Effect of Glycemic Index and Fructose Content in Mixed Meals on Substrate Utilization During Subsequent Brisk Walking

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ABSTRACT

The aims of this thesis were to, first, determine the glycemic index (GI) of traditional Chinese foods, and second, to investigate the effect of GI and fructose content in pre-exercise mixed meals on substrate utilization during subsequent brisk walking.

Study I (Chapter 4) determined the GI values of 29 traditional Chinese foods. Fifteen healthy adults (eight males and seven females; mean ± SEM: age, 25.4±1.2 year; BMI, 21.2±0.6 $kg \cdot m^{-2}$) volunteered to participate in the study. All subjects consumed either 50 g of glucose or one of 29 test foods containing 50 g of available carbohydrate (CHO) after 10-14 hrs overnight fast. Capillary blood glucose concentrations were analyzed immediately before food consumption and 15, 30, 45, 60, 90, and 120 min after consumption. The GI value of each test food was calculated by expressing the incremental area under the blood response curve (IAUC) value of glucose for the test food as a percentage of each subject's average IAUC value for the glucose. Among the 29 test foods, seven were classified as low-GI foods (i.e., Tuna Fish Bun, Egg Tart, Green Bean Dessert, Chinese Herbal Jelly, Fried Rice Vermicelli in Singapore-style, Udon Noodle, and Spring Roll), 13 as moderate-GI foods (i.e., Baked Barbecued Pork Puff, Fried Fritter, "Mai-Lai" Cake, "Pineapple" Bun, Fried Rice Noodles with Sliced Beef, Barbecue Pork Bun, Moon Cakes, Glutinous Rice Ball, Instant Sweet Milky Bun, Shanghai Noodle, Rice Vermicelli, Instant Noodle, and Salted Meat Rice Dumpling), and the remaining nine as high-GI foods (i.e., Fried Rice in Yangzhou-Style, Sticky Rice Wrapped in Lotus Leaf, Steamed Glutinous Rice Roll, Jam and Peanut Butter Toast, Plain Steamed Vermicelli Roll, Red Bean Dessert, Frozen Sweet Milky Bun, Shrimp Egg Noodle, and Spinach Noodle). The results of this study provided valuable information to both researchers and the general public on their food preference. A number of the food items in the present study were used in subsequent works, namely, Study II and Study III.

Study II (Chapter 5) investigated the effect of GI and fructose content in breakfast on substrate utilization during subsequent brisk walking. Ten healthy young males (mean ± SEM: age, 21.7±1.5 year; BMI, 20.9±1.1 $kg \cdot m^{-2}$; $\dot{V}O_{2max}$, 53.7±3.7

$mL \cdot kg^{-1} \cdot min^{-1}$) volunteered to participate in the study. All subjects completed 60-min of 46% $\dot{V}O_{2max}$ brisk walking 2-hrs after consuming one of three breakfast meals: a low-GI meal without fructose (LGI), a low-GI meal including fructose beverage (LGIF) and a high-GI meal (HGI). The three main trials were completed in a counterbalanced crossover design. Calculated GI values for LGI, LGIF, and HGI breakfast meals were 41, 39, and 72, respectively. These three isocaloric breakfast meals provided 1.0 $g \cdot kg^{-1}$ body weight CHO for each subject and approximately 20% energy from fat, 17% from protein, and 63% from CHO. In the LGIF and HGI trials, approximately 25% of energy came from either fructose or glucose beverage. Substrate utilization was measured using indirect respiratory calorimetry method. Capillary blood samples and venous blood samples were collected at certain time points during the experiment. During the postprandial period, IAUC values of glucose and insulin were higher ($p<0.05$) in the HGI trial, compared with those in the LGI and LGIF trials (HGI vs. LGI and LGIF: glucose, 223.6±19.1 vs. 70.2±7.4 and 114.1±16.4 $mmol \cdot min \cdot L^{-1}$; insulin, 4257±932 vs. 920±319 and 1487±348 $mU \cdot min \cdot L^{-1}$). During brisk walking, no difference was observed in substrate utilization between LGIF and HGI trials. Nevertheless, decreased CHO oxidation and increased fat oxidation were found ($p<0.05$) in the LGI trial when compared with the other two trials (LGI vs. LGIF and HGI: CHO, 59.3±2.4 vs. 69.8±3.9 and 72.7±3.9 g; fat, 22.7±2.0 vs. 18.5±1.7 and 17.6±1.3 g). In conclusion, compared with LGI breakfast meal without fructose, either HGI breakfast meal or the presence of fructose in a similar LGI breakfast meal decreased fat oxidation and increased CHO oxidation during subsequent brisk walking. Therefore, it appeared that both GI and fructose content in a breakfast individually affected substrate utilization during subsequent moderate intensity exercise.

Study III (Chapter 6) investigated the effect of GI and fructose content in lunch meal on substrate utilization during subsequent brisk walking. Ten healthy young male adults (mean ± SEM: age, 20.5±1.0 year; BMI, 20.8±0.7 $kg \cdot m^{-2}$; $\dot{V}O_{2max}$, 48.6±1.9 $mL \cdot kg^{-1} \cdot min^{-1}$) were recruited to participate in the study. All subjects were required to complete three main trials in a counterbalanced crossover design. The subjects completed 60-min of brisk walking at approximately 50% of individual $\dot{V}O_{2max}$ after consuming a standard breakfast meal and one of three lunch meals, i.e., a low-GI meal without fructose (LGI), a low-GI meal including fructose beverage (LGIF), or a

high-GI meal (HGI). Calculated GI values for LGI, LGIF, and HGI lunch meals were 41, 39, and 72, respectively. All lunch meals provided 1.0 $g \cdot kg^{-1}$ body weight CHO for each subject and approximately 20% energy from fat, 17% from protein, and 63% from CHO. In the LGIF and HGI trials, approximately 25% of energy came from either fructose or glucose beverage. Substrate utilization was measured using indirect respiratory calorimetry method. Capillary blood samples and venous blood samples were collected at certain time points during the experiment. During the postprandial period after lunch, IAUC values of glucose and insulin were higher ($p<0.05$) in the HGI trial, compared with those in the LGI and LGIF trials (HGI vs. LGI and LGIF: glucose, 223.5±24.4 vs. 92.5±10.4 and 128.0±17.7 $mmol \cdot min \cdot L^{-1}$; insulin, 3603±593 vs. 1425±289 and 1888±114 $mU \cdot min \cdot L^{-1}$). During brisk walking, decreased CHO oxidation was found ($p<0.05$) in the LGI trial when compared with the LGIF and HGI trials, whereas no difference was found between the latter two trials (LGI vs. LGIF and HGI: 60.8±4.0 vs. 68.1±6.0 and 74.4±4.7 g). No difference was observed in fat oxidation among the three trials (LGI vs. LGIF vs. HGI: 21.6±2.3 vs. 19.2±2.3 vs. 16.4±2.2 g). In conclusion, compared with a LGI lunch meal without fructose, either a HGI lunch meal or the presence of fructose in a LGI lunch meal induced more CHO oxidation during subsequent brisk walking. However, no differences were found in fat oxidation among the three trials, although there was a trend to be higher in the LGI trial than in the LGIF and HGI trials. Consumption of a standard breakfast appeared to reduce the effect of pre-exercise lunch meals with different GI and fructose content on substrate utilization during subsequent moderate intensity exercise to a certain degree.

According to the results of the studies conducted in this thesis, both GI and fructose content of pre-exercise mixed meals could individually affect substrate utilization during subsequent moderate intensity exercise. Furthermore, a slight difference was observed in this effect when meals were consumed after a standard breakfast and 4-hrs of fasting compared with when these were consumed after an overnight fast. The findings of this thesis enhance the understanding of the effect of pre-exercise CHO consumption on substrate utilization during subsequent moderate intensity exercise. The results likewise provide practical information for those who exercise for health or weight management.

摘要

本論文的研究目的包括：(1) 測試部分傳統中國食物的血糖指數；(2) 研究運動前混合飲食的血糖指數以及果糖含量對於進食後快步走過程中底物代謝的影響。

研究一 (第 4 章) 測試了 29 種傳統中國食物的血糖指數。15 名健康成年人自願參與本實驗 (8 名男性和 7 名女性，平均值 ± 標準誤：年齡 25.4±1.2 歲，身高體重指數 21.2±0.6 $kg \cdot m^{-2}$)。經過 10-14 小時空腹之後，所有受試者攝入 50 克葡萄糖或者含有 50 克可吸收碳水化合物的 29 種測試食物中的一種。食物攝入前即刻，攝入後 15 分鐘、30 分鐘、45 分鐘、60 分鐘、90 分鐘、以及 120 分鐘採集指尖毛細血管的血液測試葡萄糖濃度。每種食物的血糖指數通過計算攝入該食物後血糖反應曲線下面積 (IAUC) 占該受試者進食葡萄糖後血糖反應曲線下面積的百分比而得到。結果顯示，在所有的 29 種測試食物當中，7 種屬於低血糖指數食物 (吞拿魚包、蛋撻、綠豆沙、龜苓膏、星洲炒米、烏冬面和春卷)，13 種屬於中等血糖指數食物 (叉燒酥、油炸鬼、馬來糕、菠萝包、干炒牛肉河粉、叉燒包、月餅、湯圓、即食奶皇包、上海面、米粉、公仔面和鹹肉粽)，其餘屬於高血糖指數食物 (揚州炒飯、糯米雞、糯米卷、占醬多士、素腸粉、紅豆沙、速凍奶皇包、鮮蝦雞蛋面以及菠菜面)。本研究結果可以爲研究人員或者普通公眾選擇食物時提供一些有價值的資訊。部分研究結果亦應用於本論文中以下兩項實驗之配餐。

實驗二 (第 5 章) 研究了早餐中混合食物的血糖指數及果糖含量對於進食後快步走過程中底物代謝的影響。10 名健康年輕男性參與了本項研究 (平均值 ± 標準誤：年齡，21.7±1.5 歲; 身高體重指數，20.9±1.1 $kg \cdot m^{-2}$; 最大攝氧量，53.7±3.7 $mL \cdot kg^{-1} \cdot min^{-1}$)。所有受試者均要求在早餐後 2 小時完成 60 分鐘快步走，運動強度大約是 46%個人最大攝氧量。本項研究中共有三種不同的早餐：一種是不含果糖的低血糖指數早餐 (LGI)，一種是含有果糖飲料的低血糖指數早餐 (LGIF)，還有一種是高血糖指數早餐 (HGI)。三次主實驗採用平衡交叉設計。三種早餐計算得到的血糖指數值分別爲 41，39 和 72。所有的早餐將會爲受試

者提供每公斤體重 1 克碳水化合物。每一種早餐當中大約有 20% 的能量來自於脂肪，17%來自於蛋白質，另外還有 63%來自於碳水化合物。在 LGIF 和 HGI 組當中，大約有 25%的能量來自於果糖或者葡萄糖飲料。底物代謝的計算使用間接測熱法獲得。毛細血管血液樣本以及靜脈血液樣本在實驗當中特定的時間點被收集。實驗結果顯示：在餐後 2 小時內，HGI 組血糖以及血胰島素反應曲線下面積要顯著高於 LGI 和 LGIF 組 ($p<0.05$, HGI vs. LGI & LGIF: 葡萄糖, 223.6±19.1 vs. 70.2±7.4 & 114.1±16.4 mmol·min·L^{-1}；胰島素，4257±932 vs. 920±319 & 1487±348 mU·min·L^{-1})。在餐後快步走過程中，LGIF 組與 HGI 組底物代謝情況比較相似。然而，與這兩組結果相比，LGI 組碳水化合物氧化減少而脂肪利用增加 ($p<0.05$, LGI vs. LGIF & HGI：碳水化合物，59.3±2.4 vs. 69.8±3.9 & 72.7±3.9 g；脂肪, 22.7±2.0 vs. 18.5±1.7 & 17.6±1.3 g)。研究結果提示：與不含果糖的低血糖指數早餐相比，高血糖指數早餐或者相似低血糖指數早餐中果糖的存在均使得餐後快走過程中動員了較多的碳水化合物以及較少的脂肪。因此，早餐食物的血糖指數和果糖似乎均會影響餐後中等強度運動中的底物代謝。

實驗三 (第 6 章) 研究了午餐中食物的血糖指數及果糖含量對於進食後快步走過程中底物代謝的影響。10 名健康年輕男性自願參與本項研究 (平均值 ± 標準誤：年齡，20.5±1.0 歲; 身高體重指數，20.8±0.7 kg·m^{-2}; 最大攝氧量，48.6±1.9 mL·kg^{-1}·min^{-1})。所有的受試者均完成了採用平衡交叉設計的三次主實驗。一個標準早餐及一種午餐之後，所有受試者進行了 60 分鐘的快步走，運動強度大約是 50%個人最大攝氧量。三種等能量的午餐用於此項研究，它們分別是：不含果糖的低血糖指數食物 (LGI)，包含果糖飲料的低血糖指數食物 (LGIF)，以及高血糖指數食物 (HGI)。三種午餐計算得到的血糖指數值分別爲 41，39 和 72。所有的午餐將會爲受試者提供每公斤體重 1 克碳水化合物。午餐當中脂肪供能大約占總能量的 20%，蛋白質供能約 17%，碳水化合物供能約 63%。在 LGIF 和 HGI 組當中，大約有 25%的能量來自於果糖或者葡萄糖飲料。底物代謝的計算使用間接測熱法獲得。毛細血管血液樣本以及靜脈血液樣本在實驗中特定的時間點被收集。實驗結果顯示：在午餐後 2 小時內，HGI 組血糖以及血胰島素反應曲線下面積要高於 LGI 和 LGIF 組 ($p<0.05$, HGI vs. LGI & LGIF：葡萄糖,

223.5±24.4 vs. 92.5±10.4 & 128.0±17.7 mmol·min·L^{-1}；胰島素，3603±593 vs. 1425±289 & 1888±114 mU·min·L^{-1})。在快步走過程中，LGI 組碳水化合物氧化要少於 LGIF 組和 HGI 組 ($p<0.05$, LGI vs. LGIF & HGI： 60.8±4.0 vs. 68.1±6.0 & 74.4±4.7 g)，而後兩組之間則沒有顯著性差異。三組之間脂肪氧化量均無顯著性差異 ($p>0.05$, LGI vs. LGIF vs. HGI： 21.6±2.3 vs. 19.2±2.3 vs. 16.4±2.2 g)。上述研究結果提示：與不含有果糖的低血糖指數午餐相比，高血糖指數午餐或者相似低血糖指數午餐中果糖的存在均使得餐後快走過程中動員了較多的碳水化合物。然而，三種不同的午餐並沒有導致運動中脂肪動員的差異，儘管 LGI 組與其他兩組比較有增加的趨勢。標準早餐的存在似乎減輕了不同血糖指數和果糖含量的午餐對於之後中等強度運動時底物代謝的影響。

綜上所述，運動前混合飲食中的血糖指數和果糖含量似乎均會對隨後中等強度運動中的底物代謝產生影響。並且，與較長時間空腹之後進行的試驗結果比較，當食物攝取於一種標準的早餐和 4 小時空腹之後，試驗結果似乎有少許不同。此項研究結果有助於進一步理解運動前補充不同碳水化合物對於中等強度運動過程中底物代謝的影響，並且對於那些希望通過運動來進行健康和體重管理的人來講也提供了一些有價值的參考資訊。

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PUBLICATIONS

The findings presented in this thesis have been reported, in part, in the following publications.

Peer Reviewed Full-Paper

Sun, F.H., Wong, S.H., Chen, Y.J., & Huang, Y.J. Effect of glycemic index and fructose content in lunch on substrate utilization during subsequent brisk walking. ***Applied Physiology, Nutrition, and Metabolism*** (In 2nd review). ***(Impact factor: 2.215)***

Sun, F.H., Wong, S.H., Chen, Y.J., & Huang, Y.J. Substrate utilization during brisk walking is affected by glycemic index and fructose content of a pre-exercise meal. ***European Journal of Applied Physiology*** (In 2nd review). ***(Impact factor: 2.214)***

Sun, F.H., Wong, S.H., Chen, Y.J., & Huang, Y.J. (2010) Evaluation of a glucose meter in determining the glycemic index of Chinese traditional foods. ***Diabetes Technology and Therapeutics***, *12*(3): 193-199. ***(Impact factor: 2.146)***

Chen, Y.J., **Sun, F.H.**, Wong, S.H., & Huang, Y.J. (2010) Glycemic index and glycemic load of selected Chinese traditional foods. ***World Journal of Gastroenterology***, *16*(12): 1512-1517. ***(Impact factor: 2.240)***

Abstracts in Refereed Journals

Sun F.H., Wong S.H., Chen Y.J., & Huang Y.J. (2011) Substrate utilization during brisk walking is affected by glycemic index and fructose content of a pre-exercise meal. ***Medicine & Science in Sports & Exercise***, *43*(5): S410.

Sun F.H., Wong S.H., Chen Y.J., & Huang Y.J. (2010) Glycemic index and glycemic load of selected Chinese traditional foods. ***Medicine & Science in Sports & Exercise***, *42*(5): S229.

Wong S.H., **Sun F.H.**, Chen Y.J., & Huang Y.J. (2009) Determination of the glycemic index of selected Chinese traditional foods using different glucose analyzers. ***Medicine & Science in Sports & Exercise***, *41*(5): S444.

Conference Proceedings

Sun F.H., Wong S.H., Chen Y.J., & Huang Y.J. Effect of glycemic index and fructose content in breakfast on substrate utilization during subsequent brisk walking. Paper presented at ***The 3rd HKASMSS Student Conference on Sport Medicine, Rehabilitation and Exercise Science***, The Chinese University of Hong Kong, Hong Kong, June 19, 2010.

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ABBREVIATIONS

BMI	Body mass index
CHO	Carbohydrate
FFA	Free fatty acid
GI	Glycemic index
GL	Glycemic load
Hb	Hemoglobin
Hct	Hematocrit
HFCS	High fructose corn syrup
HGI	High glycemic index
HR	Heart rate
IAUC	Incremental area under the blood response curve
IMTG	Intramuscular triacylglycerol
LGI	Low glycemic index
LGIF	Low glycemic index meal including fructose beverage
MGI	Moderate glycemic index
PB	Postprandial period after breakfast consumption
PL	Postprandial period after lunch consumption
RAD	Rating of abdominal discomfort
RCT	Randomized controlled trial
RER	Respiratory exchange rate
RPE	Rating of perceived exertion
RPT	Rating of perceived thirsty
TG	Triglyceride

CHAPTER 1

INTRODUCTION

1.1 Background

First introduced by Jenkins et al. (1981), the glycemic index (GI) is regarded as an alternative system for classifying different carbohydrate (CHO) foods. It has been demonstrated that GI was a good summary of postprandial glycemia, and predicted well the peak response, maximum glucose fluctuation, and other attributes of the response curve (Brand-Miller, Stockmann, Atkinson, Petocz & Denyer, 2009). High-GI (HGI) diet consumption appears to be related to several chronic diseases, such as diabetes (Salmeron, Ascherio et al., 1997; Salmeron, Manson et al., 1997), metabolic syndrome (McKeown et al., 2004), cardiovascular disease (Liu et al., 2000), and certain types of cancers (Augustin, Gallus, Negri & La Vecchia, 2004). A Low-GI (LGI) diet may contribute to reduction in body weight (BW) among overweight or obese adolescents (McMillan-Price et al., 2006), coronary heart disease (CHD) (Barclay et al., 2008), and has a small but clinically useful effect on medium-term glycemic control in patients with diabetes (Brand-Miller, Hayne, Petocz & Colagiuri, 2003). Therefore, the GI concept is tightly related to human health.

The relevance of dietary GI remains to be a topic of debate (Atkinson, Foster-Powell & Brand-Miller, 2008). However, the availability of reliable GI table is critical for resolution of the controversy. To date, GI values of several thousands of food items have been determined, and over 2,480 individual food items have been listed in the more recent edition of the international GI table (Atkinson et al., 2008).

Unfortunately, among these food items, only approximately 50 Chinese foods have been selected. Although certain styles are very popular and well-known worldwide, traditional Chinese foods remain to be very different from Western foods.

In studies that investigated the effect of food intake on local people (Hui & Nelson, 2006; Woo et al., 2003), no precise GI values were identified for many local Chinese foods. The researchers had to reply on international GI table to find similar foods or seek for a "best estimate" from experts in this field. These studies indicated certain differences between the estimated GI values and real values. Furthermore, GI values of different local foods have been reported in recent years (Aston, Gambell, Lee, Bryant & Jebb, 2008; Sugiyama, Tang, Wakaki & Koyama, 2003; Yang et al., 2006). Therefore, determining the GI values of traditional Chinese foods is worthwhile to advise local individuals on their daily diets and provide tools for undertaking related studies in this area.

The GI concept likewise introduced a new tool for investigating CHO metabolism in sport science. In recent years, many studies have been conducted to investigate the effect of GI on metabolic responses and/or exercise performance, which has been summarized in recent reviews (Donaldson, Perry & Rose, 2010; O'Reilly, Wong & Chen, 2010; Siu & Wong, 2004). Evidence has been found to support the claim that a benefit existed in relation to endurance performance and capacity when a LGI meal was compared with a HGI meal (O'Reilly et al., 2010; Wong et al., 2008; Wu & Williams, 2006). As for substrate utilization, several studies have reported that LGI meals consumption appeared to result in higher fat oxidation and lower CHO oxidation during subsequent exercise compared with when HGI meals were consumed (Chen, Wong et al., 2008b; Stevenson, Williams, Mash, Phillips & Nute,

2006; Wee, Williams, Gray & Horabin, 1999; Wong et al., 2008; Wu & Williams, 2006). However, in majority of these studies, endurance-trained athletes were used as subjects. More importantly, moderate to high intensity exercise, specifically around 70% maximal oxygen uptakes ($\dot{V}O_{2max}$) or above, was typically used. In any case, CHO metabolism and insulin action after different CHO intake suggested that consideration of food choices before exercise was important due to their potential for influencing substrate utilization acutely during subsequent exercise (Achten & Jeukendrup, 2004; Chen, Wong et al., 2008a; Stevenson, Astbury, Simpson, Taylor & Macdonald, 2009; Wong et al., 2008).

This type of investigation presented merits for ordinary people who intend to reduce body fat mass for health or weight management. Previous studies revealed that moderate intensity exercise, i.e., between 45% and 65% $\dot{V}O_{2max}$, appeared to be most favorable for eliciting substantial short-term increase in fat oxidation (Achten & Jeukendrup, 2003b; Romijn et al., 1993). However, only a few studies used untrained subjects and moderate intensity exercise protocol when investigating the effect of different GI meal consumption on substrate utilization during subsequent exercise. A recent study (Stevenson, Astbury et al., 2009) demonstrated that LGI breakfast consumption produced less CHO oxidation and greater fat oxidation during both postprandial period and subsequent 50% $\dot{V}O_{2max}$ brisk walking, compared with HGI breakfast consumption. However, in another similar study using the same exercise protocol (Backhouse, Williams, Stevenson & Nute, 2007), no significant effect of GI meal on the amount of fat oxidized during exercise was noted. This inconsistent result indicated that further studies were needed to clarify this effect. Furthermore, it resembled more closely the general practice of ordinary people who consume several forms of CHO foods prior to exercise.

Fructose is a type of monosaccharide and one of the most important naturally occurring sweeteners. In the human diet, fructose is consumed in various amounts with fruits, honey, or sugar-sweetened beverages. Recently, consumption of dietary fructose has increased in conjunction with the rising intake of fructose-containing sugars, largely in the form of sugar-sweetened beverages (Marriott, Cole & Lee, 2009; Storey, Forshee & Anderson, 2006). Although fructose can be regarded as LGI CHO (Atkinson et al., 2008), recent evidence suggested that consumption of fructose may be related to the development of obesity, metabolic syndrome, and diabetes (Bray, Nielsen & Popkin, 2004; Johnson et al., 2009). Therefore, it appeared that and fructose content in mixed meals might be an important potential influencing factor when discussing the effect of different GI meals on substrate utilization.

According to earlier studies, compared with glucose beverage that is a well-known HGI CHO, fructose beverage ingestion prior to exercise caused similar substrate utilization during exercise at 60% (Burelle, Peronnet, Massicotte, Brisson & Hillaire-Marcel, 1997; Décombaz et al., 1985; Yannick Guezennec et al., 1989), 70% (Fielding et al., 1987; van Zant & Lemon, 1997), or 75% $\dot{V}O_{2max}$ (Hargreaves, Costill, Fink, King & Fielding, 1987; Hargreaves, Costill, Katz & Fink, 1985). When fructose is consumed as part of a mixed meal, its effect on substrate utilization during subsequent exercise may be more complicated. Results of studies examining the effects of fructose beverage alone may not be applicable to the fructose content in a normal diet. However, there was a paucity of studies, if any, that were conducted to investigate this effect specifically. Therefore, investigating the effect of fructose content in meals on the metabolic responses of humans is a worthwhile endeavor.

In majority of the previously mentioned studies, meals were provided to subjects after an overnight fast to avoid the influence of previous meals consumed before the study. A previous study (Montain, Hopper, Coggan & Coyle, 1991) mentioned that at least 6-hrs of fasting was necessary to induce similar substrate utilization and plasma glucose homeostasis during 70% $\dot{V}O_{2max}$ exercise as a 8-12 hrs of fasting. Therefore, when different GI meals are consumed after an overnight fast or only several hours of fasting (e.g., 3-4 hrs after breakfast), their effect on substrate utilization during subsequent exercise may be different. However, to our knowledge, no studies have been conducted to investigate this specifically.

No consistent results have been derived when a breakfast is consumed several hours before different lunch consumption. A previous study (Sparks, Selig & Febbraio, 1998) found that after a standard breakfast and 4-hrs of fasting, a pre-exercise LGI meal consumption produced less CHO oxidation than a HGI meal during subsequent 67% $\dot{V}O_{2max}$ cycling. However, in a more recent study (L. J. S. Moore, Midgley, Thurlow, Thomas & Mc Naughton, 2010), when HGI or LGI meals were consumed after a 6-hrs of fasting, more CHO oxidation was found in the LGI trial than that in the HGI trial during subsequent 40 km time trial (TT) cycling. This result was contrary to most previous studies and the authors were unable to explain this inconsistency. Because of limited studies, it was still unclear whether changing the GI of a lunch meal would influence substrate utilization during subsequent exercise. Similarly, it was unknown whether the fructose content of lunch would affect substrate utilization during subsequent exercise. The results from previous studies conducted in the morning could not be directly applied to studies conducted in the afternoon.

It is worth mentioning that in these two studies, endurance athletes were used as subjects, and high exercise intensity was used to test whether exercise performance was influenced by different pre-exercise GI meals. It must be noted that ordinary people occasionally exercise in the afternoon. In addition, a previous study revealed that lipolysis during exercise increased in direct proportion to the length of fasting (Montain et al., 1991), which may likewise affect substrate utilization. Therefore, it was necessary to investigate this effect for ordinary people, and for low to moderate intensity exercise.

1.2 Purposes

The purposes of this thesis are as follows:

i. To determine the GI values of a significant number of traditional Chinese foods in Hong Kong.

ii. To investigate whether both GI and fructose content in breakfast meals would affect substrate utilization during subsequent brisk walking.

iii. To investigate whether both GI and fructose content in lunch meals would affect substrate utilization during subsequent brisk walking.

1.3 Operational Definitions

1.3.1 Glycemic index

Glycemic index is defined as the incremental area under the blood response curve (IAUC) value of glucose after a portion of food containing 50 g of available CHO expressed as a percentage of that after the same amount of CHO from a reference

food, usually glucose or white bread, taken by the same subject.

$$GI = \frac{\text{IAUC value after test food}}{\text{IAUC value after reference food}} \times 100$$

In general, GI is classified into three categories: LGI, Moderate-GI (MGI), and HGI. The LGI food is generally determined as the food with a GI value of less than 55. Food with GI value between 56 and 69 is considered as MGI food, while that with GI value greater than 70 is considered as HGI food.

1.3.2 Fructose

Fructose is a type of monosaccharide and an important naturally occurring sweetener. In the human diet, fructose is consumed in various amounts with fruits, honey, or sugar-sweetened beverages. As a sweeter, fructose is typically used either as such or as a component of high fructose corn syrup (HFCS) or sucrose. High Fructose Corn Syrup can be produced with various fructose-glucose ratios, with the most commonly used being HFCS-55, which contains 55% fructose and 45% glucose.

1.3.3 Substrate utilization

Substrate utilization is defined as the source of energy. In the present thesis, it represents total CHO oxidation and total fat oxidation.

1.3.4 Breakfast

Breakfast pertains to the meal consumed after 10-14 hrs overnight fast. In this thesis, it is required to be consumed at around 8:00 a.m.

1.3.5 Lunch

Lunch refers to the meal consumed after breakfast and several hours of postprandial period. In this thesis, it is required to be consumed 4 hrs after breakfast consumption, i.e., around 12:00 p.m.

1.3.6 Second-meal effect

When previous CHO meal absorption is prolonged, there is less of a tendency for the blood glucose to undershoot basal levels. This may result in a smaller counter-regulatory response and improved glucose disposal after the next meal, i.e., second-meal effect.

1.4 Limitations

In the present study, indirect respiratory calorimetry method was used to measure substrate utilization. This method assumes that the exchange of O_2 and CO_2 measured at the lungs reflects the actual gas exchange from macronutrient catabolism in the cell. This assumption is reasonable during rest and steady-rate exercise conditions with little reliance on anaerobic metabolism. In addition, this method could not estimate the protein metabolism in the body. However, proteins play only a minor role as a substrate during exercise of less than one hour duration, with fat and CHO serving as the major sources of energy during exercise. Therefore, when using indirect respiratory calorimetry method to predict fuel utilization during exercise, the role that protein contributes to energy metabolism is usually ignored.

Another limitation of this measurement method is that only total CHO oxidation and total fat oxidation could be calculated. Essentially, there are four major sources of

substrate for exercise: muscle glycogen, blood glucose, plasma free fatty acids (FFA) and intramuscular triacylglycerol (IMTG). Among these, glycogen and glucose belong under CHO, while FFA and IMTG are included in fat. Therefore, we could not clarify the amounts of glycogen or glucose oxidized. Similarly, we could not identify the percentage of FFA or IMTG oxidized in total fat oxidation. Further studies are required to clarify this matter.

Except for above mentioned method limitation, another limitation of the present study was that only young healthy male subjects were recruited to participate in the present studies. All subjects had moderate physical activity level. Because of the potential differences in substrate utilization among different populations, such as obese people, sedentary middle-aged people, and so on. The results of the present studies could not be applied to other populations directly. However, the findings of this thesis could also provide some valuable information for them. Further studies are needed to clarify the effect of GI and fructose content in meals on substrate utilization during subsequent moderate intensity exercise in different populations.

1.5 Delimitations

i. Young healthy subjects were recruited in the studies. Only male subjects participated in Study II and Study III.

ii. All test foods were provided by the same investigator for the subjects.

iii. Subjects were ignorant of the function of fructose or GI meals.

iv. The first blood sample for the test was taken after 15-20 min of rest.

v. The present studies were approved by the Clinical Research Ethical Committee of the Chinese University of Hong Kong.

1.6 Significance

Precise GI values of close to 30 kinds of traditional Chinese foods were provided in Study I. These served as preliminary information acting as basis for the development of a GI database for traditional Chinese foods. Findings of the present study provided valuable information to the general population in terms of food choice and served as a reference for researchers.

The experimental protocol in this thesis resembled more closely the practice of ordinary people consuming a CHO diet prior to exercise. However, the exact influence of different GI meal consumption on substrate utilization during subsequent moderate intensity exercise, particularly for ordinary people, was not sufficiently investigated. Although fructose is a well-known LGI CHO, its effect on substrate utilization appeared to be different from other LGI CHO. When fructose is consumed as part of a mixed meal, its effect on substrate utilization may be more complicated. However, limited research related to this topic has rendered conducting a conclusive recommendation difficult. Therefore, findings of Study II and Study III would help in further understanding the exact influence of pre-exercise CHO supplementation on substrate utilization during subsequent moderate intensity exercise. These would offer important practical implications for those exercising for health or weight management.

CHAPTER 2

REVIEW OF LITERATURE

The concept of glycemic index (GI) was originally introduced as a method of classifying different carbohydrate (CHO) and CHO-rich foods according to their postprandial glycemic responses (Jenkins et al., 1981). Since then, several hundred scientific articles and numerous popular diet books have been published on the topic (Ludwig, 2002). Although the clinical significance of GI has remained to be the subject of debate, dietary GI appeared to be linked to several chronic diseases (Brand-Miller, McMillan-Price, Steinbeck & Caterson, 2009; Ludwig, 2002). Therefore, many studies have been conducted to investigate the effect of GI on human health. The GI concept likewise introduced a new tool for investigating CHO metabolism in sport science. In recent years, it was largely applied to researches in this research area as well, especially for endurance capacity and exercise performance (Donaldson et al., 2010; O'Reilly et al., 2010).

Fructose is a type of monosaccharide and an important naturally occurring sweetener. In recent years, many researchers have posited that increase in fructose consumption may be an important factor in the development of several chronic diseases such as obesity, diabetes, metabolic syndrome, and so on (Bantle, 2009; Johnson et al., 2007; Laville & Nazare, 2009; Tappy & Lê, 2010). The benefits of fructose consumption in exercise have been investigated a lot as well (Jeukendrup, 2008).

According to its GI value, fructose can be regarded as Low-GI (LGI) CHO (Atkinson et al., 2008). However, some researchers suggested that fructose should not be considered as a typical LGI CHO, at least when discussing the effect of

different GI meals on substrate utilization (Díaz, Galgani & Aguirre, 2006). Therefore, it is worth to further investigate the difference between the fructose and other LGI CHO, and to clarify the mechanism behind this.

In this chapter, emphases are placed on the application of GI and fructose in human health and sport science, particularly effect of GI and fructose on substrate utilization. Some basic information about GI and fructose are discussed as well. In addition, results of related studies in this area are summarized in this review.

2.1 Measurement of glycemic index

Glycemic index was defined as the incremental area under the blood response curve (IAUC) of glucose after a portion of food containing 50 g available CHO expressed as a percentage of that after the same amount of CHO from a reference food, usually glucose or white bread, taken by the same subject (Jenkins et al., 1981). The GI of a CHO depends on its rate of intestinal absorption, which can be influenced by its composition and ease of digestion (Frost & Dornhorst, 2000). Many other factors such as food form, particle size, cooking methods, presence of other macronutrients and starch structure, may affect the GI of foods (Bjorck, Granfeldt, Liljeberg, Tovar & Asp, 1994; Wolever et al., 2003). Food and Agriculture Organization (FAO) developed a standard protocol for GI determination to decrease the impact of variations in certain methodology-related variables on obtained GI value (1998). Guidelines for the measurement of GI were provided in this protocol. A number of important methodological factors that may influence the accuracy of GI determination were discussed in this part of the review. More information on the methodology of GI determination was likewise provided in a previous review (Brouns et al., 2005).

2.1.1 Glycemic index of single food

Typically, GI of a single food is determined by measuring real glycemic responses after target food consumption. Both capillary and venous blood were recommended for GI determination (FAO, 1998). However, according to an inter-laboratory study (Wolever et al., 2003), GI values of foods were more precisely determined using capillary than venous blood sampling. The results of this study revealed that the use of venous blood sample was associated with greater within-subject variation of both glycemic responses and GI values, and non-normal distribution of GI values. A recent study (Hatönen et al., 2006) likewise found that the coefficient of variation (CV) of the IAUC values was significantly lower for capillary than for venous blood. Furthermore, compared with venous blood samples, capillary blood samples were easier to obtain. Therefore, capillary blood was preferred for GI determination.

In GI determination, FAO recommended that the reference food, i.e., white bread or glucose, should be repeated at least three times for each subject (1998). Several later studies proved that the use of two or three reference tests resulted in lower standard deviation (SD) compared to the use of only one (Hatönen et al., 2006; Wolever et al., 2003). According to a recent study, however, no evidence was found to justify the conduct of three rather than two tests because the difference was small and insignificant (Wolever, Brand-Miller et al., 2008). Therefore, conducting either two or three rounds of reference food testing appeared to be acceptable in GI determination.

A recent study (Wolever, Brand-Miller et al., 2008) revealed that GI value was negatively related to the within-individual CV for the repeated reference food tests (CVref). The researcher suggested that low within-subject variation (CVref < 30%)

was required for accuracy in GI determination. Another study likewise found that most of the variation in GI determination was due to within-subject variation, and in normal subjects the mean CVref was approximately 25% (Wolever, 2006).

Although many methods were used to calculate the area under the blood glucose response curve (AUC), FAO recommended using IAUC method which ignores the area beneath the fasting concentration (1998). In a later study, several different ways of calculating the AUC were compared and the IAUC was deemed best for GI determination (Wolever, 2004).

According to guidelines for GI determination (FAO, 1998), the portion of food tested should contain 50 g of available CHO. In practice, available CHO is often measured as total CHO minus dietary fiber. A previous study (Wolever & Bolognesi, 1996b) found that relative glycemic response to foods containing different levels of available CHO intake were the same, ranging from at least 25 g to 100 g. At times, the portion of one food containing 50 g available CHO is too large for subjects to consume. Therefore, selecting the portion of food containing 25 g available CHO appeared to be acceptable for determining GI values when necessary.

A recent study suggested that the composition and characteristics of the previous dinner may influence glucose tolerance in the next morning (Granfeldt, Wu & Bjorck, 2006). However, another study revealed that controlling subjects' activities and dinner intake did not reduce within-subject variation of postprandial glycemic response to foods in the next morning (J. E. Campbell, Glowczewski & Wolever, 2003). Furthermore, a more recent report suggested that simply advising subjects to avoid certain types of foods was almost as good and possibly more cost-effective (Wolever, Brand-Miller et al., 2008). Therefore, strictly controlling the previous

dinner appeared to be unnecessary for GI determination. Moreover, the FAO only recommended that subjects should be studied on separate days in the morning after a 10-12 hrs overnight fast (1998).

Aside from the previously mentioned requirements, all subjects were advised to refrain from alcohol consumption and vigorous physical activities 24-hrs prior to the test. When several foods were used for GI determination, they should be randomized in blocks. Intervals between the two tests were at least two days (Brouns et al., 2005; FAO, 1998). A recent study likewise proved that GI value was unrelated to age, sex, ethnicity, and body mass index (BMI) of subjects (Wolever, Brand-Miller et al., 2008). Therefore, it appeared that these factors did not need to be strictly controlled for GI determination.

In summary, to determine the GI value of single food in an accurate manner, standard protocol must be conducted strictly according to the guidelines.

2.1.2 Glycemic index of mixed meals

Unlike GI determination of a single food, GI value of mixed meals can be obtained by calculating their weighted GI value. The calculation method was developed by Wolever and Jenkins (Wolever & Jenkins, 1986), and recommended by FAO (1998). Calculation of the GI value of mixed meals was based on the sum of the GI contributions of each CHO component of the meals. It was proved that in using this type of calculation, good correlation would exit between the calculated GI values and the observed glycemic response of meals (FAO, 1998; Wolever, Yang, Zeng, Atkinson & Brand-Miller, 2006). A recent study likewise found that for mixed meals, CHO content and GI collectively explained approximately 90% of the variation in

the mean glycemic response, whereas protein and fat had negligible effects (Wolever et al., 2006). Therefore, it appeared that accurate GI value of mixed meal could be calculated only if there were accurate GI value and CHO component of single food in mixed meal.

2.1.3 International glycemic index table

The availability of reliable GI values of different foods is critical not only for researchers but for the general public as well. A recent study (Brand-Miller, Stockmann et al., 2009) analyzed a database of over 1,000 foods and found that GI provided a good summary of postprandial glycemia. The GI likewise predicted the peak or near-peak response, maximum glucose fluctuation, and other attributes of the response curve. More importantly, a close relationship was observed between food GI and human health (Brand-Miller, McMillan-Price et al., 2009; Ludwig, 2002). Labeling the GI of different foods is being either proposed or carried out in countries such as Australia, South Africa, Sweden, United Kingdom, and Germany, with several commercial laboratories measuring the GI of foods (Wolever, Brand-Miller et al., 2008). Therefore, developing a reliable international GI table is a worthwhile endeavor.

The first edition of the *"International Tables of Glycemic Index"* was published in 1995 (Foster-Powell & Miller, 1995). A total of 565 food items were included in this table. Since then, the table has been cited as a reference in many scientific papers. More importantly, it has served as a dietary epidemiologic tool that allows for novel comparisons of the effects of different CHO on disease risk. The second edition, entitled "*International table of glycemic index and glycemic load values: 2002*", was published in 2002 (Foster-Powell, Holt & Brand-Miller, 2002). The table contains

close to 1,300 food items, representing more than 750 different types of foods. In this table, the user can appreciate the variation for any one food; if possible, one can use the GI value for the food found in one's country.

