VIRTUAL INTEROCCLUSAL REGISTRATION USING INTRA-ORAL SCANNING

by

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Abstract

Purpose: The aims of this study were to assess if virtual interocclusal records taken at different locations on the arch have an effect on the alignment of the virtual casts, and to assess whether quadrant scans and full arch scans have an effect on the alignment of the virtual casts when articulated using virtual interocclusal records.

Materials and Methods: Three sites of close proximity (SCP) and three sites of clearance were identified in each sextant on mounted zirconia master models. SCP and SC were confirmed using shimstock foil and transillumination of an interocclusal impression. Full arch and quadrant scans of the master models were taken using an intra-oral scanner and different virtual interocclusal record were taken. SCP and SC on each virtual alignment produced by the intra-oral scanner were compared to each other, and to an independent software. Sensitivity, specificity, and predictive values were utilized for the comparison

Results: A change in the location of the SCP was found depending on the location of the virtual interocclusal record. The intra-oral scanner software displayed contacts showed higher sensitivity and negative predictive value (92.86% and 84.21% respectively) when compared to the contacts displayed on the independent software (69.05% and 70.45% respectively). However, the intra-oral scanner software had lower specificity and PPV (41.03% and 62.90% respectively) compared to the independent software (79.49% and 78.38% respectively). Quadrant scans showed higher sensitivity when compared to full arch scans.

Conclusion: There is a significant difference in occlusal contacts obtained from bite scans of different segments. This difference is more obvious in full arch scans, in which a “tilting effect” towards the site of the bite scan can be observed. Occlusal contacts obtained from bite scans taken for quadrant virtual arches exhibited higher sensitivity when compared to those obtained from bite scans taken for full virtual arches.

Lay Summary

Digital dentistry and the use of intra-oral scanners is becoming increasingly common as technological advancements are made and introduced in the dental profession. This project aimed to assess how virtual interocclusal records (bite scans) would influence the alignment of full arch and quadrant scans taken using an intra-oral scanner.

Preface

This research project was conducted under the direct supervision of Dr. Chris Wyatt. The research committee members included Drs. Chris Wyatt, Alan Hannam, and David Tobias.

Aurum Ceramic Dental Laboratories (17 Ave SW, Calgary, Alberta) fabricated the standardized zirconia master model by digital design, 5-axis milling and finishing. They also assisted in converting the scan files obtained from the Omnicam Scanners into Standard Tessellation Language files. Aurum Ceramic Dental Laboratories (1928 Oak Bay Ave, Vancouver, British Columbia) assisted in the mounting of the zirconia models onto a semi-adjustable articulator. Patterson Dental (6651 Fraserwood Pl, Richmond, British Columbia) provided access to the CEREC® Omnicam intra-oral scanner. Dr. Saraa Abdulatif contributed to the review of the literature due to her involvement in clinical research centered on this topic. All data collection and measurements were done by Dr. Faraj Edher independently.

Human or animal subjects and bio-hazardous materials were not used in this study; therefore, ethical approval from the UBC Ethics Board was not required.

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List of Abbreviations

CEREC®	Chairside Economical Restoration of Esthetic Ceramics
MIP	Maximum Intercuspal Position
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
STL	Standard Tessellation Language
SCP	Sites of Close Proximity
SC	Sites of Clearance

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Dedication

To my parents, Amal Hab-Rumman and Dr. Mohammad Edher. Your everlasting support and care never cease to push me forward. I am everything that I am because of your sacrifices. Thank you.

To my brothers, Hamza and Ziyad Edher. You have always been and always will be a constant source of encouragement. Thank you.

To my mentor, Dr. Richard Simonsen. The impact you have had on my life has made me a better professional, and more importantly, a better human being. Thank you.

Chapter 1: Introduction

1.1 Occlusal Indicators

It is of crucial importance not only to examine the occlusion, but also to record, store, and transfer the information in a predictable way in order to analyze and restore the dentition.[1] Occlusal contacts are defined as contacts made between opposing teeth, and occlusal indicators are used to identify them.[2, 3] Identification of occlusal contacts is the first step in understanding how mastication forces are dispersed, how the jaw functions, and the effects occlusion has on biological tissues, and dental materials used in oral reconstructions.[4] In addition, occlusal indicators are used to locate interferences and modify occlusal contacts during prosthodontic treatment. Therefore, invasive clinical decisions are often made based on, or partially influenced by, the results of occlusal indicators.

