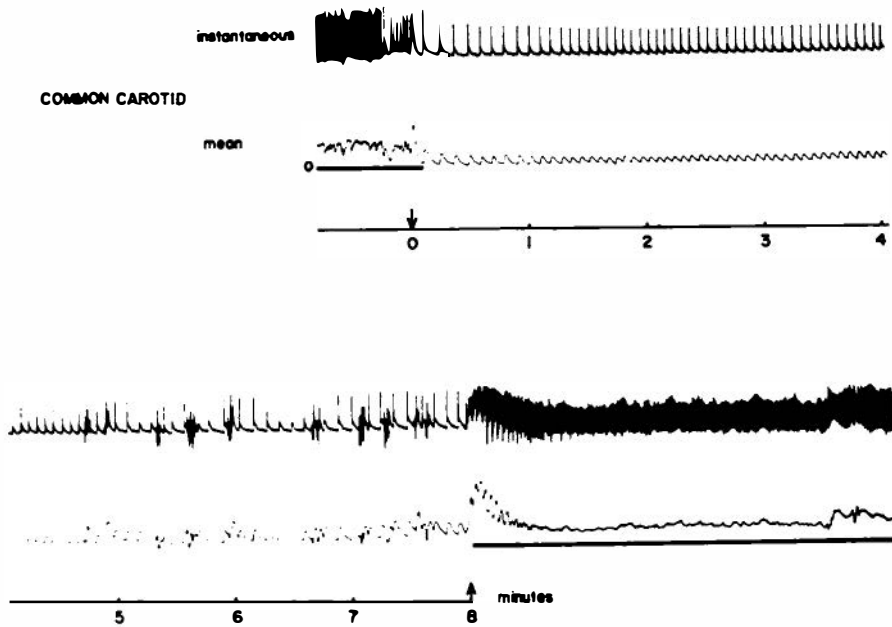


Figure 9. Blood Flow in the Common Carotid of a Seal Phoca Vitulina During a Dive of Eight Minutes⁽³⁾.

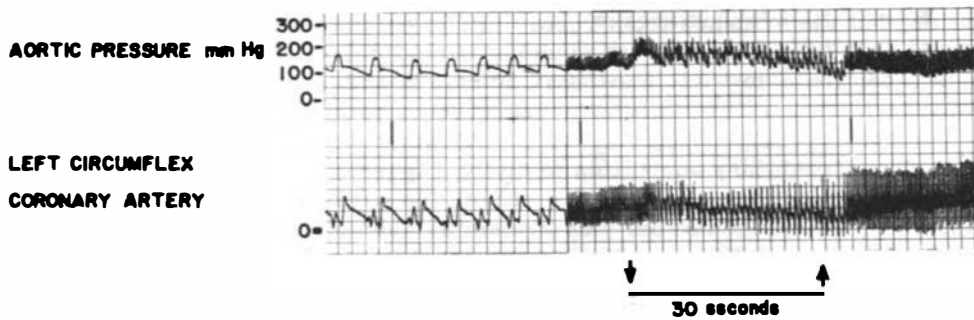


Figure 10. Aorta Pressure and Blood Flow in a Coronary Artery of a Dog During an Experimental Dive of 30 Seconds⁽³⁾.

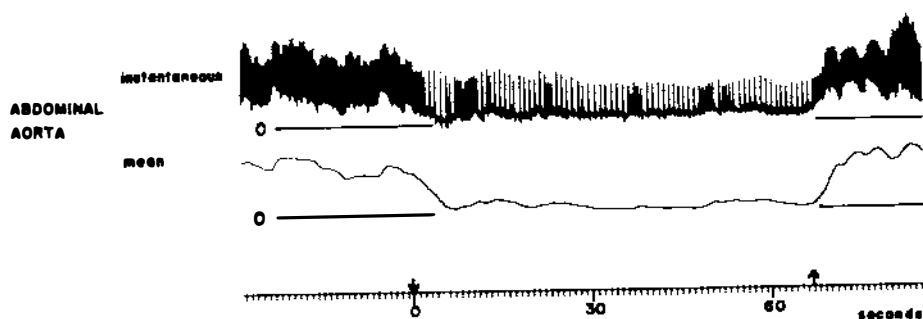


Figure 11. Instantaneous and Mean Blood Flow in the Abdominal Aorta of a Trained Seal *Phoca Vitulina* During a Commanded Dive (indicated by arrows)⁽³⁾.

of six to ten beats per minute. The blood flow was still markedly decreased by nearly complete elimination of the steady or "DC" component of blood flow.

The tachycardia following atropinization in one dog persisted during forced dives without change. The blood flow in the renal and mesenteric arteries and abdominal aorta were, however, drastically reduced during this procedure. The effects of non-diving asphyxia were observed in several animals by the simple expedient of closing the nostrils for brief periods. In neither seals nor dogs were the responses as extensive as those seen during underwater immersions.

The results substantiated Irving's hypothesized selective ischemia of diving. Although decreased blood flow occurred in all arterial circuits measured, vasoconstriction was more intense in organs which endure oxygen lack well. Experiments reported here do not furnish proof of a maintained cerebral circulation, but the evidence from recordings of common carotid flow suggest such a conclusion. The fragmentary evidence of maintained flow in coronary circulation of a dog indicates also that heart muscle is adequately perfused during the dive.

The circulatory adaptation to diving suggests a control of the circulation brought about by intense stimulation of both the parasympathetic and sympathetic divisions of the autonomic nervous system as seen by the simultaneous occurrence of extreme bradycardia and intense peripheral vasoconstriction. The use of atropine in the dog experiment distinguished between these two effects by abolishing the bradycardia while vasoconstriction persisted.

Human Studies: Although the clarification of the diving response has been accomplished through the lessons learned from comparative physiology, some of the circulatory events can also be traced in man. Bradycardia of diving was first observed in man by Irving in his 1940 study of an experienced swimmer⁽⁸⁾. Heart slowing of 50 per cent was commonly seen.

Scholander and coworkers studied the experienced trochus shell divers in the region of Thursday Island adjacent to the coast of Cape York in northern Australia. Electrocardiograms, blood pressure measurement and circulating blood lactate determinations were obtained⁽¹⁴⁾. Bradycardia of diving was routinely observed (Fig. 12). Blood pressure was measured by a sphygmomanometric device during quiet dives at the surface. It was generally well maintained.

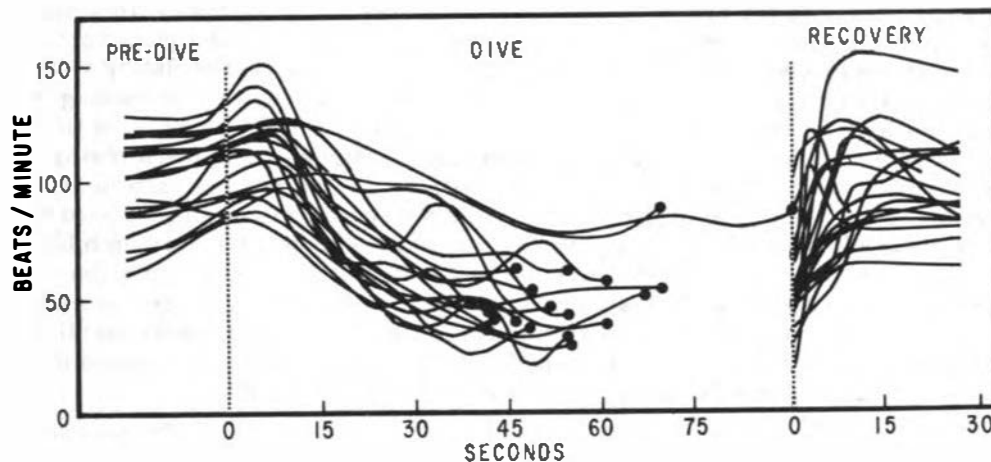


Figure 12. Bradycardia in Human Pearl Divers⁽⁸⁾.

The flushout of lactate produced by vigorous activity during the dive was postponed until after the dive as in animals. This latter, however, cannot be regarded as good evidence for a lack of communication between muscle and circulating blood as in the seals, because of the brief duration of the dives. Cardiac arrhythmias during the dives were commonly seen by these workers and were subsequently studied by Olsen, Fanestil and Scholander⁽⁹⁾. In another study reported by these latter workers, brachial arterial pressure was measured directly by catheterization during underwater dives preceded by hyperventilation⁽¹⁰⁾. A slight increase in pressure was noted, but a delayed runoff during diastole was always observed as the heart slowing progressed.

Limb Blood Flow: Studies were undertaken in our laboratory in a search for ischemic reactions in human limbs during dives. Nine young adult male subjects of varying diving experience were used in this investigation. It was soon discovered that the full bradycardia of diving could be produced as well by immersion of the face alone as by total body immersion. Blood flow measurements in the calf were obtained with the Whitney mercury-in-rubber strain gauge plethysmograph⁽¹⁵⁾. During experiments an arterial occlusion cuff at the ankle was inflated to a pressure of 200 mm Hg to exclude the foot circulation from the measurements. The venous occlusion cuff situated just above the knee was inflated to a pressure of 50 mm Hg to obtain a record of limb segment filling. Care was taken to assure that the limb was elevated slightly above heart level in order that filling after venous occlusion could proceed with the limb initially drained of

venous blood. In some experiments the subject was requested to perform mild standard exercise by pushing repeatedly against a spring-loaded foot pedal to a cadence established by a metronome. Face immersion "dives" customarily lasted for one minute. They were performed after moderate inspirations or expirations without hyperventilation⁽⁴⁾.

All subjects experienced bradycardia during the dives, sometimes with dramatic effects. In one experiment a subject held his face under water for 30 seconds beginning at the end of expiration. He began the procedure with a heart rate of approximately 90 which slowed to 13 beats per minute. Subjects varied widely in the response, usually slowing to about two-thirds of the resting value (Fig. 13). Bradycardia was generally slight or absent during breath holding in air. Blood flow measurements were obtained before and after the dive as well as at 15, 30 and 45 seconds during the immersion. Figure 14 shows a plethysmogram recorded continuously for one minute before, during and one minute after a face immersion. The rate of limb filling after venous occlusion is indicated by the steepness of the filling curves. In this subject it can be seen that limb blood flow fell nearly to zero during the dive. The artifacts produced by inflation and deflation of the venous occlusion cuff are clearly visible. Changes in heart rate can be seen superimposed on the record. Results of experiments on all subjects are plotted in Figure 15. The limb blood flow consistently decreased more during face immersion than during simple breath holding in air.

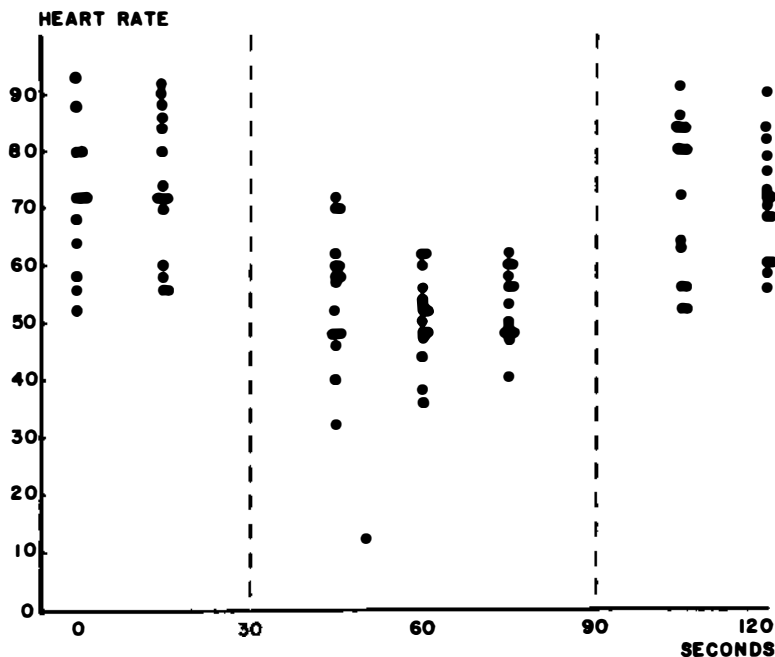


Figure 13. Heart Rate in Human Subjects During Experimental Dives. Face immersion occurred between dotted lines⁽⁴⁾.

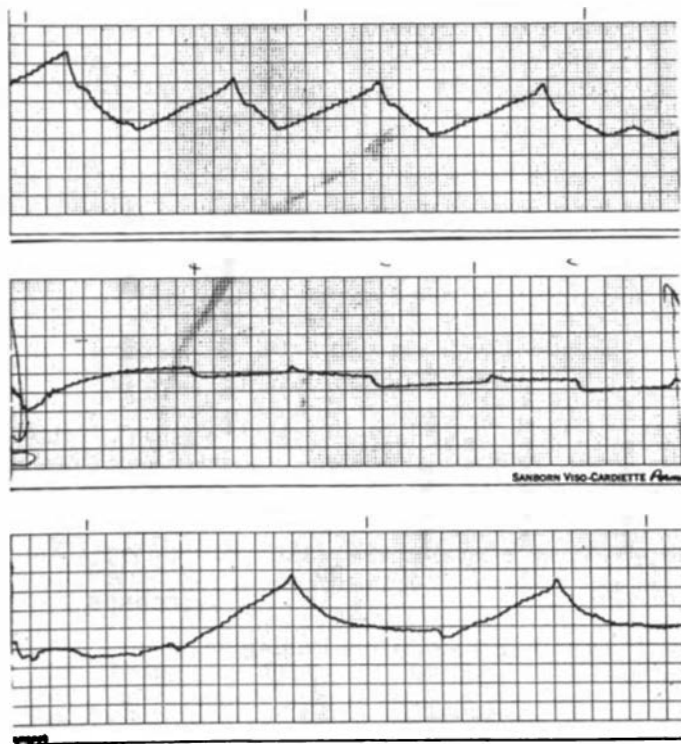


Figure 14. Continuous Plethysmographic Record Obtained One Minute Before (above), During (middle) and After (below) Experimental Face Immersion in a Human Subject. Venous occlusion (rising curve) occurred at intervals throughout. Falling curve indicates release of cuff pressure(4).

form of general reaction to asphyxia. It has been shown by many investigators during the last hundred years to be a widespread response common to vertebrates from fish taken out of water to diving man. The evidence suggests that the changes observed in the diving animal are the same physiological responses which operate in compensated shock and infant asphyxia of birth.

In three of the more responsive subjects the usual post-exercise hyperemia was overridden by face immersion. This is demonstrated in Figure 16. The blood flow before and after 15 seconds of standard foot pedal exercise without diving or breath holding showed the usual hyperemia and recovery. The subjects also performed the same exercise during one minute period of face immersion. In this case the hyperemia was delayed until after the subject had removed his face from the water. Blood flow measurements taken immediately after exercise, but still during the immersion did not show the customary post-exercise increase in blood flow. It has not been possible to demonstrate any consistent differences in circulatory responses to apneic face immersions in water between experienced and inexperienced divers.

The circulatory response to apneic diving appears to be a special

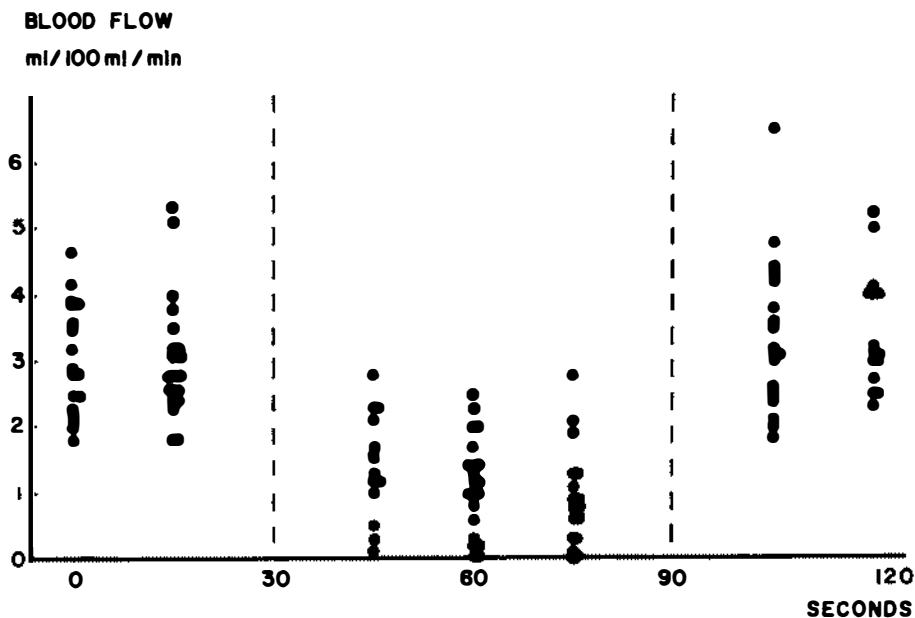


Figure 15. Limb Blood Flow in Human Subjects During Face Immersion(4).

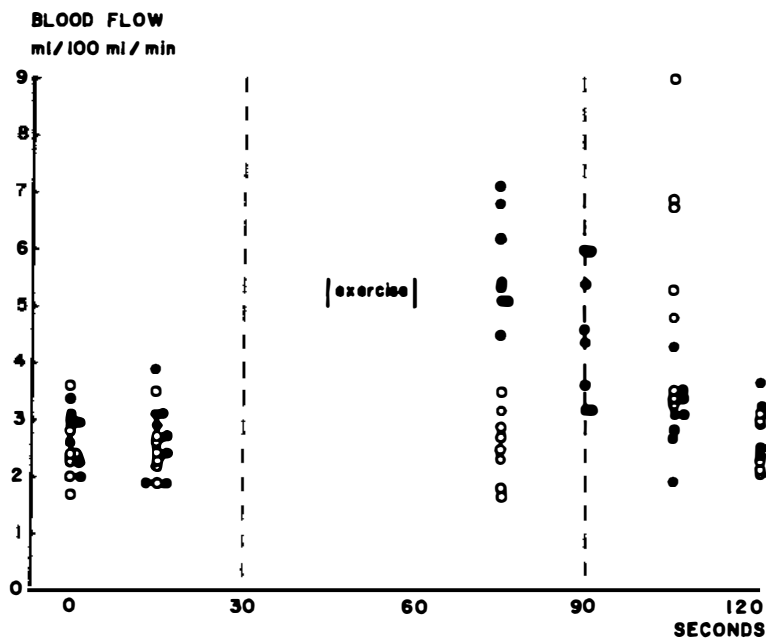


Figure 16. Limb Blood Flow in Selected Human Subjects Before and After Standard Foot Pedal Exercise Without Face Immersion (solid circles) and with Face Immersion (open circles) for One Minute (interval between vertical dashed lines)(4).

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EFFECTS OF SUBMERSION AND PULMONARY MECHANICS ON CARDIOVASCULAR FUNCTION IN MAN

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Diving bradycardia occurs in many species including man. Although the slowing of the heart rate is most dramatic and best studied in aquatic mammals, bradycardia is a well documented response in many groups of human divers.

In our experience, diving bradycardia occurs in man irrespective of his experience in the water⁽¹⁾. Profound slowing has been observed even in subjects who have an aversion to water. Age seems to be a factor in respect to the rapidity of onset of slowing after the beginning of the dive. The heart rate of younger subjects decreases much faster than that of adults. This observation may be related to the lability of the heart rate as expressed in the more marked normal sinus arrhythmia of younger people. We have demonstrated that diving bradycardia is unrelated to the depth of the dive. There was no difference in the heart rate response of the subject just under the surface of the water as compared to being down 15 or 23 meters.

The effect of exercise on the diving bradycardia still seems to be an unsettled question. It has been proposed that diving bradycardia is not influenced by exercise⁽⁸⁾. However, Elsner has demonstrated that during exercise and breath holding with the face submerged in water, the heart rate is faster than without exercising during the apnea⁽²⁾.

Finally, bradycardia does not occur during a simulated "dive" in a compression chamber. There was no slowing of the heart rate when the ambient pressure was increased to two atmospheres during the initial five to seven seconds of a breath hold.

These various observations relating to diving bradycardia in man have been useful indications that the cardiovascular functions of man are probably altered by water. Diving may be analyzed as a compound stress. Basically it is breath holding in a buoyant medium, water. The subject is most often in water before the dive which means that he experiences negative pressure breathing⁽⁴⁾. A diver usually makes a maximal or near maximal inspiration, closes the mouth and nose, and relaxes the inspiratory muscles. Under these conditions, the intrapleural pressure becomes positive⁽⁶⁾. Additional airway pressure may be necessary to maintain pressure equilibrium across the tympanic membrane particularly during a head-first descent. Essentially, the diver is making a Valsalva maneuver.