Glycemic load (GL) values of most foods were firstly included in this table. Glycemic load (GI × dietary CHO content) was first introduced by researchers in Harvard University (Salmeron, Ascherio et al., 1997; Salmeron, Manson et al., 1997), and was used to allow comparisons of the likely glycemic effect of realistic portion sizes of different foods. Both quantity and quality of CHO may influence the glycemic responses, whereas GI only provided a measure of CHO quality but not the quantity. The inclusion of GL may reflect the quantity of CHO to a certain degree.

The latest edition of the GI table was published in 2008 and entitled *"International Tables of Glycemic Index and Glycemic Load Values: 2008"* (Atkinson et al., 2008). This table listed the GI and GL values of over 2,480 individual food items, and improved the quality and quantity of reliable data available for research and clinical practice.

In recent years, GI values of several local foods have been measured in different countries prior to their utilization in research and clinical settings among the local population (Aston et al., 2008; Sugiyama et al., 2003; Yang et al., 2006). However, little information was available on GI values of traditional Chinese foods in Hong Kong in extant literature, thus limiting related research in this area (Hui & Nelson, 2006; Woo et al., 2003). Although many traditional Chinese foods are popular worldwide, GI values of only around 50 Chinese foods were reported in the latest international GI table. A large number of traditional and special Chinese foods are very different from Western foods. Therefore, establishing a GI and GL database for

traditional Chinese foods is worthwhile as it can aid local researcher and people.

2.2 Glycemic index and its application

2.2.1 Role of glycemic index in human health

According to the definition of GI, CHO foods were ranked based on their actual postprandial glycemic responses (Jenkins et al., 1981). In general, differences in the glycemic response to food products, specifically GI, are mainly related to differences in the rate at which CHO is digested and absorbed (Granfeldt et al., 2006). It is determined primarily by the nature of CHO consumed and by other dietary factors that affect nutrient digestibility or insulin secretion (Ebbeling & Ludwig, 2001). Despite the individual differences in postprandial glycemic responses, a high-GI (HGI) meal usually induces higher responses compared to a LGI meal containing identical nutrients and energy. Moreover, blood glucose concentration usually falls rapidly between 2-4 hrs after HGI meal consumption, often into the hypoglycemic range. This type of rapid change in blood glucose concentrations challenges the homeostatic mechanism in regulating blood glucose concentrations in the body, including secretion of insulin, glucagon, epinephrine, cortisol, growth hormone, and so on. By contrast, hypoglycemia usually does not occur during the postprandial period after LGI meal consumption, which may contribute to continued CHO absorption and rising hepatic glucose output (Ludwig, 2002). Therefore, consumption of meals with different GI would produce markedly different physiological responses, which may potentially serve as influencing factors to human health.

2.2.1.1 Glycemic index and diabetes

Diabetes is widely known to be a metabolic disorder resulting from a defect in insulin secretion, insulin action, or both. Prevalence of diabetes has increased dramatically over the past three decades, and current estimates predict a further 50% increase worldwide by the year 2030 (Shaw, Sicree & Zimmet, 2010). As mentioned previously, a HGI meal would produce higher glucose concentration during the postprandial period compared to a LGI meal. Similar changes were found in insulin secretion as well (Brand-Miller, 1994; Wolever & Bolognesi, 1996b), which were assumed to be related to the development of diabetes. A hypothetical model in which GI alters risk for Type 2 diabetes has been provided (Ludwig, 2002), in which the effects of GI on hyperinsulinemia, insulin resistance, beta cell demand, and ultimately beta cell function played a role in diabetes. Compared with LGI meal consumption, primary hyperinsulinemia after HGI meal consumption may cause insulin resistance by decreasing whole body glucose disposal, or directly compromising the beta cell function (Del Prato et al., 1994; Ludwig, 2002). In addition, hyperglycemia after HGI meal consumption may directly induce insulin resistance or impaired beta cell function as well (Ludwig, 2002; Rossetti, Giaccari & DeFronzo, 1990).

Several epidemiologic studies have been conducted to investigate this issue. Two studies conducted in 1997 showed an inverse relation between GI and the risk of developing diabetes using a validated food frequency questionnaire (Salmeron, Ascherio et al., 1997; Salmeron, Manson et al., 1997). The Nurses' Health Study is a large, prospective cohort study of US women followed for several years (Salmeron, Manson et al., 1997). A total of 65,173 female nurses were enrolled in this study, and

the results revealed that dietary GI was positively associated with risk of diabetes after adjustment for age, BMI, smoking, physical activity, family history of diabetes, alcohol and cereal fiber intake, and total energy intake. In another study (Salmeron, Ascherio et al., 1997), a total of 42,759 male subjects were included in the analysis. In this study, positive association between GI and diabetes was observed after adjustment for potential influencing factors. More importantly, neither sugar nor total CHO intake was associated with increased risk in these two studies. Two more recent large-scale prospective studies likewise indicated that diabetes was linked to overall diet GI and was independently of fiber (Schulze, Liu et al., 2004; C. Zhang, Liu, Solomon & Hu, 2006). Overall, majority of epidemiologic studies supported the relationship between GI and diabetes, although some study do not support such significant associations (Meyer et al., 2000). The inconsistent result may partly be attributed to the older subjects in this study.

A controversy remains to question GI's usefulness in meal planning for people afflicted with diabetes. The most recent position statement from the American Diabetes Association (ADA) considered that use of GI or GL may possibly provide only a modest secondary benefit above consideration of total CHO alone (2008). Therefore, more experimental evidences are needed to clarify this issue. A recent systematic review on this topic analyzed 11 published studies that were all randomized controlled trials (RCTs), with interventions of at least four weeks; it indicated that glycemic control in people with diabetes improved significantly with a LGI diet, compared with a HGI diet (Thomas & Elliott, 2009). A study likewise revealed that whole body peripheral insulin sensitivity, measured by euglycemic-hyperinsulinemic clamp, was significantly higher after LGI diet consumption compared with after HGI diet consumption (Rizkalla et al., 2004).

Another study, although excluded in the systematic review, found that the LGI diet reduced postprandial glucose concentration and C-reactive protein. Therefore, it was beneficial to the ongoing management of Type 2 diabetes (Wolever, Gibbs et al., 2008). All these studies suggested that a LGI diet is beneficial to people with diabetes, especially in improving glycemic control. This suggestion may be applied to a broad spectrum of age groups or any type of diabetes (Brand-Miller, McMillan-Price et al., 2009; Thomas & Elliott, 2009).

2.2.1.2 Glycemic index and cardiovascular diseases

Nowadays, cardiovascular diseases (CVD) especially coronary heart disease (CHD), have become the major cause of death worldwide. Prevalence of CHD continues to increase across the globe (Murray & Lopez, 1997). Postprandial hyperglycemia appeared to be an important risk factor for CVD among people with or without diabetes (Balkau et al., 1998; Coutinho, Gerstein, Wang & Yusuf, 1999; Ludwig, 2002). The mechanism behind this phoneme may be increased protein glycation, oxidative stress, and impaired endothelial function (Brand-Miller, 2003; Ceriello, 2000; Ludwig, 2002; Title, Cummings, Giddens & Nassar, 2000). Hyperinsulinemia was believed to be related to increased risk of CVD as well (Brand-Miller, 2003; Despres et al., 1996; Ludwig, 2002; Mather, Anderson & Verma, 2000). Postprandial hyperglycemia and hyperinsulinemia were often observed after HGI meal consumption. Therefore, it was not strange that a relationship between the GI of meal and CVD was expected to be found.

Several epidemiologic studies were conducted as well to investigate this issue. Data from the Nurses' Health Study revealed a negative relationship between fatal and nonfatal myocardial infarctions and GI in women after a 10-year follow-up (Liu et

al., 2000). Two additional studies observed the association between the LGI diet and higher high density lipoproteins (HDL) cholesterol concentrations (Ford & Liu, 2001; Frost et al., 1999), suggesting a potentially positive effect of LGI meal on reducing CHD risk. Although one study did not find an association between GI and CHD in older men (Van Dam, Vlsschier, Feskens, Verhoef & Kromhout, 2000), most such studies demonstrated higher HDL cholesterol levels, lower triglyceride (TG) levels, or lower myocardial infarction rates after LGI meal consumption compared with HGI meal consumption, after adjusting for several potentially confounding factors (Ludwig, 2002).

Because an epidemiologic study can merely detect an association between two variables but not prove causation (Pi-Sunyer, 2002) and such observational studies may be prone to confounding and other biases, a systematic review was conducted recently to assess the effect of GI on total mortality, CHD events, and risk factors for CHD (Kelly, Frost, Whittaker & Summerbell, 2004). In this review, a total of 21 RCTs were included into the analysis. All studies merely reported the effect of LGI diet on risk factors for CHD. However, no studies reported the effect of LGI diet on CHD mortality or CHD events and morbidity. In general, meta-analysis revealed limited and weak evidence of slightly lower total cholesterol with LGI diets. Little evidence suggested that a LGI diet has an effect on LDL cholesterol, HDL cholesterol, TG, glycosylated hemoglobin (HbA1c), fasting glucose, or fasting insulin levels. The review concluded that there was insufficient evidence that healthcare professionals should prescribe LGI diets for the purpose of reducing the risk factors for CHD. However, because many of the trials identified in this review were short-term, conducted on small sample sizes, and many poor quality studies failed to meet the review criteria, more well-designed studies are needed to assess

this effect further.

2.2.1.3 Glycemic index and obesity

Nowadays, the prevalence of obesity and overweight in both adults and children continues to increase in most countries around the world. In Western countries, obesity has been suggested to be the third most common risk factor for non-communicable diseases such as heart diseases (Lopez, Mathers, Ezzati, Jamison & Murray, 2006). The underlying reasons for this phoneme are very complex. Genetic susceptibility, reduced physical activities, high energy-dense foods, and social and economic influences tend to contribute to the rising prevalence (Brand-Miller, Holt, Pawlak & McMillan, 2002). Recently, several researchers believed that LGI diet may benefit weight control (Brand-Miller et al., 2002; Ludwig, 2000). First, LGI foods typically induce higher satiety than do HGI foods, even if the appearance and nutrient content are matched (Ludwig, 2000). Mixed LGI meals were found to induce greater satiety during the postprandial period as well (Holt, Brand-Miller, Soveny & Hansky, 1992). Conversely, HGI meals have been associated with appetite stimulation and higher energy intake (Ludwig, 2000). The marked hyperinsulinemic, hyperglycemic, and hypoglycemic effects of HGI foods appeared to explain in part the lower satiety observed in the postprandial period (Brand-Miller et al., 2002; Holt & Brand-Miller, 1995). Second, LGI meals may promote fat oxidation at the expense of CHO oxidation (Brand-Miller et al., 2002). The hyperinsulinemic and hyperglycemic responses after HGI meal consumption may increase CHO oxidation acutely through activation of certain enzymes (Wolfe, 1998). Longer exposure to chronic hyperglycemia and hyperinsulinemia may decrease expression of the related enzymes and alter the potential for fat oxidation

(Brand-Miller et al., 2002).

Several previous short-term studies have shown that LGI foods are more satiating, delaying the return of hunger or decreasing food intake (Ludwig, 2000). A recent study found that a HGI diet was prospectively associated with changes in body weight, body fat, and waist circumference over a 6-year period in women (Hare-Bruun, Flint & Heitmann, 2006). Several small intervention studies likewise revealed that energy-restricted diet based on LGI foods produced greater weight or body fat loss than equivalent diet based on HGI foods, suggesting a connection between HGI diet and obesity (Slabber, Barnard, Kuyl, Dannhauser & Schall, 1994; Spieth et al., 2000). Recently, a systematic review (Thomas, Elliott & Baur, 2007) analyzed the data of six eligible RCTs studies, including a total of 202 subjects and five-week to six-month intervention durations. The said review found that the decrease in body mass (BM), total fat mass, and BMI was significantly greater in subjects receiving LGI compared to HGI diets. The author concluded that weight loss was greater in overweight and obese people with LGI diet than in people given comparison diets, including HGI diet and conventional diet. Therefore, lowering the GI of foods in the diet appeared to be an effective method for losing weight, especially for the obese.

2.2.1.4 Glycemic index and cancers

In recent years, dietary GI has been linked with the risk of various cancers, although evidence remains limited. The suggested reason for the role of GI in the development of cancer was that hyperinsulinemia and hyperglycemia may promote the transformed cells and result in the development and growth of tumors (Brand-Miller, 2003). Several studies have found a direct relationship between GI

and colon cancer (Franceschi et al., 2001; Giovannucci, 1995; Slattery et al., 1997). In one study, those in the highest quintile had a relative colon cancer risk of 1.7, compared with the lowest quintile of GI (Slattery et al., 1997). A comprehensive meta-analysis of GI and cancer risk likewise suggested a direct association with colon cancer (Gnagnarella, Gandini, La Vecchia & Maisonneuve, 2008). However, a recent meta-analysis revealed that although most case-control studies observed positive associations between GI and colon cancer, pooled cohort study results showed no association between colon cancer risk and GI (Mulholland, Murray, Cardwell & Cantwell, 2009).

One case control study first reported . n association between dietary GI and risk of breast cancer (Augustin et al., 2001). From then on, more studies have been conducted to investigate this issue. A recent meta-analysis did show a statistically significant direct relationship between GI and breast cancer risk (Barclay et al., 2008). However, another meta-analysis did not support this conclusion (Mulholland et al., 2009). Several recent studies likewise suggested the relationship between GI and endometrial cancer (Augustin, Galeone et al., 2004; Gnagnarella et al., 2008). However, overall the evidence was limited. Therefore, it may be necessary to investigate further the exact relationship between GI and certain cancers.

2.2.2 Application of glycemic index in exercise

The importance of CHO for exercise has been recognized since 1930s, especially when the biopsy technology was introduced in sport science (Bergström, Hermansen, Hultman & Saltin, 1967). Since then, numerous studies have been conducted to investigate the effect of CHO consumption on exercise. Many have focused on the ideal nutritional strategies to maximize CHO stores, minimize the adverse effect of

CHO depletion, and improve exercise performance (Hargreaves, Hawley & Jeukendrup, 2004). Typically, this kind of investigations was divided into three phases: before, during, and after exercise (Coyle, 1995; Sherman, 1995). Glycemic index was a reliable classification of foods according to CHO content. Therefore, in recent years, the GI concept has been widely used in the area of sport science, especially for exercise performance (Donaldson et al., 2010; O'Reilly et al., 2010). This part of the review proposes an overall strategy for its application in exercise.

2.2.2.1 Effect of glycemic index before exercise

Unlike the CHO ingestion during and after exercise, less agreement has been achieved in terms of pre-exercise CHO ingestion. One of the major reasons behind this may be the potential decline in blood glucose levels at the onset of exercise after CHO consumption. Carbohydrate ingestion in the hour before exercise has been demonstrated to result in an increase in plasma glucose and insulin concentrations during the postprandial period. However, at the onset of exercise, a decline in blood glucose concentrations was often observed (Coyle, 1995; Hargreaves et al., 2004). This kind of hypoglycemia after CHO ingestion was believed to have the potential to impair the exercise performance in earlier studies (Costill et al., 1977; Foster, Costill & Fink, 1979). However, majority of later studies appeared to produce no effect (Febbraio, Keenan, Angus, Campbell & Garnham, 2000; Febbraio & Stewart, 1996; Hargreaves et al., 1987; Jentjens & Jeukendrup, 2003b; Sparks et al., 1998) and even enhance exercise performance (Gleeson, Maughan & Greenhaff, 1986; Kirwan, O'Gorman & Evans, 1998; Sherman, Peden & Wright, 1991; Thomas, Brotherhood & Brand, 1991). Therefore, avoiding CHO ingestion before exercise appeared to be unnecessary. However, the type and amount of pre-exercise CHO ingestion may

influence the substrate utilization and exercise performance, which merits further investigation.

Interestingly, the amount of CHO may be an important influencing factor for determining exercise performance. In one study (Sherman et al., 1989), subjects were fed with either a placebo, 0.6, 2.0, or 4.5 $g \cdot kg^{-1}$ body weight (BW) CHO 4-hrs before a 95-min interval exercise followed by a time trial (TT) exercise. When 4.5 $g \cdot kg^{-1}$ BW CHO (~320 g) was consumed, the subjects significantly improved their TT performance by 13%. However, for the two smaller amounts of CHO ingestion (~45 g and ~156 g), the TT performance was not improved. Improved performance may be caused by increased CHO availability before exercise and increased CHO oxidation during exercise (Hargreaves et al., 2004).

In recent years, the relationship between GI and exercise performance has become an interest research topic in pre-exercise nutrition, partly because LGI foods have possibility to minimize the changes in plasma glucose and insulin concentrations before exercise. In this part of the review, the effect of GI on exercise performance will be highlighted, and its influence on substrate utilization will be discussed later.

The use of GI as a method for potentially improving exercise performance has generated a considerable amount of scientific researches over the past two decades. Two recent review articles (Donaldson et al., 2010; O'Reilly et al., 2010) focused on this topic and suggested that although pre-exercise LGI meal consumption, compared with HGI meal consumption, produced a favorable metabolic response and potential benefit for exercise performance during subsequent exercise, no conclusive issues could be derived. A number of studies found improved exercise performance after LGI meal consumption (DeMarco et al., 1999; Kirwan et al., 2001;

L. J. S. Moore et al., 2010; Thomas et al., 1991; Wong et al., 2008; Wu & Williams, 2006), while others did not find the same results (Chen, Wong et al., 2008b; Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996; Sparks et al., 1998; Thomas, Brotherhood & Miller, 1994; Wee et al., 1999). Therefore, more studies are needed to clarify this further.

It was not until the 1990s that GI was first investigated for its potential role in affecting exercise performance (Thomas et al., 1991). In this study, eight trained cyclists were fed with lentils (LGI), potatoes (HGI), glucose solutions (HGI), or water 1-hr before exercise to exhaustion (ETE) at 65%-70% $\dot{V}O_{2max}$. The results observed longer time to exhaustion by 20-min in the LGI trial than in the HGI trial. This result elicited exciting as it introduced the potential to improve exercise performance by adjusting the GI of foods consumed before exercise. However, a similar study conducted later by the same researcher did not find improved performance (Thomas et al., 1994). Several other studies were conducted to investigate this issue using the ETE protocol as well. However, no consistent results were observed. A number of studies found improved exercise performance (DeMarco, Sucher, Cisar & Butterfield, 1999; Kirwan, O'Gorman et al., 2001; Wu & Williams, 2006), while others did not (Wee et al., 1999). It was worth mentioning that pre-exercise LGI meal in majority of these studies produced an increase in fat oxidation and better maintenance of glucose concentrations during subsequent exercise.

It has been argued that the ETE protocol was not sufficiently sensitive to detect differences. Moreover, it was said not to match the real requirements of athletes (McLellan, Cheung & Jacobs, 1995). Therefore, several studies used TT protocol,

which entails completing a set amount of work in the fastest possible time, or performance trial (PT) protocol, which entails completing maximal work during a set amount of time. However, inconsistent results were still observed for either TT or PT protocol. Several studies found improved exercise performance after LGI meal consumption (L. J. S. Moore et al., 2010; Wong et al., 2008), while others did not (Chen, Wong et al., 2008b; Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996; Sparks et al., 1998; Stannard, Constantini & Miller, 2000). It is worth mentioning that in two studies that most closely resembled a competitive sporting situation, an improvement was found after consumption of LGI CHO (L. J. S. Moore et al., 2010; Wong et al., 2008). In one of the studies (Wong et al., 2008), eight endurance-trained runners completed two trials consisting of a 21-km performance run on a level treadmill. Two hours before the run, each subject consumed an isocaloric meal containing either LGI (37) or HGI (77) foods that provided 1.5 $g \cdot kg^{-1}$ BW CHO at random order. All subjects were observed to achieve a faster performance time after consumption of the LGI meal. The result indicated that consumption of a LGI meal 2-hrs before a 21-km performance run was more effective in improving the run time when compared to an isocaloric HGI meal. This improvement was in part due to increased fat oxidation.

Endurance athletes typically consume CHO not only before but during exercise as well. Earlier studies revealed that pre-exercise CHO meal consumption, together with CHO-electrolyte solution ingestion during exercise, improved exercise performance, compared with when only the meal was consumed before exercise or when the subjects exercised after an overnight fast (Chryssanthopoulos & Williams, 1997; Chryssanthopoulos, Williams, Nowitz, Kotsiopoulou & Vleck, 2002; Wright, Sherman & Dernbach, 1991). Two studies found that pre-exercise CHO meal

consumption and CHO-electrolyte solution ingestion during exercise increased running time by 9% more than when only the meal was consumed before exercise (Chryssanthopoulos & Williams, 1997; Chryssanthopoulos et al., 2002). Therefore, available evidence supported the recommendation that the combination of a pre-exercise CHO meal and CHO ingestion during exercise may offer benefits for enhancing exercise performance. However, the interaction of pre-exercise meals with different GI and CHO ingestion during exercise has received only brief attention. In two recent studies from our laboratory (Chen et al., 2009; Wong et al., 2009), trained male runners were fed with isocaloric meals that were either HGI, LGI, or low energy jelly (control) 2-hrs prior to completing a 21-km TT run. Immediately before, and every 2.5 km throughout the run, subjects ingested 2 $mL \cdot kg^{-1}$ BW CHO-electrolyte solution. There was no difference in exercise performance between HGI and LGI trials. Similar results were found in a previous study (Burke, Claassen, Hawley & Noakes, 1998). Based on these results, CHO ingestion during exercise appeared to reduce the disparity in metabolic response seen when feeding HGI or LGI CHO before exercise.

In summary, compared with exercise in the fasted state or after placebo ingestion, a relatively large amount of CHO ingestion before exercise appeared to improve exercise performance, especially when CHO was consumed several hours prior to exercise. The combination of a pre-exercise CHO meal and CHO ingestion during exercise is even more effective in enhancing exercise performance. Thus far, no sufficient evidence has been found to argue that LGI meal consumption before exercise would improve exercise performance compared with HGI meal consumption, especially when exercise was conducted in the TT model. Carbohydrate consumption during exercise would reduce the effect of different GI

CHO consumption before exercise. However, several studies did find improved exercise performance and a potential benefit existed in relation to metabolic responses after LGI meal consumption. Therefore, further studies are still required to investigate this issue in greater depth.

2.2.2.2 Effect of glycemic index during exercise

Numerous studies have been conducted to investigate the effect of CHO consumption during exercise. It has been recommended that to maximize performance in endurance events lasting over 1-hr, CHO solution should be ingested during exercise (Jeukendrup, 2004; Sawka et al., 2007). However, it was difficult to tolerate solid food or a large bolus of food while exercising. Therefore, majority of studies that investigate CHO consumption during exercise used CHO solutions such as glucose, fructose, sucrose, and so on. These CHO solutions have different GI values. For example, fructose is widely known to be a LGI CHO, whereas glucose is a HGI CHO (Atkinson et al., 2008). However, it has been suggested that the different influences between fructose and glucose among previous studies were most likely due to lower absorption rate and special metabolism of fructose, and not different GI (Jentjens, Moseley, Waring, Harding & Jeukendrup, 2004). A recent study examined the effect of HGI or LGI CHO feedings during a 64 km TT cycling (Earnest et al., 2004). During exercise, subjects were given 15 g of either a LGI gel (honey), HGI gel (dextrose), or artificially flavored placebo every 16 km. The results of this study showed no differences in the time taken between the HGI and LGI trials. However, it is widely known that honey is abundant in fructose content. Therefore, the exact effect of GI of CHO consumed during exercise to metabolic responses or exercise performance remains unclear.

2.2.2.3 Effect of glycemic index after exercise

One of the most important aspects of recovery after exercise is glycogen replenishment, especially for short-term recovery. Evidently, this process can be affected by CHO consumption after exercise, such as the CHO amount, timing, or even frequency (Jentjens & Jeukendrup, 2003a). Previous studies suggested that when the interval between the exercises was short (4-8 hrs), CHO should be consumed as soon as possible after exercise to maximize recovery (Ivy, Katz, Cutler, Sherman & Coyle, 1988). This may be attributed to increased glucose uptake and increased glycogen synthesis activity (Jentjens & Jeukendrup, 2003a; Price et al., 1994). However, in case of longer recovery times and sufficient CHO consumption, CHO ingestion time did not appear to be a very important influencing factor, while CHO amount appeared to be more important (Coyle, 1991). It has been recommended that CHO intake after exhaustive exercise should average 50 g per 2-hrs of mostly moderate-GI (MGI) and HGI CHO foods. The aim should be to ingest a total of approximately 600 g in 24-hrs after exercise (Coyle, 1991).

It is reasonable to recommend MGI to HGI CHO during the recovery period, because glycogen re-synthesis is influenced by the insulin and CHO source (Burke, Kiens & Ivy, 2004). However, this remains to be a matter of debate (O'Reilly et al., 2010). A previous study reported that increased muscle glycogen synthesis was still evident 24-hrs following the consumption of a HGI CHO meal in comparison with an isocaloric LGI meal (Burke, Collier & Hargreaves, 1993). However, the authors posited that the differences in muscle glycogen could not be completely explained by the different glycemic and insulinemic responses after HGI or LGI meal consumption. Another study (Stevenson, Williams & Biscoe, 2005) suggested that

GI of CHO consumed immediately after exercise may not be important as long as a sufficient amount of CHO is consumed. However, consuming HGI CHO later in the recovery period may facilitate further muscle glycogen re-synthesis through increased glycemic and insulinemic responses.

Although HGI meal consumption appeared to facilitate muscle glycogen synthesis during the recovery period, it was found not to improve subsequent exercise performance. In a study examining the effects of GI of post-exercise CHO intake on endurance capacity the following day (Stevenson, Williams, McComb & Oram, 2005), time was shown to be longer in the LGI trial compared with HGI trial. In this study nine active male subjects ran at 70% $\dot{V}O_{2max}$ for 90-min on Day 1. Subsequently, they consumed either HGI or LGI meals during the following 24-hrs. On Day 2, after an overnight fast, they were required to run to exhaustion at 70% $\dot{V}O_{2max}$. The higher fat oxidation rate and blood free fatty acid (FFA) concentrations were regarded as a reason for improved performance in the LGI trial. However, no difference in glucose and insulin concentrations between the two trials was found during exercise. An additional two studies reported an increase in the availability of FFA and a decreased dependence on intramuscular triacylglycerol (IMTG) as a fuel source after LGI recovery meal consumption (Stevenson, Thelwall et al., 2009; Trenell, Stevenson, Stockmann & Brand-Miller, 2008). However, in these two studies, no difference in muscle and liver glycogen usage was found between the LGI and HGI trials during exercise. These findings may partly explain the improved exercise performance after LGI recovery meals consumption, because there was growing evidence that IMTG may provide a very important substrate during endurance exercise (van Loon, 2004).

A previous study (Siu et al., 2004) investigated the effect of different feeding patterns during a short-term recovery period on subsequent endurance capacity. In this particular study, eight men exercised on a treadmill before and after consuming a HGI meal by either "gorging" in a single bolus or "nibbling" small portions during the 3-hrs of post-exercise period. The results demonstrated similar exercise performance, although after "nibbling" greater reliance on CHO oxidation was observed during subsequent exercise. Another study (Burke et al., 1996) likewise investigated whether consuming food in a gorging pattern or nibbling pattern over a 24-hrs period influenced muscle glycogen storage. The results suggested that the frequency of consumption of CHO did not influence glycogen re-synthesis during the 24-hrs period. Because glycemic responses and insulinemic responses after CHO consumption with these two patterns were similar with those after HGI and LGI CHO consumption, the authors suggested that another mechanism other than lowered glucose and insulin concentrations may partly explain the reduced muscle glycogen re-synthesis after LGI meal consumption.

In summary, it appears that HGI CHO consumed after strenuous exercise would increase muscle glycogen re-synthesis. When interval between the exercises is short, CHO should be consumed as soon as possible after exercise, and MGI to HGI CHO are recommended. However, if the recovery duration is longer, GI of CHO does not appear to be an important influencing factor for glycogen synthesis. Although increased muscle glycogen concentrations were often observed during the recovery period after HGI CHO consumption, improved subsequent exercise performance was observed after LGI CHO consumption in certain studies. The mechanism may be increased blood FFA availability and decreased IMTG utilization. However, the mechanism behind this phenomenon is far from conclusive. Evidently, more studies

are required.

2.2.3 Pre-exercise carbohydrate consumption, glycemic index, and substrate utilization

It is widely known that energy used to sustain steady state aerobic exercise in humans is derived predominately from the oxidation of CHO and fat (Coyle, 1995). The four major sources of energy for exercise are muscle glycogen, blood glucose, FFA, and IMTG (Coyle, 1995; Romijn et al., 1993). Adipose tissue is the largest depot of fuel in the body; theoretically, it can support exercise for several days, while limited CHO stores are located in muscle and liver in the form of glycogen, or in the blood in the form of glucose (Coyle, 1995; Sherman, 1995). The limited CHO stores appeared to be the preferred fuel for maintaining exercise at intensity of over 65% $\dot{V}O_{2max}$. Therefore, CHO deficiency may be an important factor for inducing muscle fatigue and limiting the quality of high intensity exercise (Sherman, 1995).

When exercising in a fasted states, the percentage of energy derived from CHO and fat oxidation varies with increasing exercise intensity (Romijn et al., 1993). In this often cited study, substrate utilization was measured in male subjects when they exercised at 25%, 65%, and 85% $\dot{V}O_{2max}$ after an overnight fast. During low intensity exercise (25% $\dot{V}O_{2max}$), almost all of the energy for exercise was derived from plasma FFA. As exercise intensity was increased from 25% to 65% and then to 85% $\dot{V}O_{2max}$, the availability of plasma FFA for oxidation declined. However, during 65% $\dot{V}O_{2max}$ intensity exercise, total fat oxidation was highest, supplying almost one-half of total energy and reflecting increased oxidation of IMTG. When exercise intensity increased from 65% to 85% $\dot{V}O_{2max}$, the absolute rate of fat oxidation was significantly decreased. Therefore, the results of this study, together with several

recent studies (Achten, Gleeson & Jeukendrup, 2002; Achten & Jeukendrup, 2003b; Romijn et al., 1993; Venables, Achten & Jeukendrup, 2005), showed that moderate intensity exercise - usually between 45% and 65% $\dot{V}O_{2max}$ - can maximize fat oxidation. However, this would vary among different subjects, depending on sex, training status, $\dot{V}O_{2max}$, and diet. When exercise intensity further increased to above 70% $\dot{V}O_{2max}$, fat oxidation was markedly decreased and CHO oxidation was markedly increased (Achten & Jeukendrup, 2003b; Romijn et al., 1993). Therefore, moderate intensity exercise was most favorable for eliciting a substantial short-term increase in fat oxidation.

Without a doubt, substrate utilization will be affected by the nutrition status before and during exercise (Achten & Jeukendrup, 2004; Bennard, Imbeault & Doucet, 2005; Coyle, 1995; Hargreaves et al., 2004). Carbohydrate metabolism and insulin action after CHO intake with different GI suggested that food choices were important for consideration of their potential to acutely influence substrate utilization especially during subsequent exercise. Studies investigating the effects of GI of CHO consumed before exercise can be divided into two categories: CHO ingested 1-hr or less before exercise, and CHO ingested more than 1-hr but less than 4-hrs prior to exercise (Donaldson et al., 2010).

2.2.3.1 Carbohydrate consumption during the hour before exercise

Earlier studies compared substrate utilization during exercise after CHO or placebo ingestion, or in a fasted state. Majority of studies demonstrated that pre-exercise CHO ingestion could increase CHO oxidation during subsequent high or moderate intensity exercise (Achten & Jeukendrup, 2003a; Costill et al., 1977; Coyle, Jeukendrup, Wagenmakers & Saris, 1997; DeMarco et al., 1999; Febbraio, Keenan et

al., 2000; Febbraio & Stewart, 1996; Foster et al., 1979; Gleeson et al., 1986; Goodpaster et al., 1996; Kirwan, Cyr-Campbell, Campbell, Scheiber & Evans, 2001; Sparks et al., 1998; Thomas et al., 1991). However, several studies maintained that pre-exercise CHO ingestion did not affect substrate utilization during subsequent exercise (Devlin, Calles-Escandon & Horton, 1986; Kirwan et al., 1998; Kirwan, O'Gorman et al., 2001; Neufer et al., 1987; Sherman et al., 1991). It is worth pointing out that certain evidences support the tendency to increase CHO oxidation in these studies. For example, in one study the amount of CHO oxidized during exercise in CHO ingestion group was greater than that in control group (Sherman et al., 1991). Another study observed higher Respiratory exchange rate (RER) in the CHO ingestion group than in the control group (Kirwan, O'Gorman et al., 2001). Furthermore, the amount of CHO ingested may be an influencing factor, for small amount of CHO ingestion before exercise, specifically 40 g or 45 g CHO, did not appear to induce more CHO oxidation during subsequent exercise (Neufer et al., 1987). However, CHO ingestion time appeared to have no effect on substrate utilization during subsequent exercise (Moseley, Lancaster & Jeukendrup, 2003). Therefore, increased CHO oxidation was usually observed during subsequent exercise after CHO ingestion.

It has been well established that pre-exercise CHO ingestion produces an immediate hyperglycemic and hyperinsulinemic responses, followed by a rapid decline in plasma glucose concentration at the onset of subsequent exercise (Costill et al., 1977; Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996; Sparks et al., 1998). Previous studies revealed that insulin and muscle contraction produces a synergistic effect on muscle glucose uptake (Bourey et al., 1990; Febbraio, Keenan et al., 2000). Moreover, pre-exercise glucose ingestion was found to result in increased muscle

glucose uptake and reduced liver glucose output during exercise (Marmy-Conus, Fabris, Proietto & Hargreaves, 1996). Therefore, an enhanced uptake and oxidation of blood glucose by skeletal muscle may account for such changes in glycemic responses during exercise. The rapid fall in glucose concentration at the onset of exercise may be a consequence of the combined effects of hyperglycemia, hyperinsulinemia, and contractile activity of muscle (Hargreaves et al., 2004).

A previous study (Febbraio, Keenan et al., 2000) calculated glucose oxidation and glycogen oxidation during exercise after CHO ingestion following an indirect measurement method. The study found that augmented CHO oxidation was largely due to increased glucose oxidation, but not increased glycogen oxidation. Other studies likewise found that muscle glycogen usage during exercise was unaffected by pre-exercise CHO ingestion (Febbraio, Chiu, Angus, Arkinstall & Hawley, 2000; Febbraio & Stewart, 1996; Kirwan, Cyr-Campbell et al., 2001; Kirwan et al., 1998; Kirwan, O'Gorman et al., 2001). However, it must be noted that the contribution of glucose to total substrate oxidation during exercise was minimal (8%-11% of total energy) (Febbraio, Chiu et al., 2000). This may be the reason why no difference in glycogen usage was found. Furthermore, a previous study observed augmented muscle glycogenolysis during exercise after CHO ingestion (Costill et al., 1977). Therefore, increased glucose uptake and oxidation by the muscle appeared to result in increased CHO oxidation. However, further studies are needed to clarify whether muscle glycogen usage during exercise will be influenced by pre-exercise CHO ingestion.

Carbohydrate ingestion during the hour before exercise may result in a marked reduction in fat oxidation as well (Febbraio & Stewart, 1996; Kirwan et al., 1998;

Thomas et al., 1991). This type of suppression may be applied to a wide range of exercise intensities and result in a marked reduction in maximal fat oxidation rate (Achten & Jeukendrup, 2003a). Therefore, decreased fat oxidation was usually observed during subsequent exercise after CHO ingestion. A significant increase in insulin concentration after CHO ingestion may explain the decrease in fat oxidation. In vivo studies at rest have demonstrated that even very small increases in insulin have a marked suppression effect on lipolysis (Bonadonna, Groop, Zych, Shank & DeFronzo, 1990; P. J. Campbell, Carlson, Hill & Nurjhan, 1992). Previous studies likewise revealed that CHO intake suppressed lipolysis during exercise (Horowitz, Mora-Rodriguez, Byerley & Coyle, 1997; Montain et al., 1991). A lower rate of lipolysis induced by increased insulin concentrations resulted in reduced FFA concentration, thereby decreasing the availability of FFA for oxidation. To investigate whether the suppression of lipolysis reduced fat oxidation during exercise, Horowitz et al. (Horowitz et al., 1997) compared lipolysis and fat oxidation rates during 60-min of exercise at approximately 44% $\dot{V}O_{2max}$ either after an overnight fast or after ingestion of 0.8 $g \cdot kg^{-1}$ BW of CHO (glucose or fructose). The results revealed that fat oxidation was less than lipolysis after an overnight fast, whereas after CHO ingestion a relatively small increase in insulin concentrations reduced lipolysis to the point that it became equal to fat oxidation. In an additional trial, lipolysis was simultaneously increased by infusing intralipid and heparin (glucose + lipid) throughout the resting and exercise periods, compared with glucose. This elevation of lipolysis increased fat oxidation by 30% above glucose, confirming that lipolysis limited fat oxidation. However, this increase in lipolysis did not restore fat oxidation to fasting levels, suggesting it was not the only mechanism responsible for the reduction in fat oxidation after pre-exercise CHO ingestion.

Compared with fasting, CHO supplement would provide additional CHO availability; this may be a reason behind the change in substrate utilization during subsequent exercise. Two previous studies (Sidossis, Stuart, Shulman, Lopaschuk & Wolfe, 1996; Sidossis & Wolfe, 1996) found that glucose plus insulin decreased plasma long-chain fatty acids (LCFA) oxidation at rest when fatty acid availability remained constant, via infusion of exogenous lipids. These findings suggested that accelerated CHO oxidation and/or insulin directly inhibited fatty acid oxidation by a mechanism other than inhibition of lipolysis. This notion was supported by the evidence that CHO availability could directly regulate fat oxidation during exercise (Coyle et al., 1997). This study likewise demonstrated that the effect of glucose ingestion on reducing total fat oxidation during exercise was a function of reduced mobilization of both plasma FFA and FFA from IMTG. A later study (Horowitz, Mora-Rodriguez, Byerley & Coyle, 1999) indicated that increased glucose uptake may account for decreased fat oxidation under conditions. Therefore, after CHO ingestion, both the decrease in lipolysis and increase in CHO availability appeared to account for the decreased fat oxidation during exercise.

In majority of these earlier studies, a control trial, specifically exercising after placebo ingestion or in a fasted state, was often used. Therefore, the metabolic effects of pre-exercise CHO ingestion were obviously a consequence of hyperglycemia, hyperinsulinemia, and increased CHO availability. Recently, strategies to minimize changes in plasma glucose and insulin before exercise have generated interest as a research area in pre-exercise nutrition. GI provided a tool for ranking foods rich in CHO according to their glycemic responses, and therefore was largely investigated.

When CHO with different GI was consumed during the hour before exercise, LGI CHO consumption appeared to produce less hyperglycemia and hyperinsulinemia at rest, but maintain glucose concentrations sufficiently during subsequent exercise, compared with when HGI CHO was consumed (DeMarco et al., 1999; Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996; Thomas et al., 1991; Thomas et al., 1994). LGI CHO consumption resulted in higher FFA concentrations and less CHO oxidation during exercise, especially the first part of activity. However, no difference in muscle glycogen usage was observed between LGI and HGI trials (Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996). Differences in insulin concentrations after ingestion of HGI or LGI CHO meal may explain the differences in substrate utilization during exercise. In addition, several studies found that LGI CHO ingestion 1-hr before exercise induced similar CHO and fat oxidation during exercise compared with placebo ingestion or in a fasted state (DeMarco et al., 1999; Febbraio, Keenan et al., 2000). Interestingly, although no difference in total CHO oxidation during exercise was observed, in one study the calculated amount of glucose oxidized was greater in the LGI trial than in the control trial (Febbraio, Keenan et al., 2000).

For majority of the mentioned studies, the meals were consumed after an overnight fast. When fasting time was less, however, inconsistent results were observed. A previous study (Sparks et al., 1998) investigated the effect of HGI or LGI meal consumption on endurance exercise performance after 4-hrs of fasting. The exercise protocol consisted of 50-min of cycling at 67% $\dot{V}O_{2max}$, followed by 15-min of self-paced performance ride in which total work was recorded. LGI meal produced less hyperglycemia and hyperinsulinemia at rest, and maintained sufficient glucose levels during exercise compared with when HGI meal was consumed. LGI trial

produced less CHO oxidation during exercise than in the HGI trial. However, no difference in total work output was found between two trials. In a more recent study (L. J. S. Moore et al., 2010), ten male trained cyclists were recruited to participate in a 40 km TT cycling. Each subject reported to the laboratory after 6-hrs of fasting. Two meals of different GI providing 1 $g \cdot kg^{-1}$ BW of CHO were ingested 45-min prior to TT. Similar to previous studies, LGI meals produced less hyperglycemia and hyperinsulinemia during the postprandial period compared with the HGI trial. In this study, however, the LGI trial produced more CHO oxidation than in HGI trial, which was contrary to the findings of most previous studies. Improved performance was observed in the LGI trial, which was considered to be a result of additional CHO for oxidation. Therefore, it appears that more studies are required to clarify this effect in such situation.