Occlusal indicators can generally be classified into two categories based on their measurement capacity: qualitative and quantitative indicators. Articulating papers, silks, waxes, putties, plastic strips, shimstock foil, and elastomeric impression materials are examples of qualitative occlusal indicators, which are used to determine the number and location of tooth contacts. Quantitative indicators can also measure the timing and/or force characteristics of tooth contacts. Electro-optic and resistive techniques, such as Photocclusion systems, Dental Prescale systems, and T-Scan (Tekscan, South Boston, MA, USA), are the most common examples of quantitative indicators.[1, 4, 5] Recently, occlusal contacts have been identified virtually by the digitization of casts, interocclusal records, and intra-oral scans.[4, 6, 7]

Qualitative indicators vary greatly in their marking and handling characteristics.[8] The marks made are not only dependent on the tooth to tooth contacts, but are also affected by the thickness of the material, the type of the dyes, the presence or absence of moisture, the number of applications, hardness, tooth cusp characteristics, and the properties of the material itself.[9] They have been found to lack specificity and sensitivity, and show variations in markings amongst different systems or even within the same system at different time intervals. These factors may explain the significant variations seen in the size and number of markings, and the incidence of false positive markings.[9, 10] Therefore, these indicators require interpretation by the clinician, in addition to feedback from the patient.[11]

Quantitative indicators on the other hand, provide quantitative information relative to load, balance of the right and left side, and timing of contacts.[10] It has been reported that they have poor accuracy and sensitivity in their registration elements.[11] The limitations of quantitative indicators are that their sensors could interfere with or even alter occlusion and, because the results are two dimensional, the contacts are not directly related to the three-dimensional occlusal anatomy.[4]

Ideally, any occlusal indicator should be: a) accurate and reliable, by marking only the designated contacts; b) sensitive to changes in occlusion characteristics; and c) thin enough to not change the occlusion parameters or tooth contacts measured.[3, 5]

1.1.1 Articulating Ribbon:

Occlusal contact identified using articulating ribbon is qualitatively defined by its shape, size and position. However, different indicators give a variety of markings of the same contact. Even when the same indicator is used, variations are also often present. Therefore, clinical judgment will certainly depend on the choice of an occlusal indicator.[3] Occlusal marking materials vary in thickness, strength, type of ink, and backing material, all of which can lead to differences in occlusal contact marking. The sizes of contact areas differ according to the thickness of the paper; however, even papers of same thicknesses with different ink colors give marking of varying patterns and surface areas. The occlusal articulating ribbons may contain waxes, oils, pigments and solvents as marking ingredients, in addition to compounds to soften, harden or wet the surface and to release the pigment, all of which play a role on marking occlusal contacts.[3, 12]

There is an ongoing misperception that large, dark marks indicate heavy occlusal contacts, while small, light marks indicate lighter occlusal contact. It is also believed that observing many similar sized marks on adjacent teeth indicate equally distributed occlusal contact.[13] There are no published studies suggesting that articulating paper can measure occlusal loads. On the contrary, research has shown that the size of a paper mark does not represent occlusal forces. It has been shown that a mark of a given size could represent a range of loads; hence similar sized marks on adjacent teeth do not represent equal loads.[14, 15] Therefore, a clinician cannot determine the locations of excessive force for occlusal adjustment based on only the visual analysis of the markings. When comparing indicator markings made at different time intervals, it was found that 50% of the marking were not reproducible.