Our experimental approach has been to dissect these various physiological stresses. We have tried to define the heart rate response as a function of the airway pressure voluntarily maintained during a breath hold. Figure 1 illustrates the

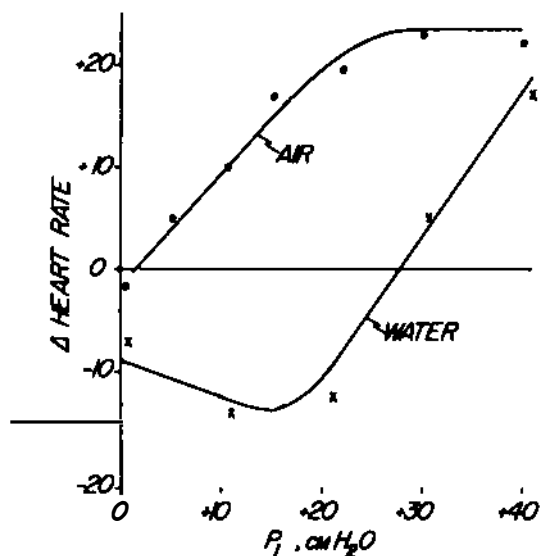


Figure 1. Heart Rate Responses to a 30-Second Breath Hold as a Function of Intrapleural Pressure in One Subject. Each point represents the average response to five breath holds.

and +20 cm H₂O, there was a bradycardia, but at greater pressures there was an increase in the heart rate.

It should be noted that the maximum slowing occurred when the intrapleural pressure was between +10 and +20 cm H₂O. This is approximately the relaxation pressure at 80 per cent lung volume⁽⁶⁾. In other words, these conditions would approximate the expected intrapleural pressure change for most divers if they inspired to 80 per cent lung volume and relaxed the respiratory muscles against a closed external airway.

It is also important to know that the heart rate response to breath holding is independent of the lung volume. When the heart rate response is plotted as a function of intrapleural pressure change, one cannot detect different responses of the cardiovascular system whether the lung volume is 40 per cent or 90 per cent.

Quantification of the heart rate response to the Valsalva maneuver has been a useful tool for studying other influences. It is not practical to use an esophageal balloon in all subjects, but it is possible to execute the breath hold after inspiring a known volume of air. Eighty per cent lung volume has been chosen because this has been found to be the amount of air Korean diving women inspired preparatory to descent⁽⁵⁾. It is also a volume which our subjects could inspire quickly and without undue effort.

Figure 2 shows the response of the heart rate to a 30-second breath hold at 80 per cent lung volume as a function of mouth pressure voluntarily maintained

heart rate responses to breath holding at various pressures. The subject inspired to a pre-determined volume (80 per cent of vital capacity), and developed the desired pressure while watching a water manometer. The esophageal pressure measurements were considered to represent intrapleural pressure. In fact, esophageal pressure was always less than mouth pressure by the predicted amount⁽⁶⁾. The heart rate between 20 and 30 seconds of the breath hold was compared to the heart rate during the 30 seconds before the apnea.

When the subject was seated in air, the increased heart rate response to breath holding was a direct function of the intrapleural pressure to pressures of about +20 cm H₂O. By contrast, there was a slowing of the heart rate when the subject did the same breath-holding experiment while submerged in water. When the intrapleural pressure was between 0

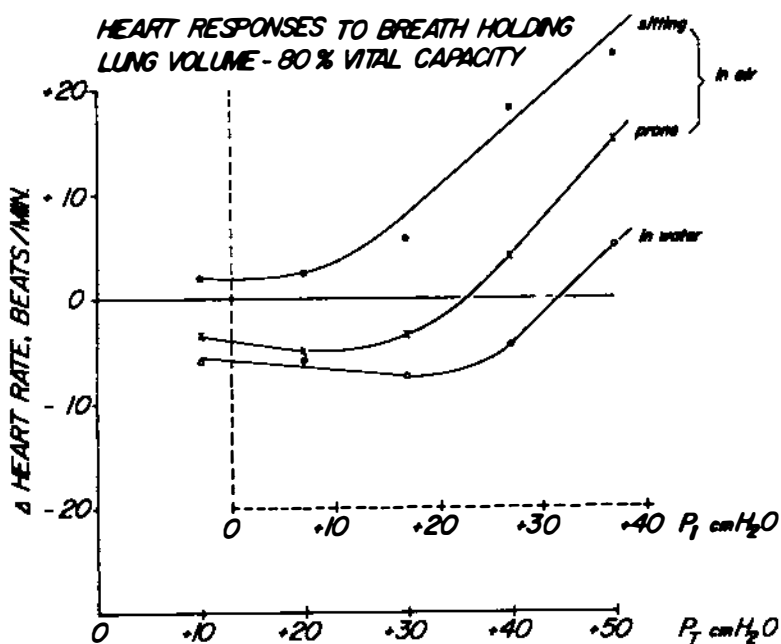


Figure 2. Average Heart Rate Responses to Breath Holds (30 seconds) as a Function of Total Airway Pressure in Ten Subjects. In water the subjects were standing with the level of water at the chin. The coordinates indicated by the broken line indicate the predicted change in intrapleural pressure at this lung volume (80 per cent). Water temp. 30-32°C.

during the period of apnea. Three breath holds were executed at each pressure, and the points represent the average responses in ten subjects. When the subjects were seated in air, the increase of the heart rate in response to the breath hold was greater at the higher pressures than at the lower. Lying prone in air decreased the response. During breath holding while standing in water, the heart rate response was less than when the subject was either sitting or prone in air.

These results may be explained by the effect of position on venous return when the subject is in air. At the beginning of a breath hold at increased intrapleural pressure the venous return from the periphery to the thorax is momentarily impeded until the peripheral venous pressure increases and exceeds the intrapleural pressure(3). In the prone position, the response of the venous system is probably more prompt than when the subject is seated. In other studies we have found that the heart rate response to breath holding can be a tachycardia or a bradycardia depending on the maneuvers employed to alter the response of the venous pressure(1).

When the subjects were standing in water up to their necks, the heart rate response was different from either the sitting or prone position in air. We can expect that the buoyant effect of water would partially or completely eliminate the effects of position in this medium. It seems reasonable to compare the prone position in air to the standing position in water. It is evident that the heart rate response to breath holding at various pressures in water is different than when the subject is in air.

Further definition of the differences of the cardiovascular function in air and water was found in the comparison of the systolic pressure response to breath holding. The results of such studies are shown in Figure 3. When the intrapleural pressure change was $+31$ cm H_2O , the decrease in systolic pressure was less when the subject was in water than when he was seated in air. Even more dramatic was the lack of an "overshoot" of the systolic pressure after the breath hold when

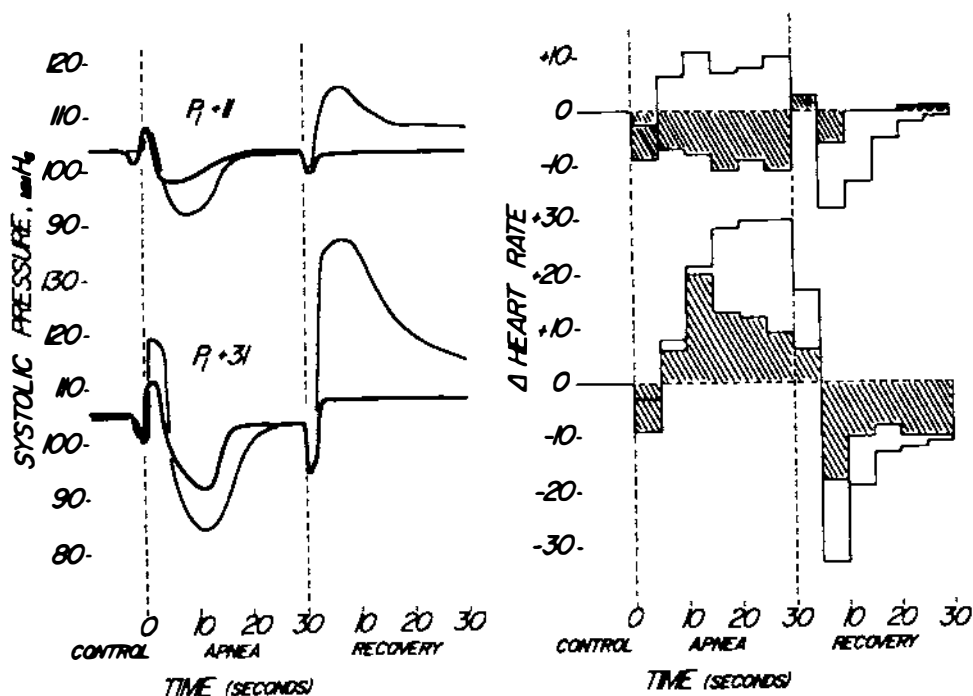


Figure 3. Systolic Blood Pressure and Heart Rate Responses to Breath Holding at Increased Intrapleural Pressures. The bolder line in graphs on the left and the hatched areas in the graphs on the right indicate the responses when the subject is in water. The lighter lines which show greater deviations from the control pressures indicate the pressure responses when the subject was seated in air. The unhatched area in the right graph shows the heart rate response when the subject was seated in air. The upper graphs illustrate the responses to an intrapleural pressure change of $+11$ cm H_2O , and the lower to a pressure change of $+31$ cm H_2O as measured by an esophageal balloon. Lung volume was 80 per cent of vital capacity in all experiments.

the subject was in water. The effect of water in attenuating the arterial pressure responses was also apparent when the breath hold was executed, maintaining only +11 cm H₂O intrapleural pressure. Under these latter conditions there is a slight tachycardia when the subject is in air, but a bradycardia when the subject is submerged.

These studies have led us to suspect that the venous pressure responses in the two media might be very different. Figure 4 shows tracings of the venous pressure responses to breath holding with the subject in air and in water. During each breath hold, the mouth pressure, esophageal pressure, and heart rate were also recorded. Lung volume was 80 per cent during each breath hold. The venous catheter was placed in the antecubital vein and advanced until a pressure tracing of venous pressure of the thorax was obtained. The catheter was then withdrawn until it lay in the vein about 5 cm from the point of entrance of the vein into the thorax. The pressure transducer was placed at the level of the second intercostal space when the subject was seated in air and when he was standing in water.

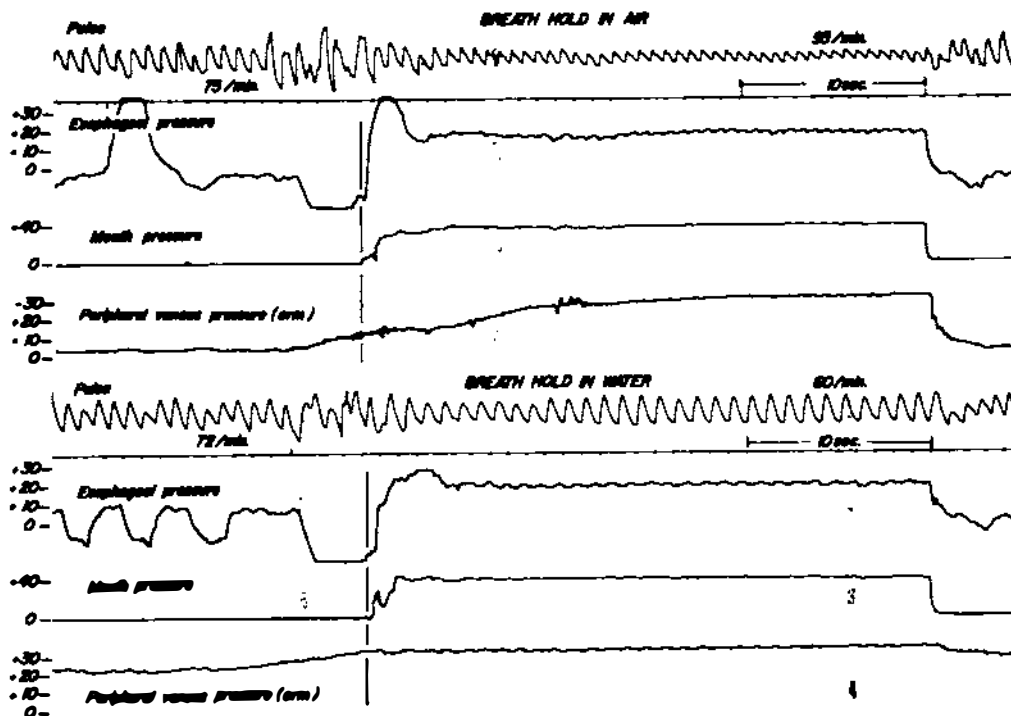


Figure 4. Photographs of Records Made During 30-Second Breath Holds with the Subject Seated in Air (upper tracing) and with the Subject Standing in Water (lower tracing). The pulse was detected with the photoelectric pulse pressure pick-up. Esophageal pressure was recorded as pressure change in an esophageal balloon and was referred to atmospheric pressure. Large deflection in the esophageal record preceding the breath hold in air was an artifact produced by a propulsive wave descending the esophagus. Peripheral venous pressure was measured in an arm vein approximately 5 cm before the vein entered the thorax.

When the subject was seated in air, the control venous pressure was about 5 cm H₂O and increased slightly during the inspiration preceding the breath hold. After the development of the mouth pressure, there was a further increase of the venous pressure until it equalled 31 cm H₂O which is about 10 cm H₂O more than the intrapleural pressure. This increase in venous pressure occurred during the first 15 seconds of the 30-second breath hold.

By contrast the venous pressure of the subject standing in water appeared to be about 23 cm H₂O and increased to 32 cm H₂O during the inspiration preceding the apnea. At the beginning of the breath hold when the intrapleural pressure was increased to 20 cm, there was no further increase in the venous pressure.

One might question the validity of measuring the venous pressure when the subject was in water and the pressure transducer was placed at the same reference point as when the subject was seated in air. However, the final venous pressure measured during the breath hold in either air or water was 10 cm H₂O greater than the intrapleural pressure. When the intrapleural pressure is increased, there must be an increase in the peripheral venous pressure in order to re-establish venous return to the right heart. Our measurements indicated that the same final pressure difference existed between the peripheral arm vein and the intrapleural space whether the subject was seated in air or standing in water.

The major difference noted between these two environments was that when the subject was standing in water, the venous pressure before the breath hold was increased. The further increase during the inspiration preceding the breath hold was enough to elevate the venous pressure above the intrapleural pressure which was developed at the end of inspiration. Therefore, during the entire 30-second period of apnea, venous return to the right heart was maintained. When the subject was seated in air, the peripheral venous pressure was less than the intrapleural pressure until about half-way through the period of apnea. Thus, one of the major effects of submersion on the cardiovascular response to the Valsalva maneuver may be on the response of the venous system to the increased pressure.

The lack of "overshoot" of the arterial pressure after the Valsalva maneuver when the subject was submerged may also indicate a difference attributable to the venous system. When the subject is in air, the peripheral venous pressure increases from 3-5 cm H₂O to some pressure which exceeds the intrapleural pressure. At the end of the breath hold the intrapleural pressure again returns to negative values. During the apnea and period of increased venous pressure, the veins distend with a volume of blood which must be released when the intrapleural is decreased at the end of the breath hold. Cardiac filling and output may suddenly be increased. Arterial pressure also increases transiently despite a decrease in vasoconstriction at the end of the apnea⁽⁷⁾. At the end of the breath hold when the subject is in water, there may be no release of the large quantity of blood and therefore no "overshoot" of the arterial pressure because the relative decrease in venous pressure is less than in air.

This hypothesis concerning the effect of submersion on responses to the stresses of the Valsalva maneuver implicates the venous circulation. In addition, it suggests that the negative pressure breathing experienced by the submerged

subject before and after the breath hold plays a major role in determining the circulatory responses to the Valsalva maneuver. Therefore, we have methods with which we can test the basic ideas.

These experiments and ideas have lead to the conclusion that diving bradycardia is the observed strain resulting from a compound stress. Slowing of the heart rate may be the expected response to apnea under these conditions in view of the effects of submersion on the cardiovascular system of man. We prefer to approach the problem from the vantage point of many known physiological reflexes rather than considering it to be part of a single "diving reflex."

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HEAT EXCHANGE AND BASAL METABOLISM OF AMA¹

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While the Ama are working in the sea, they are exposed to a degree of cold stress that varies with the season. For instance, the water temperature of the diving location in Pusan, Korea varies from 25°C in the summer to as low as 10°C in the mid-winter, while the air temperature varies from 28°C to 1°C (Fig. 1). Despite this great seasonal variation in the environmental temperature, they engage in daily diving work throughout the year, although the duration of a work period varies with the water temperature. In fact, the duration of a shift is linearly proportional to the sea water temperature⁽⁸⁾, indicating that the extent of cold stress constitutes one of the most important limiting factors in determining the work capacity of the Ama. In view of these facts, we have studied the heat exchange of the Ama during various seasons while they are working in the water⁽⁹⁾ and, in addition, studied the seasonal variations in the basal metabolic rate as a part of investigations on the pattern of cold acclimatization acquired by the Ama during the course of engaging in the diving profession for a long time⁽⁸⁾.

CHANGES IN BODY TEMPERATURE

Originally, the oral temperature was measured before and after the dive⁽⁸⁾. As summarized in Table I, the oral temperature dropped during all seasons to a variable extent. The greatest reduction was seen in winter when it routinely fell to 33°C or less. Although such a reduction in the oral temperature is quite impressive, a question arises as to what extent this reflects a decrease in deep body temperature as measured, for example, from deep in the rectum. Consequently, the rectal temperature was determined in the Ama while diving during the summer and winter⁽⁹⁾.

The time course of the rectal temperature, mean skin temperature, and mean body temperature while the Ama are working in water is shown in Figure 2. Although there were certain individual variations, the rectal temperature remained unchanged during the first five to ten minutes in water, after which it fell. By the end of a 45 minute work period in the summer, the average rectal temperature was lowered to 35.3°C. Although in the winter the duration of a shift was usually 30

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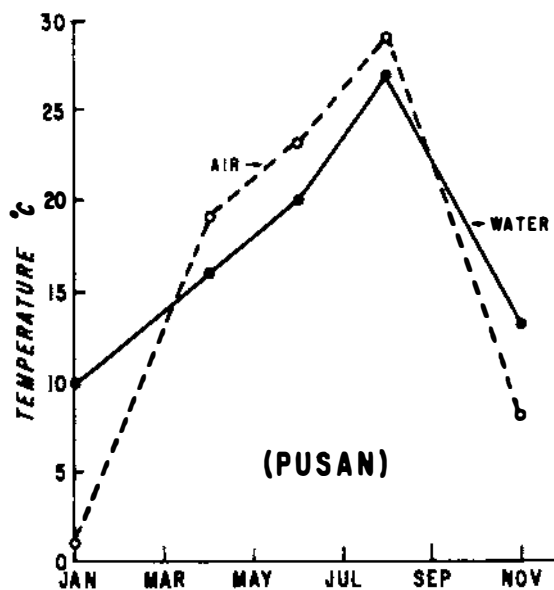


Figure 1. Seasonal Variation in Air and Sea Water Temperatures in Pusan Area⁽⁵⁾.

a slight further increase during the rest of the work period (Table II). However, the magnitude of increase in the oxygen consumption was much greater in the winter than in the summer. On the average, the oxygen consumption increased by two-fold in the summer and three and one-half-fold in the winter due to combined effects of exercise and shivering, which was marked from the beginning of a work period in winter and mild to marked toward the end of a shift in summer.

The observed increase in oxygen consumption, coupled with the reduction in both rectal and mean body temperatures, clearly illustrates the degree of cold water stress to which the Ama are exposed daily. Lampietro *et al.*⁽⁶⁾ exposed young men nude for two hours to cold wet environments and studied the heat exchange. A comparison of these data with ours indicates that the increase of oxygen consumption of the Ama in summer is roughly equal to that of nude subjects exposed to an air environment of 50°F, 30-90 per cent relative humidity, and a wind speed of 10 miles per hour. However, the reduction in mean body temperature is greater in the Ama compared to the subjects employed by Lampietro *et al.* In other words, the daily cold stress of the Ama even in summer is more severe than that of Lampietro's subjects. Therefore, it is not difficult to imagine how severe the cold stress must be in winter, leading us to conclude that the Ama is subject to a more severe voluntary cold stress than any other group of human beings yet described.

HEAT EXCHANGE

In three Ama, the rectal temperature and oxygen consumption were measured simultaneously during the work shift in summer as well as in winter allowing

minutes or less, the average rectal temperature was reduced to 34.8°C. These findings indicate that the reduction in deep body temperature while diving is considerably less than that of oral temperature and is about the same regardless of season. However, the calculated mean body temperature at the end of a work shift was considerably higher in the summer than in the winter, and this fact supports a view that tolerance to cold is increased in winter. In the opinion of the author, this increased tolerance to cold in the winter may be taken as one aspect of the cold acclimatization acquired by the Ama during the cold seasons.