It must be noted that in majority of the mentioned studies, higher intensity exercise was used. As for moderate intensity exercise, to our knowledge, only two studies currently focused on this topic. A study (Kirwan, Cyr-Campbell et al., 2001) investigated the influence of HGI or MGI meals consumed 45-min before exercise to glucose availability during exercise and exercise performance (60% $\dot{V}O_{2max}$ ETE protocol). Six male volunteers ingested 75 g of CHO with different GI or water alone. The GI values of two meals were 82 and 61, respectively. At 30 min and 45 min of the postprandial period, plasma glucose levels were higher in the HGI trial than in the MGI trial. Meanwhile, at 60 min and 90 min during exercise, plasma glucose levels were higher in the MGI trial than in the HGI trial. During exercise, no differences in FFA levels, total CHO oxidation, or muscle glycogen usage were observed between the two trials. However, compared with the control trial, MGI trial induced more CHO oxidation and improved exercise performance; this was not

observed in the HGI trial. In another study (Bennard & Doucet, 2006), eight active young men ran at FATmax (exercise intensity that elicited maximal fat oxidation, average exercise intensity in this study was approximately 51% $\dot{V}O_{2max}$) until energy expenditure was equal to 400 kcal (~45 min). Each subject consumed meals of different GI providing ~80 g of CHO 1-hr prior to exercise. The GI values of the two trials were 48.3 and 103.3, respectively. The results revealed that during exercise no difference was found between the HGI trial and LGI trial, either in glucose and insulin concentrations or in total CHO and fat oxidation. Interestingly, in this study, no difference in glucose or insulin concentrations was found during the postprandial period between the two trials, although there was a great difference in GI values. The postprandial serum insulin levels appeared to be greater in HGI trial compared with the LGI trial (not significant). The researcher attributed this confusing result to the hourly samples; in this situation, a rapid rise and subsequent return in glucose might have been missed. Nonetheless, more studies are needed to clarify the exact effect of GI meals on substrate utilization during subsequent moderate intensity exercise

In summary, compared with exercising in a fasted state or after placebo ingestion, CHO ingestion during 1-hr before exercise appeared to induce greater CHO oxidation and less fat oxidation during subsequent exercise. Increased CHO oxidation appeared to be largely due to increased blood glucose oxidation, but not to muscle glycogen usage. Decreased fat oxidation was caused by both reduced mobilization of plasma FFA and oxidation of FFA from IMTG. Hyperinsulinemia and increased CHO availability may be the major reason behind this phonon. The amount of CHO ingested may likewise influence substrate utilization during subsequent exercise. Low-GI CHO ingestion during 1-hr before exercise appeared to induce similar substrate utilization compared with placebo ingestion or in a fasted

state. However, LGI CHO ingestion appeared to result in less CHO oxidation during subsequent moderate to high intensity exercise compared with HGI CHO ingestion. The possible mechanism behind this is the difference in glycemic and insulinemic responses after the HGI and LGI CHO ingestion. As for moderate intensity exercise, more studies are needed to clarify this effect.

2.2.3.2 Carbohydrate consumption several hours before exercise

To avoid a decline in blood glucose at the onset of exercise, it is reasonable to recommend that CHO meals should be eaten several hours before exercise. This will allow for sufficient time for plasma insulin concentration to return to basal concentrations. A number of earlier studies investigated the effect of CHO ingestion several hours before exercise on metabolic responses and exercise performance. Certain evidence suggested that exercise performance was improved when a relatively large CHO meal was consumed 3-4 hrs before prolonged exercise compared with when nothing was consumed (Neufer et al., 1987; Schabort, Bosch, Weltan & Noakes, 1999; Sherman et al., 1989; Wright et al., 1991). Improved exercise performance may be attributed to increased CHO availability before exercise and increased CHO oxidation during exercise (Hargreaves et al., 2004).

In majority of these studies, despite plasma glucose and insulin concentrations returning to basal levels, a transient fall in glucose concentrations at the onset of exercise and increased CHO oxidation were often observed after CHO ingestion. A previous study (Coyle, Coggan, Hemmert, Lowe & Walters, 1985) investigated the effect of a high CHO meal consumed 4-hrs before 105-min 70% $\dot{V}O_{2max}$ exercise on metabolic responses and substrate utilization. Compared with a 16-hrs of fasting, the pre-exercise meal produced a transient elevation of plasma insulin and blood glucose,

which returned to fasting basal levels prior to the initiation of exercise. However, blood glucose declined when exercise commenced. Greater CHO oxidation and muscle glycogen utilization were found after CHO consumption. This appeared to be derived from the glycogen synthesized following the meal. These results indicated that pre-exercise feedings altered substrate availability despite a return of plasma insulin to fasting levels prior to exercise; these effects persisted until the end of exercise. Although greater CHO oxidation appeared to be derived from the muscle glycogen, it was unclear whether increased muscle glycogen availability was the only source of increased CHO oxidation. It may possibly be due to increased blood glucose uptake and oxidation (Coyle, 1995).

Therefore, pre-exercise high CHO meal appeared to be of benefit to CHO oxidation and exercise performance several hours later. The next question was whether there was an advantage in selecting one type of CHO over another. As mentioned previously, earlier studies investigated the effect of GI on substrate utilization or exercise performance (DeMarco et al., 1999; Sparks et al., 1998; Thomas et al., 1991; Thomas et al., 1994). In these studies, however, either a single GI food was used or mixed CHO meals were consumed less than 1-hr prior to exercise. This was not customary in daily life or during training. Furthermore, although CHO content was similar between HGI and LGI trials in these studies, other macronutrients such as fat, protein, and energy, usually were not matched between the two trials. Therefore, pre-exercise meals were not isocaloric or of the same macronutrient composition, which may influence metabolic responses or substrate utilization during exercise to a certain degree (Martin et al., 2000; Whitley et al., 1998; Whitley et al., 1997). Therefore, recent studies focused on mixed CHO meals with different GI consumed several hours prior to exercise. This resembled more closely the practice adopted by

athletes or normal people before training or exercising. Moreover, macronutrient and energy were sufficiently matched between the HGI and LGI trials. This type of study design is beneficial for investigating the exact effect of GI on metabolic responses during exercise.

Wee et al. (1999) first investigated the effect of different pre-exercise GI breakfast meals on metabolic responses. In this study, five male and three female runners were required to run to exhaustion at 70% $\dot{V}O_{2max}$ 3-hrs after breakfast consumption. The results revealed that consuming a LGI breakfast produced less hyperglycemia and hyperinsulinemia during the postprandial period, compared with when HGI breakfast was consumed. At the beginning of exercise, glucose concentrations in both trials returned to the fasting level, while insulin concentrations did not. At 20 min of exercise, glucose concentrations declined sharply in the HGI trial and were lower than those in the LGI trial. However, no differences in glucose and insulin concentrations between the two trials were observed at other time points. Both at rest and during exercise, FFA levels were higher in the LGI trial than in the HGI trial. In this study, CHO oxidation was observed to be lower in the LGI trial and a compensatory higher fat oxidation was noted during either postprandial or exercise period compared to the HGI trial. More recent studies (Chen, Wong et al., 2008b; Stevenson et al., 2006; Wee, Williams, Tsintzas & Boobis, 2005; Wong et al., 2008; Wu, Nicholas, Williams, Took & Hardy, 2003; Wu & Williams, 2006) demonstrated similar metabolic responses during postprandial period. However, there were several different metabolic responses during exercise among these studies. In majority of these studies, blood glucose concentrations were sufficiently maintained in the LGI trial but not in the HGI trial, especially during the first part of exercise, with the exception of one study (Stevenson et al., 2006) in which glucose concentrations were

sufficiently maintained in both trials. In most studies, FFA levels were higher in the LGI trial than in the HGI trial during exercise. However, one study did not observe the difference in FFA levels throughout the exercise between the two trials (Chen, Wong et al., 2008b). Only one study demonstrated that FFA levels were higher in the LGI trial than in the HGI trial during the postprandial period (Wee et al., 2005). Similarly, results of all these recent studies demonstrated that during exercise CHO oxidation was lower and a compensatory increase in fat oxidation was observed in the LGI trial than in the HGI trial. However, no difference in substrate utilization was found during the postprandial period, which was inconsistent with the previous study (Wee et al., 1999).

The difference in substrate utilization during exercise between the two trials may partly be explained by reduced hyperinsulinemia during the postprandial period following the LGI meal, which reduced the suppression of fat oxidation compared to when a HGI meal was consumed. This allowed a shift in substrate utilization toward fat oxidation during the subsequent exercise, as well as provided a sustainable source of CHO (Wu et al., 2003). A recent study (Wee et al., 2005) reported that the lower rate of CHO oxidation following a LGI breakfast may be explained by a lower rate of muscle glycogen utilization. A 15% increase in muscle glycogen concentration was observed in the vastus lateralis muscle at the end of 3-hrs postprandial period after consumption of the HGI meal, but not after consumption of the LGI meal. However, net muscle glycogen utilization was 46% greater in the HGI trial compared with the LGI trial. At the end of exercise, muscle glycogen concentrations did not differ between the two trials. Rapidly digested and absorbed foods in the HGI meal most likely supplied the necessary glucose to the blood and muscle for glycogen synthesis within the 3-hrs postprandial period. A better maintained fat

oxidation appeared to explain the sparing of muscle glycogen during exercise following the LGI meal consumption.

Therefore, LGI meal consumption appeared to result in higher fat oxidation and lower CHO oxidation during subsequent exercise compared with when HGI meals were consumed (Chen, Wong et al., 2008b; Stevenson et al., 2006; Wee et al., 1999; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003; Wu & Williams, 2006). Since the same amount of CHO was consumed before exercise following an overnight fast on both occasions and total pre-exercise CHO oxidation was similar in the two trials in majority of these studies, CHO availability did not appear to be the major reason behind the change in substrate utilization during subsequent exercise. Because substrate utilization during exercise would be influenced not only by nutrition status (e.g., type, amount, and time of CHO ingestion), but also nature of exercise (e.g., exercise intensity and exercise duration) and characteristics of the individual (e.g., training level, gender, and body composition) (Achten & Jeukendrup, 2004; Bennard et al., 2005; Venables et al., 2005), results of related studies should be cautiously explained.

In majority of these studies, endurance-trained athletes were used as subjects. More importantly, 70% $\dot{V}O_{2max}$ was usually used as the exercise intensity to test whether exercise performance was influenced by pre-exercise meals with different GI. Changes in fat oxidation during exercise were important for ordinary people as well, especially those aiming to reduce body fat mass. Although exercising in the fasted state will maximize fat oxidation, people generally cannot continue to perform exercises in such a situation from a practical point of view. Furthermore, in the context of physical activity, a moderate or high CHO meal may simply be a more

natural choice because it should maintain adequate levels of muscle glycogen for sustained activities. If the differences in substrate utilization after HGI or LGI meal consumption actually exist, then increase in fat oxidation can be achieved by simply changing the GI of foods consumed prior to exercise; this will have important implications for those who are exercising for health or for weight management purposes. Thus, more studies should be conducted to investigate the effect of pre-exercise meals with different GI on substrate utilization during subsequent low to moderate intensity exercise.

In a recent study (Stevenson, Astbury et al., 2009), eight healthy, sedentary females were recruited to participate in a study that examined the effects of breakfast containing HGI or LGI meals on substrate utilization during rest and walking exercise. Exercise intensity was approximately 50% $\dot{V}O_{2max}$. The results demonstrated similar glycemic and insulinemic responses during the postprandial period with previous studies. However, no difference in FFA levels was observed between the two trials either at rest or during exercise. During the 3-hrs postprandial period, fat oxidation was suppressed following both breakfast meals, but it remained higher in the LGI trial. During exercise, total CHO oxidation was lower and a compensatory increase in fat oxidation in the LGI trial was observed. In this study, 1 $g \cdot kg^{-1}$ BW CHO was consumed and the GI values of two meals were 78 and 44, respectively. However, in another study (Backhouse et al., 2007), no significant effect of meal GI on the amount of fat oxidized during exercise was noted. It is worth mentioning that although exercise protocol was the same in these two studies, the amount and type of CHO consumption was different. The difference in CHO may explain the difference in substrate utilization between the two studies. In the latter study, approximately 2 $g \cdot kg^{-1}$ BW CHO was consumed and GI values of two

meals were 77 and 51, respectively. In addition, two meals produced similar metabolic responses during the postprandial period in this study. The only notable difference was a trend for lower serum insulin concentrations in the LGI trial compared with the HGI trial, which became significant at the end of the 3-hrs postprandial period. Interestingly, blood lactate concentrations in this study were significantly elevated following the ingestion of LGI breakfast. By contrast, increase was minimal following the HGI breakfast. In the present study, LGI breakfast contained more fructose than the HGI breakfast, owing to the former's fruit content. Because CHO with high fructose content is well known to result in higher blood lactate concentrations (Koivisto, Karonen & Nikkila, 1981; M. C. Moore, Cherrington, Mann & Davis, 2000), this may explain the higher blood lactate concentrations in the LGI trial. However, the authors did not discuss whether this difference would influence the substrate utilization during subsequent exercise.

In majority of the mentioned studies, meals were provided to the subjects after an overnight fast to avoid the so-called "second meal effect". Two previous studies (Stevenson, Williams, Nute, Humphrey & Witard, 2008; Stevenson, Williams, Nute, Swaile & Tsui, 2005) revealed that an overnight second meal effect occurred in both male and female healthy subjects who consumed a LGI mixed evening meal compared to when an energy-matched HGI mixed meal was consumed. Despite the lower glycemic and insulinemic responses during the postprandial period following breakfast in the LGI trial, no differences in substrate utilization were observed during the postprandial period following the same standard breakfast or during subsequent 60-min of 65% $\dot{V}O_{2max}$ running. Therefore, the researchers suggested that a LGI meal must be consumed 2-3 hrs prior to exercise to achieve the shift in substrate utilization. Based on this result, we suspect that an overnight fast is

sufficient to eliminate the second meal effect for substrate utilization.

When fasting time was less, however, different results would be produced. In another study (Stevenson, Williams & Nute, 2005), nine active males completed a 60-min of 70% $\dot{V}O_{2max}$ running after consumption of both breakfast and lunch with different GI. The results revealed that during the postprandial period following lunch consumption, the amount of fat oxidized was significantly higher in the LGI trial than in the HGI trial. Meanwhile, no difference was found in substrate utilization during subsequent exercise. Similar to previous studies, lower glycemic and insulinemic responses were observed after LGI lunch consumption. Interestingly, during the postprandial period after breakfast, no difference was observed in substrate utilization between the two trials. This inconsistent result indicated that the different breakfast meals consumed 3-hrs before lunch consumption did affect substrate utilization during subsequent exercise. According to the results of this study, together with two previous studies (L. J. S. Moore et al., 2010; Sparks et al., 1998), it appeared that substrate utilization during exercise could be influenced not only by GI of meals consumed before exercise, but by different fasting times before meal consumption as well. Therefore, results from previous studies which were conducted in the morning could not directly be applied to the studies conducted in the afternoon or at night. Furthermore, a previous study (Montain et al., 1991) indicated that at least 6-hrs of fasting was necessary to induce similar substrate utilization and plasma glucose homeostasis during 70% $\dot{V}O_{2max}$ exercise as 8-12 hrs of fasting (Montain et al., 1991). Thus, fasting time may be another important factor that should be considered in such studies.

In summary, compared with exercising in the fasted state or after placebo ingestion,

a relatively large amount of CHO ingestion several hours before exercise appeared to induce increased CHO oxidation during exercise, which was similar to CHO consumed during 1-hr before exercise. However, increased CHO oxidation appeared to be mainly derived from muscle glycogen, although it may not be the only source of increased CHO oxidation. Pre-exercise LGI CHO ingestion appeared to induce greater fat oxidation and less CHO oxidation during subsequent exercise compared with when HGI meals were consumed. The possible reason for this phenomenon is reduced hyperinsulinemia during the postprandial period following the LGI meal. However, when exercise intensity was lower or when there was less fasting time before different GI meal consumption, inconsistent results may be observed. Evidently, more studies are needed to clarify this effect further.

2.3 Fructose and its application

2.3.1 Fructose consumption

Humans tend to overfeed when presented with a palatable diet, in which a sweet taste is highly favored by many. Sugars are naturally occurring sweeteners, the most common in our nutrition being sucrose, fructose, and glucose. Fructose and glucose are monosaccharide, while sucrose is disaccharide, which is formed by one molecule of glucose and one molecule of fructose. Fructose and glucose possess different structures, which cause different properties and metabolic processes in the body. In the diet, fructose is consumed in various amounts with fruits, honey, sugar-sweetened beverages. As a sweeter, it is usually used either as such or as a component of high fructose corn syrup (HFCS) or sucrose. High fructose corn syrup can be produced with various fructose-glucose ratios; the most commonly used is HFCS-55, which contains 55% fructose and 45% glucose (Tappy & Lê, 2010).

Two commonly used methods assessing the sugar or fructose intake are "per capita disappearance data" and "individual food intake reports". According to reports from the United States Department of Agriculture (USDA), per capita added sugar consumption amounted to ~90 g·day^{-1} in 1970 (Tappy & Lê, 2010). From 1970 to 1985, sucrose disappearance progressively declined by almost 50%, while a sharp increase in HFCS disappearance was recorded. In 2007, per capita disappearance of total caloric sweeteners increased by 15%. A previous study using data from the USDA's 1994-1996 Continuing Survey of Food Intakes by Individuals revealed that during the 2-year period, Americans consumed an equivalent of 82 g of CHO per day from added sugars, which accounted for 16% of total energy intake (Guthrie & Morton, 2000). A recent analysis of energy consumed as beverages in the US population, using 1999-2002 National Health and Nutrition Examination Survey (NHANES) data, reported that the percentage of energy consumed from sugar-sweetened beverages averaged 18.5% for males and 13.5% for females (Storey et al., 2006). More recent data suggested that 16% of the studied population consumed over 25% of daily energy requirements from sugar-sweetened beverages (Stanhope & Havel, 2008a).

Dietary fructose consumption increased in conjunction with rising intake of fructose-containing sugars, largely in the form of sugar-sweetened beverages. A previous study reported that in 1977-1978, the average daily fructose intake was 37 g per day (Park & Yetley, 1993). The highest consumers were adolescents and young adults (19-22 years) of both sexes. Another study (Vos, Kimmons, Gillespie, Welsh & Blanck, 2008) found that in 1988-1994, mean consumption of fructose was estimated to be 54.7 g per day, accounting for 10.2% of total caloric intake. Consumption was highest among adolescents (12-18 years) at 72.8 g per day, which

accounted for 12.1% of total calories. One-fourth of adolescents consumed at least 15% of calories from fructose. The largest source of fructose was sugar-sweetened beverages. A more recent study (Marriott et al., 2009) showed that compared with 1977-1978, mean individual intake of total fructose increased by ~32% in 1999-2004. Moreover, fructose intake has increased in all gender and age groups since 1978. Similar to previous studies, it was found that nonalcoholic beverages and grain products were the predominant sources of added fructose in the diet.

In other parts of the world, however, less data on fructose or sugar consumption were available. Overall, world average per capita sugar consumption has increased by 16% over the past 20 years, from 56 g per day in 1986 to 65 g per day in 2007 (Tappy & Lê, 2010). Although the lower sugar consumption was recorded in Asia, the most impressive rise - a 50% increase - was observed during this period. Moreover, both sugar and fructose consumption evidently increased significantly over the past decades. Therefore, it is worthwhile to investigate whether this kind of increase affected the recently increased prevalence of obesity, diabetes, metabolic syndrome, and so on.

2.3.2 Fructose metabolism

A major portion of fructose is extracted by splanchnic tissues. It is transported into the enterocyte through a specific fructose transporter - glucose transporter 5 (GLUT5) - located at the apical pole of enterocyte. Contrary to glucose, this process does not require adenosine triphosphate (ATP) hydrolysis and is independent of sodium absorption (Douard & Ferraris, 2008; Lê & Tappy, 2006; Tappy & Lê, 2010). Fructose absorption appeared to be quantitatively limited. For certain individuals, fructose consumption may cause gastrointestinal symptoms and cannot be

completely absorbed (Skoog & Bharucha, 2004). However, dietary sources of fructose usually contain glucose, which can increase fructose absorption in healthy subjects (Skoog & Bharucha, 2004; Truswell, Seach & Thorburn, 1988). Once absorbed, part of the fructose will be converted to lactate and released into the portal circulation, which has been demonstrated to account for approximately 12% of absorbed fructose (Bjorkman, Sahlin, Hagenfeldt & Wahren, 1984). However, the functional significance of this intestinal metabolism of fructose remains unknown (Tappy & Lê, 2010).

Most absorbed fructose entered into the portal blood and was extracted by the liver rapidly. In the liver, fructose was first phosphorylated to form fructose-1-phosphate, subsequently entering gradually into different metabolic pathways. The glycolytic pathway in the liver was the most important, and the final products were glucose, glycogen, lactate, and pyruvate (Elliott, Keim, Stern, Teff & Havel, 2002). The detailed metabolic process could be obtained from other studies (Elliott et al., 2002; Mayes, 1993). In the present paper, only a few major differences in the metabolic process between fructose and glucose will be highlighted. First, although only a moderate increase in blood glucose and insulin was observed, ingestion of fructose elicited a marked stimulation of whole body CHO oxidation (Lê & Tappy, 2006; Tappy et al., 1986). By contrast, a rapid and sharp increase in blood glucose and insulin was recorded after glucose consumption (Tappy et al., 1986). This result was in agreement with the fact that fructose was regarded as LGI CHO (Atkinson et al., 2008). Second, almost all fructose absorbed had a nearly complete hepatic extraction, rapidly metabolizing into fructose-1-phosphate. Typically, fructose metabolism does not occur in extrahepatic cells to any significant extent under usual conditions (Tappy & Lê, 2010). However, the main part of an oral glucose load was

metabolized in peripheral tissues. Due to its LGI effect and its metabolite, i.e., fructose-1-phosphate, fructose was initially regarded as a potential beneficial sweetener for patients with diabetes. Fructose-1-phosphate could acutely increase glucokinase activity, which played a key role in the control of glucose homeostasis (Lê & Tappy, 2006). Third, fructose metabolism would bypass the main rate-controlling step in glycolysis, 6-phosphofructokinase. By contrast, hepatic glucose metabolism was limited by the capacity to store glucose as glycogen, and by the inhibition of glycolysis as well. Lactate was one important product in fructose metabolism in the liver; because fructose uptake by the liver was not inhibited, fructose consumption would result in larger increase in circulating lactate than a comparable amount of glucose consumption (Bjorkman, Gunnarsson, Hagstrom, Felig & Wahren, 1989; Elliott et al., 2002). Finally, part of fructose could be converted to fatty acids in hepatocytes through the process of de novo lipogenesis (Parks, Skokan, Timlin & Dingfelder, 2008). Simultaneously, fructose could inhibit hepatic lipid oxidation, thus favoring fatty acid re-esterification and very low-density lipoprotein (VLDL) synthesis (Tappy & Lê, 2010). Fructose administration likewise resulted in greater postprandial hypertriglyceridemia than that observed with isocaloric glucose (Swarbrick et al., 2008).

In summary, when fructose was absorbed, it was quickly extracted by the liver. In the liver, there were several metabolic pathways for fructose metabolism. Certain evidence supported that at least 50% of fructose was converted to glucose, and this was the major pathway for hepatic fructose disposal (Delarue et al., 1993; Tappy & Lê, 2010). A certain amount of glucose derived from fructose then could be directly stored as hepatic glycogen (Petersen et al., 2001; Tappy & Lê, 2010). Another important metabolic product was lactate, and this was one significant pathway for

hepatic fructose disposal (Teff et al., 2004). Finally, part of fructose was converted to fatty acids through the process of de novo lipogenesis (Parks et al., 2008). However, this was only a minor pathway in fructose metabolism (Chong, Fielding & Frayn, 2007).

2.3.3 Role of fructose in human health

A small dose of fructose consumption appeared to aid in the control of homeostasis, possibly through increasing glucokinase activity by fructose-1-phosphate (Lê & Tappy, 2006). However, feeding high fructose diets to various animals was shown to be associated with several metabolic and cardiovascular adverse effects such as dyslipidemia, insulin resistance, impaired glucose homeostasis, increased body fat, and high blood pressure (Lê & Tappy, 2006; Tappy & Lê, 2010).

2.3.3.1 Fructose and diabetes

A number of epidemiological studies have shown a remarkable association of sugar intake with diabetes rates, which were summarized in a recent review (Johnson et al., 2009). The introduction of HFCS in the 1970s resulted in a 30% increase in total fructose intake in the last 20 years, and this is associated with remarkable increase in diabetes rate (Johnson et al., 2009). In the Nurses' Health Study II, over 50,000 women free of diabetes were included in the investigation. Results revealed that women consuming one or more sugar-sweetened soft drink per day had a higher risk for diabetes, being independent of BMI or energy intake (Schulze, Manson et al., 2004). Another prospective study supported the positive association between sugar intake and the risk of developing diabetes (Montonen, Jarvinen, Knekt, Heliovaara & Reunanen, 2007; Palmer et al., 2008). However, a study failed to identify this

relationship, especially when analysis was restricted to fructose intake (Janket, Manson, Sesso, Buring & Liu, 2003).

Assessing the association between fructose and diabetes in human studies was very difficult. The results of several intervention studies were summarized in a recent review (Laville & Nazare, 2009), which concluded that "concerning fructose, there are still discrepancies between studies' conclusions about the long-term deleterious effect on diabetes development. But its effect on lipogenesis and triglyceridemia has to be taken into account, considering the growing use of fructose in food industry and sugar-sweetened drinks". Maintaining a high fructose diet for more than one week has been long acknowledged to increase plasma total and VLDL in both healthy subjects and patients with diabetes (Tappy & Lê, 2010). Hepatic de novo lipogenesis may play a role in fructose-induced hypertriglyceridemia (Parks et al., 2008). Interestingly, administration of equivalent amounts of fructose, sucrose, mixtures of glucose and fructose, or HFCS led to similar increases in postprandial TG (Stanhope et al., 2008). At present, it is generally admitted that both high NEFA and high plasma TG concentrations are related to insulin resistance, while insulin resistance plays a major role in the development of diabetes (Shulman, 2000). Therefore, although specific evidences remained missing in terms of the effect of fructose on diabetes, it was reasonable to suspect that increased fructose consumption was related to the increased prevalence of diabetes nowadays. Furthermore, high fructose feeding undoubtedly could cause insulin resistance in rodents, although evidence in humans was less impressive (Tappy & Lê, 2010).

2.3.3.2 Fructose and cardiovascular diseases, metabolic syndrome

Several researchers suggested that fructose content of sugar may be the critical component associated with the risks of obesity and heart diseases (Elliott et al., 2002). A number of striking epidemiologic associations between sugar intake and the epidemic of CVD were found as well (Johnson et al., 2007). In a recent study (Fung et al., 2009), the relationship between sweetened drink intake and occurrence of CHD was assessed in 88,520 women. Sweetened beverage consumption was significantly associated with an increased incidence of heart disease. This relationship remained significant after adjusting for body weight, and it could be ascribed to the high fructose content of sweetened beverages. In another study from Switzerland (Aeberli et al., 2007), dietary fructose was found to predict an increased level of LDL cholesterol in children, which was known to be associated with high CVD risk.

Metabolic syndrome is a constellation of pathologies including obesity, insulin resistance, dyslipidemia, and hypertension (Elliott et al., 2002). All these factors were related to the development of CVD (Stanhope & Havel, 2008b). In the Framingham Heart Study (Dhingra et al., 2007), soft drink consumption was linked to the development of cardiovascular risk factors and the metabolic syndrome. Individuals consuming one or more bottles of soft drink per day were observed to have a higher prevalence of the metabolic syndrome and an increased risk for developing metabolic syndrome over 4-years of follow-up. Fructose consumption was likewise found to be associated with new markers of cardiovascular risk in recent years, such as cytokines, plasminogen, oxidative stress, and so on (Tappy & Lê, 2010). A possible mechanism behind the relationship between fructose

consumption and metabolic syndrome, CVD has been discussed considerably (Johnson et al., 2007; A. Miller & Adeli, 2008; Rutledge & Adeli, 2007; Stanhope & Havel, 2008b). In summary, fructose consumption appeared to induce postprandial hypertriglyceridemia, hepatic insulin resistance, up-regulated VLDL production, and high serum uric acid levels, which all contributed to the development of CVD.

2.3.3.3 Fructose and obesity

As mentioned previously, both sugar and fructose consumption undoubtedly increased significantly over the past decades. At the same time, the prevalence of obesity has significantly increased globally. Therefore, a number of researchers have suggested that dietary fructose content may play a role in the increasing prevalence of obesity (Bray et al., 2004; Elliott et al., 2002). Although many epidemiological studies supported the link between these, the results of these studies must be carefully interpreted as epidemiological studies were incapable of providing cause-and-effect conclusions. Furthermore, many studies did not assess directly the effects of total fructose consumption, but of "sugars" or sugar-sweetened beverages.

Several cross-sectional studies assessed the relationship between sugar-sweetened beverages and BW. Majority of these studies showed a positive association between them (Ludwig, Peterson & Gortmaker, 2001; Schulze, Manson et al., 2004; Troiano, Briefel, Carroll & Bialostosky, 2000). However, a number of studies failed to demonstrate such association (Blum, Jacobsen & Donnelly, 2005). Several intervention studies provided a clearer view of this topic. In two studies, the addition of sugar-sweetened beverages resulted in significant weight gain compared with the control group (Raben, Vasilaras, Moller & Astrup, 2002; Tordoff & Alleva, 1990). Conversely, several studies showed a significant reduction in energy intake and/or

BW if daily intake of sugar-sweetened beverages was reduced (Ditschuneit, Flechtner-Mors, Johnson & Adler, 1999; Ebbeling et al., 2006). Recently, several systematic reviews were conducted to investigate this association and yielded inconsistent results; three found positive association between soft drink consumption and BW (Olsen & Heitmann, 2009; Vartanian, Schwartz & Brownell, 2007), while another did not report such association (Forshee, Anderson & Storey, 2008).

There is a theoretical possibility that dietary fructose may increase the risk of obesity. First, dietary fructose may increase energy intake. It has been demonstrated that postprandial hyperinsulinemia played an important role in the mechanisms controlling satiety and food intake (Saad et al., 1998), possibly through stimulating leptin release. Leptin is produced primarily in fat cells and may result in a marked decrease in food intake (Pelleymounter et al., 1995; Y. Zhang et al., 1994). Fructose is a well-known LGI CHO; it usually elicits less glycemic and insulinemic responses. Therefore, lower circulating insulin and leptin after fructose consumption may inhibit appetite less than consumption of other CHO, leading to an increase in food intake. A recent study revealed that ingestion of fructose-containing meals elicited lesser suppression of the appetite-stimulating hormone ghrelin and a lower increase in leptin than meals containing an equivalent amount of glucose (Teff et al., 2004). Furthermore, a high fructose intake may impair leptin's action, thus causing a state of leptin resistance (Tappy & Lê, 2010). Second, as mentioned, part of fructose may be converted to fatty acids in hepatocytes through the process of de novo lipogenesis (Parks et al., 2008). In addition to altering plasma lipid profile, fructose may modulate intracellular lipid deposition such as hepatocytes and muscle fibers (Unger, 2003). In a more recent study (Stanhope et al., 2009), fructose and glucose were compared by replacing 25% of the calories with either a glucose containing drink or

a fructose containing drink for 10 weeks. It was found that a high fructose diet - but not a high glucose diet - increased visceral adiposity, promoted dyslipidemia, and increased insulin resistance.

Altogether, studies in this area appeared to yield inconsistent results and no conclusive comment could be drawn. A reason behind this inconsistency may be explained by the fact that it was very difficult to calculate accurately the amounts of fructose or sugar consumed. Moreover, many other confounding factors, such as other nutrients consumption and physical activity, were difficult to control. However, from previous studies, strong evidence supported the association between fructose consumption and obesity, at least in children and adolescents (Tappy & Lê, 2010).

In summary, the potential danger of fructose consumption and its links to various metabolic disorders such as diabetes, metabolic syndrome, CVD, obesity, and so on have been widely documented. Dietary fructose consumption appeared to have adverse effects on plasma lipids in both diabetic and healthy populations. However, many well-designed long-term intervention studies are needed to clarify further the association between fructose consumption and these chronic diseases, and to explain the mechanism behind this.

2.3.4 Application of fructose in exercise

As mentioned, numerous studies have been conducted to investigate the effect of CHO consumption on exercise. The amounts and types of CHO may be critical to all phases of training and competition, and even for physical activity. This part of the review will focus on the studies investigating the relationship between fructose consumption and metabolic responses in exercise.

2.3.4.1 Effect of fructose before exercise

As mentioned earlier, several studies found improved exercise performance when CHO, especially a large amount, was consumed before exercise (Gleeson et al., 1986; Kirwan et al., 1998; Neufer et al., 1987; Schabort et al., 1999; Sherman et al., 1989; Sherman et al., 1991). This may be attributed to increased CHO availability late in exercise. Fructose was advocated as a pre-exercise CHO feeding. In a previous study, 12 trained males were studied to examine the effect of pre-exercise fructose ingestion on endurance capacity during prolonged cycling exercise (Okano et al., 1988). Sixty minutes prior to exercise, subjects ingested either 60 g or 85 g of fructose or a sweet placebo. Initial exercise intensity was 62% $\dot{V}O_{2max}$, which was subsequently increased to 72% and 81% $\dot{V}O_{2max}$ after 90 and 120 min of exercise, respectively. Exercise time to exhaustion was significantly increased after fructose ingestion, as compared to placebo ingestion. During exercise, no difference was observed between trials for serum glucose, insulin, FFA, and glycerol levels. The researcher concluded that fructose ingestion was of benefit before prolonged exercise, possibly through providing a CHO source to contracting muscles without transient hypoglycemia and a depression of fat utilization.

In theory, fructose can produce lower blood glycemic and insulinemic responses. Therefore, it will not produce an initial lowering of blood glucose and may produce a more beneficial effect on exercise performance than other CHO. This was similar to the consumption of LGI CHO versus HGI CHO. However, majority of studies did not find this to be a beneficial effect. A previous study (Décombaz et al., 1985) first investigated whether glucose beverages or fructose beverage ingested 1-hr before exercise would affect exercise performance. No difference was found in 15-min total

maximal work output between the two trials in this study. Two later studies likewise found similar result after glucose, fructose, or placebo ingestion (Hargreaves et al., 1987; van Zant & Lemon, 1997). Therefore, it appeared that fructose consumption prior to exercise did not induce more advantages than other CHO in improving exercise performance. This may be a reason why not many studies have been conducted recently to investigate this effect further. Furthermore, fructose consumption may cause adverse influence on exercise performance, such as gastrointestinal symptoms (Skoog & Bharucha, 2004).

Therefore, based on literature, pre-exercise fructose beverage consumption was not recommended for athletes in improving exercise performance. However, dietary sources of fructose usually contain other CHO such as glucose, which may increase fructose absorption in healthy subjects (Truswell et al., 1988). Therefore, more studies should be conducted to investigate the effects of fructose content in mixed meals on subsequent exercise.

2.3.4.2 Effect of fructose during exercise

It is now generally accepted that CHO feeding during exercise can improve endurance capacity and exercise performance during prolonged exercise (Jeukendrup, 2004). The mechanism behind this improvement is likely to be related to the maintenance of high rates of CHO oxidation, prevention of hypoglycemia, sparing of endogenous glycogen, or a central effect of CHO. Evidently, the amount and type of CHO consumed during the exercise will significantly affect this process. It appeared that relatively small amounts of CHO, specifically over 16 g per hour, could provide certain benefit to exercise performance; no further improvement has been observed with the ingestion of larger amounts of CHO, specifically over 75 g per hour

(Jeukendrup, 2004). A recent study observed positive effects of CHO ingestion during relatively high intensity exercise that lasted approximately 1-hr (Carter, Jeukendrup, Mundel & Jones, 2003).

In addition, previous studies reported that type of CHO has little or no effect on exercise performance (Jeukendrup, 2004). However, type of CHO consumed during exercise appeared to affect certain metabolic responses during exercise. Recently researchers divided CHO into two arbitrary categories: CHO that can be oxidized at rates up to approximately 30-50 g per hour, and those up to 60-70 g per hour (Jeukendrup, 2008). It has been suggested that oxidation of a single exogenous CHO is limited to approximately 60 g per hour in view of a limitation in the rate of intestinal absorption of that CHO (Jeukendrup, 2004). Therefore, athletes who ingest a single type of CHO are advised to ingest approximately 60-70 g per hour for optimal CHO delivery. Ingesting more than this amount will not increase CHO oxidation rates any further, and is likely to be associated with gastrointestinal discomfort (Jeukendrup, 2008).

Glucose is a CHO that is oxidized quickly as it does not require digestion and is readily absorbed. A previous study showed that exogenous CHO oxidation rates of maltose, sucrose, and glucose polymers are comparable to those of glucose (Saris et al., 1993). Fructose consumption during exercise was found to induce lower CHO oxidation rate than glucose consumption (Burelle, Lamoureux, Peronnet, Massicotte & Lavoie, 2006). However, simultaneous consumption of glucose, fructose, and/or other sugars was observed to increase CHO oxidation rates further (Adopo, Peronnet, Massicotte, Brisson & Hillaire-Marcel, 1994; Jentjens, Achten & Jeukendrup, 2004; Jentjens, Moseley et al., 2004). In one study (Jentjens, Moseley et al., 2004), when

glucose ingestion rate was 1.8 g·min^{-1}, the exogenous CHO oxidation rates peaked at 0.83 g·min^{-1} at the end of 120-min of exercise. However, when a mixture of isocaloric glucose and fructose was ingested, total exogenous CHO oxidation rate peaked at 1.26 g·min^{-1}. In a following study (Jentjens, Achten et al., 2004), when combined ingestion of glucose, fructose, and sucrose was at a rate of 2.4 g·min^{-1}, peak exogenous CHO oxidation rate reached at 1.7 g·min^{-1}. The increased exogenous CHO oxidation may be attributed to a different transport mechanism between fructose and glucose. Fructose was transported by GLUT5, whereas glucose was transported across the luminal membrane by GLUT1 (Ferraris & Diamond, 1997).

In theory, increased exogenous CHO oxidation will spare endogenous sources of CHO, specifically liver and muscle glycogen. Therefore, it may offer certain benefits for endurance capacity and/or exercise performance. It was reasonable to assume that multiple types of CHO ingestion during exercise would increase exercise performance than a single type of CHO. Recently, a study confirmed this assumption, reporting that ingestion of glucose and fructose during exercise led to an 8% improvement in TT cycling performance compared with ingestion of only glucose (Currell & Jeukendrup, 2008). Furthermore, compared with a single source of CHO, ingesting multiple CHO sources resulted in a smaller amount of CHO remaining in the intestines. Therefore, these are possibly less likely to cause gastrointestinal discomfort (Jeukendrup, 2008). A recent study (Jeukendrup & Moseley, 2008) likewise found that multiple transportable CHO can enhance gastric emptying and fluid delivery compared with a single CHO. Different techniques to measure gastric emptying and fluid delivery resulted in the same findings. In addition, fructose ingestion has been shown to result in an increase in plasma lactate compared with glucose (Jentjens et al., 2006). It is possible that increased lactate was oxidized in the

muscle, therefore providing another energy source (B. F. Miller et al., 2002).

In summary, it appeared that fructose should be consumed, combined with other types of CHO, during prolonged exercise. Multiple transportable CHO could increase exogenous CHO oxidation and fluid delivery, and even have the possibility to increase exercise performance compared with single CHO ingestion. However, the ideal fructose level consumed during exercise has not been sufficiently demonstrated, and more studies are needed to clarify this further.