The methods and techniques of application also have an effect on the markings made; it was shown that dental students produced different marking compared to those made by experienced clinicians. Also, using the same piece of occlusal marking or film has shown to result in fewer markings, therefore, it is recommended that each indicator be used once or twice and then replaced. Not only that, but differences in the patients' positions result in different occlusal contact. Therefore, if occlusal modifications are being done with the patient in supine position, it is important to also have the occlusal contacts checked with the patient in an upright position.[10, 11, 16, 17]

In addition to previously mentioned points, disadvantages of using articulating ribbon are: the oral environment influences the observed occlusal markings, so fewer marks are seen in the presence of moisture, while more marks are seen if the teeth are mobile. Highly smooth surfaces reduce the number of marks and make it harder to detect areas that need adjustment. There is also no direct way to quantify or store marking for future comparisons. The advantages of using articulating ribbon are: the ease of applicability and immediate visual display; the ability to record and differentiate between static and dynamic contacts; and the minimum resistance to closing forces. [3, 17]

Variation exists because opposing cusps may be round, flat or sharp. Forces on the indicator are an outcome of the force of closure, in addition to the shape of the opposing cusps. This results in an eruption of the small ink capsules that make up the colorants on the film. Articulating film is thin and smooth, and so does not engage the numerous irregularities in an occlusal contact. Articulating paper on the other hand is thick and coarse, creating resistance and friction on occlusal contact.[3] An in-vitro study showed that using thin plastic backings resulted in less false positive markings than paper based materials due to the adaptation of the material to the occlusal surfaces during loading.[9] When comparing Accufilm (25 µm) with articulating paper (60 µm), Saad et al[10] concluded that both systems lack the ability to reliably identify contact areas and generally do not give an accurate outline of the tooth contact. Other studies have found that the film thickness affected the size of the markings, and that the thinner film materials produced the most reliable results.[12, 18]

These variations have significant clinical impact, and it is crucial that the clinician uses cautious judgment when correcting or modifying occlusal contacts, keeping in mind the unreliability and numerous drawbacks of articulating paper, before making any irreversible changes to the dentition.

1.1.2 Shimstock Foil:

Patients are able to detect occlusal discrepancies as low as 8 µm to 10 µm.[19, 20] Articulating ribbons are thicker than the limit of occlusal tactile sensibility for natural teeth, and therefore may mark near contacts in addition to actual contacts. Shimstock is thinner than most articulating ribbons and can range from 2 µm to 13 µm[12, 21]. When the patient is occluding on the shimstock foil, the clinician pulls the strip out, and a comparative assessment is made with regards to the degree of resistance found between the occlusal surfaces around the arch. Subjective judgments of contacts are made as heavy, medium, or light contacts. This however does not give any information about the number, location, size, or force of the contacts.[21]

Assessments made with shimstock must also be interpreted carefully, and the clinician must be aware of this tool's limitations. The removal forces detected when using shimstock increase as the patient bites down with increased occlusal forces. The removal force was found to be highest with gaps between 0 µm to 4 µm. In addition, there are limitations in differentiating between different sized gaps. 8 µm shimstock could not differentiate between gaps less than 4 µm, and gaps of 8 µm may still be recorded as light contact. It is important to note that these results are from in vitro studies, and do not take into account physiologic tooth mobility and mandibular flexure.[21]

Shimstock foil, in conjunction with articulating strips, paper or silk, are the most commonly used indicators for identifying occlusal contacts clinically, due to their complementary properties.[21] Articulating ribbon visually marks the contacts, but has a tendency to produce false-positive results[12], and so clinicians more confidently rule out false-negatives when shimstock is used to confirm a contact.[22] That being said, both articulating ribbon and shimstock are considered to be subjective measures of occlusal contacts.[4]

1.1.3 Silicone Interocclusal Recording Materials and Transillumination:

The stability and accuracy of certain impression materials, such as addition silicones, allows their use to record contacts. In addition, their low viscosity allows adequate flow properties and uniform distribution of the material over the occlusal surfaces, with minimum interference during closure.[3, 4] Given these properties, some researchers claim that addition silicones are ideal materials for identifying occlusal contacts, although contacts determined by the silicone interocclusal records differ from those marked using occlusal indicator papers.[4, 8]