OXYGEN CONSUMPTION

When the Ama entered water, the oxygen consumption increased almost immediately in all cases, followed by

TABLE I

Duration of a Work and a Rest Period and the Changes in Oral Temperature of the Ama (mean and range)(8)

Month (water temp °C)	Duration of work shift (min)	Resting period between work shifts (min)	Oral temp (°C) at the beginning and end of a work shift	
January (10°C)	16 (15-20)	1 shift/day - - -	37.2 (36.8-37.5)	33.3 (32.4-33.8)
April (16°C)	28 (25-30)	120 (115-125)	37.2 (37.0-37.4)	34.2 (33.7-34.9)
June (20°C)	63 (42-90)	61 (50-70)	37.0 (36.6-37.1)	35.1 (34.6-35.8)
August (27°C)	70 (42-150)	100 (70-130)	37.0 (36.6-37.0)	34.9 (34.3-35.7)
November (13°C)	16 (15-20)	1 shift/day - - -	37.3 (37.1-37.4)	34.0 (33.9-34.1)

their heat balance to be computed quantitatively⁽⁹⁾. The results are illustrated in Figure 3. The rate of heat production was of the order of 2 Kcal/min during the rest period on the boat in both the summer and winter. As the changes in oxygen consumption in Table II indicate, heat production during the diving shift increased two-fold in the summer and three to three and one-half-fold in the winter. Despite this greater increase in winter heat production, the mean body temperature was lowered more in the winter than in the summer, indicating a greater rate of heat loss.

The extra heat production above resting values during the diving shift was 94 Kcal in summer, as compared to 109 Kcal in winter. The reduction in body heat content during the diving shift was 293 and 466 Kcal in summer and winter, respectively. Therefore, by the time the Ama terminated the diving shift, they had lost an equivalent of 387 Kcal in summer and 575 Kcal in the winter. Since the duration of a work shift is shorter in winter, it

may be concluded that the rate of heat loss is approximately twice as great when diving in the winter as in the summer. However, the Ama take three shifts a day in the summer and only one or, rarely, two shifts in the winter. Therefore, the total extra heat loss for diving work is of the order of 1000 Kcal/day at all seasons.

The observations on temperature and heat loss suggest that the critical factor for termination of a diving work period is the degree of reduction in rectal temperature rather than the amount of total heat loss. When the rectal temperature is lowered to a level of 35°C, the Ama is no longer able to withstand cold on a voluntary basis and returns to the shore to rewarm around a fire until body temperature returns to the pre-dive level⁽⁸⁾.

As indicated earlier, the total extra heat loss for diving work amounts to approximately 1000 Kcal a day at all seasons. This represents the minimal amount of energy which ought to be supplied to the Ama in order to compensate for heat lost to the water. Actual dietary surveys indicate that the Ama are satisfying this need rather well. Regardless of the season, they consume approximately 3000 Kcal/day whereas the caloric intake of non-diving women of comparable age is of the order of 2000 Kcal/day.

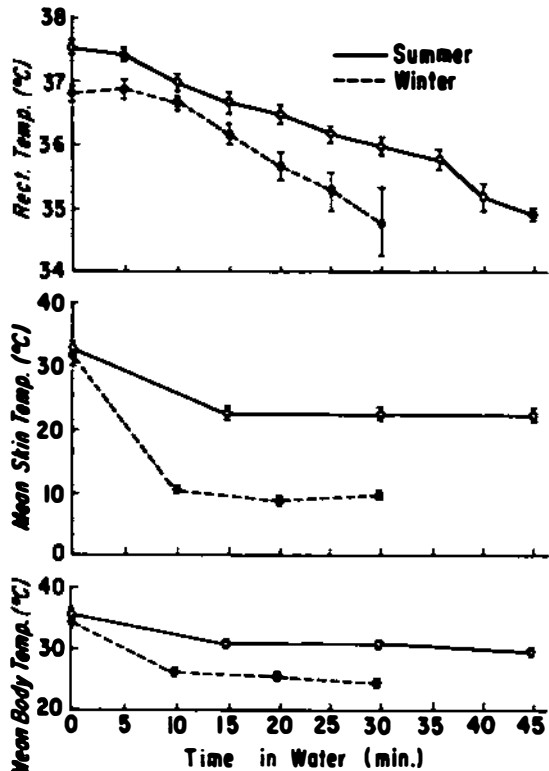


Figure 2. Changes in Rectal, Mean Skin, and Mean Body Temperature During a Diving Work Shift (Mean \pm SE)⁽⁹⁾.

TABLE II
Oxygen Consumption During the Period
of Diving Work (cc/min, STPD)(9)

Subject	Date	Before Dive	Minutes in Water					
			5	10	15	20	25	40
Summer (Water temp 22-26°C; Air temp 30°C)								
A	Aug., 1961	379	--	--	841	--	--	1144
A	July, 1962	386	--	819	--	--	1045	1062
A	" "	527	--	908	--	--	840	1150
B	" "	479	--	634	--	--	776	830
B	" "	507	--	832	--	--	996	1105
C	" "	469	--	--	1039	--	1120	1122
C	" "	486	--	1045	--	--	1073	1075
D	Aug., 1961	458	--	--	764	--	--	667
E	" "	396	--	--	562	--	--	482
Mean (9 observations)		454	--	847	801	--	975	960
Winter (Water temp 10-13°C; Air temp 5-9°C)								
A	Jan., 1962	375	--	936	--	1186	--	
A	Jan., 1963	274	1110	--	1351	--	--	
A	" "	423	1325	--	1364	--	1562	
A	" "	468	1171	--	1455	--	1679	
B	Jan., 1962	377	--	945	--	1290	--	
B	" 1963	301	1016	--	1213	--	--	
B	" "	438	902	--	1086	--	1137	
B	" "	537	1109	--	1098	--	1328	
C	" 1962	246	--	--	--	932	--	
C	" 1963	423	699	--	1177	--	--	
C	" "	433	1170	--	1217	--	1272	
C	" "	362	1312	--	1186	--	--	
Mean (12 observations)		388	1090	940	1238	1136	1395	

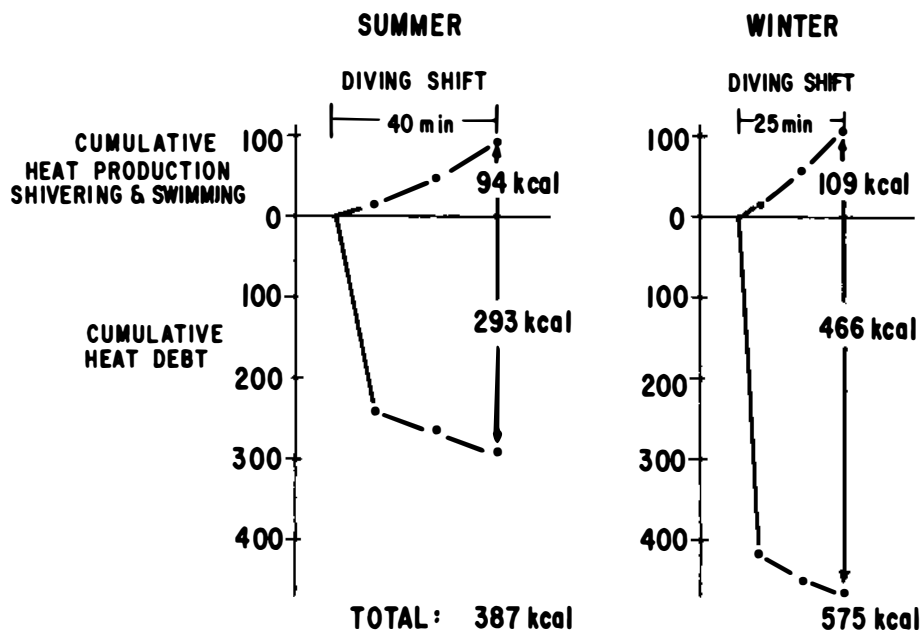


Figure 3. Increment in Caloric Expenditure Due to Diving Work in Summer and Winter. Cumulative calories generated by shivering and swimming, estimated from O_2 consumption, are indicated as upward deflections. Cumulative heat debt during a diving shift, estimated from weighted water temperature and rectal temperatures, are indicated as downward deflections.

BASAL METABOLIC RATE (BMR)

In view of the extreme cold to which the Ama are exposed daily the question has been raised whether cold adaptation occurs among diving women. From what is known about cold adaptation in animals, it appeared logical to study both the changes in basal heat production and maximal tissue insulation that might occur during the course of a year. The changes in BMR alone will be dealt with here since the changes in tissue insulation are discussed by Rennie elsewhere in this publication.

Twenty divers and twenty non-diving women were selected at random from a community in the Pusan area for measurements of basal oxygen consumption in April 1961, August 1961, November 1961 and January 1961. These subjects had previously been used for respiration studies⁽¹⁵⁾ and thus were not apprehensive about the metabolism equipment or the investigators. Before the determination of BMR, each subject was instructed to eat a light supper and come to the laboratory the next morning between 6:30 and 7:30 am, without breakfast. All subjects lived within a five minute walk of the laboratory. After 30 minutes of bed rest, oxygen consumption was measured with a nine-liter Collins spirometer and converted to kilocalories per hour per square meter by a standard nomogram⁽³⁾. The BMR was

expressed also as per cent deviation from the DuBois standard⁽³⁾. Subsequently, most of these subjects were restudied in August 1963 and January 1964.

The mean BMR of Ama and non-diving women at consecutive periods over a three year period are summarized in Figure 4 and Table III. Although there were considerable individual variations, the BMR of the non-divers was constant

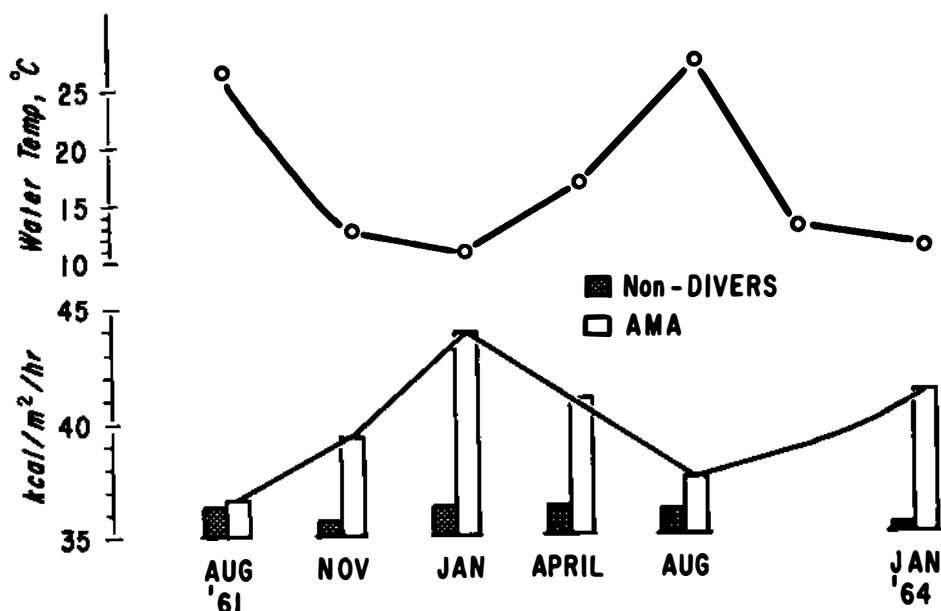


Figure 4. Top: Mean Sea Water Temperature in the Diving Area of Pusan at Various Months of the Year.

Bottom: Mean Value of BMR of Ama (open bars) and Non-Diving Women (solid bars) During Various Seasons over a Three-Year Period.

throughout the year and did not differ significantly from the DuBois standard. However, BMR of the Ama increased progressively from values that were the same as non-divers in summer to a maximum in the winter of 1961 that was 25 per cent greater than that of non-divers ($p < 0.005$)³ and in the winter of 1964 to a value 20 per cent greater than non-divers ($p < 0.005$). This maximal BMR occurred at the season when the water was the coldest, i.e., 10°C. By April 1961, when sea water temperature was 16°C, the BMR of the Ama had declined somewhat but was still 17 per cent above that of non-divers ($p < 0.05$). By August 1963, there was no significant difference between the two groups.

³Two Ama having winter BMR's 120 per cent above the DuBois standard have been omitted from this presentation, although there was no detectable disease in either.

TABLE III
Basal Metabolism of the Ama in Summer and Winter (Mean \pm SE)
(Unpublished data of Hong et al)

Season		Basal Metabolic Rate	
		Kcal/m ² /hr	%deviation from DuBois standard
Summer (August 1963)	Ama	37.5 \pm 1.15	+ 7.9 \pm 1.6
	Control	36.0 \pm 1.33	+ 2.0 \pm 2.4
		p > 0.1	p > 0.05
Winter (January 1964)	Ama	41.2 \pm 1.17	+19.9 \pm 3.4
	Control	35.4 \pm 1.13	+ 0.8 \pm 3.2
		p < 0.005	p < 0.005

Although such a seasonal variation in BMR of the Ama is quite convincing, it is by no means simple to find the reason(s). A similar seasonal variation in BMR has been repeatedly reported in the Eskimo by many investigators^(1, 2, 11, 12, 14), and it was taken as a manifestation of cold acclimatization acquired by the Eskimo^(1, 2). However, Rodahl⁽¹⁴⁾ attributed the elevated BMR of the Eskimo to their high protein intake, not to cold exposure. In our investigation, all subjects were selected at random from the same socio-economic level in Pusan; thus race, sex, and subtle effects of clothing and housing were the same throughout both groups. Moreover, their general health, as determined by a thorough physical examination, was excellent. Erythrocyte concentration, hemoglobin concentration and hematocrit ratio were the same in both groups, though somewhat less than normal Western standards. Therefore, this rules out anemia or polycythemia as a cause for the increased BMR. The daily excretion of ordinary nitrogen was measured in November when the BMR of the Ama was significantly greater than that of the non-divers. Twenty-four-hour urine samples were collected from all subjects and analyzed for nitrogen⁽⁸⁾. The Ama and non-divers excreted an average of 7.1 and 6.3 g nitrogen per day, respectively, a difference that is not significant (p > 0.10). The amount of nitrogen excreted is well below the average of 24 g per day excreted by Eskimos and also below the daily nitrogen excretion according to Western standards. However, it is normal for the Korean⁽¹⁰⁾ and tends to rule out any specific dynamic action effect of protein in the Ama group. In order to further study this matter, the actual protein intake was determined in both the summer and winter⁽⁹⁾. The protein intake was approximately 90 g per

day in both seasons, substantiating the earlier conclusion that the observed increase in BMR of the Ama in the winter is not related to higher protein intake.

Having ruled out various factors which can possibly elevate the BMR of the Ama in winter, one is left with the only difference between the Ama and non-divers; the cold water stress. As discussed before in this communication, the Ama are daily exposed to severe cold while non-divers are not. Moreover, the increased BMR of the Ama was at its peak in mid-winter when water temperatures are coldest and when the degree of daily hypothermia which the women experience is greatest. These facts suggest that this unusual degree of cold stress stimulated the resting metabolism of the Ama. In other words, the Ama seem to have developed a metabolic acclimatization in response to a continuous cold water stress. Although this metabolic response to cold has been sought for many years in studies of chamber acclimatization, field acclimatization, and among populations indigenous to cold climates, the present data seems to provide unequivocal evidence that repeated cold exposure can stimulate metabolism of human beings. Interestingly enough, a seasonal variation in the BMR, similar to that observed in the Ama of Korea, has been reported in non-divers by several Japanese investigators(16, 17). Although the extent of increase in BMR was much less than that observed in the Korean Ama, the BMR of ordinary Japanese increased regularly in the winter and decreased again during the warm seasons. However, Tatai et al(16) indicated that this seasonal variation in BMR was evident only in cold-resistant subjects and not demonstrable in cold-susceptible subjects. It should be noted in this connection that we repeatedly failed to observe any seasonal variation in BMR of the ordinary, non-diving population.

Although the observed increase in BMR of the Ama in winter has physiological significance, the practical value must be minor as a defense against body cooling in winter. Even if the extra heat is generated internally and thus is more likely to maintain central body temperature than that due to muscular activity the increment is only 10Kcal/hr/m² at most, which is a small fraction of what could be generated by shivering and the voluntary muscular movements of swimming. Nevertheless, for the more usual case of humans exposed to cold air, an increase in metabolism of this magnitude could appreciably reduce critical air temperature, particularly if it is accompanied by increased tissue insulation which is shown to be the case in winter(5).

On the basis of these considerations, it seems likely that increased resting metabolism is a latent human adaptation to severe body cooling, rarely if ever aroused in modern man by cold air exposure, but manifest in the diving women during the winter because of the unusual degree of daily hypothermia that they endure. We may speculate whether this increase in resting metabolism is an extension of the shift from shivering to non-shivering thermogenesis(4, 7) for chamber cold-acclimated men and also whether the complex endocrine factors that operate in cold-acclimatized small animals may not have their counterpart in the Ama. Further investigations concerning these matters are now under way in our laboratories.

SUMMARY

Heat exchanges and the BMR of the Korean women divers have been studied during various seasons of the year and the results may be summarized as follows:

1. The oral temperature was lowered by 2-4°C during the course of a diving shift. The magnitude of reduction was greatest in the winter and was least in the summer. On the other hand, the rectal temperature was lowered by approximately 2°C in both the summer and winter. However, the mean body temperature was higher by as much as 5°C in the summer than in the winter. This difference was taken as evidence for increased tolerance to cold in the winter as a part of cold acclimatization.
2. The oxygen consumption increased rather rapidly as the Ama entered water and remained at the elevated level throughout the work period. It increased by two-fold in the summer and by three- to three and one-half-fold in the winter.
3. On the basis of changes in the oxygen consumption and the mean body temperature during the course of a work period, the total extra heat loss was computed. It amounted to 387 Kcal in the summer and 575 Kcal in the winter. Considering the seasonal difference in the number of shifts per day, it was further estimated that the total extra heat loss was approximately 1000 Kcal/day in all seasons.
4. Dietary survey revealed that the daily caloric intake was approximately 1000 Kcal greater in the Ama as compared to non-divers of comparable age.
5. The BMR of the Ama underwent a characteristic seasonal elevation during the winter but was normal in the summer. In general, the BMR were inversely related to the sea water temperature. However, the BMR of non-divers was normal throughout the year. This elevation of BMR of the Ama during cold seasons is interpreted as evidence for the long-sought metabolic acclimatization of human beings to cold.

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THERMAL INSULATION OF KOREAN DIVING WOMEN AND NON-DIVERS IN WATER

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The ability of Korean diving women to perform diving work the year around without benefit of protective clothing has prompted several studies of their body temperature, metabolic heat production and heat loss under controlled conditions of water immersion^(11, 14, 17). This research has been carried out in Korea under the guidance of Dr. S. K. Hong of Yonsei Medical College following preliminary experiments at the State University of New York at Buffalo. The emphasis in these studies to date has been placed upon the comparative ability of diving women and others to tolerate long periods of immersion without shivering and upon the maximal over-all body insulation that diving women and others can develop during such exposure to cold. Differences in maximal body insulation due to sex, age and season of the year have also been investigated.

Methods

To provide a reproducible, uniform degree of cold exposure in all experiments, subjects clothed in cotton swim suits were immersed except for their faces in a well-stirred, constant temperature water bath regulated to within 0.01°C of the desired temperature. Bath temperature was kept slightly warmer than "critical water temperature," abbreviated CWT defined as the lowest water temperature subjects tolerated for three hours without shivering⁽¹⁷⁾. It is well known from the work of Burton and Bazett⁽⁵⁾ that over-all body insulation is maximal under these conditions. In cold water, as shivering supervenes, skin heat loss rises, rectal temperature falls and body insulation decreases. By thus adjusting water temperature to the CWT we achieved a cold stress for each individual sufficient to increase his or her body insulation to a maximum.

Tissue insulation, I , was computed from measurements of rectal temperature, water bath temperature and oxygen consumption during the nearly steady-state conditions of the third hour of immersion: $I = (\text{rectal temp.} - \text{bath temp.}) / \text{rate of skin heat loss}$. Skin heat loss was assumed to equal metabolic rate minus respiratory heat loss plus loss of stored body heat during the third hour⁽¹⁷⁾.

Subcutaneous fat was determined by measuring skinfold thickness at ten sites⁽¹⁾ with a Best caliper⁽⁴⁾; 40 mm was subtracted from the total to allow for skin thickness and the remainder divided by 20 to determine mean fat thickness.

General Conditions of Experiments

U.S. subjects were studied in Buffalo to establish certain facts about the environmental conditions of the experiments and to test equipment prior to the more extensive studies in Korea. From these early studies we found that CWT lay within the range 29°C to 33°C for most subjects, depending largely upon the thickness of their subcutaneous fat⁽¹⁷⁾. The results are summarized in Figure 1.