2.3.4.3 Effect of fructose after exercise

As mentioned earlier, one of the most important aspects of recovery after exercise was glycogen replenishment, especially for short-term recovery. Evidently, this process could be affected by CHO consumption after exercise, such as the CHO amount, timing, or even frequency (Jentjens & Jeukendrup, 2003a). CHO-rich foods with a MGI to HGI appeared to offer certain advantages over LGI choices in promoting glycogen synthesis. However, the form of CHO did not appear to affect glycogen synthesis (Burke, Loucks & Broad, 2006). Fructose is a well-known LGI CHO, and it must be catabolized in the liver before it can enter circulation through the blood and contribute to glycogen synthesis within the skeletal muscle. Therefore, it appeared that fructose should not be considered as a major CHO source after exercise, at least during the first several hours' recovery. A previous study (Blom, Hostmark, Vaage, Kardel & Maehlum, 1987) showed that the rate of muscle glycogen synthesis after exercise was similar for feedings of glucose or sucrose, but feedings containing only fructose produced a rate of muscle glycogen synthesis that was 50% lower. However, as discussed previously, multiple transportable CHO ingestion during exercise appeared to increase CHO oxidation rates and have the

possibility to improve exercise performance (Jeukendrup, 2008). Whether this kind of multiple transportable CHO ingestion, i.e., fructose was added into MGI or HGI CHO, after exercise would further increase muscle glycogen synthesis appeared to be an interesting topic. Actually, a very recent study (Décombaz et al., 2011) demonstrated that when ingested at a rate designed to saturate intestinal CHO transport systems, maltodextrin (MD) drinks with added fructose were twice as effective as MD drinks with added glucose in restoring liver glycogen during short-term post-exercise recovery. Evidently, more studies are needed to investigate this effect.

2.3.5 Pre-exercise carbohydrate consumption, fructose, and substrate utilization

As discussed previously, substrate utilization and/or exercise performance during exercise appeared to be influenced by different pre-exercise CHO ingestion, possibly through different glycemic and insulinemic responses. Therefore, many studies focused on strategies that may minimize the changes in plasma glucose and insulin prior to exercise. Among these studies, LGI CHO was deemed more advantageous and investigated considerably. Fructose, as a LGI CHO, was investigated by several researchers as well (Décombaz et al., 1985; Fielding et al., 1987; Hargreaves et al., 1987; Hargreaves et al., 1985; Horowitz et al., 1997; Koivisto et al., 1985; Koivisto et al., 1981; Levine, Evans, Cadarette, Fisher & Bullen, 1983; van Zant & Lemon, 1997; Yannick Guezennec et al., 1989). In recent years, however, almost no studies were conducted to investigate this effect further. The major reason may be the potential adverse influence of fructose consumption on exercise, such as gastrointestinal symptoms (Skoog & Bharucha, 2004). Furthermore, a number of

studies did not observe improved exercise performance after fructose ingestion (Décombaz et al., 1985; Hargreaves et al., 1987; van Zant & Lemon, 1997). Athletes were used as subjects in these studies, and moderate to high intensity exercise was used to investigate the effect of pre-exercise fructose ingestion on exercise performance. In majority of these studies fructose beverage was ingested solely. For ordinary people, however, this is not the common practice. Dietary fructose consumption has increased in conjunction with rising intake of fructose-containing sugars, largely in the form of sugar-sweetened beverages (Marriott et al., 2009; Park & Yetley, 1993; Vos et al., 2008). Furthermore, dietary sources of fructose usually contain other CHO such as glucose, which could increase fructose absorption in healthy subjects (Truswell et al., 1988). Therefore, it was worthwhile to investigate whether the increased fructose content in meals would affect substrate utilization during rest or subsequent exercise, especially for ordinary people.

2.3.5.1 Fructose ingestion solely

In some earlier studies on the effect of pre-exercise CHO consumption on metabolic responses during exercise, fructose beverage was often used. Two earlier studies (Koivisto et al., 1985; Koivisto et al., 1981) investigated metabolic responses during exercise after consumption of glucose beverage, fructose beverage, or placebo. During the postprandial period, glucose beverage ingestion was observed to induce higher glycemic and insulinemic responses than fructose beverage ingestion or placebo ingestion. Meanwhile, glucose concentrations were sufficiently maintained during subsequent exercise after fructose beverage or placebo ingestion, but not after glucose beverage ingestion. These results were expected because glucose was HGI CHO and fructose was LGI CHO. One study found no difference in muscle glycogen

usage during exercise among the three trials (Koivisto et al., 1985). It is worth mentioning that two different exercise intensities were used in these two studies, specifically 75% and 55% $\dot{V}O_{2max}$. Therefore, this kind of metabolic responses appeared to be independent of exercise intensity. Unfortunately, in these two studies, substrate utilization was not measured. A very similar study later found no difference in RER among the three trials during exercise (Hargreaves et al., 1985), which indicated that total CHO or fat oxidation was similar after glucose, fructose, or placebo ingestion. This result was different from studies in which LGI meal consumption usually induced higher fat oxidation and less CHO oxidation than those after HGI meal consumption.

A previous study (Décombaz et al., 1985) first investigated whether glucose beverage or fructose beverage ingestion 1-hr before exercise would affect exercise performance. No difference was found in 15-min total maximum work output after glucose or fructose beverage ingestion. The results revealed that glucose beverage induced higher glycemic and insulinemic responses during the postprandial period than fructose beverage, whereas no difference was found in substrate utilization during subsequent exercise between the two trials, including muscle glycogen usage. Interestingly, although no difference in RER was found during exercise in this study, average RER during the postprandial period was higher after fructose consumption than after glucose consumption. We could suspect from this result that during postprandial period, there was an increase in CHO oxidation after fructose consumption, which may be a consequence of earlier oxidation of fructose than glucose. This result was consistent with a later study (Blaak & Saris, 1996), in which fructose and sucrose consumption produced more CHO oxidation than glucose and starch consumption during the 6-hrs of postprandial period. It was likewise found in

this study that the initial inhibition of lipid oxidation was higher with sucrose and fructose consumption than with glucose and starch consumption, whereas the integrated decrement in lipid oxidation was merely higher with fructose consumption compared with glucose and starch consumption.

Similar results were found in some later studies as well (Fielding et al., 1987; Hargreaves et al., 1987; Levine et al., 1983; van Zant & Lemon, 1997; Yannick Guezennec et al., 1989), although small difference was observed in two of them (Fielding et al., 1987; Levine et al., 1983). One study found that glucose beverages induced higher RER during subsequent exercise than placebo ingestion, while fructose beverages did not (Fielding et al., 1987). Another study found higher fat oxidation after fructose beverage consumption than glucose beverage consumption during the first 5-min of exercise (Levine et al., 1983). The inconsistent results may be caused by different subjects or different exercise intensity.

In majority of previous studies, fructose beverage was ingested during 1-hr before exercise. One study (Burelle et al., 1997) compared the oxidation of glucose or fructose ingested as a pre-exercise CHO between 180 min and 90 min before exercise on six subjects when either a placebo or sucrose was ingested during exercise. The results revealed that sucrose ingestion during exercise did not affect the exogenous glucose or fructose oxidation, which was ingested before exercise. However, exogenous glucose oxidation was higher than exogenous fructose oxidation, possibly because of the higher absorption rate. The researcher suggested that in terms of availability for oxidation of CHO provided by the pre-exercise meal, glucose should be favored over fructose. It was worth mentioning that although certain differences in exogenous glucose and fructose oxidation were observed

during exercise, total CHO or fat oxidation was similar between glucose trial and fructose trial.

This inconsistent result in substrate utilization between fructose beverage and other LGI meal may be explained by the special metabolism of fructose in the liver. First, fructose metabolism could bypass the first rate-limiting enzymes of glycolysis, and thus be expected to be more readily oxidized (Lê & Tappy, 2006). Previous studies have revealed that ingestion of fructose elicited a marked stimulation of whole body CHO oxidation, although only a moderate increase in blood glucose and insulin was observed (Lê & Tappy, 2006; Tappy et al., 1986). Fructose and sucrose consumption was found to produce greater CHO oxidation than glucose and starch consumption at rest (Blaak & Saris, 1996). Similarly, in another study (Delarue et al., 1996), the subjects were provided with an oral dose of glucose and fructose on two separate days. The higher glycemic and insulinemic responses were observed in the glucose trial than in the fructose trial, while CHO oxidation was 25% higher in the latter trial. By contrast, fat oxidation was 35% lower in the fructose trial than in the glucose trial. Second, in the liver, part of fructose could be converted to fatty acids in hepatocytes through the process of de novo lipogenesis (Parks et al., 2008). Simultaneously, fructose could inhibit hepatic lipid oxidation, thus favoring fatty acid re-esterification and VLDL synthesis (Tappy & Lê, 2010). This process could inhibit whole body fat oxidation. Several studies have observed decreased lipolysis and whole body lipid oxidation after fructose consumption (Abdel-Sayed et al., 2008; Chong et al., 2007), which supported this speculation to a certain degree. Therefore, compared with glucose beverage ingestion, although less insulinemic responses after fructose beverage ingestion were favorable to fat oxidation during subsequent exercise, the metabolism of fructose in the liver produced an opposite effect on fat

oxidation. The interaction of all these effects induced similar substrate utilization during exercise after fructose or glucose beverage ingestion.

In another study (Horowitz et al., 1997), six healthy, active men cycled for 60-min at 44% $\dot{V}O_{2max}$ exactly 1-hr after ingesting 0.8 $g \cdot kg^{-1}$ BW glucose beverage (Glc), fructose beverage (Fru), or after an overnight fast (Fast). Mean plasma insulin concentrations during the 50-min before exercise were different among the three groups, with the highest concentration in Glc trial and the lowest in the Fast group. After 25-min of exercise, whole body lipolysis and fat oxidation were highest in the Fast trial and lowest in the Glc trial. Therefore, the results indicated that fructose beverage ingestion induced greater fat oxidation than glucose ingestion, but less than that in the fasted state. This inconsistent result may be caused by different exercise intensity. Nonetheless, this study suggested that small elevations in plasma insulin before exercise suppressed lipolysis during exercise to the point at which it equaled and appeared to limit fat oxidation.

In summary, compared with glucose beverage ingestion, fructose beverage ingestion before exercise resulted in less increase in postprandial plasma glucose and insulin concentrations, and induced more stable blood glucose concentrations during subsequent exercise. However, it appeared that there were no differences in total CHO or fat oxidation, including muscle glycogen usage during subsequent exercise with moderate to high intensities. Therefore, it appeared that pre-exercise fructose beverage ingestion solely did not induce more advantages than glucose beverage, and fructose should not be considered as a typical LGI CHO when discussing fuel metabolism.

2.3.5.2 Fructose ingestion in mixed meals

When fructose was consumed as part of a mixed meal, its effect on substrate utilization during subsequent exercise may be more complicated. Despite the fact that dietary fructose consumption has increased significantly in recent years around the world, to our knowledge, not many studies were conducted to specially investigate the effect of fructose content in mixed meals consumed before exercise on substrate utilization during subsequent exercise and/or exercise performance. Therefore, more studies are needed to clarify this effect further.

As mentioned earlier, it appeared that fructose should not be considered as a typical LGI CHO when discussing fuel metabolisms. Although fructose beverage ingestion solely before exercise induced similar glycemic responses and insulinemic responses as LGI meal, no differences in substrate utilization were usually observed during subsequent exercise after fructose beverage or glucose beverage ingestion. Meanwhile, according to majority of previous studies, LGI meal consumption often induced greater fat oxidation and less CHO oxidation than those after HGI meal consumption.

When fructose beverage was consumed as part of a mixed meal, its effect on substrate utilization may differ from that of fructose beverage ingestion solely to a certain degree. Several studies have revealed that fructose consumption produced more CHO oxidation than glucose consumption during the postprandial period (Blaak & Saris, 1996; Delarue et al., 1996), while the differential effect of fructose on fat oxidation tends to disappear when fructose was not provided as the only source of energy but instead combined with other foods in the same meal (McDevitt, Poppitt, Murgatroyd & Prentice, 2000). Although the glycemic and insulinemic

responses were not measured in this study, other studies have found that when fructose beverage or glucose beverage was consumed in mixed meals, glycemic and insulinemic responses were higher in glucose trial (Stanhope et al., 2008; Teff et al., 2009). This type of glycemic and insulinemic responses agreed well with that after HGI and LGI meal consumption. Therefore, it appeared that when fructose was consumed as part of mixed meals, it would produce similar glycemic and insulinemic responses as other LGI meals. However, it remains unknown whether the fructose content in mixed meals would affect substrate utilization during the postprandial period or during subsequent exercise. A recent review article compared the effect of LGI CHO consumption and fructose consumption on fuel partitioning in humans and concluded that fructose should not be considered as a LGI CHO, at least when discussing fuel metabolism assessment (Diaz et al., 2006).

Several epidemic studies and intervention studies have observed a positive association between the consumption of sugar-sweetened beverage and BW (Ludwig et al., 2001; Raben et al., 2002; Schulze, Manson et al., 2004; Tordoff & Alleva, 1990; Troiano et al., 2000). Additionally, a recent study (Stanhope et al., 2009) found that a 10 wk high fructose diet, but not a high glucose diet, increased visceral adiposity. Exercise, especially moderate intensity exercise, could increase fat oxidation, so as to decrease the adverse effect of fructose consumption to a certain degree. Therefore, it is important to investigate the exact effect of fructose content in meals on substrate utilization both at rest and during exercise.

In summary, the effect of fructose content in mixed meals consumed before exercise on substrate utilization during exercise has not been sufficiently investigated. Certain evidence supported the claim that high fructose content in mixed meals would

induce less glycemic and insulinemic responses than high glucose content in mixed meals. However, it remains unknown whether and how the interaction of this metabolic response and fructose content affect substrate utilization. Therefore, more studies are needed to clarify this effect.

CHAPTER 3

GENERAL METHODOLOGY

3.1 Subjects

Young healthy male and female subjects were recruited in Study I, whereas only young healthy male subjects participated in Study II and Study III. All studies were approved by the Clinical Research Ethical Committee of the Chinese University of Hong Kong. All subjects were required to complete a medical-history questionnaire (Appendix A) before the experiment. If any subject reported a history of diabetes or took any medication during the past four weeks prior to the study, he would be excluded from the research. All subjects were fully informed about the experimental procedures as well as the potential risks and discomforts which might incur. They were also required to give a statement of informed consent (Appendix B). All subjects also were required to complete the International Physical Activity Questionnaire (Appendix C). Only those who had moderate physical activity levels were included in this study. In order to exclude any residual effects of previous meals or exercise on the treatment, all subjects were required to refrain from alcohol consumption and vigorous physical activities 24-hrs before the test. They were also required to report to the laboratory after 10-12 hrs overnight fast. This was to ensure an empty stomach and minimize the effect of a previous dinner meal on gastric emptying rate of the test meals. In order to maintain euhydration condition before each main trial testing, all subjects were instructed to ingest approximately 500 ml. of water the night before.

3.2 Equipment and instrument

Two calibrated motor-driven treadmill were used in Study II (Jaeger, LE 500C, Germany) and Study III (h/p/cosmos®, model pulsar, Germany), respectively. The treadmill fulfilled the requirement of experimental testing in the studies.

3.3 Sample collection and measurement

3.3.1 Body weight, height, body mass index, and heart rate

Body weight (BW) was measured using an electronic digital balance scale (Model BWB 600, Tanita, Japan). The subjects were weighed wearing only running shorts. Height was measured using a wall mounted stadiometer (Holtain Ltd, Britain). Body mass index (BMI) was calculated by BW and height value (BMI = BW ÷ height^2, kg·m^{-2}). Throughout the process of each experimental testing, heart rate (HR) of subjects was continuously monitored using a HR monitor (Sport Tester RS800CX, Polar Electro, Finland).

3.3.2 Capillary blood sample collection and measurement

The capillary blood samples were collected from the thumb of a pre-warmed hand using an automatic lancet (ACCU-CHEK® Softclix, Roche, Germany) and capillary dispensers. Then the samples were used to determine the blood glucose concentration, blood lactate concentration, hemoglobin (Hb) concentration, and hematocrit (Hct). Blood lactate and glucose concentrations were determined immediately after collection, using a lactate analyzer (Model 1502, YSI, USA) and a glucose analyzer (Model 1502, YSI, USA). Hematocrit was determined using a reader (Clay Adams, Autocrit Ultra 3, Englewood, NJ), and Hb was determined by

automatic clinical chemistry analyzer (Reflotron® System, Boehringer Mannheim, Germany).

3.3.3 Venous blood sample collection and measurement

The venous blood samples were collected in Study II and Study III. An indwelling cannula (Angiocath, 22GA 1.00-in., Becton Dickinson, USA), which was connected to a 3-way stopcock (Connecta Plus 3, Becton Dickinson, USA) with a 10 cm extension tube, was inserted into the antecubital vein of the forearm after the subjects arrived at the laboratory and had a rest. The cannula was remained in the place throughout the main trial and it was kept patent by the infusion of sodium chloride solution (0.9%, B.Braun, Malaysia). The venous blood samples were withdrawn via the extension tube. The first 4 mL of venous blood samples were discarded to avoid contamination with saline. Another 5 mL of samples were dispensed into a non-heparinized plastic tube and left to clot at room temperature for 60-min. Serum samples were then obtained after centrifugation at 8,500 rev·min^{-1} for 10-min at 4 degree (Biofuge Primo R, Heraeus, Germany). The aliquoted serum was stored in microtubes in a -35 degree medical freezer and was analyzed using commercially available reagents later for serum insulin (Insulin ELISA, Mercodia, Sweden). The serum glycerol (GY 105 kit, Randox Laboratories Ltd, UK) and free fatty acids (FFA) (FA 115 kit, Randox Laboratories Ltd, UK) concentrations were measured using semi-automatic clinical analyzer (RX monza, Randox, UK).

3.3.4 Expired air sample collection and measurement

Expired air samples were collected and analyzed using a metabolic testing system (MAX-II, Physio-Dyne, New York). During the collection, subjects wore a nose clip

and vinyl plastic soft mouthpiece (Hans Rudolph Inc., USA). Volume of oxygen consumed ($\dot{V}O_2$), volume of carbon dioxide produced ($\dot{V}CO_2$), and respiratory exchange ratio (RER) were analyzed by this system.

Rates of CHO and fat oxidation were calculated from $\dot{V}O_2$ and $\dot{V}CO_2$ values using stoichiometric equations (Frayn, 1983). The equations were listed as following:

CHO oxidation rate ($g \cdot min^{-1}$) = 4.55 $\dot{V}CO_2$ 3.21 $\dot{V}O_2$

Fat oxidation rate ($g \cdot min^{-1}$) = 1.67 $\dot{V}O_2$ – 1.67 $\dot{V}CO_2$

The amounts of carbohydrate (CHO) and fat oxidized were estimated from the area under the rate of oxidation versus time curve for each subject. The energy expenditure during exercise was calculated by applying the equation described previously (McArdle, Katch & Katch, 2006). This equation was following:

Energy Expenditure ($kcal \cdot min^{-1}$) = [(1.1 × RER) + 3.9] × $\dot{V}O_2$

3.3.5 Perceptual variables

During the preliminary test and the main trial test, the rating of perceived exertion (RPE) of subjects was estimated using the 6- to 20-point Borg scale (Borg, 1973), where 6 was "very very light" and 20 was "maximal hard" (Appendix D). The rating of perceived thirst (RPT) was assessed using a 10-point scale (Sandick, Engell & Maller, 1984), where 1 was "not thirsty" and 10 was "very very thirsty" (Appendix E). The rating of abdominal discomfort (RAD) was assessed using a 10-point scale (Noakes et al., 1988), where 1 was "completely comfortable" and 10 was "Unbearable Pain" (Appendix F).

3.3.6 Dietary analysis

In the present study, each subject was required to have three-day dietary records before main trial test. They were required to repeat the same diet before each main trial as well to minimize the variation in muscle and liver glycogen concentrations. Subjects were given an electronic weighing scale (HL-2000, A & D Co. Ltd., Japan) and precise written instructions (Appendix G & H) on how to weight and record all the foods and fluids consumed over the three-day period. The dietary records were analyzed using computer software (Food Processor 10.5, ESHA, USA).

3.4 Preliminary test

3.4.1 Familiarization

Subjects were required to be familiar with the motorized treadmill, the laboratory environment, and the experimental protocols during the first visit to the laboratory. This familiarization could help alleviate the subjects' anxiety. They were introduced to be familiar with the methods of collecting expired gas and blood samples as well during the period of visit.

3.4.2 Speed - oxygen uptake test

The first preliminary test was conducted to determine the relationship between the brisk walking speed and $\dot{V}O_2$ on a level treadmill. The speeds were chosen with reference to each subject's physical activity levels and were set between around 40% and 70% of individual $\dot{V}O_{2max}$. Because there are 4 different speeds, subjects had to do brisk walking or jogging for 4-min at each stage continuously. Expired air samples were collected during the last minute of each stage and were analyzed.

Heart rate and RPE were monitored throughout the exercise and were recorded at 15th second of last minute during each stage. The relationship between the brisk walking speed and $\dot{V}O_2$ of each subject was established by using linear regression to the four coordinate values of these two variables.

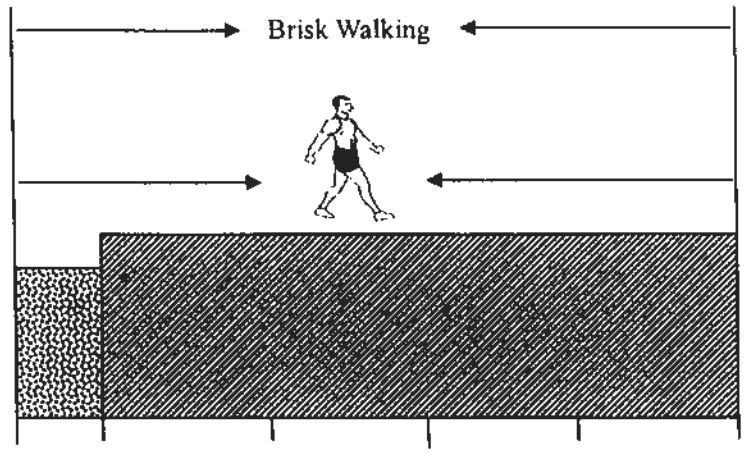
3.4.3 Maximal oxygen uptake test

A continual, incremental graded uphill treadmill running test to volitional exhaustion was used to determine the maximal oxygen uptake ($\dot{V}O_{2max}$) for each subject. The protocol was modified from previous study (Taylor, Buskirk & Henschel, 1955). The submaximal running speed was kept constant throughout the test and the inclination of the treadmill was increased by 2.5% every 3-min from an initial gradient of 3.5%. Subjects had to run for as long as possible to achieve the maximal exertion. Expired air samples were collected when subjects indicated that they could not sustain the required intensity for one more minute. Strong verbal encouragement was given throughout the test. Both the RPE and HR were recorded at 15th second of last minute during each period. The highest value of $\dot{V}O_2$ when it met at least two of the following criteria was considered as the $\dot{V}O_{2max}$ value (Howley, Bassett & Welch, 1995). The criteria included: (1) a plateau of $\dot{V}O_2$ with increasing work rate; (2) a RER greater than 1.1; (3) a HR within 5 beats·min^{-1} of age-predicted maximum HR; (4) a post-exercise blood lactate concentration that exceeded 8 mmol·L^{-1}.

3.5 Exercise protocol

A standard "brisk walking" protocol was used in Study II and Study III. Firstly a 5-min warm-up at 40% $\dot{V}O_{2max}$ was performed. Then subjects completed a 60-min of brisk walking at a speed that equalled to 50% of predicted individual $\dot{V}O_{2max}$. During

exercise, 2 mL·kg^{-1} BW of distilled water was given to the subjects every 30 min to reduce the effect of dehydration. Expired air samples, capillary blood samples, venous blood samples, HR, RPE, RAD, and RPT were obtained at specific time points, as shown in figure 3.1.



HR: Heart rate; RPE: Rating of perceived exertion; RPT: Rating of perceived thirsty; RAD: Rating of abdominal discomfort.

FIGURE 3.1 Schematic representation of the exercise protocol

3.6 Statistical analysis

Data in the text, tables, and figures were presented as Mean ± standard error of the mean (SEM). SPSS software (version 17.0) was used for data analysis. T-test was used in Study I. Analysis of variance (ANOVA) with repeated measures was used in Study II and Study III. Statistical significance was set at the 0.05 level.

CHAPTER 4

GLYCEMIC INDEX OF SELECTED TRADITIONAL CHINESE FOODS

4.1 Introduction

As discussed previously, glycemic index (GI) of foods have been suggested to related to some chronic diseases, such as diabetes (Salmeron, Ascherio et al., 1997; Salmeron, Manson et al., 1997), metabolic syndrome (McKeown et al., 2004), cardiovascular disease (Liu et al., 2000) and even some types of cancers (Augustin, Gallus et al., 2004). LGI diets may contribute to a reduction in body weight (BW) in overweight, obese adolescents (McMillan-Price et al., 2006), or coronary heart disease (CHD) (Barclay et al., 2008). A recent systematic review indicated that LGI diets had a small but clinically useful effect on medium-term glycemic control in patients with diabetes (Brand-Miller et al., 2003). Therefore, the GI concept is tightly related to human health.

The GI values of over 2,480 individual food items were listed in the more recent edition of the international GI table (Atkinson et al., 2008), among which only about 50 Chinese foods were selected. Traditional Chinese foods, although some styles are very popular and well-known worldwide, are very different from Western foods (Woo & Woo, 2001). Previous study has revealed that considerable variation in the GI values of foods is existed even for the same food produced in different countries or by different manufactures (Henry, Lightowler, Strik, Renton & Hails, 2005). Therefore, it is impossible to predict the accurate GI value of a particular traditional Chinese food with any certainty from GI values of Western foods in published GI

table. In many studies investigating the effect of food intake to local people (Hui & Nelson, 2006; Sea, Woo, Tong, Chow & Chan, 2004; Villegas et al., 2007; Woo et al., 2003), the researchers faced with the same problem, i.e., there were no precise GI values for many local Chinese foods. They had to use international GI table to seek for similar foods or seek for a 'best estimate' from experts in this area. They considered as well that there might be some differences between the estimated GI values and the real values, and further studies examining accurate GI values of Chinese foods might be beneficial. Furthermore, in recent years, GI values of many different local foods have been reported (Aston et al., 2008; Sugiyama et al., 2003; Yang et al., 2006).

Therefore, it is worthwhile to determine the GI values of traditional Chinese foods, so as to advise local individuals on their daily diets and provide tools to undertake related studies in this area. The purpose of study I was to determine GI values of several traditional Chinese foods in Hong Kong, which would be preliminary information for the development of a GI database for traditional Chinese foods.

4.2 Methods

4.2.1 Subjects

Fifteen healthy adults (8 males and 7 females) volunteered to participate in the study. Their age and body mass index (BMI) were (mean ± SEM): 25.4±1.2 years, and 21.2±0.6 $kg \cdot m^{-2}$, respectively. All subjects reported no history of diabetes. All female subjects were non-pregnant and non-lactating.

4.2.2 Procedures

The GI values of 29 traditional Chinese foods were determined using a standard method recommended by the Food and Agriculture Organization (FAO) (1998). After 10-14 hrs overnight fast, the subjects were required to report to the lab between 8:00-10:00 a.m. On arrival, the subjects rested for approximately 15-min and the baseline finger-prick capillary blood samples were collected. Then subjects consumed either reference (50 g of anhydrous glucose) or test foods containing 50 g of available carbohydrate (CHO). The macronutrient content of each food was based on the information from the label of food or from the food nutrition content table provided by the Center of Food Safety, the Government of the Hong Kong Special Administrative Region ("Centre for Food Safety, HKSAR," 2008). Each subject was given 50 g of anhydrous glucose for three times as references. Because only three foods containing 25 g of available CHO was selected because of food size limitation, each subject was also required to consume 25 g of anhydrous glucose for two times as references. Among the three foods, two of them, which contained both 50 g and 25 g of available CHO, were selected to test twice in order to compare whether the different portion sizes gave the same result.

The intervals between two tests were at least two days. Foods for testing were randomized in blocks of four foods (Brouns et al., 2005). A drink of 250 mL water was served with test food in each test and all foods were required to be consumed within 10-min. The further blood samples were collected at 15, 30, 45, 60, 90, and 120 min after starting to eat. All the blood samples were analyzed with YSI glucose analyzer (YSI 1502, YSI, USA).

4.2.3 Prescribed foods

All test foods were prepared on the test morning or the day before test. When necessary the foods were steamed by hot water. The detailed information of each food was listed in table 4.1.

TABLE 4.1 Portion size, macronutrient composition and preparation method of the test foods

Food Items	Serving (g)	Energy (kcal)	Protein (g)	Available CHO(g)	Fat (g)	Fiber (g)	Sugar (g)	Method of preparation
BBPP	161	708	14.3	50.0	50.0	2.1	9.2	Hoixe Cake Shop, H.K.; Instant;
FRYS	217	412	15.2	50.0	17.1	4.8	1.3	Instant;
FF	139	653	12.0	50.0	44.5	1.8	1.3	Ocean Empire International Ltd., H.K.; Instant;
MLC	114	319	7.8	50.0	9.2	3.0	19.4	Instant;
TFB	139	417	15.3	50.0	16.7	1.9	19.5	Maxim's MX, H.K.; Instant;
SRWLL	167	351	12.7	50.0	11.2	2.0	3.0	Maxim's MX, H.K.; Instant;
SGRR	109	283	5.6	50.0	7.1	1.9	6.4	Instant;
PAB	91	319	7.8	50.0	10.0	1.5	9.1	Hoixe Cake Shop, H.K.; Instant;
JPBT	106	350	11.7	50.0	11.7	5.5	12.7	Instant;
FRNSB	250	350	10.0	50.0	12.8	5.5	1.8	Instant;
ET	143	458	7.4	50.0	25.7	1.4	27.2	Maxim's MX, H.K.; Instant;
PSVR	238	262	3.1	50.0	5.2	Trace	1.5	Instant;
GBD	333	243	8.3	50.0	1.1	5.3	30.6	NISSIN brand, Nissin Foods Co., LTD.; Instant;
BPB	119	309	8.7	50.0	8.7	1.9	16.7	Maxim's MX, H.K.; Instant;
RBD	263	247	9.5	50.0	1.0	7.6	26.3	NISSIN Brand, Nissin Foods Co., LTD.; Instant;
MC	80	324	6.6	50.0	10.9	2.5	NA	Kee Wah Bakery Shop, H.K.;

Food Items	Serving (g)	Energy (kcal)	Protein (g)	Available CHO(g)	Fat (g)	Fiber (g)	Sugar (g)	Method of preparation
GRB	115	424	5.8	50.0	23.1	Trace	30.6	Lee Chun Brand, Lee Chun Food Ltd., H.K.; Boiled;
CHJ	333	212	0	50.0	0	0	36.4	Guang Jian Tang Brand, Kwong Tai Agency Co., Ltd.; Instant;
ISMB	114	285	4.9	50.0	7.3	2.2	31.9	Instant;
FSMB	114	285	4.9	50.0	7.3	2.2	31.9	AMOY Brand, Amoy Food Ltd., H.K.; Frozen, Steamed;
SEN	83	365	9.2	50.0	14.3	0	2.9	NISSIN Brand, Nissin Foods Co., LTD.; Boiled;
SPN	95	349	17.5	50.0	4.9	0	0	Tong-I Brand ; Uni-President Enterprises Corp.; Taiwan; Boiled;
SHN	68	235	8.6	50.0	0	0	1.3	SAU TAO Brand; Sun Shun Fuk Foods Co. Ltd.; H.K.; Boiled;
UN	182	227	5.5	50.0	0.2	0.5	0	Chan Kee Holding Ltd.; H.K.; Boiled;
RV	68	250	4.3	50.0	3.1	0.8	0.4	Chewy Brand, Chewy Foods Ltd., H.K.; Boiled;
IN	90	419	8.0	50.0	20.0	1.6	0	Winner Food Products Ltd.; H.K.; Boiled;
FRVS(50g)	333	533	21.0	50.0	28.0	12.0	3.2	Instant;
FRVS(25g)	167	267	10.5	25.0	14.0	6.0	1.6	Instant;
SMRD(50g)	200	360	11.4	50.0	13.4	3.4	0.7	Ocean Empire International Ltd., H.K.; Instant;
SMRD(25g)	100	180	5.7	25.0	6.7	1.7	0.3	Ocean Empire International Ltd., H.K.; Instant;
SR(25g)	114	388	10.4	25.0	27.4	2.2	2.5	Instant;

BBPP: Baked Barbecued Pork Puff; FRYS: Fried Rice in Yangzhou-Style; FF: Fried Fritter; MLC: "Mai-Lai" Cake; TFB: Tuna Fish Bun; SRWLL: Sticky Rice Wrapped in Lotus Leaf; SGRR: Steamed Glutinous Rice Roll; PAB: "Pineapple" Bun; JPBT: Jam and Peanut Butter Toast; FRNSB: Fried Rice Noodles with Sliced Beef; ET: Egg Tart; PSVR: Plain Steamed Vermicelli Roll; GBD: Green Bean Dessert; BPB: Barbecue Pork Bun; RBD: Red Bean Dessert; MC: Moon Cakes; GRB: Glutinous Rice Ball; CHJ: Chinese Herbal Jelly; ISMB: Instant Sweet Milky Bun; FSMB: Frozen Sweet Milky Bun; SEN: Shrimp Egg Noodle; SPN: Spinach Noodle; SHN: Shanghai Noodle; UN: Udon Noodle; RV: Rice Vermicelli; IN: Instant Noodle; FRVS: Fried Rice Vermicelli in Singapore-style; SMRD: Salted Meat Rice Dumpling; SR: Spring Roll.

4.2.4 Statistical analysis

The individual GI value was calculated by expressing the incremental area under the blood response curve (IAUC) of glucose for each test food as a percentage of each subject's average IAUC for the glucose beverage. The IAUC values were calculated ignoring area beneath the fasting level (FAO, 1998; Wolever, 2004). The mean of all the individual GI values for each test food calculated from all subjects was the GI value for that food.

The differences in IAUC and GI values between male and female subjects were compared with independent samples T-test. The differences in IAUC and GI values between FRVS (50 g) and FRVS (25 g), SMRD (50 g) and SMRD (25 g) were compared with paired T-test. The differences in the mean IAUC value and within-subject coefficient of variation for repeated references (CVref) between Reference (50 g) and Reference (25 g) were also compared with paired T-test.

4.3 Results

All subjects completed the experiment, except for one subject who did not consume the foods containing 25 g available CHO for individual reasons. The determined GI values of test foods were shown in table 4.2.

TABLE 4.2 Determined glycemic index values of test foods (n=15)

Food Items	IAUC (mmol·min·L^{-1})	95% CI (mmol·min·L^{-1})	GI	95% CI
Foods containing 50 g of available carbohydrate				
BBPP	092.14±10.75	069.08-115.21	55±8	39-72
FRYS	133.70±13.85	103.99-163.40	80±6	67-92
FF	110.83±16.18	076.14-145.52	69±9	50-89
MLC	095.63±12.43	068.97-122.29	61±8	44-79
TFB	79.91±9.78	058.94-100.89	46±4	38-55
SRWLL	137.55±10.81	114.36-160.73	83±5	73-93
SGRR	143.03±12.96	115.24-170.83	89±8	071-107
PAB	106.39±11.69	081.32-131.46	65±8	48-83
JPBT	116.51±11.36	092.15-140.87	72±8	54-90
FRNSB	107.17±12.36	080.66-133.69	66±7	50-81
ET	74.70±7.82	57.93-91.46	45+3	38-53
PSVR	153.15±18.87	112.67-193.62	90±8	074-107
GBD	090.24±11.54	065.49-114.99	54±6	40-68
BPB	112.11±9.280	092.21-132.01	69±9	51-87
RBD	122.20±11.45	097.65-146.76	75±8	58-91
MC	90.96±9.65	070.26-111.66	56±7	42-70
GRB	098.76±13.04	070.78-126.74	061±10	37-82
CHJ	84.19±7.29	68.45-99.93	47±3	41-52
ISMB	115.44±12.42	088.80-142.07	67±5	57-78

Food Items	IAUC (mmol·min·L^{-1})	95% CI (mmol·min·L^{-1})	GI	95% CI
Foods containing 50 g of available carbohydrate				
FSMB	114.33±11.52	089.61-139.04	72±8	55-90
SEN	147.39±19.14	104.74-190.04	72±8	55-89
SPN	148.52±25.09	092.62-204.43	73±9	53-93
SHN	133.44±15.08	099.85-167.04	66±5	55-77
UN	111.95±20.53	066.20-157.70	54±7	38-69
RV	114.12±14.54	081.72-146.53	58±7	42-73
IN	103.35±14.59	070.85-135.86	52±6	38-66
FRVS (50 g)	87.41±9.64	066.73-108.10	54±6	41-66
SMRD (50 g)	116.32±14.96	084.23-148.41	69±8	51-87
Foods containing 25 g of available carbohydrate				
FRVS (25 g)	64.26±11.09	40.30-88.22	58±9	39-78
SMRD (25 g)	85.99±9.15	66.24-105.75	81±7	65-97
SR (25 g)	53.05±7.27	37.34-68.75	50±5	39-60

IAUC: Incremental area under the blood response curve; GI: Glycemic index; CI: Confidence interval; BBPP: Baked Barbecued Pork Puff; FRYS: Fried Rice in Yangzhou-Style; FF: Fried Fritter; MLC: "Mai-Lai" Cake; TFB: Tuna Fish Bun; SRWLL: Sticky Rice Wrapped in Lotus Leaf; SGRR: Steamed Glutinous Rice Roll; PAB: "Pineapple" Bun; JPBT: Jam and Peanut Butter Toast; FRNSB: Fried Rice Noodles with Sliced Beef; ET: Egg Tart; PSVR: Plain Steamed Vermicelli Roll; GBD: Green Bean Dessert; BPB: Barbecue Pork Bun; RBD: Red Bean Dessert; MC: Moon Cakes; GRB: Glutinous Rice Ball; CHJ: Chinese Herbal Jelly; ISMB: Instant Sweet Milky Bun; FSMB: Frozen Sweet Milky Bun; SEN: Shrimp Egg Noodle; SPN: Spinach Noodle; SHN: Shanghai Noodle; UN: Udon Noodle; RV: Rice Vermicelli; IN: Instant Noodle; FRVS: Fried Rice Vermicelli in Singapore-style; SMRD: Salted Meat Rice Dumpling; SR: Spring Roll.

The mean IAUC value of all the test foods calculated from male subjects ($IAUC_{male}$) was lower than that from female subjects ($IAUC_{female}$) (91.10±3.09 vs. 118.60±4.05 mmol·min·L^{-1}, $p<0.001$), however there were no differences between the mean GI value of all the test foods determined from data of male subjects (GI_{male}) and that from female subjects (GI_{female}) (64±2 vs. 67±2, p=0.224). When grouped by each test food, there were no differences either in the mean IAUC or GI value between male and female subjects.

The mean IAUC value calculated from the data elicited by 50 g anhydrous glucose ($IAUC_{ref50}$) was higher than that from the data elicited by 25 g anhydrous glucose ($IAUC_{ref25}$) (167.54±14.54 vs. 108.40±8.86 mmol·min·L-1, $p<0.001$). However, there were no differences in the mean within-subject CV_{ref} (CV_{ref} = 100% × SD/mean) (28.00%±3.55% vs. 21.56%±3.74 %, p=0.163) for the 14 subjects between 50 g and 25 g anhydrous glucose.

The mean IAUC value calculated from the food containing 50 g of available CHO was higher than that elicited by the same food containing 25 g of available CHO (FRVS: 89.24±10.17 vs. 64.26±11.09 mmol·min·L^{-1}, SMRD: 117.23±16.04 vs. 85.99±9.15 mmol·min·L^{-1}, $p<0.05$). However, no difference was found between the two GI values (FRVS: 55±6 vs. 58±9, P = 0.745; SMRD: 70±9 vs. 81±7, p=0.319).

4.4 Discussion and conclusion

The availability of reliable GI values of different foods is critical for not only researchers but also common people. The University of Sydney has determined the glycemic and insulin responses to more than 1,750 foods and shown that GI is a

reproducible measure of day-long postprandial glycemia (Brand-Miller et al., 2003). In the more recent edition of international GI table (Atkinson et al., 2008), over 2,480 GI values of individual food items were listed. Because of the close relationship between the food GI and human health, labeling GI values of foods has been proposed or is occurring in Australia, South Africa, Sweden, United Kingdom, and Germany, with several commercial laboratories measuring the GI of foods (Wolever, Brand-Miller et al., 2008).

In recent years, GI values of some local foods have been measured in different countries prior to their utilization in research and clinical settings among the local population (Aston et al., 2008; Sugiyama et al., 2003; Yang et al., 2006). Since there was little information about GI values of traditional Chinese foods in Hong Kong in the literature, and that had limited the related research in this area (Hui & Nelson, 2006; Woo et al., 2003), it was worthwhile to setup a GI database for traditional Chinese foods. However, there are so many traditional and special Chinese foods, according to folk culture, district, religion, and festival. For the famous classes divided by district, there are styles of Guangdong, Beijing, Shanghai, Sichuan, North-West, *etc*. These all above mentioned styles are well-known worldwide. Quite different from Western cooking whose recipes are followed strictly like laboratory instructions, Chinese cooking allows for a creative and stylistic touch to it and it is also one important reason why Chinese foods are always absent in the international GI table. In this study, by using a recommended standard method, GI values of 29 traditional Chinese foods were determined. It is worth mentioning that the possibility of variations in composition and GI values of the same named food of different regions is existed. Therefore, the names of band and producing company of the testing foods were also provided for references.