Transillumination can be used to quantify the contacts represented on a silicone interocclusal record by converting the transparency of the record to digital data. This is possible by comparing the relative thicknesses of an imaged interocclusal record to imaged calibration units of known thicknesses, usually made of the same material.[4] Owens et al[23] considered areas of contact with a thickness at or below 50 μm as actual contacts, and near contacts as those with a thickness greater than 50 μm but less than 350 μm. The results depend on the angle of the record to the light source, and they are two-dimensional, and so should be interpreted with caution.[4] The advantages of this technique however, are that the clinician can easily distinguish locations of tooth contacts, and that the occlusal condition is saved as digital data.[24] Occlusal contacts change with different tooth clenching intensities[25, 26], so patients should be given appropriate verbal instructions to bite down with the adequate clenching force needed to register the correct occlusal contacts.[27]

Silicone interocclusal records have proven to be a reliable method for determining occlusal contacts when compared to other occlusal indicators.[28-31] Therefore, this method may serve as a "gold standard" against which other methods could be tested.[32]

1.1.4 T-Scan:

The T-Scan (Tekscan, South Boston, MA, USA) was first introduced as a prototype computerized occlusal analysis tool.[22] It utilizes a plastic coated U-shaped sensor, which incorporates conductive ink that develops increased resistance when loads are applied. The sensor is 60 µm thick and contains 1500 receptors[10], which are used to digitally record both the location and timing of tooth contacts[1]. Data analysis is displayed in colors that represent different occlusal pressures, in 0.003-second increments describing the sequence and timing of occlusal contact.[13]

There is conflicting literature when it comes to the efficacy of the T-Scan, where some research suggests that the tool helps in occlusal examinations and precise time-based analysis of the occlusion.[22, 33] Other authors have reported poor accuracy and low sensitivity, stating that it may not be a valid method for accurately measuring tooth contacts that are present when the patient occludes naturally, due to the thickness of the plastic sensor.[5, 11] Some studies have shown that the T-Scan is not as accurate as articulating ribbon in detecting occlusal contact[34], while others have concluded that it was the most reliable indicator of interceptive contacts, especially if the contacts were simultaneous and numerous[22].

1.1.5 Photocclusion:

Occlusal contacts have also been recorded and analyzed using the “photocclusion technique”. The patient occludes on a photo-elastic sheet (wafer), and analyses of the strains induced are used to record the position of occlusal contacts. After the wafer is projected under polarizing light, the areas representing occlusal contacts are traced so that quantitative and qualitative analyses can be performed. It is suggested that the firm plastic sheet may alter the proprioception that directs the mandible during closure. This method was found to be not reproducible, and enhanced posterior contacts while diminishing anterior contacts. [1, 17]

1.1.6 Occlusal Sketch:

The “occlusal sketch” technique was described by Davies et al[35] as a way of recording occlusal contacts. A diagram representation of the teeth is drawn on an acetate sheet, including the occlusal aspect of the posterior teeth, the palatal aspect of the maxillary anterior teeth, and the labial aspect of the mandibular anterior teeth. The location of the marked occlusal contacts is identified using articulating ribbon, and then recorded and conveyed on the diagram. Dental technicians can also utilize this technique to confirm occlusal contacts when articulating casts and constructing restorations. The authors found that clinicians were able to consistently record static and dynamic occlusal contacts using an occlusal sketch with a high degree of reliability and reproducibility.[1] This technique however, depends on recording markings made using articulating ribbon, and studies have shown that articulating ribbon does not give reproducible markings.[10]

1.1.7 Cone Beam Computed Tomography:

Machado et al[36] evaluated the ability to identify occlusal prematurity by the analysis of paraxial CBCT slices, and concluded that this method did not show any superiority to clinical analysis by markings. In addition to that, exposing patients to radiation for occlusal analyses might not be justified in most scenarios, which makes this method impractical.

1.1.8 Prescale Film:

Fuji (Minato, Tokyo, Japan) Prescale Film consists of pads of ink encapsulated by pressure sensitive membranes. The membranes burst and release the ink, marking the film, when occlusal contact is made. The film, which is thinner than the T-Scan sensor, can be scanned and compared with the dental arch to assess the contact size and positions.[31] This system is limited, due to the thickness of the sensor used.[26]

1.2 Digital Dentistry

With the rapid advancements in digital dentistry and CAD/CAM technology, virtual images of dental arches are being used more frequently.[37] Prior to discussing virtual occlusal indicators, the accuracy and application of intra-oral scanners to produce these records will be reviewed.