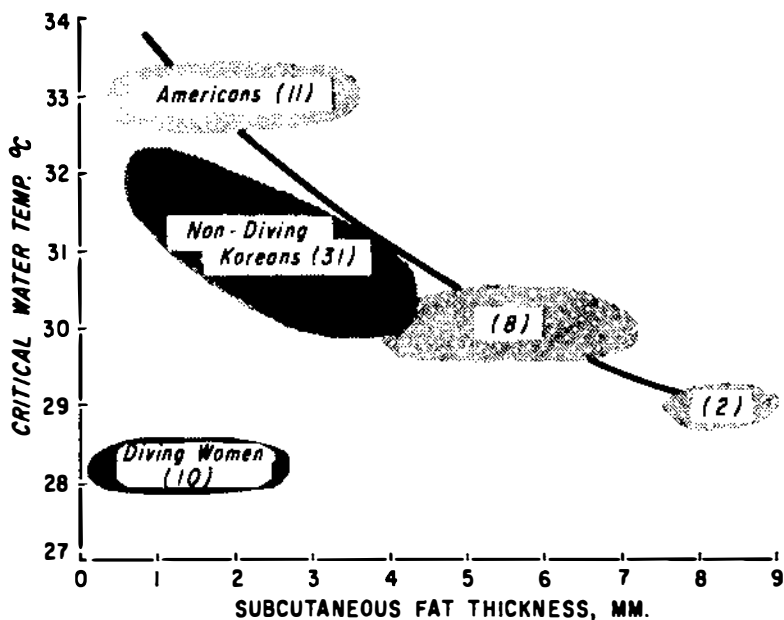


Figure 1. Critical Water Temperature (defined as the coldest water subjects tolerate for three hours without shivering) as a Function of Mean Subcutaneous Fat Thickness of U. S. Men and Women, Non-diving Korean Men and Women, and Korean Diving Women. The areas encompass the range of values for the indicated number of subjects. Note the low critical water temperature for diving women relative to their subcutaneous fat thickness.

Since CWT is comparatively warm compared to critical air temperatures, the question was raised rather early in these studies whether, in fact, there was appreciable constriction of limb and skin blood vessels under conditions of the test. No previous measurements of limb blood flow could be found for humans totally immersed in water; therefore, we have measured forearm and calf blood flow of U. S. subjects using calibrated Whitney mercury-in-rubber gauges⁽¹⁸⁾. The disadvantages of this indirect method are offset by the fact that the aqueous environment of the subject remains undisturbed. Figure 2 summarizes forearm blood flow and rectal temperature of a male subject measured during four immersions in water of neutral temperature (35.2°C to 35.5°C) followed by three hours at each of several lower temperatures: 35°, 33°, 32° and 30°C. In 35°C water there was no appreciable decline in forearm flow below control values. However, in all cooler baths forearm flow decreased dramatically. A similar result occurs when the forearm alone is immersed in water⁽⁷⁾. Rectal temperature declined but little during three hours of immersion, except in 30°C water, suggesting that cutaneous cold receptor activity initiated the vasoconstriction in water as warm as 33°C. This is consistent with results of Hensel and Boman⁽¹⁰⁾ indicating that cold receptors of human skin have thresholds exceeding 33°C although maximal firing rates occur at much cooler skin temperatures. Figure 3 illustrates the

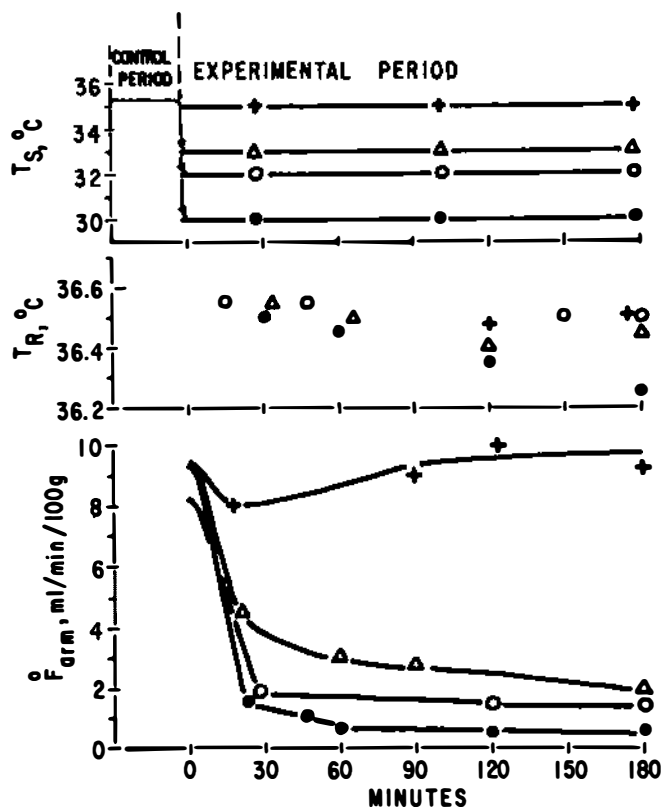


Figure 2. Time Course of Skin Temperature (water bath temperature), Top, Rectal Temperature, Middle, and Forearm Blood Flow, Bottom. Four experiments are superimposed consisting of 30 minutes immersion in water of neutral temperature followed by three hours in water of 35° (+), 33° (Δ), 32° (o) and 30° (\bullet).

18 diving women, selected from the diving community in Pusan, have been studied for comparison with non-divers.

Critical water temperature for Korean non-divers, like that for U.S. subjects, varied inversely with fat thickness, as illustrated in Figure 1. Since women generally had a thicker fat layer than men, they generally had a lower CWT. However, Korean diving women, who are unusually lean, tolerated without shivering much cooler water than non-divers of comparable fat thickness (see Fig. 1). For example, Hong⁽¹¹⁾ has reported that among Koreans unaccustomed to diving work the CWT of 50 per cent of male subjects is 31.1°C and for female subjects 29.9°C. In this same study only 30 per cent of the diving women shivered after three hours in 29°C water despite a mean fat thickness less than one-half that of diving women.

The relationship between maximal body insulation and subcutaneous fat thickness of non-diving Koreans age 20 to 40 is illustrated in Figure 4. The frequency distribution of fat thickness for 19 men and 24 women, indicated at the

relationship observed between minimal forearm blood flow (measured after three hours immersion) and bath temperature in the above subjects and two others of different physique. We conclude that limb and skin blood flow is indeed extremely low when subjects are immersed for long periods of time in water ranging from 29°C to 33°C, the temperatures employed in the Korean studies summarized below. Therefore, maximal insulation values determined under conditions of these experiments are interpreted to be measurements of over-all physical insulation uncomplicated by blood flow to superficial tissues of the body.

Studies of Korean Non-divers

A total of 41 non-diving Korean women and 36 Korean men, selected at random from communities in Pusan or Seoul, have been studied as control subjects to determine critical water temperature and the effects of subcutaneous fat thickness, sex and age on maximal body insulation. An additional

bottom, clearly illustrates that women generally have a thicker fat layer than men. The regression of maximal body insulation on fat thickness for all subjects, indicated at the top of Figure 4, clearly illustrates the insulative importance that such a fat thickness has. Superimposed on this regression are the mean values for fat thickness and body insulation for men and women. Women of this age have a 30 per cent greater maximal body insulation than men due entirely to a thicker layer of subcutaneous fat. Some 25 years ago, Hardy, Milhorat and DuBois⁽⁹⁾ arrived at the same conclusion following air-exposure studies of men and women and several studies since have emphasized the insulative protection of fat in cold air exposure^(3, 8, 13) as well as in cold water^(6, 12, 15, 16). The extra insulation against cold provided by subcutaneous fat may be one reason why, centuries ago, women were selected for diving work in Korea. Although there are perhaps other unknown socio-economic factors which could account for this distribution of labor, it is interesting to note that, in Japan, where divers work only during warm seasons, both men and women engage in diving.

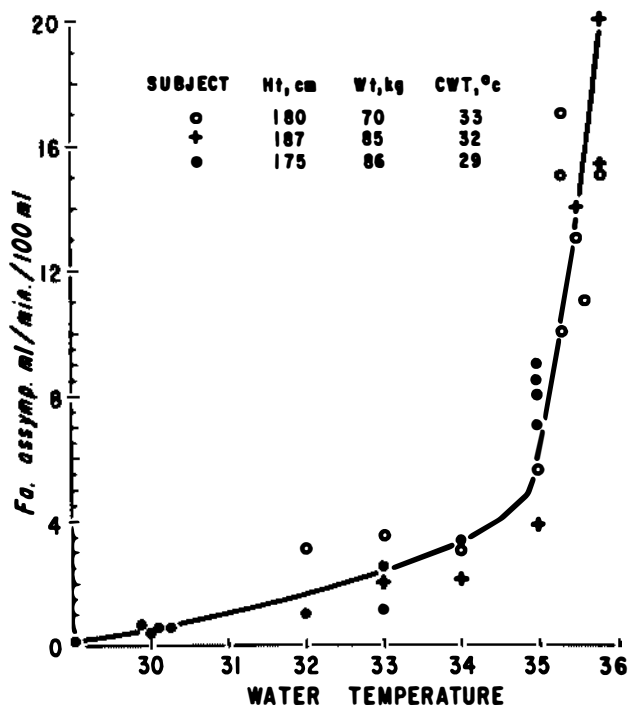


Figure 3. Forearm Blood Flow of Three U.S. Male Subjects Measured after Three Hours of Whole Body Immersion in Water of the Temperature Indicated. Note that blood flow is virtually nil in water temperature below 32°C.

Figure 5 illustrates the fat thickness-body insulation relationship of elderly Korean men and women over age 60. Comparing the frequency distribution of fat thickness for this group with that of the young adults summarized in Figure 4, it is evident that both sexes, but women in particular, lose a considerable amount of subcutaneous fat as they age. The regression of maximal body insulation on fat thickness, illustrated in the upper part of Figure 5, is identical with that of the younger group; as a consequence, the elderly population has a lower maximal body insulation than the younger due entirely to loss of fat. Women in this older age group do not have a significantly thicker layer of subcutaneous fat than men, and the maximal body insulations are the same for both sexes, unlike the case in the youthful population.

In summary, the differences in maximal body insulation between young men and women and between elderly people and young adults appear to be due entirely

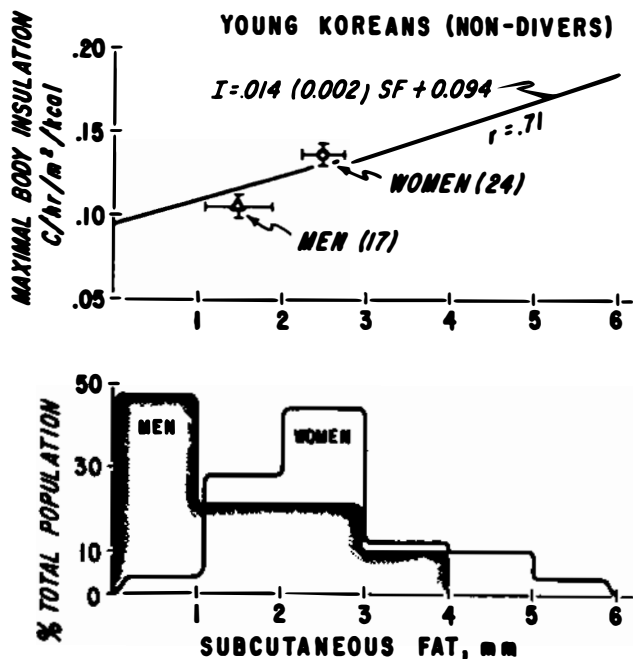
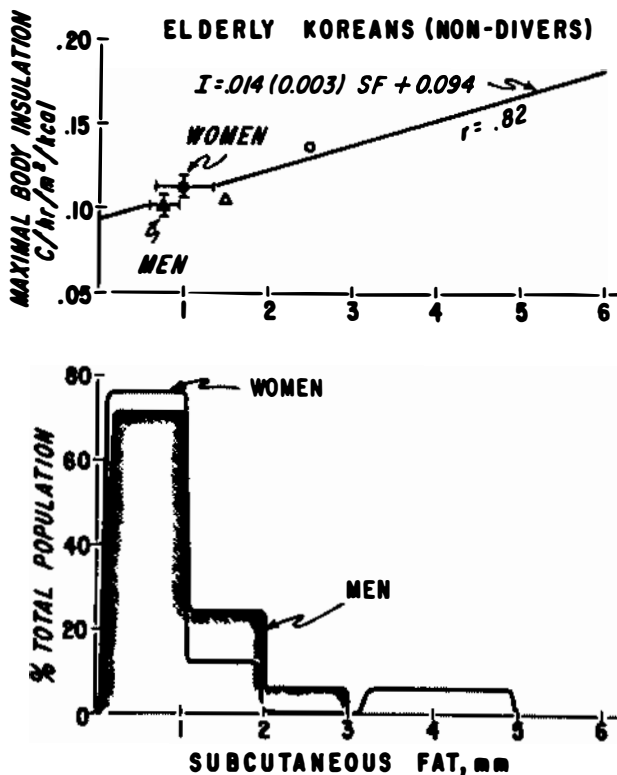


Figure 4. Maximal Thermal Insulation, Top, and Frequency Distribution of Fat Thickness, Bottom, of Young Non-diving Koreans. Mean body insulation + 1 SE of 17 men (Δ) and $\bar{24}$ women (\circ) has been superimposed upon the single regression of thermal insulation on fat thickness computed for all 41 subjects.

Figure 5. Maximal Thermal Insulation, Top, and Frequency Distribution of Fat Thickness, Bottom, of Elderly Non-diving Koreans Plotted in the Same Fashion as Figure 4. Note that the percentage of men and women having a fat thickness below 2 mm is the same for each sex, unlike the case for younger subjects. Note also that mean maximal thermal insulation of 17 elderly men (Δ) was statistically the same as that of 17 elderly women (\circ). Insulation of the younger men (Δ) and women (\circ), taken from Figure 4, are superimposed for comparison.



to differences in subcutaneous fat thickness, the insulative value of fat being equivalent to 0.8 clo/cm fat. There is no evidence that sex or age have anything but an indirect effect on maximal insulative protection of the human body to cold.

Studies of Korean Diving Women

Eight diving women from the community of Pusan were studied late in August, when air and water temperatures are maximal, and an additional ten divers during the months of January, February and March, the coldest months of the year. These studies will therefore be designated summer and winter, respectively. Comparisons are possible between the diving women and non-divers as well as among the diving women themselves at two seasons of the year.

Perhaps the most striking difference between divers and non-divers is the depressed or delayed shivering response of the diving women. This is indicated in Figure 1 as a much colder critical water temperature. It proved possible for most diving women to remain in 29°C water for three hours without shivering despite a decrease in rectal temperature to 36°C⁽¹¹⁾. This is not possible for non-divers of comparable fat thickness, who, in fact, shiver in water any colder than 33°C to 32°C and at a time when their rectal temperatures exceed 36.5°C.

As a consequence of their elevated shivering threshold the diving women sustain for long periods — at least three hours — a relatively large temperature gradient from body core to body surface (water temperature). This is illustrated in Figure 6, which summarizes the minimal average rectal and skin temperatures (measured after three hours immersion) of diving women and non-diving women of comparable age. Among women having less than 1 mm fat thickness, the maximal rectal temperature-water temperature gradient sustained for three hours without shivering was 6.8°C for divers compared to 4.4°C for non-divers. Among non-divers, it is only by increasing the thickness of subcutaneous fat deposit that one can sustain for long periods of time a rectal temperature-water temperature gradient comparable to that of divers. From Figure 6, it is evident that an increase of approximately 2 mm fat (roughly equivalent to 6 per cent body weight or 3 kg of fat) would have the same effect in maintaining the rectal temperature of a non-diver above 36°C during immersion in 29°-30°C water as does suppression of the shivering mechanism. One can only speculate about the large core temperature-water temperature gradient that might be attained by an obese diving woman or by one well-protected by modern diving clothing of the type now being used among Japanese diving women.

Voluntary muscular activity in cold water accelerates rather than retards loss of central body heat in unclothed or lightly clothed individuals⁽¹²⁾ unless the subject is invested with a thick layer of fat as, for example, is true for successful channel swimmers^(15, 16). Thus, the attenuation of shivering among diving women, who are unusually lean, can be viewed as an adaptive process favoring the maintenance of central body temperature during cold water immersion. Warmer central body temperatures are possible in cooler water than would be the case if they shivered readily. This benefit probably is of minimal practical value under the conditions of diving work, where water temperatures range from 27°C to 10°C and where there is considerable muscular activity of swimming as well as shivering; nevertheless, the controlled test conditions reveal that an acclimatization of sorts does occur among diving women to the stimulus of cold water.

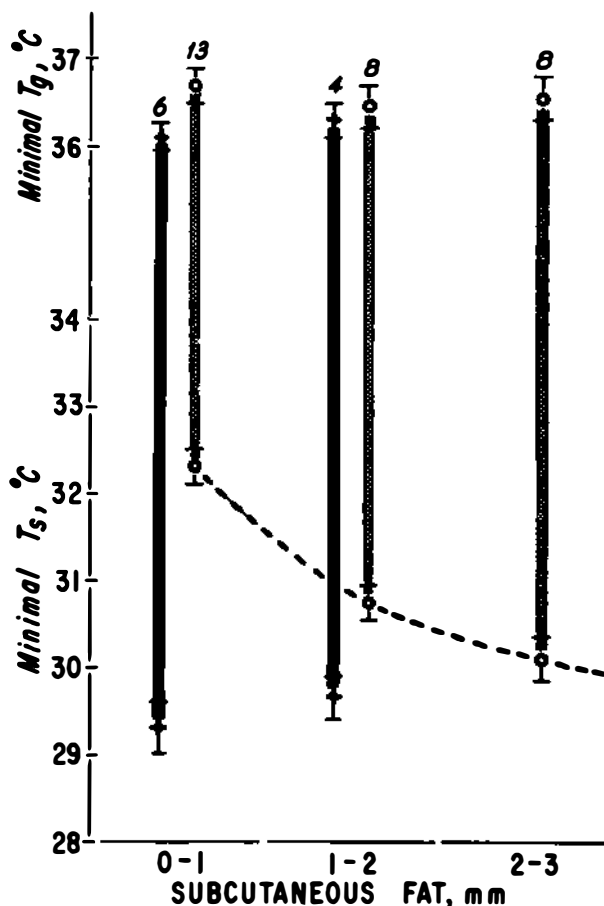


Figure 6. The Minimal Rectal Temperature, Top, and Average Skin Temperature, Bottom, of Korean Diving Women (+) and Non-diving Women (o) Immersed for Three Hours in Water of Critical Temperature. Numbers above symbols indicate the number of subjects; the small vertical bars, the SE of the mean. As subcutaneous fat thickness increases (abscissa) the (rectal-skin) temperature difference of non-divers progressively increases. However, diving women with 0-1 mm fat thickness can sustain for three hours a (rectal-skin) temperature gradient comparable to that of non-divers having 2-3 mm fat thickness.

effective counter-current heat exchange in their limbs; however, this cannot be stated with certainty until data are available on limb blood flow and regional skin

Figure 7 summarizes the mean maximal body insulation of diving women against the background of the body insulation-fat thickness regression for non-divers illustrated in Figure 4. It also illustrates the frequency distribution of fat thickness observed among diving women in summer and winter. In summer, neither mean fat thickness nor maximal tissue insulation were significantly different from non-diving women. Only critical water temperature (Fig. 1) was significantly colder. In winter, the diving women lose a considerable amount of body fat — approximately 4 per cent of body weight according to estimates made from skinfold thickness⁽¹⁾. Their mean subcutaneous fat thickness in winter is reduced to less than 1 mm in 60 per cent of the subjects. However, maximal body insulation falls only a slight and insignificant amount. At this season of the year the non-diving women of the same age have a mean fat thickness of 2.5 mm, as indicated in Figure 4, and a correspondingly greater tissue insulation. Yet the diving women in winter do have a greater insulation than one would predict statistically for non-divers of comparable fat thickness. Maximal body insulation of diving women in winter is 0.126, SE 0.005 C/kcal/hr/m². Maximal insulation predicted from 44 non-divers of comparable age (Fig. 4) is 0.108 + 0.003 at a fat thickness of 1 mm. The difference is highly significant.

The unexpectedly great maximal body insulation that diving women achieve in winter is presumably due to more extensive vascular constriction or a more

heat loss from these women at different seasons of the year. It does appear likely, however, that three types of cold adaptation are developed by these women in response to the repeated cold stress of diving in winter. Dr. Hong has discussed elsewhere the significant elevation of basal metabolism of these women in winter (see page 303, this publication). To this we would add attenuation of shivering and increase of the non-fatty insulative shell of the body. Collectively, these adaptations favor maintenance of central body temperature though their practical value in a cold aqueous environment would not appear to be great.

Summary

1. The water temperature in which non-diving subjects shiver after three hours immersion is cooler, the thicker the layer of subcutaneous fat. However, diving women, who are unusually lean, tolerate without shivering much cooler water temperatures than non-divers of comparable fat thickness.

2. Maximal body insulation⁽¹⁾ is a direct linear function of subcutaneous fat thickness (SF) such that $I = 0.014$ (SE = .002) SF + 0.0094 for Korean non-divers of all ages.

3. Young women have a significantly greater maximal body insulation than young men because of their greater average fat thickness. Among people over 60, no difference exists in either maximal body insulation or fat thickness.

4. Diving women at the end of a winter diving season have a significantly greater maximal body insulation than do non-divers of comparable fat thickness.