Although GI was a classification of the blood glucose raising potential of CHO foods, many other factors such as food form, particle size, cooking methods, presence of other macronutrients and starch structure, might affect the GI of foods (Aston et al., 2008; Wolever et al., 2003). Fat and protein added to CHO foods have been suggested to reduce the postprandial glycemic responses which occurred by different mechanisms, such as delaying gastric emptying (Wolever, 2006); however, most of the studies found that the amount of protein or fat in commonly consumed foods did not affect the glycemic responses (Henry et al., 2005; Wolever & Bolognesi, 1996a). It was also found in the present study that no relation existed between the amounts of fats or protein in foods and their GI values.

Though there was a recommended standard protocol for the determination of GI (FAO, 1998; Sun, Wong, Chen & Huang, 2010), there were still some methodological factors which will influence the accuracy in GI determination. According to an inter-laboratory study (Wolever et al., 2003), the GI values of foods were more precisely determined using capillary than venous blood sampling. A recent study (Hatönen et al., 2006) also found that the CV of the IAUC values was significantly lower for capillary than for venous blood. So in the present study, capillary blood samples were selected for determining the GI values of foods.

One study suggested that the composition and characteristics of the evening meal might influence glucose tolerance the next morning (Granfeldt et al., 2006). However, no difference was found in another study on within-individual variation influenced by subject preparation between controlled trials and uncontrolled trials (J. E. Campbell et al., 2003). Furthermore, a more recent report suggested that simply advising subjects to avoid certain types of foods was almost as good and might be

more cost-effective (Wolever, Brand-Miller et al., 2008). Thus, in the present study all the subjects were just advised to have a balanced dinner each night before the test. Furthermore, all subjects in the present study were also required to refrain from alcohol consumption and vigorous physical activities 24-hrs before test, foods for testing were randomized in blocks of four foods, and the intervals between two tests were at least two days (Brouns et al., 2005; FAO, 1998). The FAO recommended the reference food test should be repeated at least three times in each subject (FAO, 1998). A recent study suggested that no evidence to justify doing three tests rather than two tests was found because the difference was small and not significant (Wolever, Brand-Miller et al., 2008). In our study, the reference of 50 g of anhydrous glucose was tested three times to determine the GI values for 26 of the 29 foods.

In the present study, though the mean IAUC values calculated from female subjects were higher than that calculated from male subjects, there were no differences in the mean GI values between them, which is consistent with a previous study (Wolever, Brand-Miller et al., 2008).

One study showed that GI value was negatively related to the within-individual CVref, and low within-subject variation (CVref < 30%) was required for accuracy in GI determination (Wolever, Brand-Miller et al., 2008). Another study also found that most of the variation of GI values was due to within-subject variation, and in normal subjects the mean CVref was about 25.0% (Wolever, 2006). In the present study, both CVref of 50 g glucose and that of 25 g glucose were less than 30%, and there were no differences between the two values. This result might indicate that the determined GI values were accurate to a certain degree.

No differences were found between the two GI values determined for the same food containing different amounts of available CHO (50 g and 25 g) in this study. It might suggest that when the portion of one food containing 50 g of available CHO was too large for subjects to consume, it was appropriate to select the portion of the food containing 25 g of available CHO to determine the GI values. The result was consistent with a previous study which showed that the relative glycemic responses to the foods containing different levels of available CHO intake were the same, at least between 25 g and 100 g (Wolever & Bolognesi, 1996a).

In conclusion, the GI values for these traditional Chinese foods in the present study provide some valuable information both to researchers and to common individuals on their food preference. They are also preliminary references on the setup of a GI database for traditional Chinese foods later.

CHAPTER 5

EFFECT OF GLYCEMIC INDEX AND FRUCTOSE CONTENT IN BREAKFAST ON SUBSTRATE UTILIZATION DURING SUBSEQUENT BRISK WALKING

5.1 Introduction

Energy used to sustain steady state aerobic exercise in humans is derived predominantly from the oxidation of carbohydrate (CHO) and fat (Coyle, 1995), and the percentage of energy derived from CHO and fat oxidation varies with the increase in exercise intensities (Romijn et al., 1993). Previous studies revealed that moderate intensity exercise, i.e., between 45% and 65% maximal oxygen uptakes ($\dot{V}O_{2max}$), could maximize fat oxidation. Furthermore, maximal fat oxidation often occurred during approximately 50% $\dot{V}O_{2max}$ exercise for general population (Achten & Jeukendrup, 2004; Venables et al., 2005). When exercise intensity further increased, fat oxidation was decreased, whereas CHO oxidation was markedly increased (Achten & Jeukendrup, 2003b; Romijn et al., 1993). Therefore, moderate intensity exercise appears to be the most favorable for eliciting a substantial short-term increase in fat oxidation. Substrate utilization during exercise is also influenced by nutrition status, particularly CHO ingestion before or during exercise (Achten & Jeukendrup, 2004; Coyle, 1995). The CHO metabolism and insulin action after different CHO intake suggests that the consideration of food choices before exercise is important due to their potential to influence substrate utilization acutely during subsequent exercise (Achten & Jeukendrup, 2004; Chen, Wong et al., 2008a; Stevenson, Astbury et al., 2009; Wong et al., 2008).

Glycemic index (GI) is used to classify the different CHO. Usually GI is classified as low-GI (LGI, <55), moderate-GI (MGI, 55-70), and high-GI (HGI, > 70) (Brand-Miller, Foster-Powell, Colagiuri & Leeds, 1998). Recent studies showed that LGI meal consumption several hours before exercise appeared to result in higher fat oxidation and lower CHO oxidation during subsequent moderate to high intensity exercise when compared to HGI meal consumption (Chen, Wong et al., 2008b; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003). Endurance-trained subjects and usually higher intensity exercise protocol, specifically 70% $\dot{V}O_{2max}$ or above, were used in these studies. Some authors found improved exercise performance after LGI meal consumption and attributed this improvement to the increased fat oxidation and glycogen sparing (Wong et al., 2008).

This kind of investigation is also important for ordinary people, particularly for those who want to increase fat oxidation for weight management or health maintenance. However, only a few studies were conducted using untrained subjects and moderate intensity exercise protocol. In one of these studies (Stevenson, Astbury et al., 2009), it was demonstrated that LGI breakfast consumption produced less CHO oxidation and more fat oxidation both during postprandial period and during subsequent 50% $\dot{V}O_{2max}$ brisk walking, compared with HGI breakfast consumption. However, in another very similar study using the same exercise protocol (Backhouse et al., 2007), no significant effect of GI meals on the amount of fat oxidized was noted during exercise. It is worth mentioning that in these two studies only female subjects were used, whereas there might be some difference in substrate utilization during moderate intensity exercise between males and females (Tarnopolsky, MacDougall, Atkinson, Tarnopolsky & Sutton, 1990). Therefore, further studies are still needed to clarify this effect, particularly for males. Furthermore, it resembles more closely the

practice that ordinary people consume some CHO meals before exercise.

According to latest international GI tale (Atkinson et al., 2008), GI value of fructose is 15 and can be regarded as LGI CHO, whereas the GI value of glucose is 103 and can be classified as a HGI CHO. However, according to some earlier studies, compared with glucose beverage, fructose beverage ingestion alone before exercise caused similar substrate utilization during exercise at 60% (Décombaz et al., 1985), 70% (Fielding et al., 1987), or 75% $\dot{V}O_{2max}$ exercise intensity (Hargreaves et al., 1987). These findings were different from previously mentioned studies (Chen, Wong et al., 2008b; Stevenson, Astbury et al., 2009; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003), where LGI CHO consumption often increased fat oxidation and decreased CHO oxidation during subsequent exercise, particularly during the first part of exercise. This may be caused by the special metabolism of fructose. When fructose is consumed as part of a mixed meal, its effect on substrate utilization during subsequent exercise may be more complicated. Therefore, fructose content may be also an important potential influencing factor when discussing the effect of GI meals on substrate utilization. However, there was a paucity of studies, if any, that were conducted to specifically investigate this effect.

The consumption of dietary fructose has increased in conjunction with the recent rising intake of fructose-containing sugars, largely in the form of sugar-sweetened beverages (Marriott et al., 2009; Storey et al., 2006). More importantly, consumption of fructose has been suggested to be related to the development of obesity, metabolic syndrome, and diabetes (Bray et al., 2004; Johnson et al., 2009). Therefore, investigating the effect of fructose content in meals on the metabolic responses of humans is a worthwhile endeavor. The purpose of this study was to investigate

whether both GI and fructose content in breakfast could affect substrate utilization during subsequent brisk walking. It was hypothesized that compared with a pre-exercise LGI meal without fructose, either a HGI meal or the presence of fructose in a similar LGI meal would induce decreased fat oxidation and increased CHO oxidation during subsequent brisk walking.

5.2 Methods

5.2.1 Subjects

Ten healthy young male adults volunteered to participate in this study. Their age, height, body weight (BW), body mass index (BMI), and $\dot{V}O_{2max}$ (mean ± SD) were 21.7±1.5 y, 171.3±5.2 cm, 61.3±5.2 kg, 20.9±1.1 $kg \cdot m^{-2}$, and 53.7±3.7 $mL \cdot kg^{-1} \cdot min^{-1}$. None of the subjects reported any medical conditions.

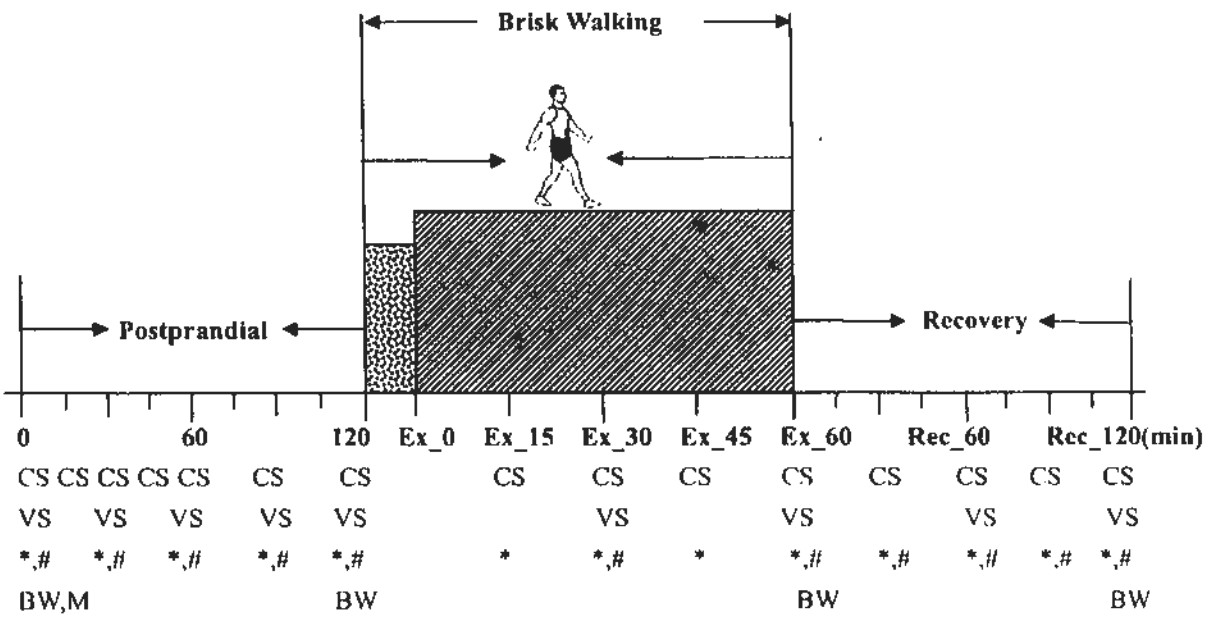
5.2.2 Procedures

As described, all subjects attended two preliminary tests to determine the walking speed equivalent to 50% of each subject's $\dot{V}O_{2max}$. Then all subjects completed three main trials in a single-blinded counterbalanced crossover design, and the duration between any two trials was at least seven days. The experimental protocol of the main trial involved a 120-min postprandial period followed by one bout of exercise and another 120-min recovery period. During exercise, each subject was required to complete 60-min of brisk walking. The exercise intensity was around 46% $\dot{V}O_{2max}$. Each subject was required to have three-day dietary records and to repeat the same diets before each main trial to minimize the variation in muscle and liver glycogen concentrations. The dietary records were analyzed using computer software (Food

Processor 10.5, ESHA, USA). To maintain a euhydration condition before each main trial, the subjects were instructed to drink approximately 500 mL of water the night before reporting to the laboratory. To exclude any residual effects of previous exercise on the experimental treatment, they were required to refrain from vigorous physical activities 24-hrs before the test.

After 10-12 hrs overnight fast, the subjects reported to the laboratory at about 8:00 a.m. This was to ensure that they had an empty stomach and to minimize the effect of previous meals on the gastric emptying rate of the test meals. Upon arrival, the subjects rested for approximately 15-min before a catheter was inserted into the antecubital vein of the forearm. Baseline venous and finger capillary blood samples, expired air samples, and other baseline data, such as BW, heart rate (HR), rating of perceived exertion (RPE), rating of abdominal discomfort (RAD), and rating of perceived thirst (RPT), were then collected. Further blood samples, expired air samples, and other data were collected at specific time points, as shown in figure 5.1.

As described previously (Chapter 3), capillary blood samples were used to measure blood glucose, lactate, hemoglobin (Hb) concentrations, and hematocrit (Hct). Venous blood samples were used to decide serum insulin, free fatty acids (FFA), and glycerol concentrations. Expired air samples were collected and analyzed using a metabolic testing system (MAX-II, Physio-Dyne, New York). Volume of oxygen consumed ($\dot{V}O_2$), volume of carbon dioxide produced ($\dot{V}CO_2$), and respiratory exchange ratio (RER) were analyzed by this system. Rates and amounts of CHO and fat oxidized were then calculated.



VS	Venous blood sample	*	Expired air sample, HR, RPE
CS	Capillary blood sample		5-min warm up at 40% $\dot{V}O_{2max}$
#	RPT, RAD		60-min brisk walking at 46% $\dot{V}O_{2max}$
M	Meal consumption	BW	Body weight

HR: Heart rate; RPE: Rating of perceived exertion; RPT: Rating of perceived thirsty;

RAD: Rating of perceived discomfort; Ex: Exercise; Rec: Recovery period.

FIGURE 5.1 Schematic representation of the experimental procedures

After the collection of baseline samples, the subjects consumed either a LGI meal without fructose (LGI), a LGI meal including fructose beverage (LGIF), or a HGI meal (HGI) in a counterbalanced randomized order. All foods were required to be consumed within 15-min. Subjects remained seated in a quiet area of the laboratory for 120-min, and their activity levels were minimal. Subjects ingested 2 $mL \cdot kg^{-1}$ BW of distilled water every 30 min to ensure adequate hydration and balance the water content of the meals.

Following the 120-min postprandial period, a standardized 5-min warm-up at 40% $\dot{V}O_{2max}$ was performed. The subjects then completed 60-min of brisk walking. During the exercise, 2 $mL \cdot kg^{-1}$ BW of distilled water was given every 15-min to the subjects to reduce the effect of dehydration. After finishing brisk walking, subjects returned to the resting area, and a 120-min recovery period was started immediately.

5.2.3 Prescribed meals

Three isocaloric meals were used in the present study. All meals provided 1.0 $g \cdot kg^{-1}$ BW CHO for each subject, and the amounts of macronutrients were also similar among the three meals (Table 5.1).

The GI values for the individual foods were taken from the recent international GI table (Atkinson et al., 2008). The GI value of the entire meal was calculated using a method described previously (Wolever & Bolognesi, 1996b). The calculated GI values for LGI, LGIF, and HGI breakfasts were 41, 39, and 72, respectively. The food contents were very similar in LGIF and HGI meals except for fructose and glucose. Fructose and glucose were dissolved in water to ensure that the concentration of glucose or fructose beverage was approximately 10%. The water content of all meals was standardized so that each meal provided the subjects with the same volume of liquids. The entire breakfast provided around 20% energy from fat, 17% from protein, and 63% from CHO. In the LGIF and HGI trials, around 25% energy came from either fructose or glucose beverage. All meals were freshly prepared in the morning of each main trial. The preparation procedure was standardized to minimize the influences of cooking methods. To avoid the occurrence of bias, the specific purpose of using the GI foods and measuring the weight of the food was not disclosed to the subjects.

TABLE 5.1 Nutritional composition of test meals (for a 60kg subject)

Meals	Quantity (g)	Energy (kcal)	CHO (g)	Fat (g)	Protein (g)	Calculated GI [a]
LGI						
Spaghetti, cooked	182	288	56.2	10. 6	1.8	
Full milk	60	38	2.9	1.9	2.0	
Egg, boiled	60	65	0.3	5.5	4.4	
Total		391	59.4	18.0	8.2	41
LGIF						
Rice vermicelli	42	158	32.3	3.1	0.1	
Egg, boiled	60	65	0.3	5.5	4.4	
Ham	46	75	1.8	7.6	4.4	
Fructose	26	96	26.0	0	0	
Total		394	60.4	16.2	8.9	39
HGI						
Rice vermicelli	45	170	33.7	3.3	0.1	
Egg, boiled	60	65	0.3	5.5	4.4	
Ham	45	73	1.3	7.5	3.9	
Glucose	25	92	25.0	0	0	
Total		400	60.3	16.3	8.4	72

[a] Calculated by a method described previously (Wolever & Bolognesi, 1996b), with GI values taken from the International GI table (Atkinson et al., 2008).

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal; CHO: carbohydrate; GI: Glycemic index.

5.2.4 Statistical analysis

Data were presented as mean ± SEM. SPSS software (version 12.0) was used for data analysis. Dependent variables of the three trials (LGI vs. LGIF vs. HGI), total substrate oxidation, and macronutrients intake for three days before the main trial; were compared using one-way analysis of variance (ANOVA) with repeated measures. Changes in concentrations of blood glucose, blood lactate, serum insulin, FFA, glycerol, and changes in RER, HR, RPE, RPT, and RAD values were analyzed by a two-way ANOVA (Treatment × Time) with repeated measures. A Bonferroni correction method was performed at the location of the variance. Statistical significance was set at the 0.05 level.

5.3 Results

All subjects completed the experiment as expected. However, the venous blood samples of two subjects were not obtained due to the difficulty in accessing veins for blood sampling. Therefore, the results of serum insulin, FFA, and glycerol concentrations coming from only 8 subjects were included in statistic.

No differences in the baseline measurements were found among the three trials (Table 5.2). There were also no differences in daily energy intake and macronutrient composition of the subjects' diet during the three days before each main trial (Table 5.3).

TABLE 5.2 Baseline data comparison among the three trials (mean ± SEM)

	N	Trial		
		LGI	LGIF	HGI
Glucose ($mmol \cdot L^{-1}$)	10	4.50±0.11	4.78±0.16	4.80±0.14
Lactate ($mmol \cdot L^{-1}$)	10	1.12±0.13	1.24±0.13	1.14±0.15
Heart Rate ($beats \cdot min^{-1}$)	10	65±2	66±3	67±3
Rating of Perceived Exertion	10	7.5±0.6	7.7±0.5	7.8±0.6
Perceived Thirsty Scale	10	2.7±0.5	2.9±0.5	3.6±0.7
Abdominal Discomfort Scale	10	1.4±0.5	0.9±0.3	0.9±0.4
Hematocrit	10	0.45±0.01	0.45±0.01	0.45±0.01
Hemoglobin ($mmol \cdot L^{-1}$)	10	8.56±0.32	8.16±0.20	8.38±0.44
Insulin ($mU \cdot L^{-1}$)	8	3.7±0.3	5.4±1.2	4.4±0.5
Free Fatty Acid ($mmol \cdot L^{-1}$)	8	0.33±0.05	0.44±0.06	0.37±0.05
Glycerol ($\mu mol \cdot L^{-1}$)	8	65.52±7.74	95.80±19.58	83.21±8.27

TABLE 5.3 Daily energy intake and macronutrient content of diets before main trial (n=10, mean ± SEM)

	Trial		
	LGI	LGIF	HGI
Daily energy intake (kcal)	1825±179	1787±161	1893±148
Energy from CHO (%)	52.4±3.1	47.7±2.2	48.2±2.2
Energy from protein (%)	19.5±1.4	21.8±1.4	19.9±1.2
Energy from fat (%)	28.0±1.8	29.7±1.8	32.0±2.9

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

5.3.1 Blood glucose

During the postprandial period, blood glucose concentrations peaked at 30 min in all trials ($p<0.05$, vs. 0 min). However, blood glycemic responses in the HGI trial were the highest among the three trials (Figure 5.2A). At 15, 30, 45, and 60 min, blood glucose concentrations in the HGI trial were higher ($p<0.05$) than those in the LGI and LGIF trials. At 45 and 60 min, these were also higher ($p<0.05$) in the LGIF trial than in the LGI trial. The incremental area under the blood response curve (IAUC) value of glucose during the postprandial period in the HGI trial was higher ($p<0.01$) than in the LGI and LGIF trials, whereas no differences were found between the latter two trials (Table 5.4).

No differences were found in blood glucose concentrations among the three trials throughout exercise and the recovery periods (Figure 5.2B). During exercise, they were lower than fasting level ($p<0.05$, vs. 0 min) in all three trials. However, only in the LGIF and LGI trials the lower glucose concentrations were found than that at the onset of exercise ($p<0.05$, vs. 120 min).

During the recovery period, they returned to baseline level in all three trials (Figure 5.2B). However, in the LGI trial they were still lower than that at the onset of exercise ($P<0.05$, vs. 120 min).

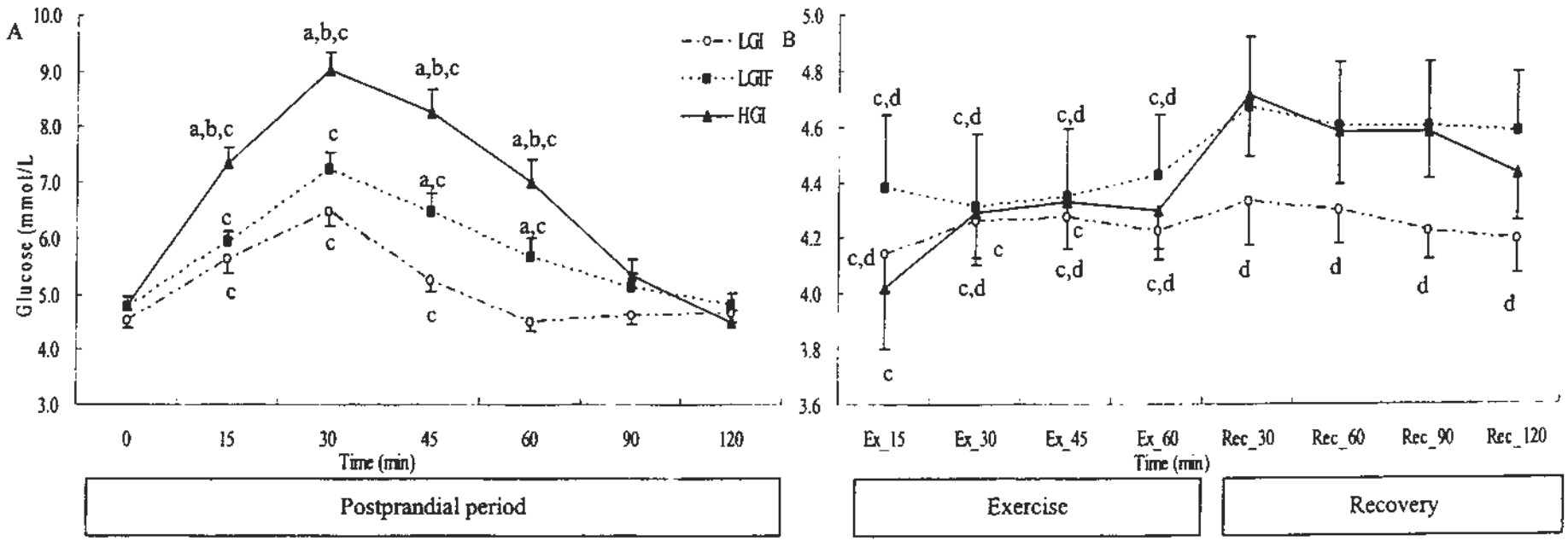


FIGURE 5.2 Glucose concentrations during the experiment

Data were presented as mean ± SEM. a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. 0min; d: $p<0.05$, vs. 120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. Ex: Exercise; Rec: Recovery period.

TABLE 5.4 Comparison of IAUC values of glucose, insulin, and lactate during the postprandial period (n=10, mean ± SEM)

Trial	IAUC value during the postprandial period		
	Glucose ($mmol \cdot min \cdot L^{-1}$)	Insulin ($mU \cdot min \cdot L^{-1}$)	Lactate ($mmol \cdot min \cdot L^{-1}$)
LGI	70.2±7.4	920±319	43.6±5.4
LGIF	114.1±16.4	1487±348	135.6±11.0 [a]
HGI	223.6±19.1 [a,b]	4257±932 [a,b]	68.4±12.9 [b]

[a] $p<0.05$, vs. LGI; [b] $p<0.05$, vs. LGIF.

IAUC: Incremental area under the blood response curve; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

5.3.2 Serum insulin

During the postprandial period, serum insulin concentrations peaked at 30 min ($p<0.05$, vs. 0 min) in the HGI and LGI trials, and at 60 min in the LGIF trial (Figure 5.3A). At the onset of exercise (120 min), these returned to baseline levels in the LGI and LGIF trials, but not the HGI trial (Figure 5.3A). At 30, 60, and 120 min, these were higher ($p<0.05$) in the HGI trial than in the LGI trial. However, the higher serum insulin concentrations ($p<0.05$) were observed only at 30 min in the HGI trial than that in the LGIF trial (Figure 5.3A). No differences were found at any time point between the LGIF and LGI trials. During the postprandial period, the IAUC value of insulin in the HGI trial was higher ($p<0.05$) than that in the LGI and LGIF trials, whereas no difference was observed between the latter two trials (Table 5.4).

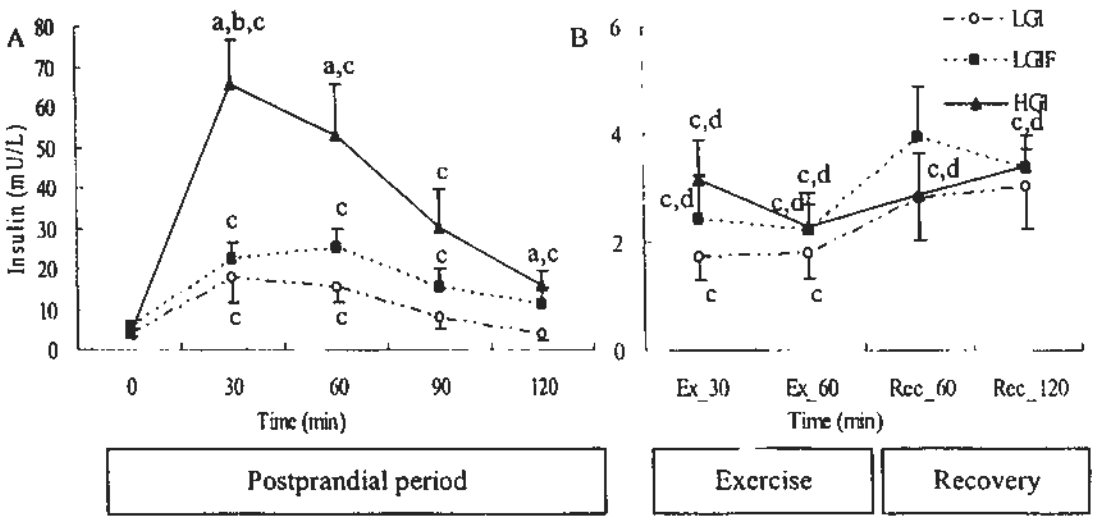


FIGURE 5.3 Serum insulin concentrations during the experiment

Data were presented as mean ± SEM. a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. 0min; d: $p<0.05$, vs. 120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. Ex: Exercise; Rec: Recovery period.

During exercise, no differences were found in serum insulin concentrations among the three trials (Figure 5.3B). However, they were suppressed to below fasting level ($p<0.05$, vs. 0 min) in all three trials (Figure 5.3B). In the LGIF and HGI trials, they were also lower than those at the onset of exercise ($p<0.05$, vs. 120 min).

During the recovery period, there were likewise no differences in serum insulin concentrations among the three trials (Figure 5.3B). However, in the HGI trial they were lower than that in the fasting ($p<0.05$, vs. 0 min) and that at the onset of exercise ($p<0.05$, vs. 120 min).

5.3.3 Blood lactate

Compared with the fasting level, blood lactate concentrations were elevated ($p<0.05$, vs. 0 min) in all trials during the postprandial period (Figure 5.4A). At 15, 30, 45, and 60 min, these were higher ($p<0.05$) in the LGIF trial than in the LGI and HGI trials. At 90 min, the higher blood lactate concentration ($p<0.05$) was only found in the LGIF trail than in the LGI trial. No differences were found at all time points between the LGI and HGI trials. During the postprandial period, the IAUC value of lactate in the LGIF trial was higher ($p<0.01$) than that in the LGI and HGI trials, whereas no difference was found between the latter two trials (Table 5.4).

During exercise, blood lactate concentration was higher ($p<0.05$) at 60 min in the HGI trial than that in the LGI trial (Figure 5.4B). During the first part of exercise (15 and 30 min), these were higher than those at the onset of exercise ($P<0.05$, vs. 120 min) in all three trials. However, at 45 and 60 min during exercise, the higher blood lactate concentrations were only found in the HGI trial ($p<0.05$, vs. 120 min).

During the recovery period, no differences were found in blood lactate concentrations among the three trials (Figure 5.4B). Also, no differences were found in them in all three trials when compared with those in the fasting level (0 min) and at the onset of exercise (120 min).

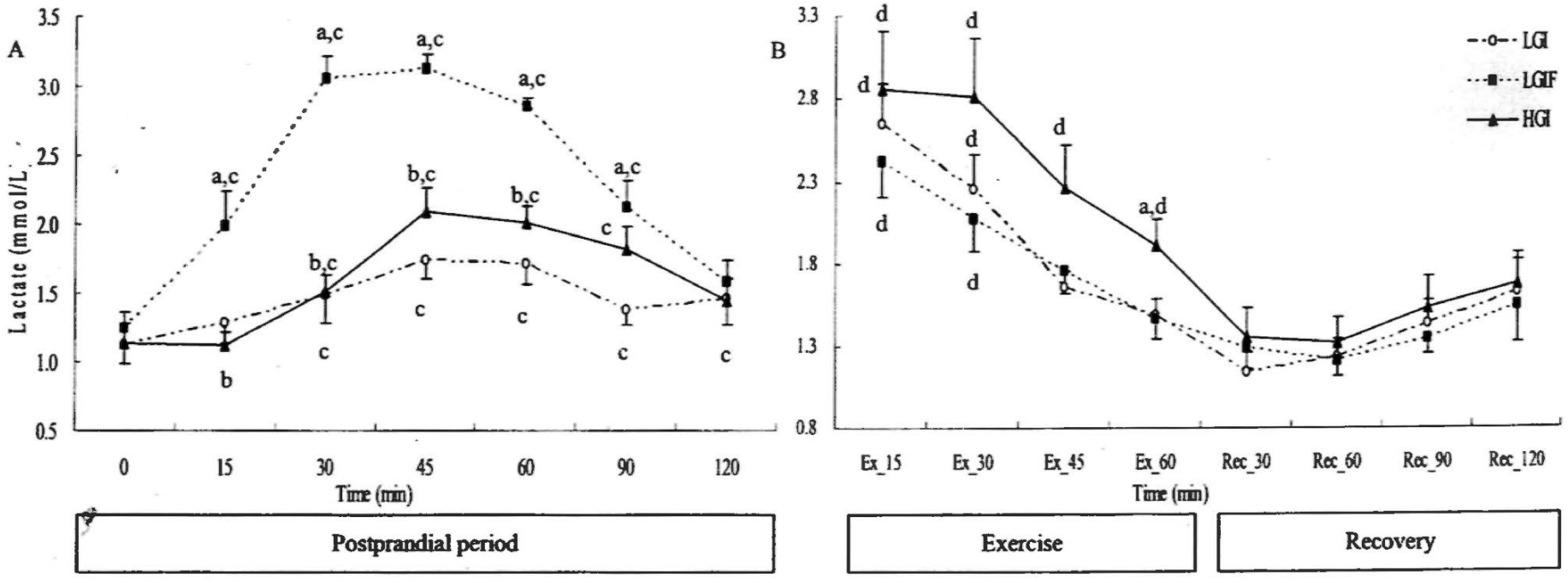


FIGURE 5.4 Lactate concentrations during the experiment

Data were presented as mean ± SEM. a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. 0min; d: $p<0.05$, vs. 120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. Ex: Exercise; Rec: Recovery period.

5.3.4 Serum FFA

During the postprandial period, serum FFA concentration was lower ($p<0.05$) in the HGI trial than that in the LGI trial at 30 min (Figure 5.5). At 120 min during the postprandial period, it was lower ($p<0.05$) in the HGI trial than that in the LGIF trial (Figure 5.5). No differences were observed at any time point between the LGIF and LGI trials. Compared with the fasting level, serum FFA concentrations decreased ($p<0.05$, vs. 0 min) in the LGIF and HGI trials, but not in the LGI trial (Figure 5.5).

After the onset of exercise, serum FFA concentration increased ($p<0.05$, vs. 120 min) in the LGIF and HGI trials, but not in the LGI trial (Figure 5.5). At 30 min during exercise, it was lower ($p<0.05$) in the HGI trial than that in the LGI trial (Figure 5.5).

During the recovery period, serum FFA concentrations in all trials were higher than those at the onset of exercise ($p<0.05$, vs. 120 min). At the end of recovery period (Rec_120 min), these were higher than fasting level ($p<0.05$, vs. 0 min) in the LGI and HGI trials, but not in the LGIF trial (Figure 5.5).

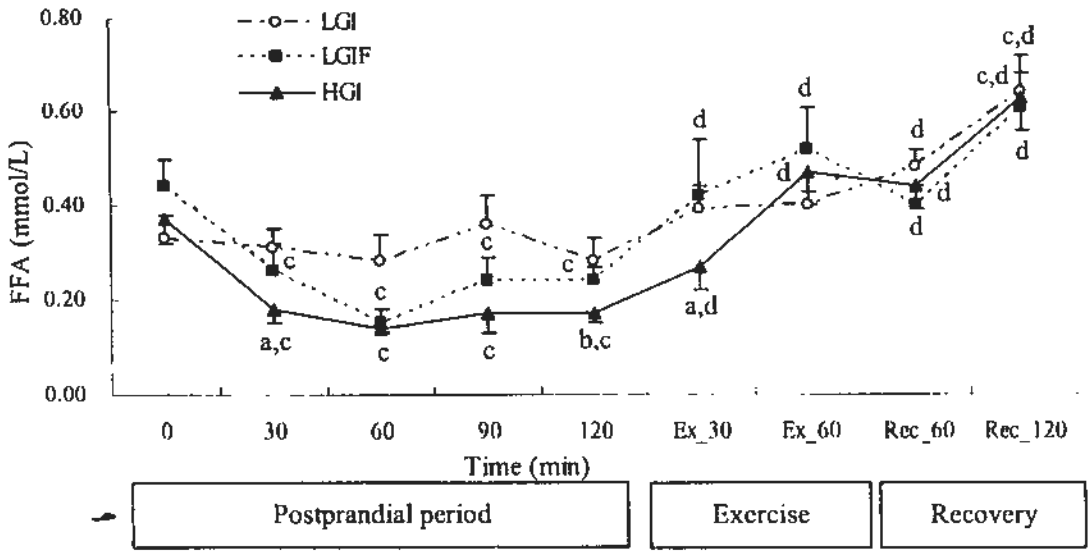


FIGURE 5.5 Serum FFA concentrations during the experiment

Data are presented as mean ± SEM. a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. 0 min; d: $p<0.05$, vs. PL_120 min.

FFA: Free fatty acid; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. Ex: Exercise; Rec: Recovery period.

5.3.5 Serum glycerol

During the postprandial period, serum glycerol concentration was lower ($p<0.05$) at 90 min in the HGI trial than that in the LGI trial (Figure 5.6). However, no differences were found at any other time points among the three trials (Figure 5.6). Compared with fasting level, serum glycerol concentration was lower ($p<0.05$, vs. 0 min) at 60 min during the postprandial period in the LGIF trial, and at 30, 60, and 90 min in the HGI trial (Figure 5.6).

Serum glycerol concentration rose gradually after the onset of exercise and peaked at

the end of exercise ($p<0.05$, vs. 120 min) in all three trials (Figure 5.6). During the recovery period, they were still higher than those at the onset of exercise ($p<0.05$, vs. 120 min) and fasting level ($p<0.05$, vs. 0 min) in the LGI and HGI trials (Figure 5.6).

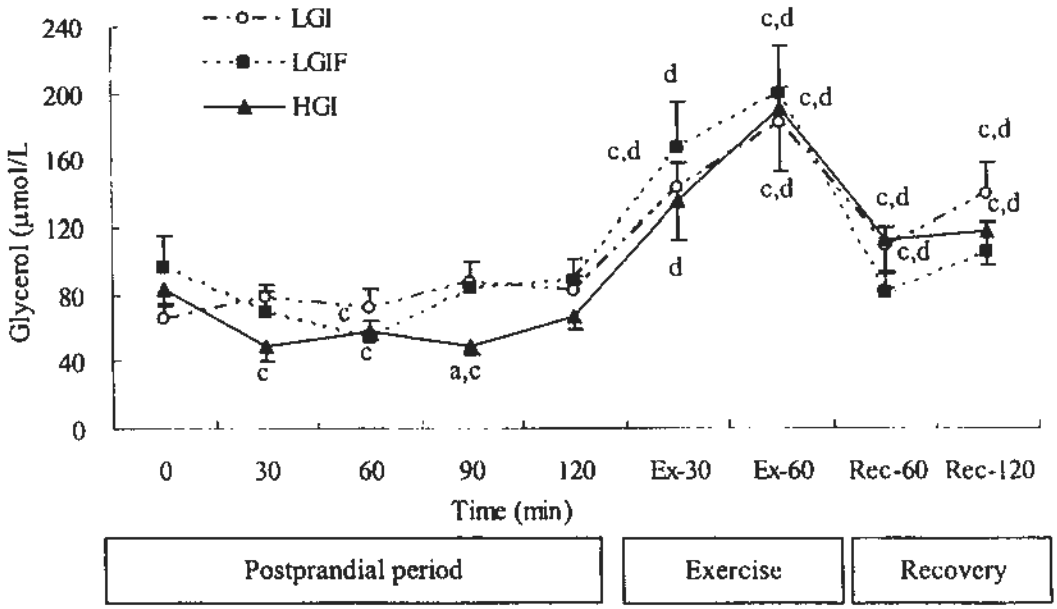


FIGURE 5.6 Serum glycerol concentrations during the experiment

Data were presented as mean ± SEM. a: $p<0.05$, vs. LGI; c: $p<0.05$, vs. 0 min; d: $p<0.05$, vs. PL_120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. Ex: Exercise; Rec: Recovery period.

5.3.6 CHO oxidation and fat oxidation

During the postprandial period, CHO oxidation rate was lower ($p<0.01$) in the LGI trial, compared with that in the LGIF and HGI trials (Table 5.5). The fat oxidation rate was higher ($p<0.01$) in the LGI trial than that in the HGI trial (Table 5.5). Although no difference was found in fat oxidation rate between the LGI and LGIF

trial, there was a trend to be higher in the LGI trial (p=0.064).

TABLE 5.5 CHO and fat oxidation rate during the postprandial period, exercise, and the recovery period (n=10, mean ± SEM)

	Fasting	Postprandial period (min)				Exercise (min)				Recovery (min)	
		30	60	90	120	15	30	45	60	60	120
CHO oxidation rate ($g \cdot min^{-1}$) [a]											
LGI	0.07 ±0.01	0.04 ±0.01	0.06 ±0.02	0.06 ±0.01	0.06 ±0.02	1.15 ±0.04	0.99 ±0.05	0.85 ±0.05	0.81 ±0.05	0.03 ±0.01	0.02 ±0.01
LGIF	0.06 ±0.01	0.14 ±0.02	0.14 ±0.02	0.13 ±0.02	0.16 ±0.04	1.26 ±0.07	1.17 ±0.07	1.10 ±0.07	1.01 ±0.09	0.05 ±0.02	0.09 ±0.04
HGI	0.08 ±0.02	0.04 ±0.02	0.12 ±0.03	0.11 ±0.01	0.17 ±0.03	1.37 ±0.08	1.20 ±0.07	1.09 ±0.06	1.00 ±0.06	0.04 ±0.01	0.05 ±0.02
Fat oxidation rate ($g \cdot min^{-1}$) [b,c]											
LGI	0.10 ±0.02	0.11 ±0.01	0.11 ±0.01	0.11 ±0.01	0.12 ±0.01	0.31 ±0.03	0.38 ±0.04	0.44 ±0.03	0.45 ±0.04	0.12 ±0.02	0.14 ±0.02
LGIF	0.09 ±0.01	0.06 ±0.01	0.08 ±0.01	0.08 ±0.01	0.07 ±0.01	0.27 ±0.03	0.31 ±0.03	0.35 ±0.03	0.37 ±0.04	0.10 ±0.02	0.11 ±0.02
HGI	0.09 ±0.01	0.09 ±0.01	0.07 ±0.01	0.08 ±0.01	0.07 ±0.01	0.22 ±0.03	0.29 ±0.02	0.36 ±0.02	0.39 ±0.03	0.10 ±0.01	0.12 ±0.02

[a] During the postprandial period and exercise, CHO oxidation rate was lower in the LGI trial, compared with that in HGI trial and LGIF trial ($p<0.01$, two way ANOVA with repeated measures).

[b] During the postprandial period, fat oxidation rate was higher in the LGI trial, compared with that in the HGI trial ($p<0.01$, two way ANOVA with repeated measures).

[c] During exercise, fat oxidation rate was higher in the LGI trial, compared with that in the HGI and LGIF trials ($p<0.05$, two way ANOVA with repeated measures).

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

During exercise, CHO oxidation rate was lower ($p<0.01$) in the LGI trial, compared with that in the LGIF and HGI trials (Table 5.5). The fat oxidation rate was higher ($p<0.05$) in the LGI trial than that in the LGIF and HGI trials. During the recovery period, no difference in either CHO or fat oxidation rate was found among the three trials (Table 5.5).

The amounts of CHO and fat oxidized were listed in table 5.6.

TABLE 5.6 CHO and fat oxidation amount during the postprandial period, exercise and the recovery period (n=10, mean ± SEM)

	Postprandial period			Exercise	Recovery period			Total
	1st hr	2nd hr	total		1st hr	2nd hr	total	
CHO oxidation amount (g)								
LGI	2.7±0.4	4.2±0.8	7.0±1.0	59.3±2.4	8.0±0.8	1.2±0.5	9.3±1.1	75.5±3.6
LGIF	7.5±1.2[a]	7.6±1.2[a]	15.2±2.4[a]	69.8±3.9[a]	10.4±1.4	3.7±1.4	14.2±2.5	99.1±7.3[a]
HGI	4.4±0.8[b]	7.6±0.7[a]	12.0±1.3[a]	72.7±3.9[a]	10.6±1.1[a]	3.0±1.0[c]	13.6±1.8[a]	98.3±6.0[a]
Fat oxidation amount (g)								
LGI	6.6±0.7	6.1±0.6	12.6±1.2	22.7±2.0	10.0±0.8	7.7±0.7	17.8±1.4	53.1±3.9
LGIF	4.5±0.6[c]	5.0±0.5	9.4±1.1	18.5±1.7[a]	8.9±1.0	6.4±0.9	15.3±1.8	43.3±4.3[c]
HGI	5.2±0.5	4.6±0.5[c]	9.7±1.0	17.6±1.3[a]	8.5±0.9	6.7±1.0	15.2±1.8	42.5±3.7[a]

[a] $p<0.05$, vs. LGI; [b] $p<0.05$, vs. LGIF; [c] $0.05<p<0.1$, vs. LGI.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

During the postprandial period, CHO oxidation amount was lower ($p<0.01$) in the LGI trial than that in the LGIF and HGI trials, whereas no difference was found in

the amount of fat oxidized among the three trials. Similar results were also found during the second hour of the postprandial period. However, during the fist hour of the postprandial period, lower CHO oxidation amount ($p<0.05$) was found in the LGI and HGI trials, compared with that in the LGIF trial.

During exercise, the CHO oxidation amount was lower ($p<0.01$), and the fat oxidation amount was higher ($p<0.05$) in the LGI trial than that in the LGIF and HGI trials, whereas no difference was found in either CHO or fat oxidation amount between the latter two trials.

During the entire recovery period, CHO oxidation amount was higher ($p<0.05$) in the HGI trial than that in the LGI trial. However, no differences were found in fat oxidation amounts among the three trials. Similar results were also found during the first hour of the recovery period. During the second hour of the recovery period, no difference was found in either CHO or fat oxidation amount among the three trials.

In totally, CHO oxidation amount was lower ($p<0.01$) in the LGI trial than that in the LGIF and HGI trials, whereas total fat oxidation amount was only found to be higher ($p<0.05$) in the LGI trial than that in the HGI trial. Although no statistical difference in fat oxidation amount was found between the LGI and LGIF trials, there was a trend to be higher in the LGI trial ($p=0.063$). No differences were found in either CHO or fat oxidation amount between the LGIF and HGI trials.

5.3.7 Energy expenditure during the experiment

No differences were found in calculated energy expenditure during the postprandial period, exercise, and the recovery period among the three trials (Table 5.7).

TABLE 5.7 Energy expenditure during the postprandial period, exercise and the recovery period (kcal, n=10, mean ± SEM)

	Postprandial			Exercise	Recovery	Total
	1st hr	2nd hr	total			
LGI	71±5	74±5	144±10	437±17	193±10	774±31
LGIF	71±4	75±3	146±6	437±15	190±9	772±26
HGI	65±3	71±3	136±6	438±15	185±9	759±24

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

5.3.8 HR, RPE, $\dot{V}O_2$, and exercise intensity during exercise

No differences were found in HR, RPE, and $\dot{V}O_2$ among the three trials during the brisk walking (Table 5.8). Also, no differences were found among the three trials (LGI vs. LGIF vs. HGI) in calculated exercise intensity (45.6%±0.8% vs. 45.5%±1.0% vs. 45.7%±0.9% $\dot{V}O_{2max}$). As expected, the HR and RPE increased during exercise in all trials.

TABLE 5.8 HR, RPE, and $\dot{V}O_2$ during exercise (n=10, mean ± SEM)

	15 min	30 min	45 min	60 min	Average
HR (beats·min^{-1})					
LGI	125±3	129±2	132±2	134±2	130±2
LGIF	126±2	129±3	131±3	133±3	130±3
HGI	125±3	131±4	133±4	136±4	131±3
RPE					
LGI	10.7±0.7	11.6±0.6	12.7±0.7	13.1±0.7	12.3±0.7
LGIF	11.0±0.9	12.3±0.9	12.7±0.8	12.5±0.8	12.2±0.7
HGI	11.0±0.6	12.9±0.6	13.8±0.6	14.3±0.8	13.2±0.6
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})					
LGI	24.1±0.6	24.6±0.8	24.6±0.7	24.7±0.7	24.5±0.7
LGIF	24.0±0.8	24.1±0.8	24.8±0.6	24.6±0.7	24.4±0.7
HGI	23.9±0.4	24.3±0.6	25.0±0.6	24.7±0.6	24.5±0.5

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. HR: Heart rate; RPE: Rating of perceived exertion.

5.3.9 Perceptual variables (RPT and RAD) during the experiment

No differences were observed in the RPT and RAD among the three trials during the entire experiment (Table 5.9). In total, the RPT and RAD were higher during exercise than those during the postprandial and recovery periods in all three trials.

TABLE 5.9 RPT and RAD during the postprandial period, exercise, and the recovery period (n=10, mean ± SEM)

	Fasting	Postprandial period (min)				Exercise(min)		Recovery (min)			
		30	60	90	120	30	60	30	60	90	120
RPT [a]											
LGI	2.7 ±0.5	1.8 ±0.4	1.8 ±0.5	1.8 ±0.4	1.5 ±0.4	2.6 ±0.5	2.5 ±0.5	1.7 ±0.4	2.1 ±0.4	1.5 ±0.4	1.2 +0.3
LGIF	2.9 ±0.5	2.1 +0.5	1.7 ±0.4	1.5 ±0.4	1.6 ±0.5	2.6 ±0.7	2.3 ±0.5	1.7 ±0.4	1.7 ±0.5	1.6 ±0.4	1.7 ±0.4
HGI	3.6 ±0.7	2.0 ±0.4	1.8 ±0.4	1.7 ±0.5	1.7 ±0.4	2.5 ±0.5	3.1 ±0.6	2.2 ±0.5	1.7 ±0.5	1.6 ±0.5	1.4 ±0.5
RAD [a]											
LGI	1.4 ±0.5	1.4 ±0.3	1.1 ±0.3	1.0 ±0.3	1.0 ±0.3	3.4 ±0.5	2.8 ±0.5	1.5 ±0.5	1.2 ±0.5	1.1 ±0.4	1.0 ±0.4
LGIF	0.9 ±0.3	1.2 ±0.3	1.1 ±0.3	1.2 ±0.3	1.2 ±0.3	2.8 ±0.5	2.8 ±0.5	1.4 ±0.3	1.2 ±0.3	1.1 ±0.3	0.9 ±0.3
HGI	0.9 ±0.4	1.2 ±0.3	1.1 ±0.3	1.1 ±0.4	1.2 ±0.4	3.6 ±0.6	4.6 ±0.7	1.6 ±0.4	1.1 ±0.4	1.2 ±0.4	1.0 ±0.4

[a] During exercise, the RPT and RAD were higher than those during the postprandial and recovery periods in all three trials ($p<0.05$, two way ANOVA with repeated measures).

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. RPT: Rating of perceived thirsty; RAD: Rating of abdominal discomfort.

5.4 Discussion and conclusion

The major finding of this study was that compared with LGI breakfast without

fructose consumption, both HGI breakfast and LGI breakfast including certain amount of fructose content induced higher CHO oxidation and lower fat oxidation during 60-min of subsequent brisk walking, whereas no differences were observed between the latter two trials. The novelty of the present study was that it firstly investigated the effect of both GI and fructose content of breakfast on substrate utilization during subsequent moderate intensity exercise.

Previous studies have indicated that GI may be an important factor influencing substrate utilization during subsequent moderate to high intensity exercise. Several studies have found higher fat oxidation and lower CHO oxidation during subsequent exercise after LGI meal consumption than HGI meal consumption (Chen, Wong et al., 2008b; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003). The mechanisms behind this also have been investigated (Wee et al., 2005; Wu et al., 2003). The difference in substrate utilization during exercise between the two trials may be partly explained by reduced hyperinsulinemia during the postprandial period following the LGI meal consumption, which reduced the suppression of fat oxidation than when HGI meal was consumed. This suppression appeared to be long lasting, even when insulin concentration had returned to basal levels (Coyle 1991; Montain et al. 1991). This reduction allows a shift in substrate utilization toward fat oxidation during subsequent exercise as well as provides a sustainable source of CHO (Wu et al., 2003). Furthermore, the lower CHO oxidation rate following a LGI meal has been explained by lower rate of muscle glycogen utilization (Wee et al., 2005).

Several studies also have been conducted to investigate this effect during low to moderate intensity exercise (Backhouse et al., 2007; Bennard & Doucet, 2006; Stevenson, Astbury et al., 2009). One recent study (Stevenson, Astbury et al., 2009)

found very similar results, i.e., higher fat oxidation and lower CHO oxidation were observed during 50% $\dot{V}O_{2max}$ brisk walking in the LGI trial than in the HGI trial. Similar results were also observed in the present study. During exercise, increased fat oxidation and decreased CHO oxidation were found in the LGI trial than those in the HGI trial (Table 5.4). Because LGI meal induced less glycemic and insulinemic responses than HGI meal during the postprandial period (Figure 5.2A, 5.3A), the difference in substrate utilization could be partly explained by this reduced hyperinsulinemia in the LGI trial. Therefore, the results of the present study, together with previous findings, indicated that GI was also an important influencing factor on substrate utilization during subsequent low to moderate intensity exercise.

In addition, several previous studies reported higher FFA concentrations during exercise, particularly at the first part of exercise, after consumption of a LGI meal than a HGI meal (Wee et al., 2005; Wong et al., 2008; Wu et al., 2003; Wu & Williams, 2006). Similar result was also observed in the present study, in which lower FFA concentration was found at 30 min during exercise in the HGI trial than that in the LGI trial (Figure 5.5). Besides, in the present study lower FFA concentration was also found at 60 min during the postprandial period in the HGI trial compared with LGI trial. This finding is in agreement with previous study (Wee et al., 2005). This phenomenon may be caused by higher insulin concentrations after HGI meal consumption. In vivo studies at rest have demonstrated that even very small increases in insulin have a marked suppression effect on lipolysis (Bonadonna et al., 1990; P. J. Campbell et al., 1992). Previous study also revealed that CHO intake suppressed lipolysis during exercise (Horowitz et al., 1997; Montain et al., 1991). Therefore, a lower rate of lipolysis results in reduced FFA concentration, which may also decrease the availability of FFA for oxidation.

However, in another very similar study using similar exercise protocol and subjects (Backhouse et al., 2007), no significant effect of GI meals on the amount of fat or CHO oxidized during exercise was noted. The inconsistent results may be partly explained by the differences in pre-exercise meals. In this study the GI values of two meals were 77 and 51, respectively. Therefore, this was more likely to be the comparison between HGI and MGI meals. In fact, in this study two meals produced similar glycemic and insulinemic responses, which was very different from the present study and the previous study (Stevenson, Astbury et al., 2009). In another study (Bennard & Doucet, 2006), similar fat and CHO oxidation during exercise was also found between the HGI and LGI trials. However, in this study, no differences in glucose and insulin concentrations were found during the postprandial period, although the GI values of the two meals were 48.3 and 103.3, respectively. The author attributed this to the hourly samples, in which the rapid rise and subsequent return in glucose might have been missed.

It is worth mentioning that in these two studies (Backhouse et al., 2007; Bennard & Doucet, 2006), more fructose content are included in the LGI trial because of more fruits, unsweetened apple juice, or fructose beverage. Unfortunately, the authors did not discuss whether this difference would influence substrate utilization.

To investigate whether fructose content in pre-exercise meal was also an important influencing factor on substrate utilization during subsequent moderate intensity exercise, another LGI meal was included in present study in which fructose beverage supply approximately 25% of total energies. As expected, the similar glycemic and insulinemic responses were found between the LGI and LGIF trials (Figure 5.2A, 5.3A). Furthermore, the IAUC values of glucose and insulin were also similar

between the two trials (Table 5.4). In addition, similar FFA and glycerol concentrations were found between the two trials (Figure 5.5, 5.6), which indicated the similar availability of FFA. Despite all of these similarities, substrate utilization was obviously different during exercise. Higher CHO oxidation and less fat oxidation were found in the LGIF trial than in the LGI trial (Table 5.6). The major reason behind this might be the influence of more fructose content in the LGIF trial than in the LGI trial.

In the present study, the energy and macronutrient contents were similar among the three trials. The food contents were almost same between the LGIF and the HGI trials except for the beverages. Therefore, the major two differences in the meals between these two trials were GI and fructose content. Despite the obviously different glycemic and insulinemic responses during the postprandial period between these two trials (Figure 5.2A, 5.3A), substrate utilization was similar not only during exercise but also during the postprandial period (Table 5.6). Therefore, the results of the present study indicated that except for GI, fructose content in pre-exercise meal could be another important influencing factor in determining substrate utilization during subsequent moderate intensity exercise.

Actually some earlier studies also found similar substrate utilization during different intensity exercises after ingesting either fructose or glucose beverages (Décombaz et al., 1985; Fielding et al., 1987; Hargreaves et al., 1987). It might be argued that fructose and glucose beverages were usually consumed 30-60 min before exercise in these studies. However, some later studies (DeMarco et al., 1999; Thomas et al., 1991) found that LGI CHO consumption 30-60 min before exercise also resulted in higher fat oxidation and reduced CHO oxidation during exercise, particularly during

the first part of exercise, when compared with HGI CHO consumption.

The results coming from studies examining the effects of fructose beverage alone may not be applicable to the fructose beverage in a normal diet. Furthermore, it has been suggested that the effect of fructose on fat oxidation tended to be different when fructose was combined with other foods (McDevitt et al., 2000). In recent years, the consumption of dietary fructose has increased in conjunction with the rising intake of fructose-containing sugars, largely in the form of sugar-sweetened beverages (Marriott et al., 2009; Storey et al., 2006). More importantly, the consumption of fructose has been suggested to be related to the development of obesity, metabolic syndrome, and diabetes (Bray et al., 2004; Johnson et al., 2009). There were also substantial experimental evidences from studies conducted in animals and some human subjects (Johnson et al., 2009; Pagliassotti, Prach, Koppenhafer & Pan, 1996; Stanhope et al., 2008). Therefore, the effect of fructose content in meals on the metabolic responses of humans is worth investigating further.

The inconsistent results in substrate utilization coming from fructose and other LGI CHO may be explained by the special metabolism of fructose in the liver. Fructose could be metabolized bypassing the first rate-limiting enzymes of glycolysis, and thus be expected to be more readily oxidized (Lê & Tappy, 2006). Fructose consumption could decrease lipolysis and whole-body lipid oxidation (Chong et al., 2007), most likely because of the stimulation of the hepatic de novo lipogenesis and a concomitant inhibition of tissue lipid oxidation. Therefore, it appeared that fructose should not be considered as typical LGI CHO, at least when discussing fuel metabolism.

In the present study, higher blood lactate concentrations were found during the postprandial period in the LGIF trial compared with those in the LGI and HGI trials (Figure 5.4A), so as the IAUC value of lactate (Table 5.4). These data suggested that glycolysis was much higher in the LGIF trial, which likewise caused by the metabolism of fructose in the liver (Lê & Tappy, 2006). It was well noted that fructose could induce higher blood lactate concentrations than glucose (Koivisto et al., 1981). Lactate was one important product in fructose metabolism in the liver, and because fructose uptake by the liver was not inhibited, fructose consumption would result in larger increase in circulating lactate than a comparable amount of glucose consumption (Bjorkman et all. 1989). It has been suggested that fructose-induced hyperlactatemia may contribute to the suppression of adipose lipolysis (Abdel-Sayed et al. 2008). The increased blood lactate during the postprandial period also could be metabolized directly in working muscle during subsequent exercise, which also could increase CHO oxidation (Ahlborg and Bjorkman 1990). In addition, a previous study (Blaak & Saris, 1996) revealed that fructose consumption produced more CHO oxidation and inhibition of lipid oxidation than glucose consumption during the postprandial period. These results indicated that fructose was more favorable for the oxidation of CHO. In previously mentioned study (Backhouse et al., 2007), blood lactate concentrations were also significantly elevated following the ingestion of the LGI meal because of more fructose content. This may be another reason that no difference in substrate utilization was found between the LGI and HGI trials.

During the postprandial period, higher CHO oxidation was found in the HGI trial than in the LGI trial, whereas no difference was found in fat oxidation between the two trials (Table 5.6). This result was a little different from the previous study (Stevenson, Astbury et al., 2009), in which higher fat oxidation was also found

during the postprandial period in the LGI trial. This inconsistent result may be partly due to the different subjects between the two studies. In the present study healthy young males were used, whereas sedentary females were used in the previous study (Stevenson, Astbury et al., 2009). Females have been reported to demonstrate greater fat utilization and less CHO and protein metabolism than equally trained and nourished males during moderate intensity exercises (Tarnopolsky et al., 1990).

A 120-min recovery period was included in the present study. It was found that CHO oxidation amount was higher in the HGI trial than that in the LGI trial during the recovery period. However, no differences were found in fat oxidation amounts among the three trials. Therefore, it appeared that the influence of GI in pre-exercise meals was extended to several hours after exercise, at least for CHO oxidation. The total amounts of CHO and fat oxidized during the entire experiment also supported these results (Table 5.6).

The consumption of a large amount of pure fructose could exceed the capacity of intestinal fructose absorption and result in abdominal symptoms (Truswell et al., 1988). However, in the present study, the nutritional protocol was similar with that adopted in previous study (Stanhope et al., 2008). It appeared that the amount of fructose used in the present study did not induce obvious abdominal symptoms. This was also supported by the result that there were no differences in RAD among the three trials even during exercise.

In conclusion, HGI meal and LGI meal including certain amount of fructose (~25% energy sources) consumption resulted in similar substrate utilization during 60-min of subsequent brisk walking, whereas LGI meal without fructose consumption induced increased fat oxidation and decreased CHO oxidation compared with them.

Therefore, both GI and fructose content of the pre-exercise meal could be important factors influencing substrate utilization during subsequent moderate intensity exercise. Further studies are required to investigate the long-term influences of fructose consumption on substrate utilization or whether a smaller amount of fructose consumption will not disturb the influence of GI.

CHAPTER 6

EFFECT OF GLYCEMIC INDEX AND FRUCTOSE CONTENT IN LUNCH ON SUBSTRATE UTILIZATION DURING SUBSEQUENT BRISK WALKING

6.1 Introduction

As discussed previously, the glycemic index (GI) concept provided a new tool for investigating carbohydrate (CHO) metabolism in sport science. In recent years, many studies have been conducted to investigate the effect of pre-exercise GI meals on metabolic responses and/or exercise performance, which have been summarized in recent reviews (Donaldson et al., 2010; O'Reilly et al., 2010; Siu & Wong, 2004). A number of studies observed higher fat oxidation and lower CHO oxidation during subsequent moderate to high intensity exercise after low-GI (LGI) meal consumption than after high-GI (HGI) meal consumption (Chen, Wong et al., 2008b; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003). For low to moderate intensity exercise, however, only a few studies were conducted to investigate this effect and no consistent results were observed (Backhouse et al., 2007; Bennard & Doucet, 2006; Stevenson, Astbury et al., 2009). Moderate intensity exercise appeared to be the most favorable for eliciting a substantial short-term increase in fat oxidation for the general population (Achten & Jeukendrup, 2004; Venables et al., 2005). Therefore, this type of investigation is important for ordinary people, particularly for those who intend to increase fat oxidation for weight management or health maintenance.

Fructose content is another potential influencing factor when discussing the effect of different GI meal consumption on substrate utilization (Díaz et al., 2006). Earlier

studies found that compared with glucose beverage, fructose beverage ingestion alone prior to exercise caused similar substrate utilization during exercise at 60% (Décombaz et al., 1985), 70% (Fielding et al., 1987), or 75% $\dot{V}O_{2max}$ (Hargreaves et al., 1987). However, in these studies, fructose beverage was used as the only pre-exercise food. Results from studies examining the effects of fructose beverage alone may not be applicable to the fructose content in a normal diet. There is a paucity of studies, if any, that were conducted to investigate specifically the effect of fructose content in mixed meals consumed before exercise on substrate utilization.

Therefore, we conducted one study to investigate this (Chapter 5). It was found that compared with LGI breakfast without fructose consumption, either the HGI breakfast or the presence of fructose in a similar LGI breakfast resulted in decreased fat oxidation and increased CHO oxidation during subsequent brisk walking. On the other hand, no difference was found in substrate utilization between the latter two trials. This finding indicated that both GI and fructose content in meals could affect substrate utilization during subsequent moderate intensity exercise.

In majority of the previously mentioned studies, the meals were provided to subjects after an overnight fast to avoid the influence of so-called "second-meal effect". Only a few studies were conducted to investigate the effect of different lunch consumption on substrate utilization during subsequent exercise. A previous study (Sparks et al., 1998) observed that after a standard breakfast and 4-hrs of fasting, LGI lunch consumption produced less CHO oxidation than HGI lunch consumption during subsequent 67% $\dot{V}O_{2max}$ cycling. In a more recent study (L. J. S. Moore et al., 2010), when HGI or LGI meals were consumed after 6-hrs of fasting, greater CHO oxidation was found in the LGI trial than in the HGI trial during subsequent 40 km

time trial (TT) cycling. This result was contrary to majority of previous studies and the authors were unable to explain this inconsistency. It is worth mentioning that in these two studies, endurance athletes were used as subjects and higher exercise intensity was used to test whether exercise performance was influenced by different pre-exercise GI meals. In view of the limited studies, a conclusive recommendation could not be drawn on the effect of different GI lunch consumption, followed by a standard breakfast and several hours of postprandial period, on substrate utilization during subsequent exercise. Furthermore, it is also unknown whether the fructose content of lunch will affect substrate utilization during subsequent exercise.

A previous study (Montain et al., 1991) mentioned that at least 6-hrs of fasting was necessary to induce similar substrate utilization and plasma glucose homeostasis during 70% $\dot{V}O_{2max}$ exercise as a 8-12 hrs of fasting. Therefore, when different GI meals are consumed after an overnight fasting or after only several hours of fasting (e.g., 3-4 hrs after breakfast), their effect on substrate utilization during subsequent exercise may be different. However, to our knowledge, no studies have been conducted to investigate this specifically. Furthermore, results from previous studies conducted in the morning could not be directly applied to studies conducted in the afternoon. It is also not uncommon for ordinary people to exercise in the afternoon. Therefore, the present study aimed to investigate the effect of lunch meals with different GI and fructose content, which were consumed 4-hrs after a standard breakfast, on substrate utilization during subsequent brisk walking. It was hypothesized that compared with a pre-exercise LGI lunch without fructose, either a HGI lunch or the presence of fructose in a LGI lunch would induce decreased fat oxidation and increased CHO oxidation during subsequent brisk walking.

6.2 Methods

6.2.1 Subjects

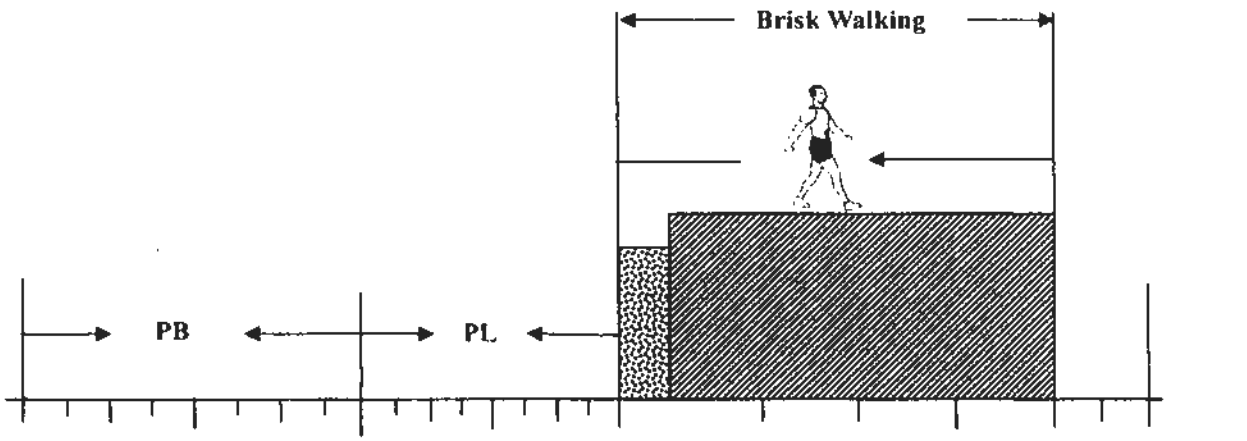
Ten healthy young male adults were recruited to participate in this study. Their age, height, body weight (BW), body mass index (BMI), and $\dot{V}O_{2max}$ (mean ± SD) were 20.5±1.0 y, 171.0±6.2 cm, 61.1±2.8 kg, 20.8±0.7 $kg \cdot m^{-2}$, and 48.6±1.9 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. None of the subjects reported any medical conditions.

6.2.2 Procedures

All subjects attended two preliminary tests to determine the walking speed equivalent to 50% of each subject's $\dot{V}O_{2max}$. All subjects were required to complete three main trials in a single-blinded counterbalanced crossover design, and the duration between any two trials was at least seven days. In each main trial, after a standard breakfast and a 4-hrs postprandial period, the subjects consumed one of three lunch meals. Two hours after lunch consumption, one bout of exercise was performed. The exercise protocol consisted of 5-min warm-up at 40% $\dot{V}O_{2max}$ and a 60-min brisk walking at a speed that was equal to 50% of predicted individual $\dot{V}O_{2max}$.

Each subject was required to maintain a three-day dietary record and to repeat the same diet before each main trial to minimize variation in muscle and liver glycogen concentrations. The dietary records were analyzed using the computer software (Food Processor 10.5, ESHA, USA). During the main trial, after 10-12 hrs of overnight fasting, the subjects reported to the laboratory at around 8:00 a.m. This was to ensure that they had an empty stomach and to minimize the effect of the

previous meals, specifically that taken during dinner, on the gastric emptying rate of the test meals. Upon arrival, the subjects rested for approximately 15-min before a catheter was inserted into the antecubital vein of the forearm. Baseline venous and finger capillary blood samples, expired air samples, and other baseline data, such as BW, heart rate (HR), rating of perceived exertion (RPE), rating of abdominal discomfort (RAD), and rating of perceived thirst (RPT) were then collected. Further blood samples, expired air samples, and other data were collected at specific time points, as shown in figure 6.1.



HR: Heart rate; RPE: Rating of perceived exertion; RPT: Rating of perceived thirsty; RAD: Rating of perceived discomfort; PB: Postprandial period after breakfast; PL: Postprandial period after lunch. Ex: Exercise; Rec: Recovery period.

FIGURE 6.1 Schematic representation of the experimental procedures

As described previously (Chapter 3), capillary blood samples were used to measure blood glucose, lactate, hemoglobin (Hb) concentrations, and hematocrit (Hct). Venous blood samples were used to decide serum insulin, free fatty acids (FFA), and glycerol concentrations. Expired air samples were collected and analyzed for volume of inhaled oxygen ($\dot{V}O_2$), volume of exhaled carbon dioxide ($\dot{V}CO_2$), and respiratory exchange ratio (RER). Rates and amounts of CHO and fat oxidized were then calculated.

After collection of baseline samples, the subjects consumed a standard breakfast. They were required to sit in a quiet area in the laboratory for 4-hrs. Subsequently, they were asked to consume one of three lunch meals in a counterbalanced randomized order. All foods were required to be consumed within 15-min. Then subjects rested for another 120-min in the lab. During the postprandial period after breakfast (PB) and postprandial period after lunch (PL), subjects were required to ingest 2 $mL \cdot kg^{-1}$ BW of distilled water every 60-min to ensure adequate hydration and balance the water content of the meals.

Following 120-min of PL, a standardized 5-min warm-up at 40% $\dot{V}O_{2max}$ was performed. The subjects then completed 60-min of brisk walking. During exercise, 2 $mL \cdot kg^{-1}$ BW of distilled water was administered every 30-min to reduce the effect of dehydration. After finishing brisk walking, subjects returned to the resting area, and a 60-min recovery period was started immediately. Then subjects were free to leave the laboratory.

6.2.3 Prescribed meals

Three isocaloric lunch meals were used in the present study: a low-GI meal without fructose (LGI), a low-GI meal including fructose beverage (LGIF), and a high-GI meal (HGI). All meals provided 1.0 $g \cdot kg^{-1}$ BW CHO for each subject, and the amounts of macronutrients were similar among the three meals. The GI values for the individual foods were obtained from the international GI tables (Atkinson et al., 2008) and GI values measured by our laboratory (Chen, Sun, Wong & Huang, 2010). The GI value of mixed meal was calculated using a method described previously (Wolever & Bolognesi, 1996b). Calculated GI values for the standard breakfast, LGI, LGIF, and HGI lunch meals were 62, 41, 39, and 72, respectively (Table 6.1).

The food contents were very similar in LGIF and HGI lunches except for fructose and glucose. Fructose and glucose were dissolved into beverages before consumption to ensure that the concentration of glucose or fructose beverage was around 10%. The water content of all meals was matched so that each meal provided the subjects with the same volume of liquids. In the standard breakfast, around 25% of energies came from fat, 13% from protein, and 62% from CHO. The lunch provided around 20% energy from fat, 17% from protein, and 63% from CHO. Among the energies provided by CHO in the LGIF and HGI lunches, around 25% was derived from either glucose or fructose in the form of the beverage.

All meals were freshly prepared in the day of each main trial. The preparation procedure was standardized to minimize the influences of cooking methods. To avoid the occurrence of bias, the specific purpose of using the GI foods and measuring the weight of the food was not disclosed to the subjects.

TABLE 6.1 Nutritional composition of test meals (for a 60kg subject)

Meals	Quantity (g)	Energy (kcal)	CHO (g)	Fat (g)	Protein (g)	Calculated GI [a]
Breakfast						
Pineapple Bun	100	351	54.9	11.0	8.6	
Fat-free milk	120	44	6.0	0.2	4.2	
Total		395	60.9	11.2	12.8	62
LGI Lunch						
Spaghetti, cooked	182	288	56.2	10.6	1.8	
Full milk	60	38	2.9	1.9	2.0	
Egg, boiled	60	65	0.3	5.5	4.4	
Total		391	59.4	18.0	8.2	41
LGIF Lunch						
Rice vermicelli	42	158	32.3	3.1	0.1	
Egg, boiled	60	65	0.3	5.5	4.4	
Ham	46	75	1.8	7.6	4.4	
Fructose	26	96	26.0	0	0	
Total		394	60.4	16.2	8.9	39
HGI Lunch						
Rice vermicelli	45	170	33.7	3.3	0.1	
Egg, boiled	60	65	0.3	5.5	4.4	
Ham	45	73	1.3	7.5	3.9	
Glucose	25	92	25.0	0	0	
Total		400	60.3	16.3	8.4	72

[a] Calculated by a method described previously (Wolever & Bolognesi, 1996b), with GI values taken from our laboratory (Chen et al., 2010) and the International GI table (Atkinson et al., 2008).

CHO: Carbohydrate; GI: Glycemic index; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

6.2.4 Statistical analysis

Data were presented as mean ± SEM. SPSS software (version 17.0) was used for data analysis. Dependent variables of the three trials, total substrate oxidation, and macronutrient intake for three days before the main trial, were compared using one-way analysis of variance (ANOVA) with repeated measures. Changes in concentrations of blood glucose, blood lactate, serum insulin, FFA, glycerol, and changes in RER, HR, RPE, RPT, and RAD values were analyzed using two-way ANOVA (Treatment × Time) with repeated measures. A Bonferroni correction method was performed at the location of variance. Statistical significance was set at the 0.05 level.

6.3 Results

All subjects completed the protocol as expected. No differences in the baseline measurements were found among the three trials, except for fasting FFA concentration which was lower ($p<0.05$) in the HGI trial than in the LGIF trial (Table 6.2). No differences in daily energy intake and macronutrient composition of the subjects' diet were observed during the three days before each trial (Table 6.3).

TABLE 6.2 Baseline data comparison among the three trials (n=10, mean ± SEM)

	Trial		
	LGI	LGIF	HGI
Baseline (before breakfast)			
Glucose ($mmol \cdot L^{-1}$)	4.24±0.10	4.25±0.04	4.32±0.06
Lactate ($mmol \cdot L^{-1}$)	0.96±0.19	0.80±0.12	0.69±0.06
Heart Rate ($beats \cdot min^{-1}$)	69±4	68±3	66±3
Rating of Perceived Exertion	6.8±0.2	6.7±0.3	6.6±0.2
Perceived Thirsty Scale	2.1±0.3	2.5±0.5	2.3±0.4
Abdominal Discomfort Scale	0.9±0.3	0.8±0.2	0.8±0.2
Hematocrit	0.46±0.01	0.44±0.01	0.44±0.01
Hemoglobin ($mg \cdot dl^{-1}$)	15.2±0.5	14.6±0.5	14.5±0.6
Insulin ($mU \cdot L^{-1}$)	4.2±0.6	5.6±0.9	4.6±0.5
Free Fatty Acid ($mmol \cdot L^{-1}$)	0.55±0.05	0.62±0.05	0.47±0.05[b]
Glycerol ($\mu mol \cdot L^{-1}$)	71.02±10.12	97.1±14.1	79.87±7.58
Baseline (before Lunch)			
Glucose ($mmol \cdot L^{-1}$)	4.10±0.12	4.06±0.10	4.04±0.08
Lactate ($mmol \cdot L^{-1}$)	0.87±0.06	0.83±0.09	0.74±0.05
Heart Rate ($beats \cdot min^{-1}$)	65±3	64±4	65±3
Rating of Perceived Exertion	6.9±0.3	6.7±0.2	6.7±0.2
Perceived Thirsty Scale	2.3±0.5	1.8±0.5	1.7±0.4
Abdominal Discomfort Scale	0.8±0.2	1.0±0.3	1.0±0.3
Insulin ($mU \cdot L^{-1}$)	4.4±0.6	4.3±0.6	4.2±0.6
Free Fatty Acid ($mmol \cdot L^{-1}$)	0.44±0.04	0.48±0.05	0.45±0.06
Glycerol ($\mu mol \cdot L^{-1}$)	79.68±13.82	81.11±9.44	80.19±9.60

[b] $P<0.05$, vs. LGIF.

TABLE 6.3 Daily energy intake and macronutrient content of diets before main trial (n=10, mean ± SEM)

	Trial		
	LGI	LGIF	HGI
Daily energy intake (kcal)	1946±174	1973±155	1922±150
Energy from CHO (%)	54.4±3.3	56.6±2.5	56.9±3.3
Energy from protein (%)	24.1±2.0	21.1±1.3	22.5±1.7
Energy from fat (%)	21.4±1.6	22.2±1.8	20.5±1.8

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

6.3.1 Blood glucose

Compared with fasting level, blood glucose concentrations were elevated at 60 and 120 min during PB in all three trials ($p<0.05$ vs. 0 min). However, no differences among the three trials were observed (Figure 6.2A).

During PL, blood glucose concentrations peaked at 30 min in all trials ($p<0.05$, vs. PB_240 min). However, glycemic responses in the HGI trial were the highest (Figure 6.2A). At 30, 45, and 60 min, blood glucose concentrations in the HGI trial were higher ($p<0.05$) than those in the LGI trial. At 45 min, it was higher ($p<0.05$) in the HGI trial than in the LGIF trial. No differences were found at any time point between the LGI and LGIF trials. During PL, IAUC value of glucose in the HGI trial was higher than that in the LGI ($p<0.01$) and LGIF trials ($p<0.05$), whereas no difference was found between the latter two trials (Table 6.4).

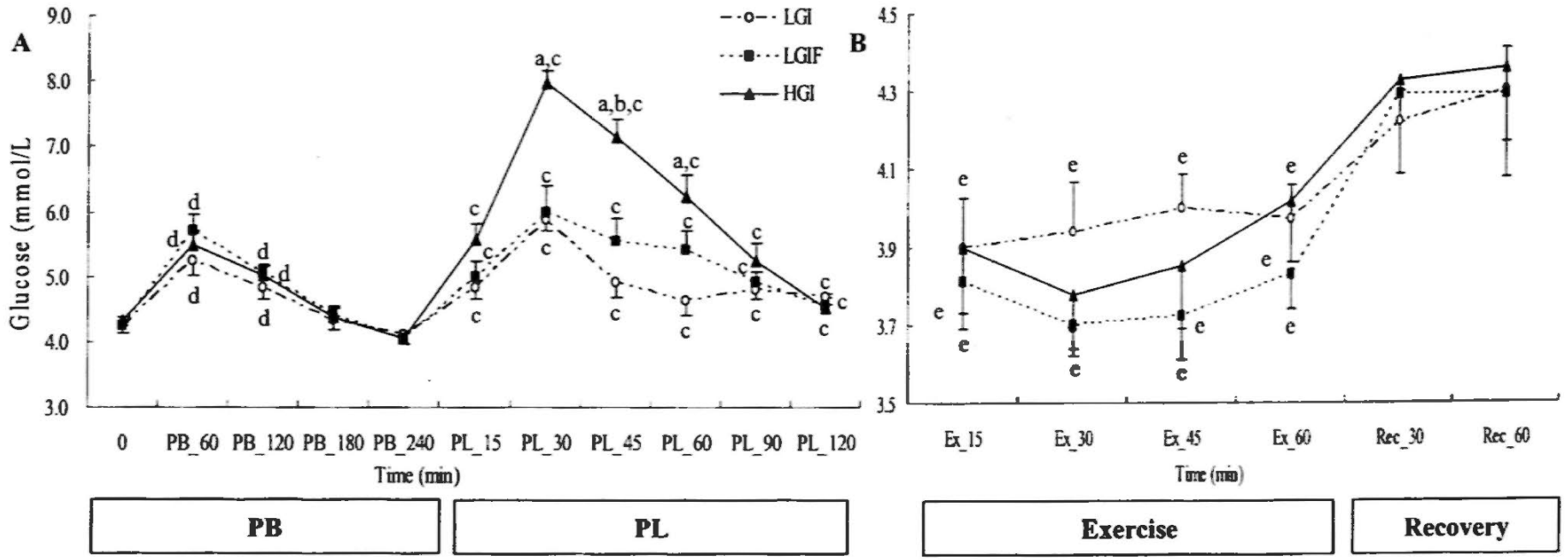


FIGURE 6.2 Glucose concentrations during the experiment

Data were presented as mean ± SEM (n=10). a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. PB_240min; d: $p<0.05$ vs. 0 min; e: $p<0.05$, vs. PL_120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal; PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption; Ex: Exercise; Rec: Recovery period.