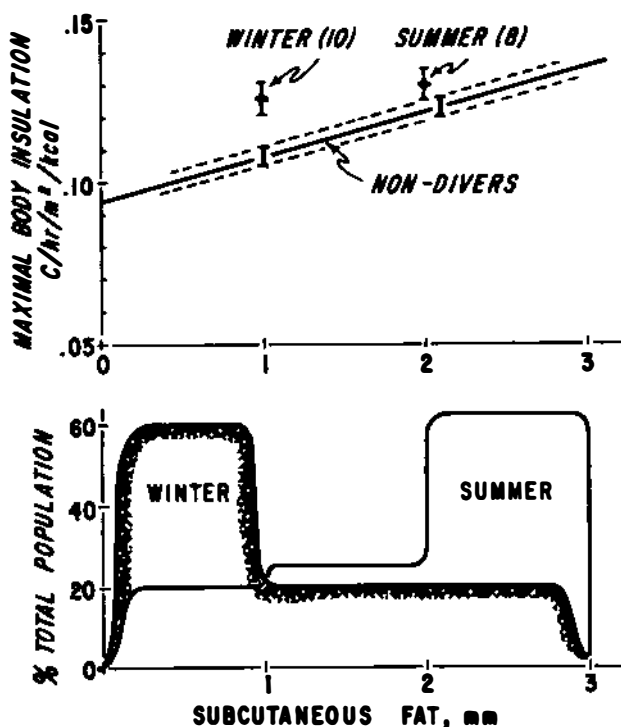


Figure 7. Maximal Thermal Insulation, Top, of Korean Diving Women in Summer and Winter. The regression ± 1 SE of insulation on fat thickness is taken from Figure 4 (young non-diving Koreans). At the bottom is indicated the frequency distribution of fat thickness for the diving population in summer and winter. Note that the women undergo a loss of insulative fat in winter. In summer, thermal insulation of diving women does not differ significantly from non-divers. However, in winter diving women have a significantly greater insulation than non-divers of comparable fat thickness.

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TEMPERATURE REGULATION IN SWIMMERS

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By the end of the 1940's, physiologists were beginning to doubt whether subcutaneous fat had any significant influence on cold water tolerance in man. In 1898, Bordier⁽²⁾ measured the thermal conductivity of beef tissue by a satisfactory method. His values for muscle were 1.8 times as high as those for fat. A few other less satisfactory measurements were made about the same time with similar results. In 1938, a paper⁽⁸⁾ on human calorimetry stated that they had measured the thermal conductivity of beef tissue and found for fat $0.00049 \text{ cal cm, cm}^{-2}, \text{ sec}^{-1}, \text{ }^\circ\text{C}^{-1}$, and for muscle $0.00047 \text{ cal cm, cm}^{-2}, \text{ sec}^{-1}, \text{ }^\circ\text{C}^{-1}$. On this basis they denied that a fat person has more insulation against cold than a thin person by reason of his subcutaneous fat. In addition to this evidence, there were the reports of ship sinkings during the war, showing that individuals who had survived unusually long periods of immersion were not obviously fat^(5, 16). In 1950, Hatfield and Pugh⁽⁹⁾ measured the thermal conductivity of fresh specimens of human tissue, and obtained values very similar to those of Bordier (Table I) on beef tissue⁽⁹⁾. They also examined specimens of beef tissue and found similar values, provided the samples were fresh; samples of muscle examined some days after death gave variable results, which may have accounted for the results of Hardy and Soderstrom⁽⁸⁾.

In order to explore this subject further, it seemed reasonable to examine a group of persons of proven ability to withstand long periods of immersion in cold water, namely channel swimmers, and in 1951 I attended a channel swimming race as an observer. On this occasion 18 of the 20 competitors swam from France to England, a distance of 21.5 miles (34.5 km) in times ranging from 12 to 20 hours. The average temperature of the water was 15.5°C . Molnar⁽¹⁶⁾ in his report on shipwreck survivals had stated that persons immersed in the sea at 15°C do not usually survive longer than five hours even when their heads are supported above water by life jackets.

No physiological observations were made on the swimmers in 1951, but after the race I accompanied one of them, Jason Zirganos, to Lake Windermere and measured his rectal and muscle temperatures after swimming for long periods in water at 13°C to 16°C . There followed a long period of collaboration during which his thermal responses and metabolism were studied in detail⁽¹⁷⁾

In 1954 and 1955, a team of investigators⁽¹⁸⁾ attended the channel swimming races and made observations of body temperature and metabolism during swimming, as well as of fat thickness, body composition and adrenal cortical function. The results of some of these investigations are presented below.

TABLE I
Thermal Conductivity of Specimens of Human Tissue⁽⁹⁾
and of Greases Used by Swimmers

Specimen No.	Fat	Muscle	Ratio
	<u>Human Tissue</u>		
1	0.000445	0.00104	2.34
2	0.000415	0.00045	1.08
3	0.000470	0.00122	2.60
4	0.000470	0.000950	2.02
5	0.000385	0.000775	2.01
6	0.000445	0.00108	2.42
Mean	0.000438	0.00092	
	<u>Grease</u>		
Lanolin			
anhydrous	0.0006		
hydrous	0.00054		
Vaseline	0.00049		

Thermal conductivity, gcal, cm, cm⁻², sec⁻¹, °C⁻¹. (To convert to kcal, cm, m⁻², h⁻¹, °C⁻¹ multiply by 3.6 x 10³.)

RESULTS

The observations at Windermere revealed striking differences between men of different physique, with respect to body temperature during swimming. JZ, being 42 years of age, was already rather fat even for a channel swimmer. G.P., on the other hand, was thin and had longer limbs.

Table II summarizes some of the physical measurements made on these subjects. Surface area was estimated from serial circumferences measured at 1.0 cm intervals, and volume by water displacement. Subcutaneous fat thickness was estimated from skinfold measurements and soft tissue X rays by methods described in the original papers^(17, 18).

Temperature and Metabolic Measurements During Swimming

Temperature readings taken immediately on leaving the water showed that the fat swimmer, JZ, maintained a normal rectal temperature for periods of up to seven hours while swimming in water at a temperature of 16°C, nor was there any fall during shorter periods of swimming in water at 13°C to 15°C (Table III). In the thin GP, rectal temperature fell to 34.5°C after only 30 minutes of swimming

TABLE IIa

Regional Surface Area and Volume, Surface/Volume Ratio and Average Subcutaneous Fat Thickness in Subjects GP and JZ

	Volume ml	Surface Area cm ²	$\frac{S.A.}{V}$	Mean Fat Thickness mm
<u>Subject GP</u>				
Age 42; Wt. 75.5 kg; Ht. 183 cm; S.A. 1.86m ² (1.98)				
2 lower limbs less feet	19850	5631	0.284	3.40
2 upper limbs less hands	6177	2722	0.441	2.16
Trunk	42579	6089	0.143	4.80
<u>Subject JZ</u>				
Age 42; Wt. 95.9 kg; Ht. 164 cm; S.A. 2.02m ² (2.04)				
2 lower limbs less feet	23204	5804	0.242	8.13
2 upper limbs less hands	8562	2922	0.341	7.35
Trunk	51800	8056	0.123	15.2

Total surface area was obtained by direct measurement; DuBois area is in parenthesis.

TABLE IIb

Surface/Volume Ratio and Fat Thickness of Lower and Upper Limbs in Relation to Trunk

Subject	GP (thin)		JZ (fat)	
	$\frac{S.A.}{V}$	Fat	$\frac{S.A.}{V}$	Fat
<u>Legs</u> Trunk	1.9	0.71	1.97	0.54
<u>Arms</u> Trunk	3.1	0.45	2.8	0.48

TABLE III

**Rectal Temperature of a Channel Swimmer,
 JZ and a Thin Subject, GP, Before and After Swimming
 in Water at 13.8 - 15.8°C in Lake Windermere**

Subject	Rectal Temperature °C		Water Temperature °C	Duration of Swim min
	Before	After		
JZ	37.8	37.8 (9 min) 37.8 (11 min) 38.2 (28 min)	13.8 - 15.8	62
JZ	37.6	37.9 (3 min) 37.7 (5 min) 37.6 (10 min) 37.5 (16 min)	13.8 - 15.8	73
JZ	-	37.4 (3 min) 37.2 (18 min)	15.8	409
GP	37.0	34.5 (4 min) 34.3 (7 min) 33.7 (14 min) 33.9 (26 min)	15.8	30

Times after leaving the water are shown in parenthesis.

in water at 16°C. We tried to define a minimum water temperature at which this subject's rectal temperature would remain constant, but even in water at 25.3°C, which was the highest we could obtain, there was still some fall over one hour of swimming (Fig. 1). Muscular weakness of rapid onset prevented further swimming on both occasions when rectal temperature fell to 34.5°C.

O₂ intakes during swimming were measured by the bag method (Table IV). The channel swimmers, JZ, used the crawl and swam usually at 56 strokes per minute with an O₂ intake of approximately 2.5 l./min. The thin subject, GP, used breast stroke at an O₂ intake of 2.10 l./min. These differences were too small to account for the differences in body cooling.

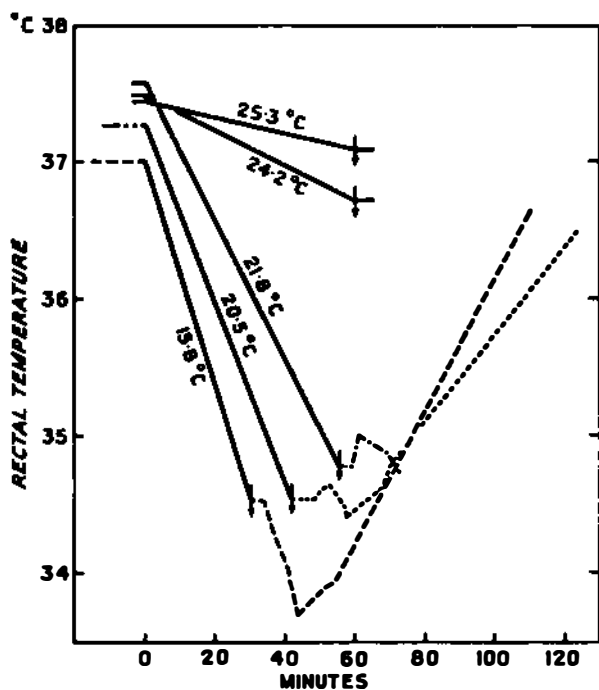


Figure 1. Rectal Temperature in GP (thin) after Swimming in Water at Various Temperatures. Water temperatures are shown above the corresponding rectal temperatures. Time 0 = time of entering water
 Time ↓ = time of leaving water.

Figure 2 shows the results of muscle temperature measurements on JZ immediately after his seven-hour swim in Windermere. The data were obtained with a narrow gauge thermocouple needle inserted obliquely. Distances shown in Figure 2 are vertical distances from the skin surfaces. The forearm measurements were made within 5 to 12 minutes of his leaving the water, and thigh measurements within 13 to 18 minutes.

After the seven-hour swim in Windermere the temperature in thigh muscles 2 cm from the bone was 37.6°C and deep forearm temperature was 34.5°C. At 1 cm depth the temperatures were 24-25°C in both regions. Estimates based on the cross sectional areas suggested that approximately 90 per cent of the forearm muscle and 75 per cent of the thigh muscle were below 30°C in temperature, in spite of the fact that these muscles are actively used in crawl swimming.

In another experiment the time course of changes in forearm temperature at 4.5cm depth after 63 minutes of swimming in water at 15.8°C was as follows:

Minutes after leaving water	Muscle Temperature
6.5	35.2
8.0	35.2
9.5	35.2
12.0	34.2

Hence the muscle temperature readings in Figure 2a are probably close to those prevailing during swimming.

Immersion in a Bath

The response of the fat subject JZ to immersion in a well stirred bath at 16°C depended on his thermal state before immersion. The results of two such experiments are shown in Figure 3. In the first the initial rectal temperature

TABLE IV

O₂ Intake in 1. STP/min in Subject JZ, an Obese Channel Swimmer, and Subject GP, a Thin Subject

SUBJECT JZ		SUBJECT GP	
REST			
Lying (non-basal)	0.31		0.29
Sitting	0.35		0.34
Bath at 16°C	0.74		1.66
	0.99		
	0.95		
SWIMMING			
(Crawl Stroke)		(Breast Stroke)	
Slow crawl	2.17	Habitual pace	2.06
Crawl 56 strokes/ min	2.40	Habitual pace	2.07
Crawl 56 strokes/ min	2.70	Habitual pace	2.16
Crawl 58 strokes/ min	<u>2.96</u>		<u> </u>
Mean	2.56		2.10

Values for bath experiments were obtained over ten minutes during shivering.

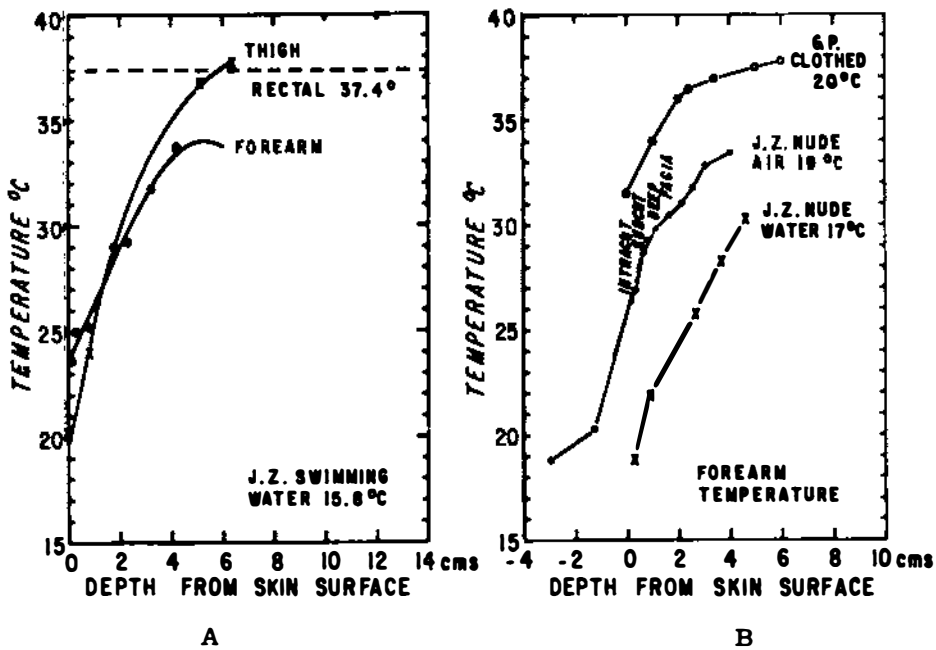


Figure 2. Temperature readings in the forearm (lateral aspect 4 cm approximately distal to head of radius) and the thigh (anterior aspect junction of upper and middle third) of subject JZ (A) after seven hours swimming in water at 15.8°C; (B) motionless in a bath at 17°C; and after two hours sitting nude in air at 19°C. In B results obtained on GP under average living conditions and with forearm clothed are shown for comparison.

was 37.7°C and rectal temperature fell continuously during 73 minutes of immersion. Slight muscle tremor was observed only from the 40th minute during which period O_2 intake rose to 0.73 l./min (Table IV).

In the second experiment the subject had been sitting nude at an ambient air temperature of 16°C for one and one-half hours before immersion and his rectal temperature had fallen to 36.9°C. This time shivering began within 15 minutes and was more intense. O_2 intake during periods of shivering rose to nearly 0.95 - 0.99 l./min, compared with 0.75 l./min in the previous experiment; rectal temperature rose in the first 30 minutes to 37.1°C, thus showing that in spite of the continued fall in rectal temperature seen in the first experiment, the subject was in fact easily capable of raising his deep body temperature in a bath at 16°C.

The response of the thin subject GP to immersion in water at 16°C was entirely different. Violent paroxysmal shivering associated with a five-fold rise

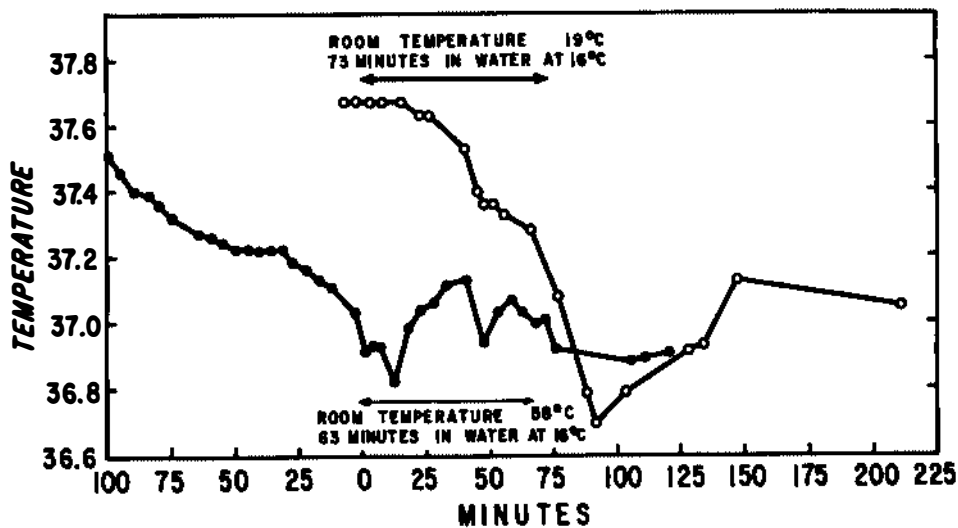


Figure 3. Rectal temperature in JZ before, during and after immersion in a bath at 16°C; o — o three hours sitting lightly dressed in room at 16°C before entering bath. Shivering began after 15 minutes in water. O₂ intake rose to 0.95 and 0.99 l./min during shivering. ● — ● one hour nude in room at 19°C, before immersion. Shivering began after 40 minutes in water. O₂ intake rose to 0.75 l./min. Arrows indicate time of immersion and time of leaving water.

in metabolism (Table IV) began almost immediately. Yet, in spite of higher metabolism, rectal temperature fell more steeply than in JZ. After 25 minutes the subject was lifted from the bath in a state of generalized rigidity and was incapable of movement. Rectal temperature, however, had only fallen 0.9°C to 36.6°C although there was a further fall to 35.9°C during rewarming.

One of the most interesting differences between the two subjects was their subjective response to this kind of immersion. JZ felt no discomfort other than boredom, and on one occasion called for a newspaper. For GP, on the other hand, the experience was so unpleasant that he was unwilling to undergo further immersion at this water temperature.

Forearm muscle temperatures on JZ, measured as he lay in the bath at 16°C are shown in Figure 2B. They are lower than those observed after swimming. Also shown are results obtained after he had been sitting for two hours nude in a room at 19°C. These are only a little higher than the readings observed after swimming. It was JZ's custom to sleep nude at about 15°C, and to wear an open-necked short-sleeved shirt in the daytime. These muscle temperatures must, therefore, be considered usual for this subject. The upper curve in Figure 2B shows forearm gradients for GP under normal living conditions — that is, fully

clothed at ambient temperatures of 18°C - 20°C. In his case temperatures of 36°C - 37°C were recorded within 2 cm of the skin surface.

Immersion in a Bath Compared with Swimming

Figure 4 compares the respective responses of JZ and GP, and of three other subjects, two fat and one thin, during swimming and immersion in water at the same temperature. The results show that thin subjects cooled more rapidly in cold water while swimming than while motionless, while the reverse was true of fat subjects.

Fat Thickness

Estimates of subcutaneous fat thickness from skin-fold measurements revealed large differences between the three fat and the two thin subjects (Figure 5). Two of the fat subjects, OGE and JM, were considerably thinner than the swimmer JZ and seen in their ordinary clothing, or indeed when stripped, did not give the impression of being fat at all. This was a significant point, because it offered a possible explanation of the finding from shipwreck survivals that persons who have survived exceptionally long periods of immersion in cold water have not been obviously fat. It also seemed to explain the superior tolerance of women, since women are generally fatter than men.

Regional Volume and Surface Area

In addition to the obvious difference in fatness between JZ and GP, the thin subject, GP, had longer limbs and a smaller trunk than the fat subject. In order to assess the possible role of these factors direct measurements of the volume and surface area of the limbs and trunk were made in these two subjects. The results are given in Table II and are compared with the fat measurements. It was surprising to find that the regional surface to volume ratios were similar in the two subjects. JZ was, however, more than twice as fat in all areas. Comparing the limbs with the trunk, (Table IIb), one sees that the fat thickness was half in both subjects and the S.A./volume ratio double or treble. The combined effect of these factors might be to make the relative heat loss from the limbs by direct conduction four to six times as great as from the trunk.