TABLE 6.4 Comparison of IAUC values of glucose, insulin, and lactate during the postprandial period after lunch consumption (n=10, mean ± SEM)

Trial	IAUC value during PL		
	Glucose (mmol·min·L^{-1})	Insulin (mU·min·L^{-1})	Lactate (mmol·min·L^{-1})
LGI	92.53±10.4	1425±289	14.84±5.05
LGIF	127.97±17.7	1888±114	82.34±12.77 [a]
HGI	223.45±24.42 [a,b]	3603±593 [a,b]	29.57±5.6 [b]

[a] $p<0.05$, vs. LGI; [b] $p<0.05$, vs. LGIF.

IAUC: Incremental area under the blood response curve; PL: Postprandial period after lunch consumption; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal.

Throughout the exercise and recovery periods, no differences were observed in blood glucose concentrations among the three trials (Figure 6.2B). During exercise, these were lower in all three trials than at the onset of exercise ($p<0.05$, vs. PL_120 min). In the recovery period, these returned to the baseline level ($p>0.05$, vs. PB_240 min & PL_120 min).

6.3.2 Serum insulin

No differences in serum insulin concentrations were observed during PB among the three trials (Figure 6.3A). However, at 120 min, the concentrations were higher than those at the fasting level in all three trials ($p<0.05$, vs. 0 min).

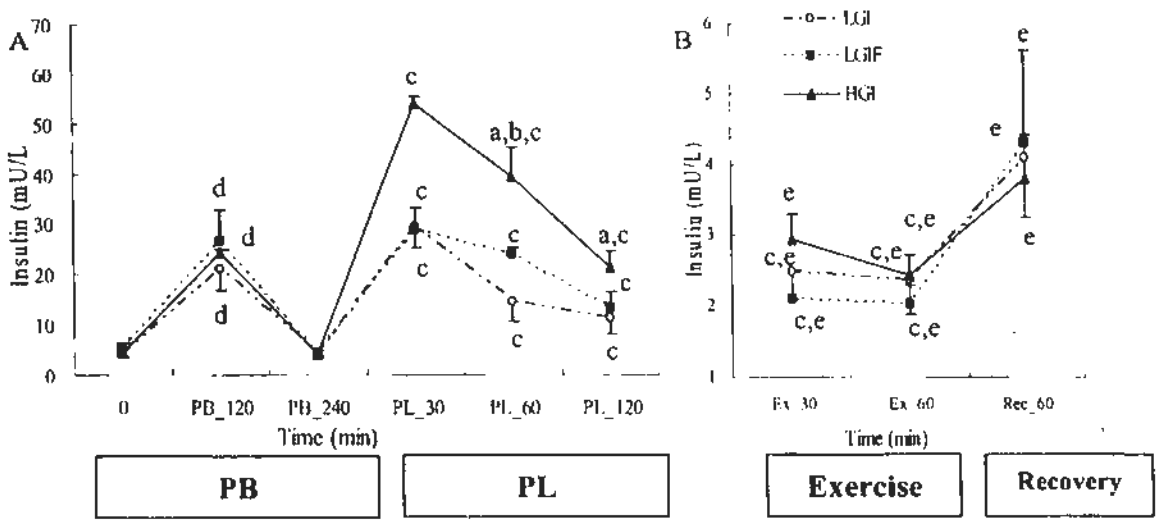


FIGURE 6.3 Serum insulin concentrations during the experiment

Data were presented as mean ± SEM (n=10). a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. PB_240min; d: $p<0.05$ vs. 0 min; e: $p<0.05$ vs. PL_120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption; Ex: Exercise; Rec: Recovery period.

After consumption of lunch, serum insulin concentrations increased and peaked at 30 min ($p<0.05$, vs. PB_240 min) in all three trials (Figure 6.3A). During PL, these were higher ($p<0.05$) at 60 and 120 min in the HGI trial than in the LGI trial. However, higher serum insulin concentrations ($p<0.05$) were found only at 60 min in the HGI trial than in the LGIF trial (Figure 6.3A). No differences were observed at any time point between the LGIF and LGI trials (Figure 6.3A). During PL, IAUC value of insulin in the HGI trial was higher ($p<0.05$) than in the LGI and LGIF trials, whereas no difference was observed between the latter two trials (Table 6.4).

No differences in serum insulin concentrations were found among the three trials throughout the exercise and recovery period (Figure 6.3B). During exercise, these decreased and became lower than those at the onset of exercise ($p<0.05$, vs. PL_120 min). These were lower than the baseline level as well before lunch consumption ($p<0.05$, vs. PB_240 min) in the three trials. During the recovery period, serum insulin concentrations reverted to the baseline level (PB_240 min) in all three trials. However, they remained lower than those at the onset of exercise ($p<0.05$, vs. PL_120 min).

6.3.3 Blood lactate

Compared with the fasting level, blood lactate concentrations were elevated at 60 min during PB in all three trials ($p<0.05$ vs. 0 min). However, no differences were observed among the three trials (Figure 6.4A).

During PL, blood lactate concentrations were elevated again and peaked ($p<0.05$, vs. PB_240 min) at 30 min in the LGIF trial, and at 60 min in the LGI and LGIF trials (Figure 6.4A). At 30, 45, 60, and 90 min, the concentrations were higher ($p<0.05$) in the LGIF trial than in the LGI and HGI trials. Meanwhile no differences were found at all time points between the latter two trials (Figure 6.4A). During PL, IAUC value of lactate in the LGIF trial was higher ($p<0.01$) as well than that in the LGI and HGI trials. No difference was observed between the latter two trials (Table 6.4).

Throughout the exercise and recovery period, no differences were observed in blood lactate concentrations among the three trials (Figure 6.4B). During exercise the concentrations were elevated in all three trials ($p<0.05$, vs. PB_240 min and PL_120 min). During the recovery period, meanwhile, these returned to the baseline level ($p>0.05$, vs. PB_240 min and PL_120 min).

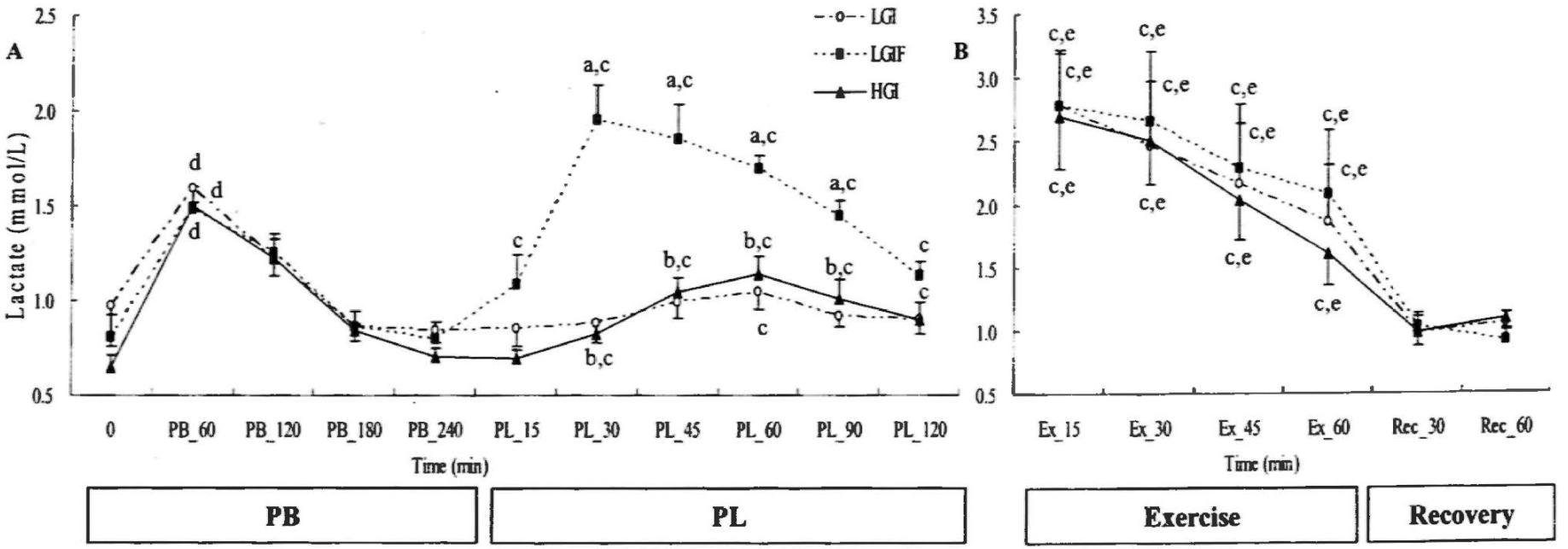


FIGURE 6.4 Lactate concentrations during the experiment

Data were presented as mean ± SEM (n=10). a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. PB_240 min; d: $p<0.05$, vs. 0 min; e: $p<0.05$, vs. PL_120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption; Ex: Exercise; Rec: Recovery period.

6.3.4 Serum FFA

In general, no differences were observed in the serum FFA concentrations among the three trials, except for two time points. The fasting serum FFA concentration (0 min) was higher ($p<0.05$) in the LGIF trial than in the HGI trial. At the end of PL (PL_120 min), it was higher ($p<0.05$) in the LGI trial than in the HGI trial (Figure 6.5).

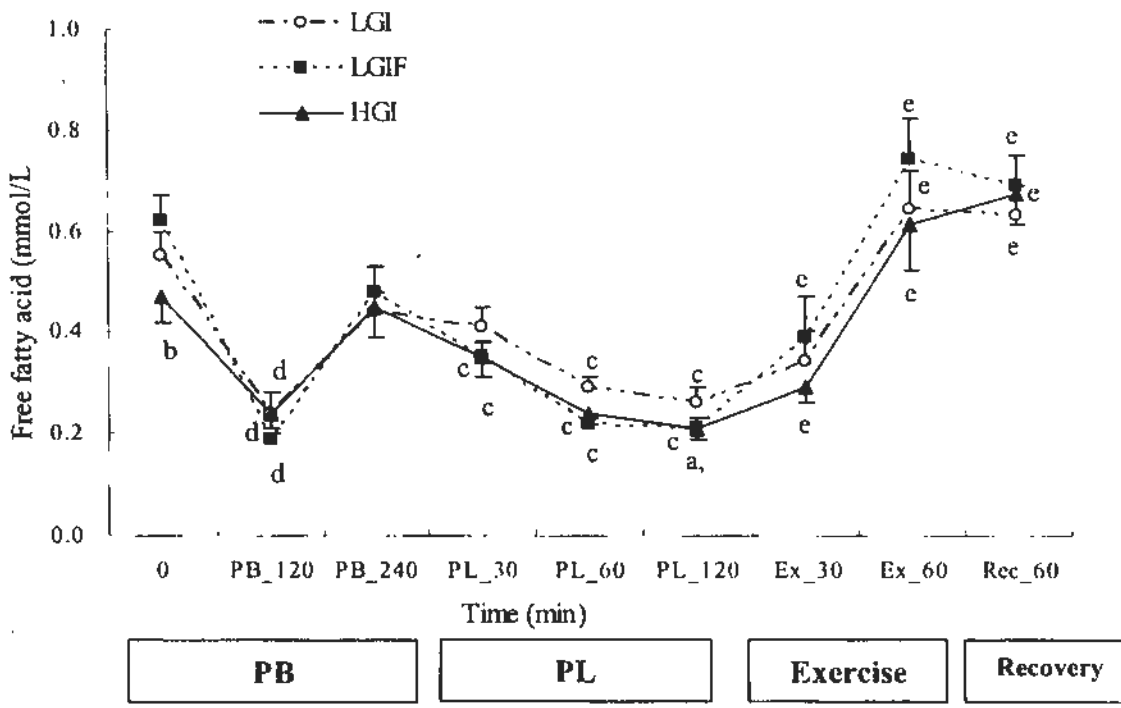


FIGURE 6.5 Serum FFA concentrations during the experiment

Data were presented as mean ± SEM (n=10). a: $p<0.05$, vs. LGI; b: $p<0.05$, vs. LGIF; c: $p<0.05$, vs. PB_240min; d: $p<0.05$ vs. 0 min; e: $p<0.05$ vs. PL_120 min.

FFA: Free fatty acid; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption; Ex: Exercise; Rec: Recovery period.

During PB, serum FFA concentrations decreased at 120 min in all three trials ($p<0.05$, vs. 0 min). Subsequently, these increased to the fasting level (0 min) at the end of PB (PB_240 min). During PL, these were suppressed again in all three trials ($p<0.05$, vs. PB_240 min).

Throughout the exercise and recovery period, serum FFA concentrations were elevated in all three trials ($p<0.05$, vs. PL_120 min). However, at 30 min during exercise, it was similar to that at the onset of exercise ($p>0.05$, vs. PL_120 min) in the LGI trial (Figure 6.5).

6.3.5 Serum glycerol

No differences were observed in serum glycerol concentrations at any time point among the three trials (Figure 6.6).

Compared with the fasting level, serum glycerol concentration decreased ($p<0.05$, vs. 0 min) at 120 min during PB in the LGIF trial (Figure 6.6). After consumption of lunch, these became lower at 30 min in the HGI trial and at 60 min in the LGIF trial ($p<0.05$, vs. PB_240 min). During exercise, these were elevated in all three trials and were higher than those at the baseline level ($p<0.05$, vs. PB_240 min), and at the onset of exercise ($p<0.05$, vs. PL_120 min). In the recovery period, serum glycerol concentrations were suppressed in all three trials but remained higher than those at the onset of exercise ($p<0.05$, vs. PL_120 min).

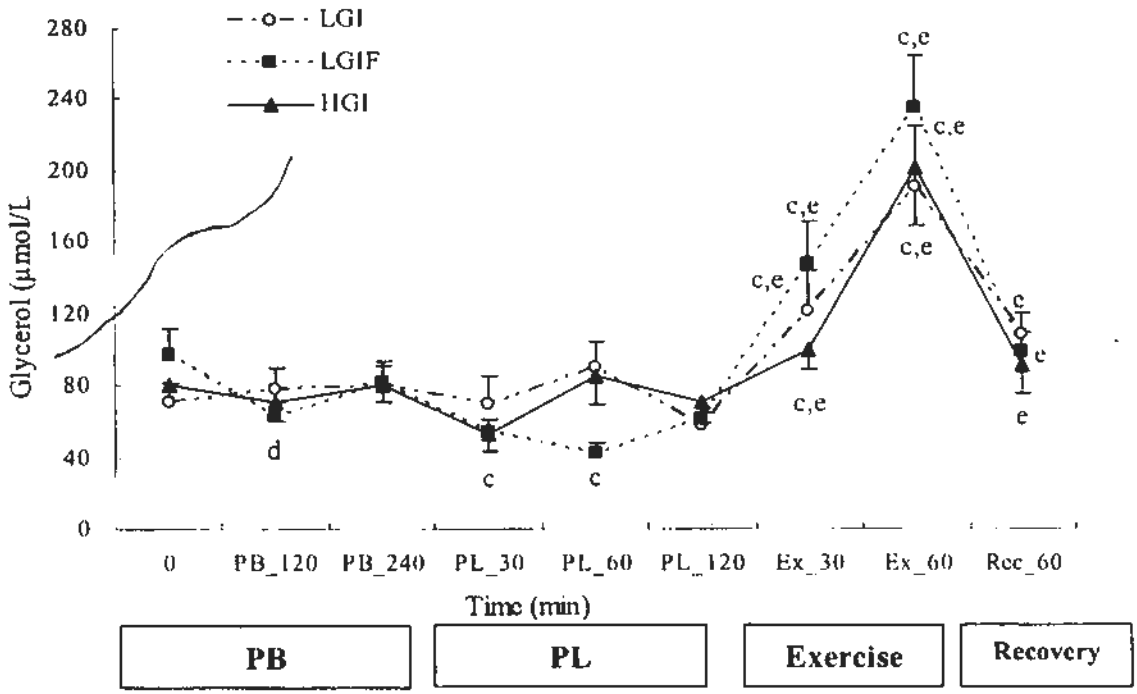


FIGURE 6.6 Serum glycerol concentrations during the experiment

Data were presented as mean ± SEM (n=10). c: $p<0.05$, vs. PB_240min; d: $p<0.05$ vs. 0 min; e: $p<0.05$ vs. PL_120 min.

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption; Ex: Exercise; Rec: Recovery period.

6.3.6 CHO oxidation and fat oxidation

During PB, no differences were observed in either CHO or fat oxidation rate among the three trials (Table 6.5). During PL, CHO oxidation rate was lower ($p<0.05$) in the LGI trial than in the LGIF and HGI trials, whereas fat oxidation rate was higher ($P<0.01$) in the LGI trial only compared with that in the LGIF trial (Table 6.5).

During exercise, CHO oxidation rate was higher ($p<0.01$) in the HGI trial than in the LGI trial, whereas no difference was found in fat oxidation rate among the three trials (Table 6.5). However, there was a trend to be higher in fat oxidation rate in the LGI trial than in the HGI trial ($p=0.077$). In the recovery period, neither CHO nor fat oxidation rate was found to be different among the three trials (Table 6.5).

TABLE 6.5 CHO and fat oxidation rate during PB, PL, exercise, and the recovery period (n=10, mean ± SEM)

	Fasting	PB (min)							
		30	60	90	120	150	180	210	240
CHO oxidation rate ($g \cdot min^{-1}$)									
LGI	0.07 ±0.02	0.07 ±0.03	0.12 ±0.02	0.11 ±0.02	0.11 ±0.02	0.14 ±0.03	0.07 ±0.02	0.05 ±0.02	0.04 ±0.02
LGIF	0.06 ±0.02	0.07 ±0.02	0.12 ±0.03	0.15 ±0.03	0.16 ±0.03	0.13 ±0.03	0.12 ±0.02	0.09 ±0.02	0.07 ±0.03
HGI	0.06 ±0.02	0.07 ±0.02	0.12 ±0.02	0.15 ±0.02	0.16 ±0.03	0.13 ±0.03	0.11 ±0.02	0.08 ±0.01	0.08 ±0.02
Fat oxidation rate ($g \cdot min^{-1}$)									
LGI	0.09 ±0.01	0.09 ±0.01	0.08 ±0.01	0.08 ±0.01	0.08 ±0.01	0.05 ±0.01	0.08 ±0.01	0.09 ±0.01	0.11 ±0.01
LGIF	0.09 ±0.01	0.07 ±0.01	0.07 ±0.01	0.07 ±0.01	0.06 ±0.01	0.07 ±0.01	0.07 ±0.01	0.08 ±0.01	0.09 ±0.01
HGI	0.09 ±0.01	0.08 ±0.01	0.08 ±0.01	0.07 ±0.01	0.07 ±0.01	0.07 ±0.01	0.08 ±0.01	0.08 ±0.01	0.08 ±0.01

	PL (min)				Exercise (min)				Recovery (min)	
	30	60	90	120	15	30	45	60	30	60
CHO oxidation rate ($g \cdot min^{-1}$) [a,b]										
LGI	0.04 ±0.02	0.07 ±0.02	0.09 +0 03	0.12 +0.02	1.17 ±0.08	1.00 ±0.07	0.88 ±0.07	0.83 +0.06	0.05 ±0 02	0 09 ±0 03
LGIF	0.12 ±0.01	0.13 ±0.02	0.17 ±0.04	0.12 ±0.01	1.27 ±0.11	1.17 ±0.12	1.00 +0.1	0.95 ±0 08	0.06 +0.02	0.09 ±0 02
HGI	0.07 ±0.03	0.16 ±0.03	0.15 ±0.03	0.15 ±0.02	1.35 ±0.09	1.25 ±0 08	1.17 ±0.09	1 04 ±0.07	0.05 +0.02	0.04 +0.02
Fat oxidation rate ($g \cdot min^{-1}$) [c,d]										
LGI	0.10 ±0.01	0.10 ±0.01	0.09 ±0.01	0.09 ±0.01	0.30 ±0.04	0.37 ±0.04	0.41 ±0.04	0.43 +0.04	0.11 +0.01	0.09 +0 01
LGIF	0.07 ±0.01	0 07 ±0.01	0.07 ±0.01	0.07 ±0.01	0.27 ±0.04	0.31 ±0.04	0.38 ±0.04	0 39 ±0.05	0.09 ±0.01	0.09 ±0.01
HGI	0.10 ±0.01	0.07 ±0.01	0.07 ±0.01	0.07 ±0.01	0.23 ±0.04	0.28 ±0.03	0.31 ±0.04	0.35 +0.05	0.11 ±0 01	0.11 ±0.01

[a] During PL, CHO oxidation rate was lower in the LGI trial, compared with that in the HGI and LGIF trials ($p<0.05$, two way ANOVA with repeated measures).

[b] During exercise, CHO oxidation rate was higher in the HGI trial than that in the LGI trial ($p<0.01$, two way ANOVA with repeated measures).

[c] During PL, fat oxidation rate was higher in the LGI trial, compared with that in the LGIF trial ($p<0.01$, two way ANOVA with repeated measures).

[d] During exercise, fat oxidation rate had a trend to be higher in the LGI trial, compared with that in the HGI trial ($p=0.077$, two way ANOVA with repeated measures).

CHO: Carbohydrate; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption.

The amounts of CHO and fat oxidized are listed in table 6.6.

TABLE 6.6 CHO and fat oxidation amount during PB, PL, exercise and the recovery periods (n=10, mean ± SEM)

	PB	PL			Exercise	Recovery	Total
		1st hr	2nd hr	total			
CHO oxidation amount (g)							
LGI	21.6±4.7	3.0±1.0	5.4±1.2	8.4±2.1	60.8±4.0	9.2±1.3	100.0±10.3
LGIF	27.1±3.6	6.6±0.8[a]	8.9±1.2	15.6±1.8[a]	68.1±6.0[c]	10.5±0.9	121.2±7.4[a]
HGI	26.7±4.1	5.8±1.4	9.0±1.4[a]	14.8±2.7[a]	74.4±4.7[a]	10.1±1.0	126.0±10.0[a]
Fat oxidation amount (g)							
LGI	19.7±1.9	6.1±0.6	5.3±0.5	11.4±1.0	21.6±2.3	8.5±0.7	61.2±5.4
LGIF	16.8±1.5	4.5±0.4[a]	4.1±0.3	8.6±0.7[a]	19.2±2.3[c]	7.6±0.9	52.1±4.2[a]
HGI	18.4±1.8	5.2±0.6	4.1±0.6	9.4±1.2	16.4±2.2[c]	8.3±0.9	52.5±5.4[c]

[a] $p<0.05$, vs. LGI; [c] $0.05<p<0.1$, vs. LGI.

CHO: Carbohydrate; LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption.

During PB, no difference was found in substrate utilization among the three trials (Table 6.6). During PL, CHO oxidation amounts were lower ($p<0.05$) in the LGI trial than in the LGIF and HGI trials, whereas fat oxidation amounts were observed to be higher ($p<0.05$) in the LGI trial only compared with that in the LGIF trial. No differences were noted in either CHO or fat oxidation amount between the LGIF and HGI trials (Table 6.6). During the first hour of PL, higher CHO oxidation amounts and lower fat oxidation amounts were found in the LGIF trial than in the LGI trial ($p<0.05$). However, during the second hour of PL, higher CHO oxidation amounts

were only found in the HGI trial than in the LGI trial ($p<0.05$).

During exercise, CHO oxidation amount was lower ($p<0.05$) in the LGI trial than in the LGIF and HGI trials, whereas fat oxidation amount only showed a trend to be higher in the LGI trial than in the LGIF and HGI trials ($p=0.094$ and $p=0.067$). No difference was found in either CHO or fat oxidation amounts between the LGIF and HGI trials. In the recovery period, no differences were observed in either CHO or fat oxidation amounts among the three trials.

In total, the amount of CHO oxidized was lower in the LGI trial than in the LGIF ($p<0.01$) and HGI trials ($P<0.05$). Fat oxidation amount was higher in the LGI trial compared with that in the LGIF trial ($P<0.05$), but not in the HGI trial ($p=0.057$).

6.3.7 Energy expenditure during the experiment

No differences were found in calculated energy expenditures during PB, PL, exercise, and recovery period among the three trials (Table 6.7).

TABLE 6.7 Energy expenditures during PB, PL, exercise, and recovery period (kcal, n=10, mean ± SEM)

	PB	PL			Exercise	Recovery	Total
		1st hr	2nd hr	total			
LGI	266±19	67±6	70±4	137±10	432±24	114±7	949±54
LGIF	260±14	67±5	71±4	139±8	436±29	112±7	947±51
HGI	273±15	71±4	73±4	144±7	434±24	116±7	967±47

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption.

6.3.8 HR, RPE, $\dot{V}O_2$, and exercise intensity during exercise

Among the three trials, no differences were found in HR, RPE, and $\dot{V}O_2$ during exercise (Table 6.8). There was also no difference in calculated exercise intensity (LGI vs. LGIF vs. HGI, 50.5%±0.6% vs. 50.6%±1.2% vs. 50.4%±0.9% $\dot{V}O_{2max}$).

TABLE 6.8 HR, RPE, and $\dot{V}O_2$ during exercise (n=10, mean ± SEM)

	15 min	30 min	45 min	60 min	Average
HR (beats·min^{-1})					
LGI	133±4	140±5	143±5	146±5	140±5
LGIF	133±6	139±6	143±7	144±6	140±6
HGI	135±4	141±4	143±5	143±4	140±4
RPE					
LGI	10.0±0.5	12.0±0.6	13.3±0.7	13.6±0.8	12.3±0.6
LGIF	10.8±0.5	12.3±0.7	13.5±0.8	14.0±1.0	12.8±0.7
HGI	11.4±0.6	12.6±0.8	13.0±0.9	13.3±0.9	12.6±0.8
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})					
LGI	24.4±1.0	24.5±0.9	24.4±0.8	24.3±0.8	24.4±0.8
LGIF	24.4±1.2	24.5±1.1	24.6±1.0	24.4±1.0	24.5±1.0
HGI	24.1±0.9	24.4±0.8	24.5±0.7	24.1±0.8	24.3±0.7

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal; HR: Heart rate; RPE: Rating of perceived exertion.

6.3.9 Perceptual variables (RPT and RAD) during the experiment

No differences were observed in RPT and RAD among the three trials during the entire experiment (Table 6.9). During exercise, RPT and RAD were higher ($p<0.05$) than those during PB, PL, and recovery period in all three trials.

TABLE 6.9 RPT and RAD during PB, PL, exercise, and recovery periods

(n=10, mean ± SEM)

	Fasting	PB (min)							
		30	60	90	120	150	180	210	240
RPT									
LGI	2.1±0.3	2.1±0.4	2.6±0.4	1.8±0.4	2.1±0.5	1.9±0.5	1.9±0.4	1.8±0.6	2.3±0.5
LGIF	2.5±0.5	2.0±0.5	2.4±0.6	1.8±0.4	1.9±0.5	1.6±0.4	2.2±0.5	2.0±0.4	1.8±0.5
HGI	2.3±0.4	1.8±0.5	2.2±0.6	1.8±0.3	2.0±0.5	2.0±0.4	1.6±0.4	1.9±0.4	1.7±0.4
RAD									
LGI	0.9±0.3	0.8±0.2	1.0±0.3	0.9±0.3	0.9±0.3	0.9±0.3	0.8±0.2	0.8±0.2	0.8±0.2
LGIF	0.8±0.2	1.0±0.3	0.9±0.2	0.9±0.2	1.0±0.3	0.9±0.2	0.9±0.2	0.9±0.2	1.0±0.3
HGI	0.8±0.2	0.8±0.2	0.8±0.2	0.8±0.2	0.8±0.2	0.8±0.2	0.9±0.3	0.8±0.2	1.0±0.3

	PL (min)				Exercise (min)		Recovery (min)	
	30	60	90	120	30	60	30	60
RPT [a]								
LGI	1.7±0.5	1.6±0.5	1.5±0.5	1.6±0.4	3.5±0.4	4.9±0.6	2.8±0.5	2.2±0.7
LGIF	1.7±0.4	1.8±0.5	1.5±0.4	1.5±0.5	3.9±0.5	5.1±0.6	3.1±0.5	2.2±0.6
HGI	1.6±0.3	1.8±0.4	1.4±0.4	1.7±0.4	4.0±0.5	5.2±0.7	2.3±0.6	2.0±0.5
RAD [a]								
LGI	0.8±0.2	0.8±0.2	0.8±0.2	0.8±0.2	2.8±0.4	3.7±0.6	1.0±0.3	0.9±0.3
LGIF	0.9±0.2	0.9±0.2	0.9±0.3	0.9±0.2	2.7±0.6	3.5±0.8	1.4±0.4	1.0±0.3
HGI	0.8±0.2	0.8±0.2	0.9±0.3	0.9±0.3	2.5±0.6	3.2±0.8	1.5±0.5	1.0±0.4

[a] During exercise, the RPT and RAD were higher than those during PB, PL, and the recovery periods in all three trials ($p<0.05$, two way ANOVA with repeated measures).

LGI: Low-GI meal without fructose; LGIF: Low-GI meal including fructose beverage; HGI: High-GI meal. PB: Postprandial period after breakfast consumption; PL: Postprandial period after lunch consumption. RPT: Rating of perceived thirsty; RAD: Rating of abdominal discomfort.

6.4 Discussion and conclusion

The major finding of the present study was that 4 hrs after a standard breakfast, either a pre-exercise HGI lunch or a pre-exercise LGI lunch including certain amounts of fructose induced more CHO oxidation during 60-min of subsequent brisk walking compared with a pre-exercise LGI lunch without fructose. However, no difference was found in fat oxidation during exercise among the three trials. To our knowledge, this was the first study to prove that both GI and fructose content in pre-exercise lunch would affect substrate utilization during subsequent moderate intensity exercise.

Previous studies indicated that pre-exercise LGI meal consumption induced higher fat oxidation and lower CHO oxidation during subsequent moderate to high intensity exercise than HGI meal consumption (Chen, Wong et al., 2008b; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003). A recent study (Stevenson, Astbury et al., 2009) and a study conducted in our lab (Chapter 5) likewise observed similar changes in substrate utilization during low to moderate intensity exercise. Therefore, GI of pre-exercise meals appeared to be an important influencing factor to affect substrate utilization during subsequent exercise. The mechanism behind this may be the reduced hyperglycemia and hyperinsulinemia during the postprandial period following the LGI meal consumption, which reduced the suppression of fat oxidation. Previous study demonstrated that compared with LGI meals consumption, a rapid increase in blood glucose and insulin concentrations during the postprandial period after HGI meals consumption facilitated the muscle glycogen synthesis and augmented its utilization during subsequent exercise (Wee et al. 2005). In addition, it is well known that insulin could suppress the lipolysis (Campbell et al. 1992).

Furthermore, this suppression appeared to be long lasting, even when insulin concentration had returned to basal levels (Coyle 1991; Montain et al. 1991). Therefore, the higher insulin concentration after HGI meals consumption has been suggested to be more favorable for CHO oxidation and therefore decrease the fat oxidation during subsequent exercise (Wu et al. 2003).

In these previously mentioned studies, however, meals were provided to the subjects after an overnight fast to avoid triggering the so-called "second-meal effect". Few studies were conducted to investigate whether only changing the GI of lunch, typically consumed several hours after breakfast would affect substrate utilization during subsequent exercise, although athletes and ordinary people alike occasionally exercise in the afternoon.

A study (Sparks et al., 1998) investigated the effect of pre-exercise HGI or LGI meal consumed 4-hrs after a standard breakfast on subsequent endurance exercise performance. The exercise protocol consisted of 50-min cycling at 67% $\dot{V}O_{2max}$ and followed by a 15-min self-paced performance ride. Similar to previously mentioned studies (Chen, Wong et al., 2008b; Stevenson et al., 2006; Wee et al., 1999; Wong et al., 2008; Wu & Williams, 2006), LGI lunch produced less hyperglycemia and hyperinsulinemia during the postprandial period, while resulting in less CHO oxidation during subsequent exercise compared with when HGI lunch was consumed. However, in a more recent study (L. J. S. Moore et al., 2010), 10 male trained cyclists were recruited to participate in a 40 km TT cycling. Each subject reported to the laboratory after a 6-hrs of fasting. Two meals of different GI providing 1 $g \cdot kg^{-1}$ body weight CHO were ingested 45-min prior to TT. Similar to previous studies, LGI meals during postprandial period produced less hyperglycemia and

hyperinsulinemia compared with the HGI trial. In this study, however, the LGI meal resulted in greater CHO oxidation than the HGI meal, which was contrary to majority of previous studies. The authors were unable to explain this inconsistency.

In the present study, amounts of CHO oxidized during exercise in the LGI trial were lower than those in the HGI trial. This result was similar with that of a previous study (Sparks et al., 1998) as well as a study conducted in our lab (Chapter 5). The difference in blood glycemic and insulinemic responses during the postprandial period (Figure 6.2, 6.3; Table 6.4) may partly explain this result (Wu et al., 2003). However, no difference was observed in fat oxidation between the two trials, although the amounts of fat oxidized during exercise exhibited a trend to be higher in the LGI trial ($p=0.067$). This result was slightly different from that of our previous study (Chapter 5), in which the amounts of fat oxidized during exercise in the LGI trial were higher than those in the HGI trial as well. This inconsistency may be attributed to the standard breakfast consumed, for this is the only difference between the present study and the previous one (Chapter 5). In the present study the standard breakfast provided and average of 61 g CHO for each subject. However, during the 4-hrs PB, the average CHO oxidation amounts in the two trials were 21.6 g, and 26.7 g, respectively. A portion of the remaining ~39 g and ~34 g of un-oxidized CHO in the two trials may have been stored as muscle and liver glycogen before lunch consumption (Coyle et al., 1985). This may increase CHO availability during PL and subsequent exercise, and decrease the amounts of fat oxidized (Coyle et al., 1997). Therefore, it may be more difficult to detect the differences in fat oxidation during exercise between the two trials. Furthermore, a previous study conducted in our lab (Chen, Wong, Xu et al., 2008) indicated that when large amounts of CHO were consumed, CHO amounts but not the GI may be the most overriding factor on

substrate utilization during the subsequent endurance run.

This speculation could not be verified by the present study as the storage and usage of liver and muscle glycogen were not measured. However, in the previous study (Chapter 5), when the same LGI meal was consumed after an overnight fast, it resulted in both less CHO oxidation and greater fat oxidation than HGI meal consumption. It was widely known that liver glycogen would decrease after an overnight fasting, and CHO re-feeding would increase liver glycogen significantly (Nilsson & Hultman, 1973). It was reasonable to assume that 4-hrs after a standard breakfast, liver glycogen content would be different from that after an overnight fasting. A recent study (Stevenson, Thelwall et al., 2009) indicated that the amount of liver glycogen used during exercise was positively related to pre-exercise liver glycogen content. These results supported the assumption that when a meal was consumed 4-hrs after consumption of a standard breakfast, it would induce more CHO oxidation during subsequent exercise, compared with when the same meal was consumed after an overnight fasting.

Several previous studies reported higher FFA concentrations during exercise, particularly at the first part of exercise, after consumption of a LGI meal than a HGI meal (Wee et al., 2005; Wong et al., 2008). In the present study, however, no difference was found in serum FFA concentrations during exercise between the LGI and HGI trails (Figure 6.5). This result was in agreement with similar fat oxidation during exercise between the two trials. In the previous study (Chapter 5), when the same HGI and LGI meals were consumed after an overnight fast, higher FFA concentration was found at 30 min during exercise after consumption of LGI meal than HGI meal. This inconsistency may be caused by increased CHO availability and

serum insulin concentrations after the standard breakfast, which had a marked suppression effect on lipolysis (P. J. Campbell et al., 1992). Although the serum FFA concentrations returned to the fasting level before lunch consumption (Figure 6.5), the persistent hyper-insulinemic effect on peripheral tissues after breakfast consumption may interact with that after different lunch meals consumption (Coyle, 1991; Montain et al., 1991).

In a previous study (Stevenson, Williams & Nute, 2005), nine active males completed 60-min 70% $\dot{V}O_{2max}$ running after consumption of both breakfast and lunch with different GI. Although lower glycemic and insulinemic responses were found after LGI lunch consumption, no difference was observed in substrate utilization during subsequent exercise conducted in the afternoon. This result was different from previously mentioned studies (Chen, Wong et al., 2008b; Stevenson et al., 2006; Wee et al., 1999; Wong et al., 2008; Wu & Williams, 2006), in which lower glycemic and insulinemic responses after LGI meal consumption induced greater fat oxidation and less CHO oxidation during subsequent exercise. This study was not designed to investigate specifically the effect of different GI lunch consumption on substrate utilization. However, the result of this study indicated that the different breakfast meals consumed 3-hrs before lunch did affect substrate utilization during subsequent exercise to a certain degree. In addition, a previous study demonstrated that adipose tissue lipolysis increased in direct proportion to the length of fasting (Montain et al., 1991), which may affect substrate utilization as well. The results of this study demonstrated that after consuming a CHO meal, at least 6-hrs of fasting was necessary to induce similar substrate utilization and plasma glucose homeostasis during 70% $\dot{V}O_{2max}$ exercise as 8-12 hrs of fasting.

Therefore, fat oxidation may be different when pre-exercise HGI or LGI meal was consumed after an overnight fast or several hours after a standard breakfast was consumed. The mechanism behind this may be varying CHO availability. It appeared that results from previous studies conducted in the morning could not directly be applied to studies conducted in the afternoon. Additional studies are needed to clarify this effect further, particularly for ordinary people and low to moderate intensity exercise. Moderate intensity exercise is more likely to be adopted by ordinary people; it appears to be most favorable for eliciting a substantial short-term increase in fat oxidation for the general population (Achten & Jeukendrup, 2004; Venables et al., 2005).

As discussed in the previous study (Chapter 5), fructose content may be another important influencing factor in determining substrate utilization during both exercise and postprandial periods. In the present study, the similar responses in blood glucose, serum insulin, FFA, and glycerol concentrations were observed between the LGI and LGIF trials. However, higher CHO oxidation amounts were observed in the LGIF trial than those in the LGI trial, not only during PL but also during exercise. These results were expected and similar results were found in the previous study as well (Chapter 5). Differences in substrate utilization between the LGI and LGIF trials may be explained by greater fructose content in the LGIF trial. Fructose metabolism could bypass the first rate-limiting enzymes of glycolysis in the liver, and thus be expected to be more readily oxidized (Lê & Tappy, 2006). The higher lactate concentrations in the present study (Figure 2B) also proved this metabolic pathway of fructose. Lactate was one important product in fructose metabolism in the liver, and because fructose uptake by the liver was not inhibited, fructose consumption would result in larger increase in circulating lactate than a comparable amount of

glucose consumption (Bjorkman et al. 1989). It has been suggested that fructose-induced hyperlactatemia may contribute to the suppression of adipose lipolysis (Abdel-Sayed et al. 2008). Furthermore, the increased blood lactate during PL also could be metabolized directly in working muscle during subsequent exercise, which also could increase CHO oxidation (Ahlborg and Bjorkman 1990). In addition, fructose consumption could decrease lipolysis and whole-body lipid oxidation (Chong et al., 2007), most likely because of the stimulation of the hepatic de novo lipogenesis and a concomitant inhibition of tissue lipid oxidation.

Similar to the previous study (Chapter 5), although IAUC value of glucose and insulin were higher in the HGI trial than in the LGIF trial, substrate utilization during PL and exercise was similar between the two trials. The interaction of GI and fructose content in these two trials may induce such results (for a detailed discussion, see Chapter 5).

In the present study, no difference in fat oxidation amounts was found during exercise between the LGI and LGIF trials, although there was a trend to be higher in the LGI trial (P=0.094). This result was slightly different with the previous study (Chapter 5). As discussed previously, this may be caused by increased CHO availability after consuming the standard breakfast.

As expected, the physiological responses were similar during PB among the three trials in the present study. After lunch consumption, serum FFA concentrations were suppressed during the whole PL in the LGIF and HGI trials, while those in the LGI trial were suppressed only at 60 min and 120 min during PL (Figure 6.5). Furthermore, lower FFA concentration was observed at 120 min during PL in the HGI trial than that in the LGI trial. The reason may be higher insulin concentrations

during PL in the HGI trial (P. J. Campbell et al., 1992). At the end of exercise, serum FFA and glycerol were elevated in all three trials (Figure 6.5, 6.6). This may be caused by the enhanced catecholamine response when the duration of exercise was extended (Horowitz & Klein, 2000). Fasting serum FFA concentrations were lower in the HGI trial than that in the LGIF trial, which was unexpected. However, after 4 hrs' resting during PB, there were no differences in serum FFA concentrations among the three trials before lunch consumption (Table 2). Therefore, it seemed that this difference in baseline FFA concentrations would not affect substrate utilization during subsequent exercise.