Thermal Conductance and Insulation

Table V contains values for effective thermal conductance and tissue insulation for the two subjects, JZ and GP, while swimming in water at 15°C and while motionless in a well-stirred bath. The values were calculated from the relations

$$K = \frac{H}{T_r - T_w} \quad \text{and} \quad I = \frac{l}{K}$$

where K is the effective thermal conductance in kcal, m⁻², h⁻¹, °C⁻¹,

I is the effective tissue insulation in °C, kcal⁻¹, m², h¹,

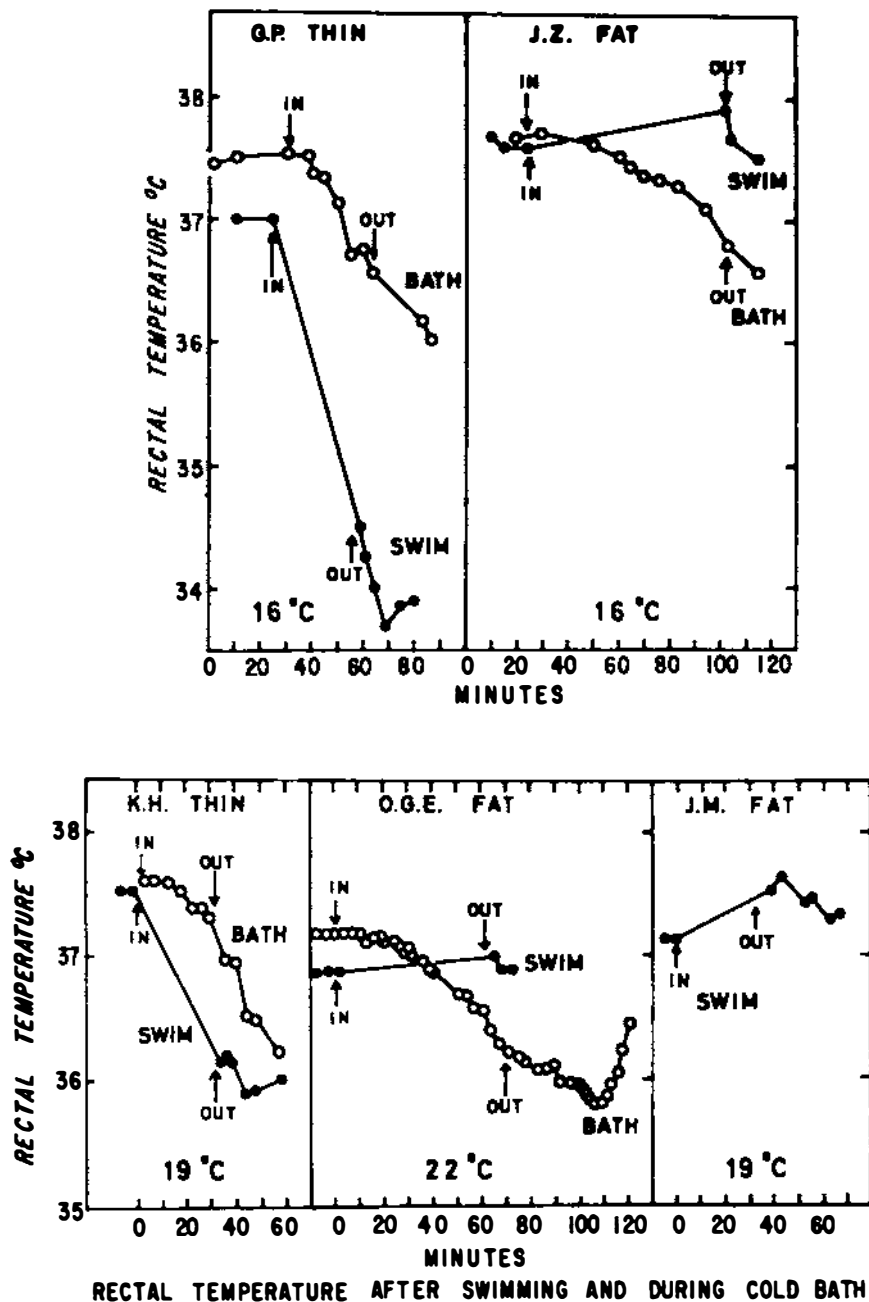


Figure 4. Rectal Temperatures Before and After Swimming and During Immersion in a Bath at the Same Temperature in Fat Subjects and Thin Subjects. ● — ● swimming. ○ — ○ bath. Water temperatures are shown above the abscissae.

TABLE V

Effective Thermal Conductance (K) and Insulation (I) of a Channel Swimmer, JZ (S.A. 2.0 m²) and a Thin Subject, GP (S.A. 1.9 m²) (a) Swimming and (b) Motionless in Bath.

Subject	M kcal, h ⁻¹	H kcal, m ⁻² , h ⁻¹	T _r °C	T _w °C	K kcal, m ⁻² h ⁻¹ , °C ⁻¹	I °C, kcal ⁻¹ , m ² , h
			SWIMMING			
JZ Fat	660	290	16.0	37.4	13.5	0.074
GP Thin	630	277	25.3	37.1	23.5	0.043
			MOTIONLESS			
JZ Fat	270	119	17.0	37.1	5.9	0.169
GP Thin	498 +31*	233	16.0	36.6	11.3	0.088

*Stored heat loss.

H is the heat transmission to water in kcal, m⁻², h⁻¹,

T_r is the rectal temperature in °C,

and T_w is the water temperature in °C.

H was calculated from heat production minus 12 per cent for heat loss from lungs and unsubmerged surfaces, plus stored heat loss⁽³⁾. No allowance was made for mechanical work. Stored heat loss was calculated as follows:

Stored heat loss = rate of fall of rectal temperature near end of

$$\text{experiment} \times 0.83 \times \frac{\text{body weight}}{\text{surface area}} \times \frac{2}{3}$$

For GP swimming, the calculation of conductance and insulation was made from observations in water at 25.3°C, at which temperature the storage factor was comparatively small (in water at 16°C the heat loss was too rapid to permit a satisfactory estimate of stored heat loss).

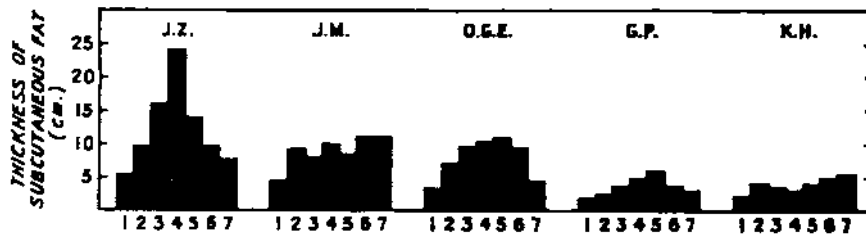


Figure 5. Thickness of Subcutaneous Fat in Five Subjects: three fat (JZ, JM and OGE) and two thin (GP and KH) at seven sites: 1. forearm; 2. arm; 3. chest; 4. abdomen; 5. back; 6. thigh; and 7. leg. Compare with Figure 4.

The results show that the effective insulation of the fat subject, JZ, was twice as great as that of the thin subject, GP, and that when they were swimming the effective conductance of both subjects was twice as great as it was when they were motionless.

CHANNEL SWIMMERS

Long distance swimmers who attempt the English Channel are of many nationalities and ages (Table VI and Fig. 6). The youngest to succeed has been a 15 year old girl and the oldest a man of 57 years (N. Barnie). The somato-types of channel swimmers are mesomorphic with an endomorphic component, very different from long distance runners and walkers(18). The older men and some of the women are frankly obese but not the younger swimmers. Attempts are made in the months of August and September when the temperature of the water is 15°C to 18°C. The shortest distance across the channel is 21.5 statute miles (34.5 km). Times for crossing have ranged from 9 1/2 to 27 hours. In 1961 the Argentinian, Abertondu, swam the channel both ways in 43 hours. Common causes of failure are missing the tide, adverse weather, fatigue, cold, cramps and vomiting. The swimmer is fed, usually at hourly or two-hourly intervals and ingests not more than 1500 kcal of food during the crossing. As a precaution against cramps, swimmers do not rest more than one minute to take food. In 1950-1955 cross-channel races were organized by various sponsors and 18 to 20 competitors took part in each race; otherwise attempts are made individually.

The physical characteristics and performances of the swimmers observed in 1954 and 1955, are shown in Table VI. Table VII gives results of estimates of mean subcutaneous fat and of total body fat by various methods(18). The distribution of subcutaneous fat in three groups of swimmers classified by performance is shown in Figure 7 and compared with data on factory workers and young girls. All of the swimmers were fatter than average. The fastest swimmers were fatter than slower swimmers and the women were fatter than the men. As regards total body fat, Park and Hief who finished first and second in 1955 had only 9.5 and 12.1

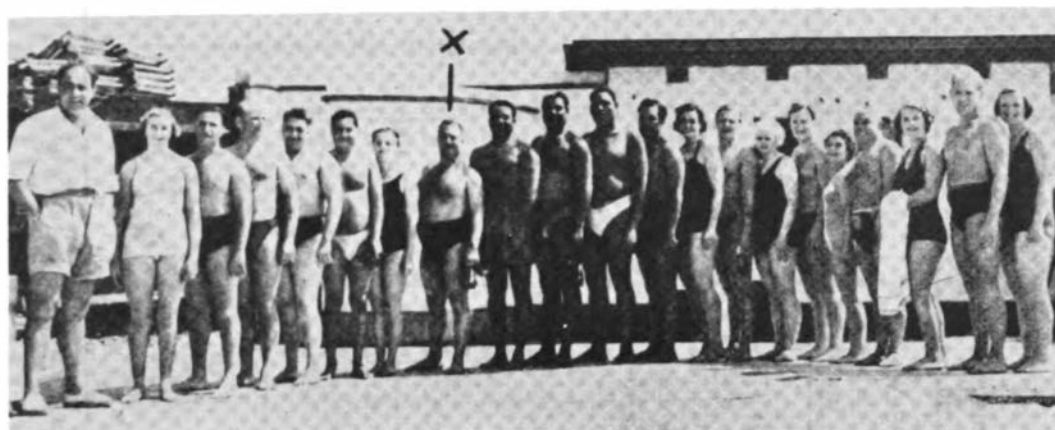


Figure 6. Competitors in the Cross-Channel Race of 1951.
JZ is marked with a cross.

per cent fat, respectively. Sen (13.2 per cent fat) was a weak swimmer and gave up on account of cold. One year later he returned 8 kg heavier and was successful. Otherwise the fat percentages by various methods range from 15 per cent to 25 per cent with two extreme values which are probably errors. These results confirmed the association between fatness and tolerance to cold water.

Metabolism

Table VIII contains the results of metabolic determinations made with a bag trailing in the water and an air intake held up by a fishing rod. The observations were made in a fresh water pool while the swimmers were training for the race. The subjects swam at a pace which they were accustomed to maintain during several hours of daily practice. More detailed observations on two subjects showed that the O_2 intake was closely correlated with the stroke rate but that one was more efficient than the other (Fig. 8).

From these results and observations of stroke rate during the race, it was calculated that the average rate of energy expenditure during the race was 900 kcal/h for fast swimmers and 760 kcal/h for slow swimmers, and that the total cost of swimming the channel was approximately 11,000 kcal and independent of the time taken. Records of food eaten by competitors yielded values ranging from 1000 to 1500 kcal, so that most of the energy expenditure must have been derived from fat. For Abertoudu who swam the channel both ways in 43 hours, the total energy expenditure 22,000 kcal!

Body Temperature

Rectal and mouth temperatures of competitors on leaving the water are shown in Table IX. The majority are in the range of 33°C - 35°C. Rectal temperature in the women tended to be somewhat higher than in the men in spite of

TABLE VI

Particulars of the Competitors in the 1955 Cross-Channel Race

Name	Country	Age (yr)	Height (cm)	Weight (kg)	Surface Area (sq m)	Mean Subcutaneous Fat Thickness (mm)
MEN						
N. Barnie	Scotland	58	164.0	91.2	1.98	7.9
D. Beltram	Mexico	37	174.5	82.6	1.97	7.7
T. Bleik	Lebanon	24	169.4	78.7	1.90	7.8
F. Gill	England	37	182.6	102.9	2.26	9.2
J. Girghiz*	Egypt	39	169.3	75.7	1.86	-
G. Guiscardo	Argentina	25	172.0	82.3	1.96	8.5
A. Heif	Egypt	26	178.6	85.6	2.02	7.4
J. McClelland	Ireland	31	171.3	98.7	2.12	9.6
T. Park	Canada	31	173.2	81.9	1.94	6.2
B. Pereira	Portugal	34	160.2	76.5	1.80	7.5
M. Sen	India	26	177.8	72.6	1.88	5.8
E. Soussi	Syria	27	170.2	87.3	2.00	10.9
R. Tarr	England	18	185.5	103.2	2.30	8.1
K. Wray	England	29	173.8	80.0	1.95	7.4
J. Zirganos	Greece	46	164.0	87.0	1.94	7.0
WOMEN						
E. Andersen	Denmark	29	158.3	69.1	1.70	12.2
M. Magrath	England	30	170.5	70.8	1.82	15.7
M. Sweeney	New Zealand	25	157.8	63.0	1.62	15.3
G. Vegni	Egypt	20	151.1	57.7	1.50	13.4

*This subject was not officially in the race but attempted to swim the Channel on the same day as the race.

TABLE VII
Results of Fat Measurements on Channel Swimmers

Subject	Density	Estimate of Total Body Fat Expressed as Per Cent of Body Weight			Mean Subcutaneous Fat Thickness (mm)
		Density	Tritium	Urea	
Barnie	1032	25.5	24.4	23.9	7.9
Beltram	1038	23.4	21.4	23.7	7.7
Gill	1040	22.6	22.7	26.4	9.2
Heif	1075	9.4	15.8	-	7.4
McClelland	1036	24.2	20.1	15.4	9.6
Park	1068	12.1	-	-	6.2
Pereira	1049	19.2	24.1	-	7.5
Sen	1065	13.2	16.0	16.7	5.8
Soussi	1022	29.7	19.9	20.5	10.9
Tarr	1047	20.0	27.1	-	8.1
Wray	1058	15.8	18.8	-	7.4

The coefficient of correlation between mean values of total body fat by three methods and subcutaneous fat was 0.63, $p < 0.05$ with nine degrees of freedom.

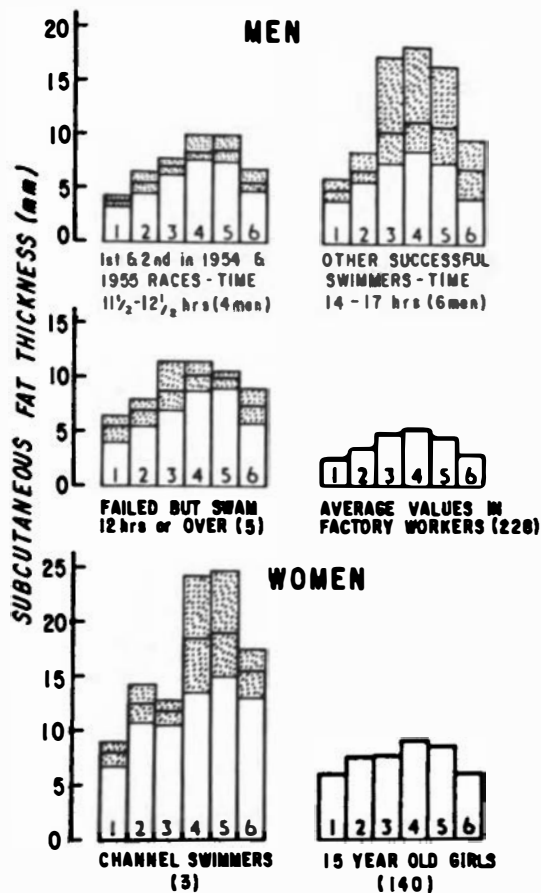


Figure 7. Subcutaneous Fat Thickness in Male and Female Channel Swimmers, Compared with Control Groups. Mean values are indicated by a heavy line, and for the Channel swimmers the range is shown by hatching. The age distribution of the factory workers and Channel swimmers is comparable. The women channel swimmers are older than the control group, and some increase in fat thickness would be expected.

The figures 1-6 in the histograms refer to the sites, i. e.,

- | | | |
|------------|----------|----------|
| 1. Forearm | 2. Arm | 3. Chest |
| 4. Abdomen | 5. Thigh | 6. Leg |

TABLE VIII

Respiratory Data on Cross-Channel Swimmers during Practice

Name	Speed		Strokes per min	Ventilation (l/min) BTPS	O ₂ intake (l/min)	Kcal per/min	Tidal volume l-BTPS	Vital capacity (l)
	mph	km/hr						
<u>MEN</u>								
Barnie	1.65	2.65	42.4	58.3	2.39	11.7	2.75	4.2
	1.63	2.62	43.8	61.9	2.56	12.4	2.83	
Girghiz	1.95	3.14	56.5	64.1	2.68	12.9	2.87	4.1
	1.85	2.98	54.5	55.0	2.43	11.5	-	
	1.75	2.82	56.5	57.5	2.23	10.8	2.47	
	1.67	2.69	-	52.3	1.98	9.5	-	
Guiscardo	2.00	3.22	50.4	54.6	3.10	15.0	2.17	
	1.87	3.01	43.1	51.1	2.84	13.8	2.36	5.8
Heif	2.01	3.23	57.1	71.5	3.22	15.4	2.50	5.2
Pereira	2.13	3.43	58.2	65.4	3.09	14.4	2.25	
	1.83	2.94	54.1	50.1	2.55	11.8	1.87	3.3
Park	3.02	4.86	73.0	99.9	2.89	14.4	3.02	5.0
Soussi	1.72	2.77	47.0	47.3	2.68	12.5	2.01	4.5
	1.72	2.77	51.0	59.2	3.28	15.4	2.32	-
Wray	1.96	3.15	53.7	68.6	3.06	14.7	2.55	6.2
<u>WOMEN</u>								
Sweeney	2.46	3.96	-	72.9	2.69	13.1	-	
	2.27	3.65	66.9	61.4	2.37	11.6	1.83	
	2.07	3.33	58.9	52.2	2.10	10.1	1.77	3.2
	2.03	3.27	-	59.0	2.32	11.5	-	
	1.93	3.11	-	54.0	2.14	10.2	-	
	1.72	2.77	-	48.2	1.96	9.3	-	

All subjects used the crawl stroke.

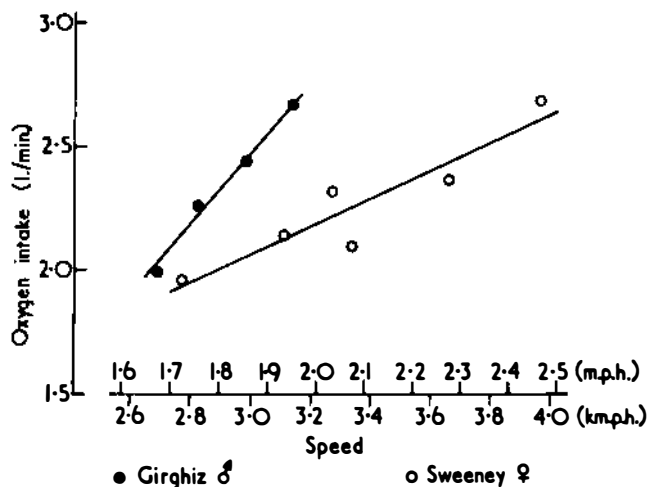


Figure 8. Relation of O₂ Intake to Speed Through the Water in Crawl Swimming in Two Channel Swimmers.

the lowest recorded. Women and older swimmers, who had lower O₂ intakes were more tolerant of cold, and were much fatter (Fig. 7).

DISCUSSION

The observations on Zirganos and the subjects with whom he was compared established a clear association between body fat and tolerance of immersion in cold water especially during swimming; the observations on channel swimmers pointed to the same conclusions. These findings were extended and confirmed by Carlson, Hsieh, Fullington and Elsner⁽⁴⁾ and Keatinge⁽¹³⁾ in subjects immersed in baths and by Baker and Daniels^(1, 6) on subjects exposed in air. Further confirmation is afforded by the work of Rennie *et al*⁽¹⁹⁾, Hong⁽¹²⁾ and Kim⁽¹⁴⁾, on the Korean diving women and other groups. These investigators have demonstrated a linear relation between maximum tissue insulation during immersion in water and subcutaneous fat thickness.

Because of the form of the basic heat equation $\Delta t = H/K$, (see page 331) the relation between superficial fat and body cooling in cold water is more easily demonstrated on swimmers than on subjects lying motionless in baths. The point is illustrated in Figure 9 by the fan of lines representing the relation between $T_r - T_w$ and $\dot{V} O_2$ under conditions of thermal equilibrium, for various values of conductance (K) and insulation (I). At low $\dot{V} O_2$ the differences in $T_r - T_w$ at different values of $K + I$ are comparatively small and careful control of initial conditions, with continuous measurement of $\dot{V} O_2$, will be necessary to demonstrate difference in K and I convincingly. But at O₂ intakes over 2 l./min as observed in swimmers, the variation in $T_r - T_w$ associated with variation in K or I becomes very large, and is further magnified when the increase in K associated

their lower O₂ consumption. Mouth temperatures during swimming (not shown in the table) were grossly misleading; mouth temperatures after leaving the water were within 1°C of rectal.

Our assessment was that the fastest swimmers, who are also the thinnest, depended largely on their high O₂ intake to keep warm. If they became exhausted and had to rest, they cooled down and had great difficulty in continuing. T. Park, for example, covered the first 16.5 miles in seven hours but took five hours over the last five miles. His rectal temperature on leaving the water was 34°C,

TABLE IX

1954 and 1955 Channel Race Observations

Order of finishing	Name	Sex	Country	Age (yr)	Time in water		Body temperature, °C		Notes
					hr	min	Rectal	Mouth	
1954 Channel Race — Water Temperature 16°C									
1	B. Pereira	M	Portugal	33	12	25	35.5		
2	H. Hamad	M	Egypt	37	12	49	34.7		
3	B. Fisher	F	England	27	14	25			Grease on face and neck only
4	J. Zirganos	M	Greece	44	16	23			Grease on trunk only
5	M. Feather	F	England	21	16	23		36.7	No grease
6	A. Abertoudu	M	Argentina	35	16	53			No grease
7	E. Soussi	M	Syria	27	17	55	34.8	34.4	5 lb grease 1-2 mm thick
<u>Competitors who did not finish</u>							<u>Cause of failure:</u>		
	N. Barnie	M	Scotland	57	17	5	Fatigue		1½ lb grease
	J. Kammergaard	F	Denmark	35	14	50	Fatigue		
	B. Toufic	M	Lebanon	23	~16		Fatigue		
	J. McClelland	M	England		~15		Unspecified		
	A. Rizzo	M	Malta	28	~14		Fatigue		
	B. Paysour	M	United States	26	~14½		Cold		
	K. Wray	M	England	28	~3		Injured shoulder muscle		8 lb grease
	D. Belgram	M	Mexico	36	~5		Cramp		
1955 Channel Race — Water Temperature 18°C									
1	A. Heif	M	Egypt	26	11	40	36.1	35.0	
2	T. Park	M	Canada	31	12	5	34.0	33.0	
3.	G. Guiscardo	M	Argentina	25	14	35	37.8		
<u>Competitors who did not finish</u>									
	F. Gill	M	England	37	9	40	38.3	39.7	
	E. Andersen	F	Denmark	29	7	47	37.0	36.7	
	M. Sweeney	F	New Zealand	25	3	50	36.3	35.0	
	M. Magrath	F	England	30	4	4			

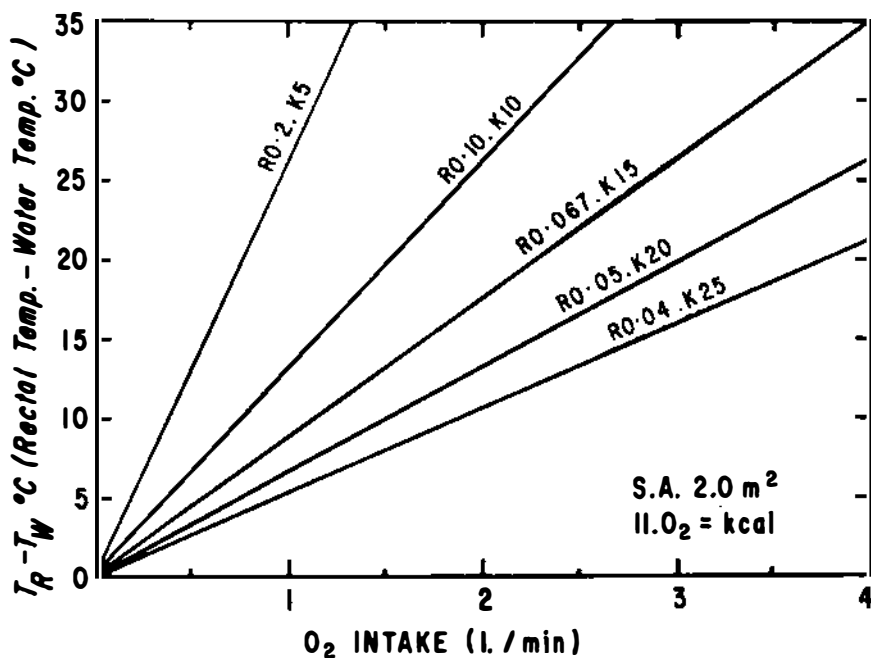


Figure 9. Difference between rectal and water temperature ($T_r - T_w$) in relation to O_2 intake at various values of conductance (K) and insulation ($I = R$) calculated for a person of $2.0m^2$ surface area assuming $1 l.O_2 = 5$ kcal and non-water heat loss of 12 per cent. K is expressed in kcal, m^{-2} , h^{-1} , $^{\circ}C^{-1}$ and I in $^{\circ}C$, kcal, $^{-1}$, m^2 , h^1 .

with muscle activity is taken into account. The result is that the minimum water temperature for thermal equilibrium at a given $\dot{V} O_2$ and T_r in fat swimmers will be much lower than in thin swimmers, and the cooling curves will be very different. In point of fact Jason Zirganos maintained a normal rectal temperature over seven hours in water at $15^{\circ}C$ while the thin subject with whom he was compared required a water temperature above $25^{\circ}C$. Zirganos had successfully competed in a long distance race in the Nile in water at $10^{\circ}C$ but $7^{\circ}C$ was below his limit, for he was taken from the water unconscious after three hours swimming in the Bosphorous at that temperature.

From Figure 9 his minimum water temperature for a rectal temperature of $37^{\circ}C$ and observed conductance of $13kcal m^{-2}$, h^{-1} , $^{\circ}C^{-1}$ would be $11.5^{\circ}C$ at a $\dot{V} O_2$ of $2.5 l./min$ and $17^{\circ}C$ at a $\dot{V} O_2$ of $2.0 l./min$. For GP with K equal to $24kcal m^{-2}$, h^{-1} , $^{\circ}C^{-1}$ the corresponding values would be $23^{\circ}C$ and $26^{\circ}C$ respectively.

For the sake of comparison, the work of Rennie and his colleagues⁽¹⁹⁾ may be cited. These investigators found that the minimum water temperature tolerated without shivering (critical temperature) during three hours of immersion in a well-stirred bath varied only from 33°C to 34°C in thin U.S. men to an average of 28°C in the Korean diving women.

Subcutaneous fat is not the only factor associated with cold tolerance in water⁽¹⁹⁾. Plotting maximum tissue insulation against subcutaneous fat and extrapolating to zero fat thickness⁽¹⁹⁾ it was found that only one-third of the total insulation was accounted for by subcutaneous fat in Korean subjects compared with two-thirds in U.S. subjects. The non-fat component expressed as centimeters thickness of non-perfused muscle was 3.2 cm in the former, compared with 1.8 cm in the latter. No comparable data are available on channel swimmers, but it is likely that similar differences would be found between them and ordinary subjects in bath experiments.

The forearm muscle temperatures in JZ, while swimming and while motionless in a bath at the same temperature, show that the heat deficit in limbs may vary widely under different conditions, even when rectal temperatures are similar. One may also infer that fat swimmers have higher muscle temperatures than thin swimmers at given rectal and water temperatures. This might explain the muscular weakness in GP when rectal temperature fell to 34.5°C, when channel swimmers with rectal temperatures of 34.5°C were unaffected. An alternative hypothesis would be that there are local differences in the muscle or their nerve supply associated with cold habituation. It is worth mentioning in this connection that Zirganos described wearing rubber bands to keep his fingers together at the beginning of the season whereas later, in water of the same temperature, he did not need them.

The change in over-all conductance associated with swimming is an interesting phenomenon, also observed in shivering and during exercise in air, as well as in water. For both JZ and GP the increase amounted to a doubling of conductance; consequently the difference in resting conduction between the two subjects was also doubled. The data on surface/volume ratios and subcutaneous fat distribution in the limbs relative to the trunk indicate that heat produced by the limb muscles will be much more rapidly dissipated by direct conduction than heat produced in the flat muscles covering the trunk or the muscles of the hip. Fortunately for swimmers, these muscles play a major part in swimming by the crawl stroke which long distance swimmers use exclusively. It is likely that the muscle temperatures recorded in Zirganos at Windermere were not very different from those actually prevailing during swimming. They show that the 37°C isotherm had retreated to within 2 cm of the bone in mid-thigh and certainly above the forearm in the upper limbs. Heat production in these muscles was therefore not contributing to the maintenance of central body temperature (T_r , 37.4°C). The relative role of direct conduction and convection by the blood in rest and exercise in water deserves further investigation.

Habituation to Cold

Channel swimmers train for two to three hours a day, some of them for ten months in the year but the water temperature to which they are habituated

varies with their country of origin and the season. In the Nile race already mentioned, 50 per cent of the swimmers gave up on account of the cold; on the other hand, some swimmers, such as Barnie and Zirganos were thoroughly accustomed to swimming in water of 10°C. Zirganos made a practice of wearing light clothing and was comfortable with a mean skin temperature of only 28°C, yet his resting metabolism did not appear to be elevated. His response to immersion in a bath of water at 15°C was characteristic of that observed in experiment on cold adapted social groups, namely absence of discomfort and minimal shivering⁽⁷⁾.

The experiments on him and on the control subject, GP, are a good illustration of how large the difference between habituated and unhabituated persons may be. The essential feature of this kind of habituation seems to be the inhibition of afferent nerve impulses from the skin. It is generally thought the inhibitory process arises in or depends on the rostral hypothalamus (for review, see Hemingway⁽¹⁰⁾), although in spinal animals it may develop at chord level⁽¹⁵⁾.

SUMMARY

1. A fat channel swimmer maintained a rectal temperature of 37.4°C after seven hours of swimming in water at 15.8°C. In a thin subject under the same conditions rectal temperature fell to 34.5°C after 30 minutes of swimming and he was unable to continue swimming on account of muscular weakness. A water temperature above 25°C was necessary for equilibrium at a rectal temperature of 37°C. Similar differences were observed in other fat and thin subject.

2. Temperature gradients are reported in the thigh and forearm after swimming, in bath experiments, and during exposure in air.

3. Thin subjects cooled more rapidly while swimming than while motionless in water at the same temperature.

4. Thermal conductance was doubled and insulation halved in both the fat and thin subjects while swimming compared with lying motionless in a bath. The reasons for this are discussed in terms of surface/volume ratios and fat distribution over the limbs and trunk.

5. In bath experiments at 16°C the channel swimmer responded like persons belonging to cold adapted racial groups exposed to low air temperatures.

6. The association between subcutaneous fat and cold tolerance was confirmed in competitors in cross-channel races; but it was concluded from metabolic measurements during swimming that their tolerance of low water temperature depended on the high O₂ intake as well as subcutaneous fat.

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ENERGY COSTS OF DIVING AMA

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INTRODUCTION

The Japanese Ama exhibit two general types of diving patterns. The Cachido dives without assistance to depths of five to seven meters and, therefore, must actively overcome her positive buoyancy as well as her drag resistance on descent and while on the bottom. During ascent she is only partly assisted by her buoyancy. The Funado is assisted in her dives to 20 or more meters. On descent she is aided by a counterweight, during ascent she is pulled up by her partner. It is only while on the bottom that she becomes active in search of harvest.

There is another interesting difference in these two diving patterns. Although the Funado will reach depths two to four times that of the Cachido, she will spend about 30 seconds on the bottom while the Cachido spends approximately 15 seconds or less. In this paper the authors will focus their discussion on the energy cost differences between these two types of diving patterns. Since there are not enough data available to make a detailed analysis, one must make certain assumptions and rough estimates. The effects of the cold environment on the increased oxygen consumption and oxygen debt will also be examined.

The Typical Diving Patterns and the Basic Characteristics for Calculation

The Funado descends to a depth of 20 to 25 meters with an average velocity of about 1.2 to 1.5 meters/second⁽¹⁰⁾. She carries a counterweight which provides for the proper negative buoyancy and the appropriate descent velocity without consuming extra energy. The size of the counterweight varies from 10 to 14 kg. Some unpublished data of Teruoka on the size of the counterweight are shown in Table I. She releases her counterweight at the bottom to swim around for about 28 seconds, using extra energy. On ascent, the partner pulls her up, maintaining an average velocity of 1.62 meters/second. The average total time for her single dive is 58 seconds⁽¹⁰⁾. The Funado therefore uses extra energy only while on the bottom where her buoyancy is negative.

TABLE I

The Body Weight of Funado and Their Counterweight

Body weight of Ama — kg	Size of counterweight — kg											Total
	12.0	12.4	12.8	13.1	13.5	13.9	14.3	14.6	15.0	15.4	15.8	
less than 45.0	0	1	0	2	2	1	5	1	1	1	1	15
45.1 to 48.0	0	2	1	2	4	6	6	5	2	1	0	29
48.1 to 52.0	1	0	1	4	0	3	4	2	1	1	0	17
52.1 to 56.0	0	0	1	2	3	2	4	2	1	1	0	16
56.1 or more	0	1	1	1	0	4	3	0	1	0	0	11
Total	1	4	4	11	9	16	22	10	6	4	1	88

The figures in the table indicate the numbers of Ama which used a certain size of counterweight. From the unpublished data of Teruoka et al.

The typical diving pattern of the Cachido's unassisted dive was taken from the report by Hong *et al*⁽⁴⁾. There is probably no significant difference between the Japanese Cachido and the Korean Ama as far as the diving schedule is concerned. The average descending and ascending velocities are about 0.57 meters/second. She can reach depths of 11 meters and remain submerged for 45 seconds. However, as shown in Table II (Cachido B) such a dive is inefficient since there

TABLE II
The Typical Diving Schedule of Cachido⁽⁴⁾ and Funado⁽¹⁰⁾

	Cachido (A)	Cachido (B)	Funado
Depth (m)	5	11	21
Descending velocity (m/sec)	0.57	0.57	*
Ascending velocity (m/sec)	0.58	0.58	
Diving time (sec)	30	45	58
Time for descent (sec)	8.8	19	17
Bottom time (sec)	12.6	7	28
Time for ascent (sec)	8.6	19	13

*Detailed values are given elsewhere.

is little bottom time. More typical is the pattern for Cachido A where a depth of 5 m is reached and the total diving time is 30 seconds. These values will be used for the computation of energy expenditure. It should be emphasized that throughout part of the Cachido's dive there is extra energy cost for overcoming her positive buoyancy as well as maintaining her diving velocities. In Table III additional physical characteristics are listed which must be considered in the over-all mechanics and energy requirements of diving.

Drag in Underwater Movements

To discuss the dynamics of the underwater movement one has to know the drag resistance of the body under any given condition. Craig (unpublished observations) measured the force necessary to tow the subject with a boat. The subjects assumed the diving position but they were horizontal and were one meter below the surface. They were counterweighted to obtain zero buoyancy. The drag forces were read from a recording strain gauge while the subjects were towed 30 meters,

TABLE III
Some Basic Characteristics used for the
Analysis of Diving Dynamics

The physical characteristics of a representative Ama:	
Age	30
Height	155 cm
Body weight in air	50 kg
Specific gravity.	1.040
Body volume	48.1 liters
Lung volumes:	
VC	3500 ml
RV	1200 ml
TLC	4700 ml
FRC	2200 ml
IC	2500 ml
RV/TLC	25.5%
Total lung volume before dive	3000 ml or 4200 ml
Calculated depth of neutral buoyancy	3.4 m or 5.3 m
The density of sea water of salinity of 3.5 ‰ at 22°C	1.024
Counterweight in sea water used by Funado	10 kg
The specific gravity of the counterweight	8.0 kg

and repeated observations were made at different constant velocities. The values indicated by the strain gauge directly gives the drag resistance of the body to a particular speed (Fig. 1).

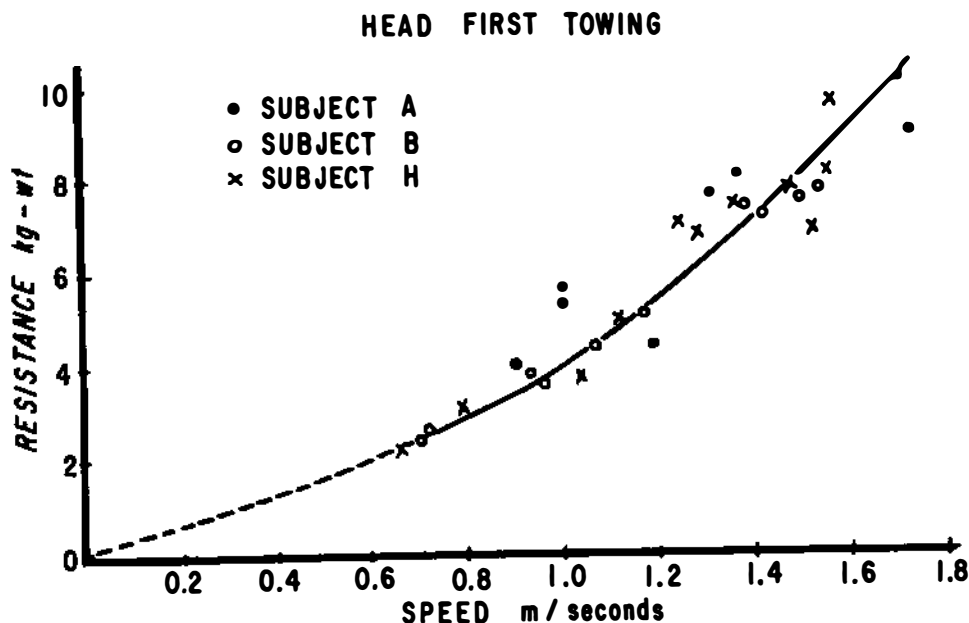


Figure 1. Drag Resistance in the Head-First Towing. (Craig, A. B. Unpublished data).

The drag, R , is considered to be equal to the drag coefficient, k , multiplied by n -th power of the towing speed, v :

$$R = k \cdot v^n.$$

This drag coefficient k is independent of the towing speed and is considered to be the all-inclusive parameter representing the resistance coefficient and the cross-section area of the body as well as the Reynolds' numbers, etc. The n -value depends on the speed and may be larger at higher speed of towing. The drag, the drag coefficient, and the n -value during the head-first towing are shown in Table IV. The drag coefficient for the latter condition was a little smaller than for the former.

Experimental dives were also done to measure the drag resistance. The subjects carried various sizes of counterweights and descended in the foot-first position along the rope installed vertically at the side of the boat. The depth of the subject was recorded continuously so that one can calculate the speed and the rate of acceleration of the subject during passive descent.

The movement of the subject may be indicated by the following differential equation:

$$(m + m') \frac{dv}{dt} = (m + m') g - R$$

TABLE IV

Resistance Characteristics in the Towing Experiments
 (Drag) = (Drag Coefficient) x (Towing Speed)ⁿ

towing speed	head-first towing			foot-first towing		
m/sec	drag-kg	n	drag coeff = k	drag-kg	n	drag coeff = k
0.8	2.89	1.22	4.48	3.92	1.22	5.14
0.9	3.33	1.21	4.29	4.67	1.35	5.38
1.0	3.82	1.24	3.82	5.56	1.45	5.56
1.1	4.52	1.35	3.98	6.48	1.47	5.65
1.2	5.18	1.38	4.03	7.44	1.48	5.69
1.3	6.10	1.47	4.14	8.64	1.54	5.77
1.4	7.00	1.51	4.22	9.76	1.55	5.79
1.5	7.85	1.52	4.24	11.20	1.60	5.86
1.6	8.75	1.61	4.11	-	-	-
1.7	9.85	1.57	4.29	-	-	-
	mean drag coefficient = 4.16			mean drag coefficient = 5.61		

where m indicates the effective body weight at any depth, m' the size of the counterweight, v the descending velocity, g the acceleration constant, and R the drag.

Since the velocity and the acceleration are known, one can compute the drag upon the foot-first passive dive with this differential equation. The experimental results on a young U. S. girl using different sizes of the counterweight are shown in Figure 2. The computed drag coefficient was found to remain nearly unchanged throughout her passive descent with the counterweights ranging from 5.5 kg to 13.6 kg. These values are essentially identical with that obtained in the previously described towing experiments.

Assisted Dive of Funado

The typical descent patterns indicating the diving velocity in terms of the depth are shown in Figure 3, which was taken from Teruoka's paper⁽¹⁰⁾. As seen in this figure the velocities reached are similar to the values obtained in the previously described experimental dives. As shown in Figure 4, the drag increased gradually as the Ama went deeper and obtained higher descent velocity. Furthermore, the calculated drag coefficient is unusually large during the beginning of her dive. This coefficient as calculated for the Funado probably includes other forces such as those for acceleration and any added resistance due to purposeful movement of the diver. It therefore represents an apparent coefficient which differs from that given in Table IV. This apparent drag coefficient decreased rapidly in the first three or four seconds, to be followed by slow change during the successive four to five seconds. The coefficient revealed rapid increase when the Ama approached the bottom.