In conclusion, compared with a LGI lunch, either a HGI lunch or the presence of fructose in a LGI lunch induced greater CHO oxidation during subsequent moderate intensity exercise. However, no differences were observed in fat oxidation among the three trials. Consumption of a standard breakfast appeared to reduce the effect of lunch meals with different GI and fructose content on substrate utilization during subsequent moderate intensity exercise to a certain degree.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUSIONS

First introduced in 1981 (Jenkins et al., 1981), GI is regarded as an alternative system for classifying CHO foods. Since then, many studies have been conducted to investigate whether the GI concept could be applied to human health. According to previous studies, LGI diet appeared to contribute to the prevention of some chronic diseases (Brand-Miller, McMillan-Price et al., 2009; Ludwig, 2002). Therefore, in recent years, GI values of many foods in different countries have been measured, and an international GI table has been developed (Atkinson et al., 2008). However, little remains to be known about the GI values of traditional Chinese foods. To date, approximately 50 Chinese foods have been listed in this international GI table, which is only a small fraction of over 2,480 individual food items included. Previous studies indicated that the lack of GI values of traditional Chinese foods has resulted in limitations to related researches (Hui & Nelson, 2006; Sea et al., 2004; Villegas et al., 2007; Woo et al., 2003). Furthermore, this situation prevented the application of GI to human health particularly for Chinese people. Study I of this thesis therefore determined the GI values of 29 popular traditional Chinese foods. Parts of the results of this study were applied to Study II and Study III in this thesis.

In recent years, the GI concept has been widely applied in the area of sport science, particularly for exercise performance (Donaldson et al., 2010; O'Reilly et al., 2010). Several studies indicated that pre-exercise LGI meal consumption induced greater fat oxidation and less CHO oxidation during subsequent moderate to high intensity exercise than HGI meal consumption (Chen, Wong et al., 2008b; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003). However, in majority of previous studies,

endurance-trained subjects and usually higher intensity exercise protocol such as 70% $\dot{V}O_{2max}$ or above were used. This kind of investigation is important for ordinary people as well, particularly those who intend to increase fat oxidation for weight management or health maintenance. Although a few studies were conducted to investigate this effect using untrained subjects and low to moderate intensity exercise, no consistent results were observed (Backhouse et al., 2007; Stevenson, Astbury et al., 2009). Therefore, Study II was designed to clarify this effect further.

Although a number of researchers have mentioned that fructose should not be considered as a typical LGI CHO when discussing fuel metabolism (Diaz et al., 2006), there is a paucity of studies, if any, conducted to investigate specifically the effect of fructose content in pre-exercise meals on substrate utilization during subsequent exercise. Fructose is often used as part of a LGI meal in relevant studies in this research area (Backhouse et al., 2007; Bennard & Doucet, 2006). This may be because more fructose content will make it easier to get a LGI meal and match the macronutrient content between the different GI meals at the same time. However, this may disturb the GI effect as well and render the results of related studies difficult to explain. Therefore, another objective of Study II was to investigate whether fructose content in a LGI meal would affect substrate utilization during subsequent moderate intensity exercise.

In majority of the previously mentioned studies (including Study II in this thesis), meals were provided to the subjects after an overnight fast to avoid the so-called "second-meal effect" (Wolever, Jenkins, Ocana, Rao & Collier, 1988). When different GI meals were consumed after an overnight fast or after only several hours of fasting (e.g., 3-4 hrs after breakfast), their effect on substrate utilization during

subsequent exercise may be different. However, to our knowledge, no studies have been devoted to investigating this specifically, although people occasionally exercise in the afternoon. Therefore, Study III in this thesis was designed to investigate the effect of lunch meals with different GI, consumed after a standard breakfast and 4-hrs of fasting, on substrate utilization during subsequent brisk walking. At the same time, the effect of fructose content in lunch on substrate utilization was investigated as well

GI values of traditional Chinese foods

As showed in Study I (Chapter 4), GI and GL values of 29 traditional Chinese foods were determined using a standard method recommended by the Food and Agriculture Organization (FAO, 1998). The results provided valuable information to both researchers and common individuals in terms of food preference. These would serve as preliminary references for the establishment of a GI database for traditional Chinese foods in the future.

Because of the close relationship between the GI of food and human health, GI labeling on foods has been either proposed or is currently occurring in Australia, South Africa, Sweden, United Kingdom, and Germany, with several commercial laboratories measuring the GI of foods (Wolever, Brand-Miller et al., 2008). In recent years, GI values of certain number of local foods have been measured in different countries prior to their utilization in research and clinical settings among the local population (Aston et al., 2008; Sugiyama et al., 2003; Yang et al., 2006). However, little has been discovered about the GI values of traditional Chinese foods. Therefore, developing a GI database for traditional Chinese foods would benefit not only the researchers in this area, but the general public as well.

It is worth mentioning that parts of the results of this study have been published in peer-reviewed journals (Chen et al., 2010; Sun et al., 2010). Since then, we have received many responses from different countries around the globe, such as Singapore, Australia, Canada, and so on. The interested parties all agreed that the information we provided were very useful for the Chinese Community in the said countries, and clamored for additional information on our research. Furthermore, we received considerable encouragement to pursue our study in this research area to develop the GI database for traditional Chinese foods. We believe that our research could significantly benefit the development of traditional Chinese foods, thus meriting further study on this topic.

Effect of GI of pre-exercise meals on substrate utilization during subsequent moderate intensity exercise

The importance of CHO for exercise has been recognized since 1930s, particularly when biopsy technology was introduced in sport science (Bergström et al., 1967). Since then, numerous studies have been conducted to investigate the effect of CHO consumption on exercise. Several studies found that pre-exercise CHO consumption could improve exercise performance (Gleeson et al., 1986; Kirwan et al., 1998; Neufer et al., 1987; Schabort et al., 1999; Sherman et al., 1989; Sherman et al., 1991). This may be attributed to increased CHO availability before exercise and increased CHO oxidation during exercise (Hargreaves et al., 2004).

In recent years, research interest in this area has been focused on the ideal nutritional strategies to maximize CHO stores, minimize the adverse effect of CHO depletion, and improve exercise performance. Pre-exercise LGI meal consumption offers the possibility of minimizing changes in plasma glucose and insulin concentrations

before exercise. Therefore, many studies have been conducted recently to investigate the effect of different GI food or meal consumption on exercise performance and/or substrate utilization during subsequent exercise. Two recent review articles (Donaldson et al., 2010; O'Reilly et al., 2010) have summarized these studies and suggested that although pre-exercise LGI meal consumption, compared with HGI meal consumption, had a favorable metabolic response and a potential benefit to exercise performance during subsequent exercise, no conclusive issues could be drawn.

However, there appeared to be a number of consistent results when discussing substrate utilization during exercise. Majority of previous studies observed that pre-exercise LGI CHO consumption would induce less CHO and greater fat oxidation during subsequent exercise compared with when HGI CHO was consumed (Chen, Wong et al., 2008b; DeMarco et al., 1999; Febbraio, Keenan et al., 2000; Febbraio & Stewart, 1996; Stevenson et al., 2006; Thomas et al., 1991; Thomas et al., 1994; Wee et al., 1999; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003; Wu & Williams, 2006). It was found that LGI CHO consumption produced less hyperglycemia and hyperinsulinemia during the postprandial period, but maintained sufficient glucose concentrations during subsequent exercise. Reduction in blood insulin concentrations during the postprandial period may decrease the suppression of fat oxidation, and this allowed a shift in substrate utilization toward fat oxidation during the subsequent exercise as well as provided a sustainable source of CHO (Wu et al., 2003). Furthermore, a recent study (Wee et al., 2005) reported that the lower rate of CHO oxidation following a LGI breakfast could simply be explained by a lower rate of muscle glycogen utilization. Better maintained fat oxidation appeared to explain the sparing of muscle glycogen during exercise following the LGI meal.

It must be mentioned that substrate utilization during exercise would be influenced by not only nutrition status (e.g., type, amount and time of CHO ingestion), but nature of exercise (e.g., exercise intensity and exercise duration) and characteristics of the individual (e.g., training level, gender and body composition) as well (Achten & Jeukendrup, 2004; Bennard et al., 2005; Venables et al., 2005). Therefore, the results of previous studies should be cautiously explained. For majority of these mentioned studies, endurance-trained athletes were used as subjects. More importantly, 70% $\dot{V}O_{2max}$ or above was usually used as the exercise intensity.

Shifts in fat oxidation during exercise were important as well for ordinary people, especially those aiming to reduce body fat mass. Although exercising in the fasted state would maximize fat oxidation, from a practical point of view, people generally would be unable to continue exercising in such a situation. Furthermore, in the context of physical activity, a moderate- or high-CHO meal may simply be a more natural choice because it should maintain adequate levels of muscle glycogen for sustained activities. If the differences in substrate utilization during low to moderate intensity exercise after HGI or LGI meal consumption actually existed, then increased fat oxidation may be achieved by simply changing the GI of foods consumed prior to exercise.

Recently, several studies have been conducted to investigate this effect during low to moderate intensity exercise (Backhouse et al., 2007; Bennard & Doucet, 2006; Stevenson, Astbury et al., 2009). One study (Stevenson, Astbury et al., 2009) found very similar results with previous works; higher fat oxidation and less CHO oxidation were observed during 50% $\dot{V}O_{2max}$ brisk walking in the LGI trial than in the HGI trial. The same results were observed as well in Study II in this thesis

(Chapter 5). Because female subjects were used in the previous study (Stevenson, Astbury et al., 2009) and male subjects were used in Study II, it appeared that these findings could be applied to both male and female subjects. The results of Study II proved that GI of pre-exercise meals was an important influencing factor on substrate utilization during subsequent low to moderate intensity exercise.

However, in another similar study using the similar exercise protocol and subjects (Backhouse et al., 2007), no significant effect of GI meals on the amount of fat or CHO oxidized during exercise was noted. In this study, GI values of two meals were 77 and 51, respectively. Therefore, this was more likely to be a comparison between HGI and MGI meals. In fact, two meals produced similar glycemic and insulinemic responses in this study. In another study (Bennard & Doucet, 2006), similar fat and CHO oxidation during exercise was observed between the HGI and LGI trials. In this study, however, no differences in glucose and insulin concentrations were found during the postprandial period, although the GI values of the two breakfast meals were 48.3 and 103.3, respectively. The researcher attributed this inconsistent result to the hourly samples, in which the rapid rise and subsequent return in glucose may have been missed. Therefore, inconsistent results from these studies may partly be explained by the differences in pre-exercise meals.

It is worth mentioning that in the two studies that did not find GI effect on substrate utilization (Backhouse et al., 2007; Bennard & Doucet, 2006), more fructose content were included in the LGI trial because of the inclusion of more fruits, unsweetened apple juice, or fructose beverage. Unfortunately, the researchers did not discuss whether this difference could influence substrate utilization.

In majority of the previously mentioned studies, the meals were provided to the

subjects after an overnight fast to avoid triggering the so-called "second-meal effect". Although athletes or ordinary people occasionally exercise in the afternoon, a few studies were conducted to investigate whether only changing the GI of lunch would affect substrate utilization during subsequent exercise.

A previous study (Sparks et al., 1998) revealed that after a standard breakfast and a 4-hrs of fasting, a LGI lunch consumption produced less CHO oxidation than HGI lunch consumption during subsequent 67% $\dot{V}O_{2max}$ cycling. In a more recent study (L. J. S. Moore et al., 2010), when HGI or LGI meals were consumed after 6-hrs of fasting, more CHO oxidation was found in the LGI trial than in the HGI trial during subsequent 40 km TT cycling. This result was contrary to most previous studies and the researchers were unable to explain this inconsistency. Because of limited studies, conclusive recommendation could not be drawn on the effect of different GI lunch consumption, followed by a standard breakfast and several hours of postprandial period, on substrate utilization during subsequent exercise.

To clarify further this effect, Study III in this thesis was conducted (Chapter 6). The results revealed that when a standard breakfast was consumed, a HGI lunch induced higher glycemic and insulinemic responses compared with a LGI lunch. For substrate utilization during brisk walking, it was observed that the CHO oxidation amount during exercise in the LGI trial were lower than in the HGI trial. However, no difference in fat oxidation amount was observed between the two trials.

This result was slightly different from that in Study II (Chapter 5), in which the amounts of fat oxidized during exercise in the LGI trial were higher than those in the HGI trial. This inconsistency may be attributed to the standard breakfast in Study III. After breakfast was consumed, it could be speculated that certain amounts of CHO

were not oxidized and thus remained in the body, possibly stored as muscle and liver glycogen before the consumption of lunch (Coyle et al., 1985). This increased CHO availability may decrease the amounts of fat oxidized during subsequent exercise (Coyle et al., 1997). Therefore, it may be more difficult to detect the differences in fat oxidation during exercise between the LGI and HGI trials. Furthermore, a previous study conducted in our lab (Chen, Wong, Xu et al., 2008) indicated that when large amounts of CHO were consumed, the CHO amounts but not the GI may be the most overriding factor on substrate utilization during subsequent endurance run. In addition, a previous study demonstrated that adipose tissue lipolysis increased in direct proportion to the length of fasting (Montain et al., 1991). This study also indicated that at least 6-hrs of fasting was necessary to induce similar substrate utilization and plasma glucose homeostasis during 70% $\dot{V}O_{2max}$ exercise as 8-12 hrs of fasting.

Therefore, for substrate utilization, it may be different when pre-exercise HGI or LGI meal was consumed after an overnight fast or fasting for several hours after a standard breakfast. The mechanism behind this may be the varying CHO availability. It appeared that results from previous studies conducted in the morning could not directly be applied to the studies conducted in the afternoon. More studies are needed to clarify this effect further.

In summary, GI of pre-exercise meal was an important influencing factor on substrate utilization during subsequent moderate intensity exercise. After an overnight fast, LGI meal consumption would induce lower CHO oxidation and higher fat oxidation during subsequent moderate intensity exercise than HGI meal. However, when a standard breakfast was consumed, results were slightly different.

LGI lunch consumption would induce less CHO oxidation than HGI lunch, whereas no differences in fat oxidation were observed between the two trials. Consumption of a standard breakfast appeared to reduce the effect of pre-exercise meals with different GI on substrate utilization during subsequent moderate intensity exercise to a certain degree.

Effect of fructose content of pre-exercise meals on substrate utilization during subsequent moderate intensity exercise

Fructose has been advocated for pre-exercise CHO feeding, as it can produce less fluctuation in glycemic and insulinemic responses during the postprandial period and subsequent exercise. This is reasonable as fructose is a well-known LGI CHO. Previous studies suggested that compared with HGI CHO, LGI CHO consumption appeared to be more beneficial for maintaining blood glucose concentrations during subsequent exercise. Although a previous study found improved endurance capacity after fructose beverage consumption than that after sweet placebo consumption (Okano et al., 1988), no obvious benefit was found between the fructose and other type of HGI CHO, such as glucose (Décombaz et al., 1985; Hargreaves et al., 1987; van Zant & Lemon, 1997). Furthermore, large amounts of fructose consumption may cause adverse influence on exercise performance, such as gastrointestinal symptoms (Skoog & Bharucha, 2004). Therefore, based on extant literature, pre-exercise fructose beverage consumption was not recommended to athletes for improving exercise performance.

As discussed earlier, compared with HGI CHO consumption, LGI CHO consumption usually resulted in greater fat oxidation and less CHO oxidation during subsequent exercise. However, no differences were found in substrate utilization

during exercise after fructose or glucose beverage consumption, while the latter was a typical HGI CHO (Décombaz et al., 1985; Fielding et al., 1987; Hargreaves et al., 1987; Hargreaves et al., 1985; Koivisto et al., 1985; Koivisto et al., 1981; Levine et al., 1983; van Zant & Lemon, 1997; Yannick Guezennec et al., 1989). Glucose beverage consumption induced higher glycemic and insulinemic responses than fructose beverages consumption during the postprandial period, which proved the different GI values of these two beverages. Therefore, similar substrate utilization during exercise could not be explained by this difference.

In the previously mentioned studies, fructose beverage typically was used and the trained athletes were recruited as the subject. For ordinary people, meanwhile, this was not a common practice. The dietary sources of fructose usually contain other CHO such as glucose, which can increase fructose absorption in healthy subjects (Truswell et al., 1988). Therefore, when fructose beverage is consumed as part of a meal, its effect on substrate utilization during subsequent exercise may be different. Furthermore, dietary fructose consumption nowadays has increased in conjunction with rising intake of fructose-containing sugars (Marriott et al., 2009; Park & Yetley, 1993; Vos et al., 2008). However, to our knowledge, this effect has not been specially investigated before. Therefore, one purpose of Study II in this thesis was to investigate this effect (Chapter 5).

In Study II (Chapter 5), fructose beverage was used as part of meals (~25% energy source) in the LGIF trial. Energy and macronutrient content were similar between the LGI and LGIF trials. The GI value was similar between them as well, which could be proved by similar glycemic and insulinemic responses during the postprandial period. However, greater CHO oxidation and less fat oxidation during

exercise were found in the LGIF trial than in the LGI trial. Therefore, the difference in substrate utilization may be caused by more fructose content in the LGIF trial. This result could be partly explained by the special metabolism of fructose in the liver. In brief, fructose was more readily oxidized; it could stimulate whole body CHO oxidation and could be converted into fatty acids in the liver. Moreover, it could inhibit hepatic lipid oxidation and whole body fat oxidation to a certain degree (Chong et al., 2007; Lê & Tappy, 2006; Parks et al., 2008; Tappy & Lê, 2010).

In recent years, consumption of dietary fructose has increased in conjunction with the rising intake of fructose-containing sugars (Marriott et al., 2009; Storey et al., 2006). More importantly, these have been suggested to be related to the development of obesity, metabolic syndrome, and diabetes (Bray et al., 2004; Johnson et al., 2009). Furthermore, substantial experimental evidence has been found by studies conducted on animals and human subjects (Johnson et al., 2009; Pagliassotti et al., 1996; Stanhope et al., 2008). Therefore, the effect of fructose content in meals on the metabolic responses of humans is worth investigating further.

Food contents were almost the same between the LGIF and HGI trials, with the exception of beverages. Therefore, the major differences in the two meals were GI and fructose content. Despite obvious different glycemic and insulinemic responses during the postprandial period between the two trials, substrate utilization was similar not only during exercise but during the postprandial period as well. The interaction of GI and fructose content between the two trials could partly explain the results. Compared with HGI meal consumption, LGI meal may increase fat oxidation and decrease CHO oxidation during subsequent brisk walking. However, more fructose content in the LGIF meal induced greater CHO oxidation and less fat

oxidation. Therefore, the results of Study II indicated that fructose content of pre-exercise meal was another important factor influencing substrate utilization during subsequent moderate intensity exercise.

As discussed earlier, a "second-meal effect" appeared to exist when discussing the effect of different GI meal consumption on substrate utilization during subsequent moderate intensity exercise. Study III in this thesis (Chapter 6) likewise investigated whether changing the fructose content of lunch would affect substrate utilization during subsequent brisk walking. The results indicated that although similar glycemic and insulinemic responses during the postprandial period were found between the LGI and LGIF trial, the presence of fructose content in the LGIF lunch increased CHO oxidation during subsequent brisk walking. As discussed previously, this may be attributed to more fructose content in the LGIF trial. However, no difference in the fat oxidation amounts was found between the two trials. This may be attributed to the standard breakfast, which increased CHO availability during the postprandial period and subsequent moderate intensity exercise.

Similarly, obvious differences in glycemic and insulinemic responses were observed during the postprandial period after lunch consumption between the LGIF and HGI trials. However, no differences were found in CHO or fat oxidation amounts during exercise between the two trials. The mechanism behind this may be the interaction of different GI and fructose content between the two trials.

In summary, fructose content of pre-exercise meals could affect substrate utilization during subsequent moderate intensity exercise. When being consumed after an overnight fast, the presence of a certain amount of fructose in LGI meals induced higher CHO oxidation and lower fat oxidation, compared with meals without

fructose. However, when the meals were consumed following a standard breakfast and 4-hrs of fasting, the presence of fructose in meals only induced higher CHO oxidation than meals without fructose. No difference in fat oxidation was found between the two trials. Therefore, consumption of a standard breakfast appeared to reduce the effect of pre-exercise lunch meals with different fructose content consumption on substrate utilization during subsequent moderate intensity exercise.

General conclusions and future studies

According to results of the studies conducted in this thesis, both GI and fructose content of pre-exercise meals would individually affect substrate utilization during subsequent moderate intensity exercise. Furthermore, consumption of a standard breakfast appeared to reduce this influence to a certain degree.

Further studies are needed to clarify the sources of the substrate utilization. For example, what kind of CHO contributes to changes in CHO oxidation during exercise, glucose or glycogen? What kind of sources can explain the differences in fat oxidation among the three trials, FFA or IMTG? Will liver glycogen usage be affected by different GI or different fructose content in pre-exercise meals?

In addition, although pre-exercise LGI meals without fructose consumption appeared to benefit short-term fat oxidation during subsequent moderate intensity exercise, will this effect be produced when consuming LGI meals for a longer time, such as several days? Will interventions combining the LGI meals and moderate intensity exercise maximize fat oxidation and therefore produce greater benefits for body weight management? Studies with effectively designed RCTs are needed to clarify these issues.

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APPENDIX A

Health History Questionnaire

Name (Chinese):_____ (English):_____

Sex: _____ Date of birth: _____

Address: _____

Telephone/Pager/Mobile phone: _____

Occupation: _____

Place of Employment/Institution: _____

Marital Status: Married_____Single_____

Tick Yes or No

Past History (Have you ever had?)	Yes	No
Rheumatic fever/heart murmur	[ ]	[ ]
High blood pressure	[ ]	[ ]
Any heart trouble	[ ]	[ ]
Disease of arteries	[ ]	[ ]
Varicose veins	[ ]	[ ]
Lung disease	[ ]	[ ]
Asthma	[ ]	[ ]
Kidney disease	[ ]	[ ]
Gout	[ ]	[ ]
Diabetes	[ ]	[ ]
Epilepsy	[ ]	[ ]
Thyroid disease	[ ]	[ ]

Family History (Have any of your immediate family or grandparents had?)	Yes	No
Heart attacks,		
who_____ age_____	[ ]	[ ]
High blood pressure	[ ]	[ ]
High cholesterol	[ ]	[ ]
Stroke	[ ]	[ ]
Diabetes	[ ]	[ ]
Congenital heart disease	[ ]	[ ]
Heart operation	[ ]	[ ]
Early death	[ ]	[ ]
Other family illnesses_____		
_____		
_____		

PRESENT SYMPTOMS REVIEW

(Have you recently had?)	Yes	No
Chest pain/discomfort	[ ]	[ ]
Shortness of breath	[ ]	[ ]
Heart palpitations	[ ]	[ ]
Skipped heart beats	[ ]	[ ]
Cough on exertion	[ ]	[ ]
Dizzy spells	[ ]	[ ]
Frequent headaches	[ ]	[ ]
Recurrent sore throat	[ ]	[ ]
Back pain	[ ]	[ ]
Arthritis/ swollen, stiff, painful joints.	[ ]	[ ]
Orthopaedic problems	[ ]	[ ]
Unexplained weight loss(>5 lb.)	[ ]	[ ]
Are you presently taking any medications?	[ ]	[ ]

HOSPITALIZATIONS Yes____ No____

Year Reason

_____

_____

_____

Any other medical problems not already indicated? Yes_____ No_____

_____

_____

_____

LIST ALL CURRENT PRESCRIPTION AND NON-PRESCRIPTION MEICATIONS (include birth control pills):

Medication	Reason for taking	How long?

Do you currently smoke? Yes_____ No_____

If so, what? _____ How much? _____

Have you ever quit smoking? Yes_____ No_____ How many years did you smoke? _____

How much alcoholic beverage do you consume in one week?

What type? Beer_____ cans; Wine_____ glasses; Hard Liquor_____ drinks

How much caffeinated beverage do you consume per day?

What type? Coffee_____ cups; Tea_____ cups; Soft Drinks_____ cans

ACTIVITY LEVEL EVALUATION

Do you engage in regular physical activity? Yes_____ No_____

If so, what type? _____

How many days per week? _____

How much time per day? (Check one) Less than 15 minutes____ 15 to 30 minutes____

30 to 60 minutes____ More than 60 minutes____

Do you ever experience shortness of breath during exercise? Yes____ No____

Do you ever experience chest discomfort during exercise? Yes____ No____

If so, does it go away with rest? Yes____ No____

How would you describe your state of well-being at this time?

Very, very good..... [ ] Poor..... [ ]

Very good..... [ ] Very poor..... [ ]

Good..... [ ] Very, very poor..... [ ]

Neither good nor poor..... [ ]

EMOTIONAL WELL-BEING (Circle the response which most appropriately describes you):

	Never	seldom	sometimes	frequently	constantly
I feel sad or depressed	1	2	3	4	5
I am under considerable stress	1	2	3	4	5
I feel tense and anxious	1	2	3	4	5
I worry about things	1	2	3	4	5
I have an intense desire to achieve	1	2	3	4	5
I am a restless sleeper	1	2	3	4	5
I am worried about my health	1	2	3	4	5
I feel like I cannot cope with daily stress	1	2	3	4	5
I feel like I need to get away	1	2	3	4	5

FOR OFFICE USE ONLY

Date: _____ Interviewer: _____

APPENDIX B

參加者同意書

研究題目：混合餐血糖指數及果糖含量對於快步走運動過程中底物代謝的影響

研究人員：王香生教授 (負責人)　孫風華先生(研究助理)

- 茲証明本人 _____(HKID : _____) 自願參加由香港中文大學核准上列的一項由王香生教授主持的研究。
- 本人完全明白王香生教授對此研究所作的詳細解釋，並曾詳細閱讀「研究說明與解釋」的內容，本人也有機會發問而且獲得滿意的答覆。
- 本人明白在實驗過程中將會提供血液樣本(60 ml)作化驗研究之用。
- 此項研究的過程，危險性和不適感已與本人詳細討論。
- 本人明白任何與本人有關的資料和數據，只作實驗研究之用，絕對保密。
- 本人明白若由此研究引致的一切身體損傷都不會獲得金錢上的賠償或免費醫療服務。
- 就本人所知和相信，本人並無任何身體上或精神上的疾病和障礙，可導致增加本人參加此項研究的危險性。
- 本人明白可隨時作出提問及取消此同意書並終止參與此研究。

出生日期	參加者簽署	日期
_____	_____	_____

研究者簽署	日期
_____	_____

本人已充份向上述參加者解釋此項研究。

當參加者在聽取此項研究的詳細解釋時，本人在場並儘本人所知和相信，參加者已完全明瞭。

見證人姓名	見證人簽署	日期
_____	_____	_____

APPENDIX C

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ **days per week**

   ☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ **hours per day**

   _____ **minutes per day**

   ☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ **days per week**

   ☐ No moderate physical activities → ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you might do solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking → ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the last 7 days, how much time did you spend sitting on a week day?

_____ **hours per day**

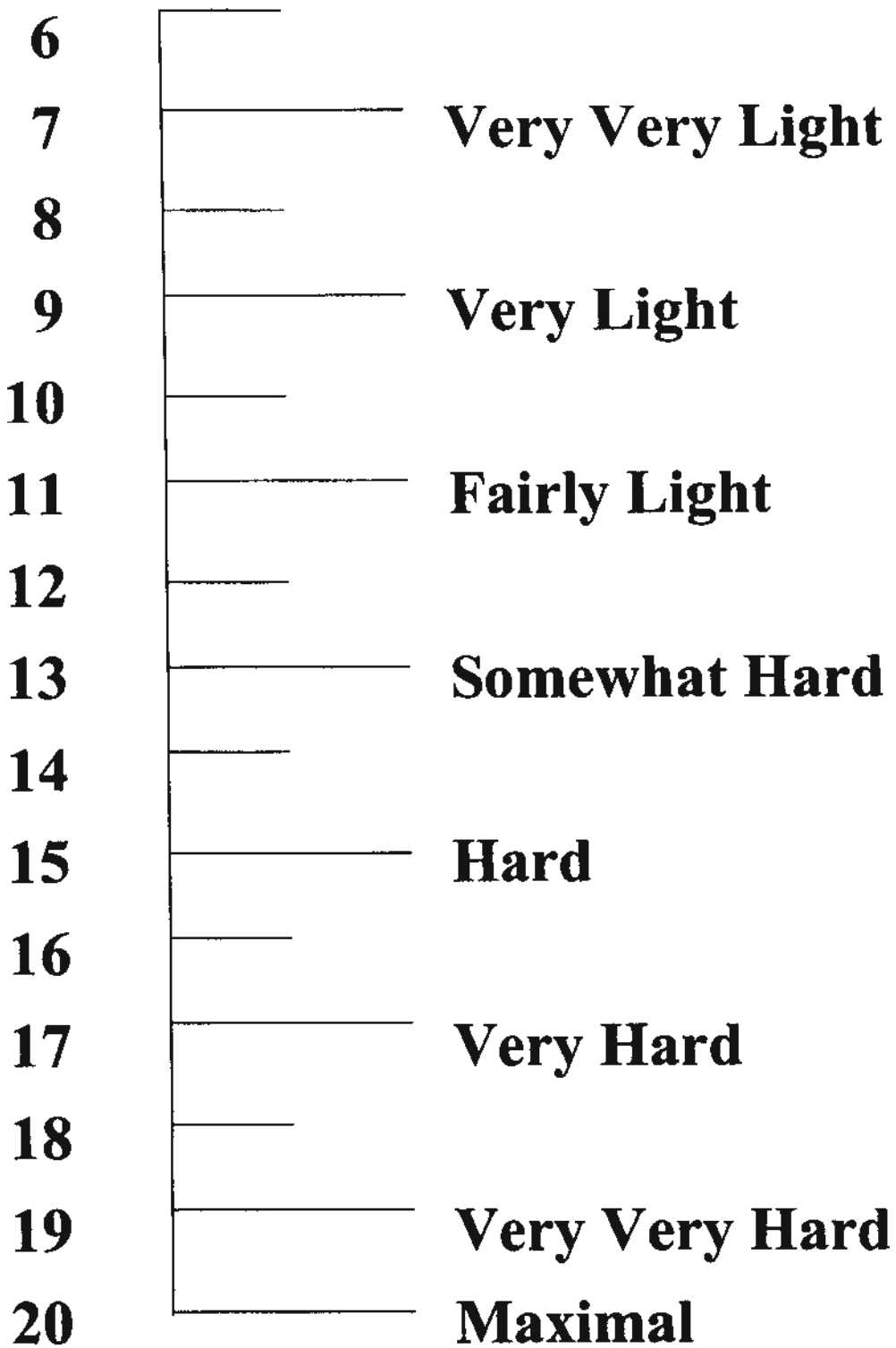
_____ **minutes per day**

☐ Don't know/Not sure

This is the end of the questionnaire, thank you for participating.

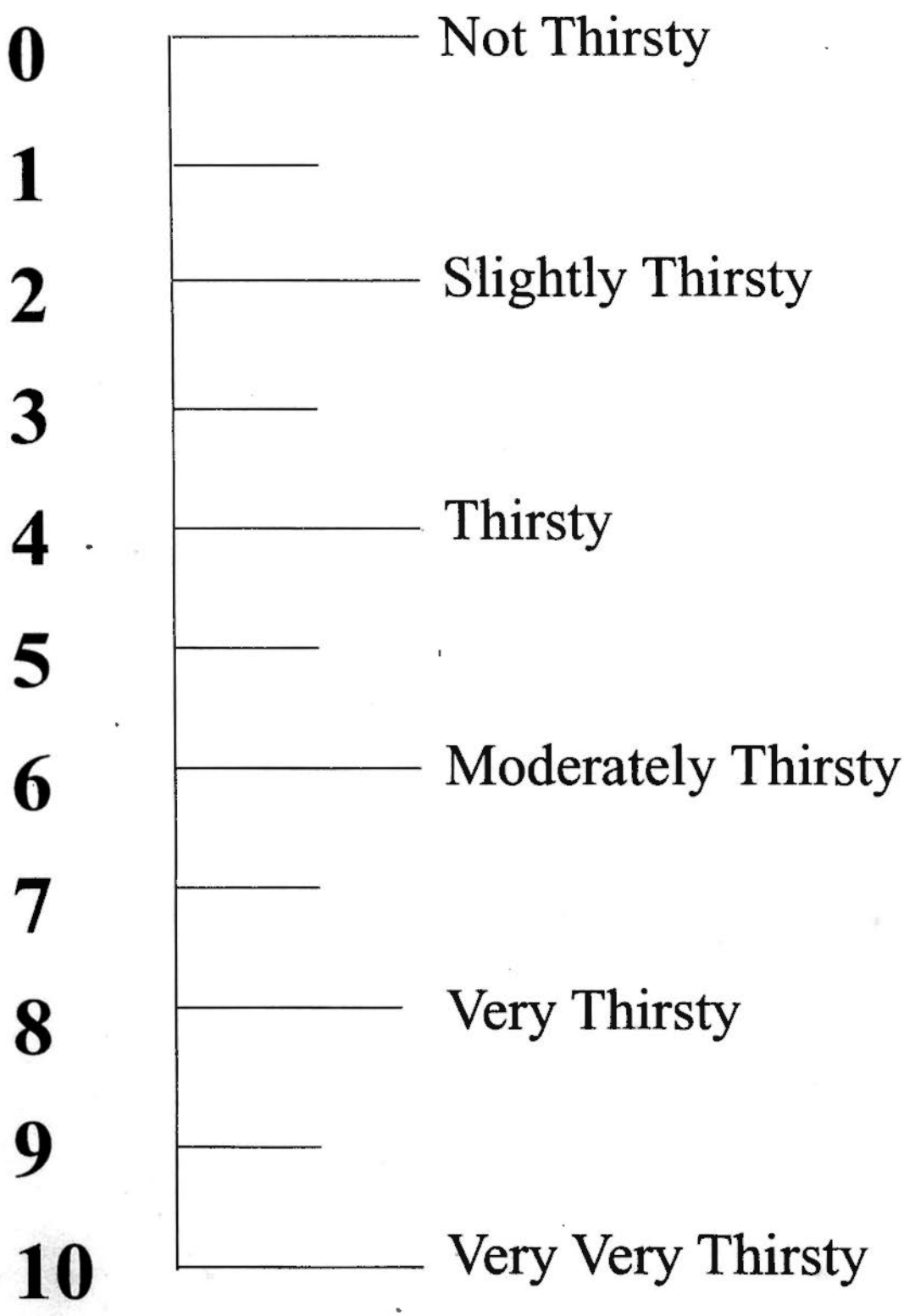
APPENDIX D

Ratings of Perceived Exertion Scale



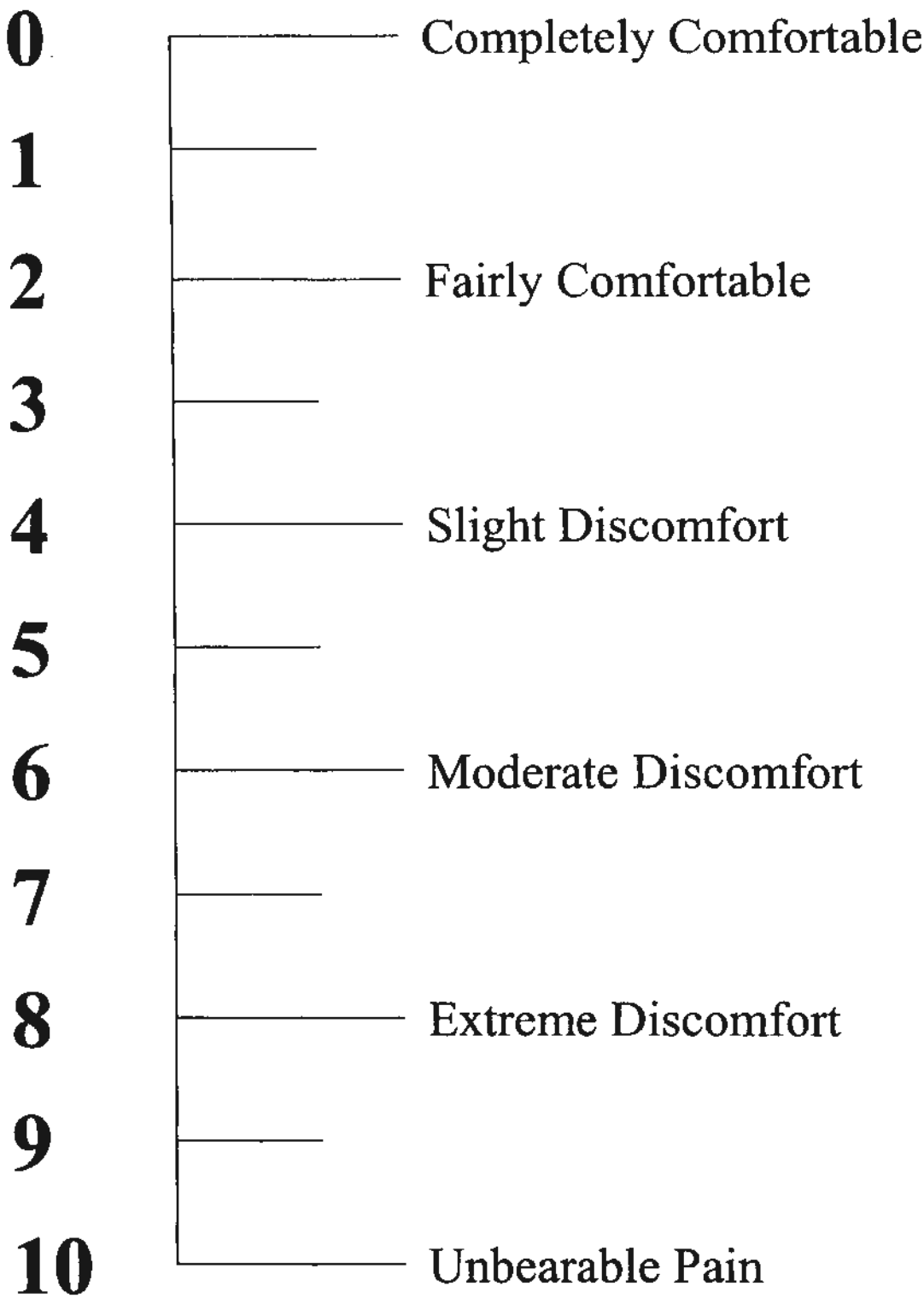
APPENDIX E

Perceived Thirst Scale



APPENDIX F

Abdominal Discomfort Scale



APPENDIX G

The form for food record diary

Name:_____	Date:_____(D/M/Y)	Day Order :_____

Please use a separate line for each item eaten: write in weight of plate: leave a line between different 'plate' entries.

A	B		C	D	E	F	For Official Use	
Time	Food eaten		Food items	Full description (Brand name; Cooking methods; Fresh, frozen, dried, or canned; etc.)	Weight of food (gms)	Weight of leftover (gms)	Actual Weight (gms)	Food Code
am/pm	home	away						

GENERAL COMMENTS ON DIET AND EXERCISE RECORD:

APPENDIX H

INSTRUCTION FOR USING THE FOOD DIARY

- Everything that you have eaten and drunk over the three days before each main trial should be weighed and the weight and type of food or drink should be recorded.
- For solid foods, the food should be placed on the scale on a plate or container. The plate or container must be weighed empty first and the scales can then be zeroed. Each item of food can then be added to the plate and weighed individually, returning the scales to zero between each item.
  e.g. Plate 150g, zero scale, then place roast beef and weigh.
  Zero the scale before weighing another item.
- For drinks, a cup or glass must first be weighed and then the scale can be returned to zero and the drink added. Please remember to record separately the weight of tea, milk and sugar put into a drink or record milk and sugar in number of teaspoons.
- Do not forget to weigh and record second helpings and between meal snacks, supplements and drinks taken during training.
- Any leftovers (e.g. apple cores) should also be weighed and recorded in the leftovers column.
- Eating Out --- Most people eat foods away from home; please do not forget to record these. Take your dairy and scales with you wherever it is possible. If this is too inconvenient just record the type of food eaten with an estimated weight --- but please indicate where a weight has been estimated.
- Most snack foods and packaged foods will have the weight of the food on the packet so they do not need weighing if you eat the whole packet yourself, like milk, chocolate bars, soft drinks etc.
- Names and descriptions of foods should be as detailed as possible, including the brand name and any other information available, like low fat, sugar free, fat free.
  e.g. Cheese-is insufficient information
  Kraft Cheese, cheddar (Shape reduced fat) - is sufficient information.
- Start a new page in your diary for each day, and record each item on a separate line. Record the time of day in the first column of each line.
  e.g. 10:30 am Mcvities Biscuits (2) 50g
- The space provided at the foot of each page is used for writing general comments and further information of your diet and your training/activity for that day.
  e.g. Steady run, morning 1 hr, 10km/hr
  Miss lunch due to stomach pains.

Please try to be as accurate as possible and try to have similar diet before each main trial.