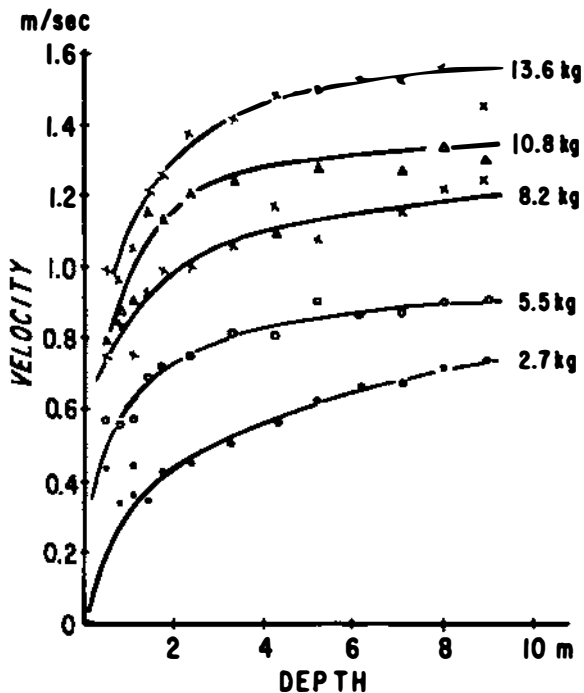


Figure 2. The Depth and the Descent Velocity in the Foot-First Passive Dives. Each line indicates a dive carrying different sizes of the counterweight. Figures on the right of each curve indicate the weight (measured in water) of the counterweight. (Craig, A. B. unpublished data.)

After staying at the bottom for a certain period, say 28 seconds according to our typical diving program, the Ama signals her partner to pull her up. As soon as he receives the signal he starts pulling her up with the rope, which goes through a pulley on the side of the boat. While the Ama remains passive her partner now has to supply the extra work. The force necessary for this job can be estimated by solving the following differential equation and allows one to compute the work necessary for the partner.

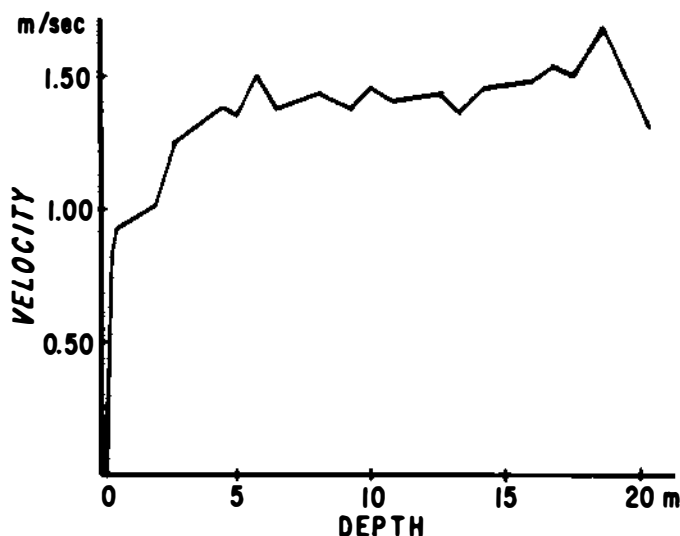


Figure 3. A Representative Tracing of the Funado's Assisted Descent, Showing the Relation between the Depth and the Descending Velocity⁽¹⁰⁾.

$$m \frac{dv}{dt} = F - mg - R$$

$$\text{if } \frac{dv}{dt} = 0$$

$$F = mg + R$$

In this equation F indicates the force which should be applied by the partner. To pull the Ama up the partner must first exert a force necessary to overcome the diver's inertia as well as to overcome resistance offered by the water. Thereafter, if the applied force is constant, the velocity will increase as the lungs re-expand and the specific gravity decreases. The authors computed the work which should be done by the partner assuming an efficiency of 20 per cent. The maximum power is 131 watts in the first second of

pulling the Ama up and decreases to 102 watts; the average power would be 121 watts.

It is of interest to point out that under steady state exercise with a crank ergometer it would be difficult to maintain a work load greater than 100 watts⁽¹⁾. How to compare this with the transient load of 100 watts of the diving partner is difficult to evaluate.

The partner, in addition to this work, has to pull up the counterweight while the Ama takes her rest, floating at the side of the boat. The partner must also row the boat and maintain it on the same spot. The total energy expenditure for the partner, therefore, might be the same as the work of the Ama herself. Thus, while the partner remains on board while the Ama is diving to get the harvest, he is also required to do considerable work.

The total excess work for the Funado to perform the 21 meters dive is estimated to be only 2715 calories to meet the energy expenditure during her swim on the bottom. This energy expenditure during her bottom swim will be discussed later. Either for descent or ascent she does not do any excess work for her movement.

Unassisted Dive of Cachido

The Cachido swims down to five or ten meters of depth by herself, overcoming her positive buoyancy as well as her drag resistance. The equation of her

movement is

$$m \frac{dv}{dt} = F + mg - R.$$

In the equation, F indicates the force she has to apply to descend at a given velocity indicated by our standard diving schedule. If one can assume the descending velocity to be constant, the force, F , could be obtained through this differential equation. By integrating the force with time, one can also compute the work necessary during her unassisted descent. The computed values are shown in Table V.

For her ascent she also has to work to obtain her indicated ascending velocity. The following differential equation indicates her movement during her unassisted ascent:

$$m \frac{dv}{dt} = F - mg - R.$$

When the Cachido (B) dives with her lung volume of 3000 ml, the work necessary for her active descent would be 38.4 kg m, or 3000 cal and for her active ascent, 8.5 kg m, or 664 cal. If the Cachido (B) dives with a lung volume of 4200 ml, her positive buoyancy is greater than that in the previous case. In this case on ascent the force which must be applied by herself may decrease to zero at the particular depth (neutral buoyancy) before she reaches the surface. Above this depth her positive buoyancy force will increase and aid in the ascent. Her work for descent was calculated as 47.5 kg m, or 3710 cal and that for ascent as 2.6 kg m, or 203 cal.

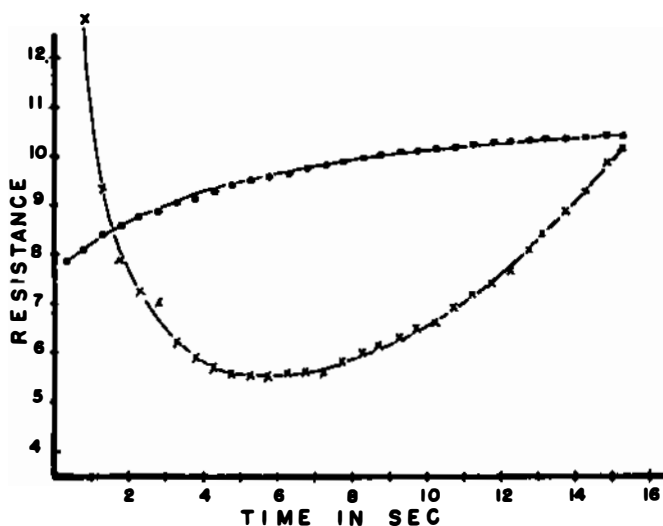


Figure 4. Change in the Drag Resistance and in the Drag Coefficient During the Funado's Descent. The values were computed from Teruoka's data shown in Figure 1. ●—●—● drag; x—x—x apparent drag coefficient.

In Table V the authors have also shown the calculated energy expenditure for the unassisted dives to five meters in depth.

TABLE V

Energy Expenditure During the Dive

		Cachido (A)	Cachido (B)		Funado	
depth		5 meters	11 meters		21 meters	
diving time		30 seconds	45 seconds		58 seconds	
gas volume		3000 ml	3000 ml	4200 ml	3000 ml	4200 ml
Descent	kg m	19.6	38.4	47.5	0	0
	efficiency	3.0 %	3.0%	3.0%	-	-
	cal	1530	3000	3710	0	0
	VO ₂ in ml	317	622	768	0	0
Bottom	kg m	23.2	12.3	12.3	34.8	34.8
	efficiency	3.0%	3.0%	3.0%	3.0%	3.0%
	cal	1726	959	959	2715	2715
	VO ₂ in ml	357	199	199	562	562
Ascent	kg m	1.8	8.5	2.6	(160+210)	(146+210)
	efficiency	3.0%	3.0%	3.0%	(20.0%)	(20.0%)
	cal	141	664	203	(1870+2454)	(1706+2454)
	VO ₂ in ml	29	138	42	(387+508)	(353+508)
	VO ₂ at rest (ml)	150	225	225	290	290
	VO ₂ for a a dive, (ml)	853	1184	1234	852	852

Figures in the parenthesis indicate the work done by the partner.

Energy Expenditure During the Bottom Swim

During horizontal underwater swimming on the bottom, the total force, F , which is necessary to maintain any particular speed is her drag resistance, F_1 , as well as her buoyancy, F_2 . These are related as follows:

$$F = \sqrt{F_1^2 + F_2^2}$$

The efficiency for the underwater swimming, which is defined as the ratio of the caloric equivalent of effective work performed and oxygen consumption above the resting value, as reported by Goff et al⁽³⁾, was measured to be very low, ranging between 1.2 and 5.6 per cent. These values were obtained with the fin swimmers. Although the Ama does not use the swimming fin for her dives, she does a very particular type of swimming, "ONNA-OYOGO" (swimming of Ama style) which is considered to be efficient enough for her underwater activities. A tentative value of three per cent for swimming efficiency of the Ama was used to compute the energy expenditure.

Theoretically one can compute the effective work by converting the drag resistance at various given speeds to kilogram-meters and computing the caloric equivalents. Since there is no precise information on the swimming speed on the bottom, one can only estimate the energy expenditure of the Ama during her bottom swim as a first approximation. Using the data presented in the U.S. Navy Diving Manual⁽¹¹⁾, the energy expenditure per unit time for Funado was tentatively assumed to be 121, and for Cachido to be 161 cal/second. As the Funado at the depth of 20 meters may not have any significant positive buoyancy, the energy for her underwater swimming may be spent just to maintain her swimming speed. The value tentatively assumed for Funado corresponds to the swimming speed of 0.45 meters/ second and that for the Cachido was estimated to be a little larger because of her positive buoyancy. The energy expenditure for the Cachido (A) to stay at the depth of five meters for 12.6 seconds is estimated to be 1726 cal and for the Cachido (B) to stay at the bottom for seven seconds to be 959 cal. The energy expenditure of the Funado to stay for 28 seconds was estimated to be 2715 cal.

Total Oxygen Consumption During the Dive and the Oxygen Debt

The changes of the alveolar gas composition during the dive are discussed elsewhere in these proceedings. During repeated dives there are already some available data on the alveolar or the expired gas composition, which enable us to compute the alveolar gas exchange during the breath-hold diving^(4, 10). The data are shown in Tables VI and VII. As can be seen in Table VI, Teruoka computed the oxygen uptake during the dive, but he had disregarded the amount of oxygen removed from the residual air⁽¹⁰⁾. If one takes the average alveolar gas composition before the dive listed in Table VII and the total gas volume before the dive to be 3000 ml, the oxygen uptake during a Funado's dive would average 303 ml. If the total lung volume is assumed to be 4200 ml, the oxygen uptake would be 424 ml. During the unassisted Cachido's dive the oxygen uptake would be between 325 and 450 ml.

TABLE VI

Gas Exchange During and After the Funado's Dives

			gas exchange during the dive			gas exchange after the dive				
	depth	diving time	vol of gas expired	$F_A O_2$	VO_2^*	no. of breaths	time, collected	V_T	\dot{V}_E	$\dot{V}O_2$
	<u>m</u>	<u>sec</u>	<u>ml</u>	<u>per cent</u>	<u>ml</u>		<u>sec</u>	<u>ml</u>	<u>l/min</u>	<u>ml/min</u>
Ama A	18.7	34	1675	7.09	231	4	30	2000	16.02	833
	25.0	42	2001	7.69	224	4	30	1930	15.44	702
	20.5	49	1279	7.35	173	5	33	1686	15.36	783
	22.6	56	2253	9.77	251	2	16	1886	14.86	685
	16.5	61	1361	6.29	206	5	32	1604	15.06	920
	19.5	61	1810	4.70	202	4	30	1955	15.63	964
	24.9	65	1880	11.32	180	4	32	1888	14.15	858
	15.5	67	924	4.65	150	5	40	1884	14.12	848
	21.5	70	1374	8.38	173	5	40	2043	15.31	828
	19.8	71	1393	5.23	218	5	38	1926	15.22	694
	9.0	118	1576	5.29	246	4	22	1763	19.20	1195
Ama B	14.7	51	2130	6.69	303	4	30	2525	20.19	1019
	9.0	53	1634	8.67	200	1	-	1718	-	-
	24.0	56	1816	7.18	249	5	37	1954	15.86	885
	8.5	57	1932	7.18	265	2	-	1715	-	-
	22.5	59	1657	5.91	248	5	37	1956	15.85	1042
	20.5	65	2001	4.19	336	4	34	1896	13.41	990
	13.5	87	1532	3.30	270	4	35	1986	13.64	839
	14.1	95	1934	6.09	286	4	32	2025	15.16	859
	12.9	95	2069	3.66	357	3	31	1865	10.82	725

Figures indicating the gas volumes are shown in ATPS.

* VO_2 during the dives indicates the oxygen uptake per single dive. From Teruoka, G. (10) and his unpublished data for the gas exchange after a dive.

TABLE VII
Alveolar Gas Composition Before, During, and After Dives⁽⁴⁾

subject	depth	duration of dive	F _A O ₂	F _A N ₂	F _A CO ₂
	<u>m</u>	<u>sec</u>	<u>per cent</u>	<u>per cent</u>	<u>per cent</u>
<u>Resting on land</u>					
mean	-	-	14.3	80.5	5.2
<u>In water, before dive</u>					
mean	-	-	16.7	79.3	4.0
<u>Under water</u>					
mean	8.2	39	11.1	85.7	3.2
<u>After dive</u>					
A	12.5	50	3.9	89.4	6.7
	10.5	45	6.4	88.2	5.4
	11.0	49	7.4	87.2	5.4
B	12.0	37	6.3	88.3	5.4
	9.7	41	6.1	87.5	6.4
	10.0	47	5.3	88.4	6.3
mean	11.0	45	5.9	88.2	5.9

According to the authors' calculations (Table V), the oxygen consumption for the unassisted dive to five meters should be about 850 ml and for the 11-meter dive, 1200 ml. The oxygen consumption for the Funado's dive was estimated at 850 ml.

If these estimates are correct, the difference between the measured oxygen uptake and the estimated oxygen consumption will indicate the oxygen debt produced during a dive. The rough calculation shows the oxygen debt for the Cachido's five-meter dive to be 450 ml and for the Cachido's 11-meter dive to be 800 ml. The oxygen debt for the Funado's dive would be about 500 ml. The oxygen debt during a dive may be covered partly by the oxygen stored in the body and partly by the anaerobic oxidation. It is difficult to estimate the amount of the stored oxygen consumed. It is also difficult in practice to measure the amount of lactic acid produced through the anaerobic oxidation during this particular period of diving; but, nevertheless, the oxygen debt should be recovered while the Ama is resting at the surface between dives. These are some unpublished data by Teruoka indicating an increased oxygen uptake during her slow and deep ventilation of 30 to 40 seconds after surfacing. The data are shown on the right of Table

VI. These particular data were collected on the Funado and show that an oxygen debt of 500 ml could be recovered in one minute while she is resting at the surface.

This rough calculation explains well the observed diving pattern of the Funado, who usually spends one minute for a dive followed by a one-minute rest at the surface. There is an interesting observation by Nukada⁽⁷⁾ which indicates that the resting times between each dive become longer during her shift, as shown in Figure 5. As can be seen in the figure, the resting time at the beginning of the shift was between 40 to 60 seconds, while at the last part of the shift it appeared to be longer than 70 seconds. In their computation of the energy expenditure the authors neglected the excess work to collect the harvest at the bottom and also the work of bringing the harvest up to the surface so that the oxygen consumption during the dive may possibly be underestimated.

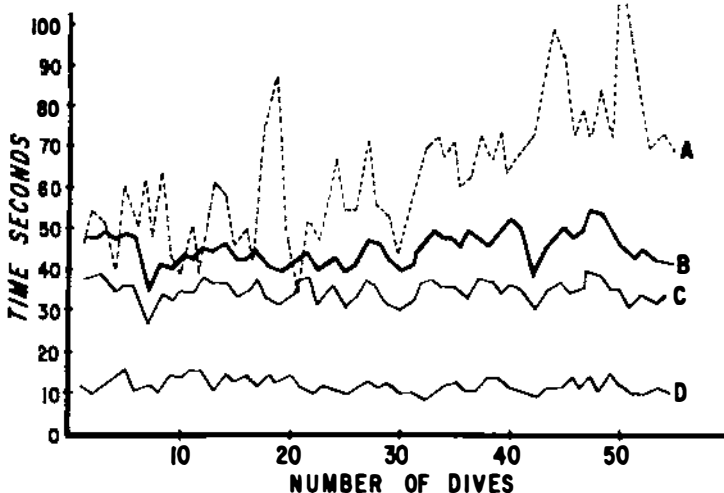


Figure 5. The Diving Time and the Resting Time of the Ama During a 55-Minute Shift of Diving Activities. Line A indicates the resting time, line B the total diving time. Lines C and D indicate the subdivisions of the diving time. Line D indicates the time for descent; distance C - D indicates the the bottom time, and distance B - C indicates the time for ascent. From Nukada⁽⁷⁾.

Kang et al⁽⁵⁾ made repeated measurements of the oxygen uptake and noted the tremendous and immediate increase of the oxygen uptake when the Ama entered the water, followed by a further increase during the diving period. This increase of

the oxygen uptake was much greater in winter and may be partly accounted for by the elevated metabolism related to the heat loss of the body in the cold environment. This increase suggests a possible accumulation of the oxygen debt. Taking these factors into consideration, repeated dives every other minute may produce an accumulating oxygen debt so that the Ama has to stay increasingly longer at the surface between dives.

In the Cachido's unassisted dives the oxygen debt produced in a single dive to five meters was estimated to be 450 ml. The Cachido usually repeats her dive every minute, spending 30 seconds underwater and another 30 seconds at the surface. If one could assume the resting oxygen uptake to be maintained at 300 ml/min, the Cachido when resting at the surface has to take up oxygen at a minimum rate of 1200 ml/min to recover the oxygen debt. Through such rough calculations

one can easily expect the accumulation of the oxygen debt which may account for the increased oxygen uptake occurring in the course of a work shift. The observation during the shift of the Cachido's repeated dives, done by Kang *et al*⁽⁵⁾, is summarized in Table VIII.

TABLE VIII
 Oxygen Consumption During the Period
 of Diving Work (ml/min, STPD)

season	water temp.	air temp.	before dive	minutes in water					
				5	10	15	20	25	40
summer	22-26C	30C	454	-	847	801	-	975	960
winter	10-13C	5-9C	388	1090	940	1238	1136	1395	-

Summarized from the data in Kang, D. H., *et al*⁽⁵⁾.

In the case of the Cachido's unassisted dives of 11 meters the Ama has to have enough time to rest at the surface, possibly more than two minutes, to recover her oxygen debt. This is indicated by the observations on the diving schedule of two Korean unassisted divers described by Hong *et al*⁽⁴⁾ as shown in Table IX.

TABLE IX
 Diving Schedule of Two Korean Unassisted
 Divers for an 11 Meter Dive

	Ama A	Ama B
No. of dives/hr	19	18.5
Average length of single dive, sec.	59	49
(a) time for descent	9	10
(b) working time	41	29
(c) time for ascent	9	10
Average length of rest between two dives, sec.	130	146

CONCLUSION

The diving activities of the Cachido and of the Funado are discussed from their dynamic aspects. Although the computations were based upon certain assumptions, the estimated energy expenditure during various types of diving enabled us to analyze the diving activities done in either type of diving.

It is interesting to learn that, as far as the energy expenditure is concerned, the Funado's 20 meter assisted dive is almost equivalent to the Cachido's five-meter unassisted dive. In our standard diving schedule the Cachido, who does the five-meter unassisted dive, will repeat her dives every minute spending 30 seconds in diving and 30 seconds at rest, while the Funado, who is assisted in her dive to 20 meters, will repeat her dive every other minute, spending 60 seconds for diving and another 60 seconds for rest. When the Ama continue their repeated dives, the Cachido will dive twice for every single dive of the Funado. Since the bottom time for the Cachido is 13 seconds and that for the Funado is 28 seconds, the total bottom time for a given period of activity will be almost the same. If one looks at these diving activities with regard to the energy expenditure, the Cachido will consume twice the energy of the Funado for the same total bottom time. In comparing these two divers, one has also to consider the energy consumed by the Funado's partner which is almost equivalent to the energy consumed by the Funado herself. When considering the energy consumption of the Ama herself, the Funado assisted dive is almost twice as efficient as that of the Cachido for the same bottom time. But when considering the total energy consumption of the Funado and her partner, the over-all energy requirements for a given bottom time are almost equivalent between the assisted and the unassisted dives. Under such circumstances the Funado is able to work at depths to 20 meters, while the Cachido is only able to reach the five-meter depth. To reach deeper with the unassisted dive the efficiency of diving, which may be expressed as the length of the bottom time for certain amounts of the total energy expenditure, would become less.

As far as the diving dynamics are concerned, it is obvious that the Funado's assisted dives are much more efficient than the Cachido's unassisted dives.

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