1.2.1 Intra-Oral Scanners

The evolution of electronic and digital technology has altered many dental procedures. Working in a virtual setting improves diagnosis and treatment planning, in addition to reducing the required time for treatment.[38] Computer-aided design and computer-aided manufacturing (CAD/CAM) have been utilized in the fabrication of prostheses since the 1980s.[39] Moreover, restorations fabricated from intraoral digital impressions have shown significant advantages over those fabricated from conventional impressions in many aspects.[40, 41]

In general, the CAD/CAM systems consist of three essential phases: an acquisition component which captures the site of interest (tooth preparation or implant) and its surroundings; a processing software that designs a virtual prosthesis and determines all the milling factors; and a milling unit that fabricates the restoration utilizing solid blocks of the selected restorative material. The accuracy of the three phases all together is crucial for the success of the system.[42]

Currently, the CAD/CAM systems can be categorized into two groups according to their ability to share files; open and closed CAD/CAM systems. The closed systems offer all the integrated steps exclusively, with no interchangeability with other systems. In such cases, the practitioner relies on one manufacturer for all the software updates. On the other hand, open systems provide the freedom of choosing between different CAD and CAM combinations.[42]

As mentioned, the accuracy and precision of each CAD/CAM system is associated with the precision of all of its three phases including the accuracy of the data acquisition, the system's software, and the milling method utilized. Hence, the quality of the final restorations is as good as the accuracy of the master models from which they are fabricated. Capturing the margins and the tooth surface apical to the crown margin are essential factors for achieving an acceptable final impression. Data acquisition for prosthetic reconstructions can differ according to the CAD systems utilized, which may in turn affect the quality of the final outcomes. Images can either be captured directly or indirectly. In the indirect system, either the stone model or the impression are digitized using an extra-oral scanner, whereas direct systems use images captured directly with an intra-oral scanner. [43]

Numerous CAD/CAM systems are now being used to design and fabricate dental restorations indirectly.[44] While the accuracy of the extra-oral scanning process is acceptable, the possibility of including errors is significant due to the deformation of impression and stone materials. Intra-oral scanning can reduce such errors. Furthermore, it saves the time and costs required for taking conventional impressions and making the stone models.

There is remarkable progress being made in the field of intra-oral scanners, with a significant number of restorations now made utilizing this technology.[42]

1.2.1.1 Advantages of Intra-oral Scanning Systems [45]

- Early assessment of the digital impression can be performed during or immediately after the scanning process.
- Ease and speed in repeating scans.
- Inaccurate image details within the master image can be digitally cut and the flawed area rescanned.
- Does not require disinfecting the impression.
- Detailed evaluation of the tooth preparation parameters, such as occlusal clearance, amount of reduction, and restoration design are possible at the time of the scan.
- No damage or wear to the model while fabricating and trying the restoration.
- Ease of communication with other dentists and lab technicians.
- Simple and efficient storage and retrievability of data.
- Negates cost of impression material.
- Reduces the time for clinical treatment and laboratory fabrication of indirect restorations.

- Allows for simple comparison of previous virtual casts during follow-up appointments.
- Allows fusion with other digital diagnostic records such as CBCT scans and facial scans.
- True color models of hard and soft tissue are possible enabling the assessment of color changes and shade selection.

1.2.1.2 Disadvantages of intraoral Scanning Systems [45]

- Technique sensitive.
- Stitching of multiple scans is often required.
- High initial cost.
- Some systems require additional steps such as powder application to the teeth.
- Intra-oral scanning heads are large, which makes it difficult to access posterior teeth.

1.2.1.3 CEREC®

One of the first intra-oral scanning and CAD/CAM systems brought to market was the CEREC® I.[46] This system was designed to work with the triangulation of light, in which three linear light beams intersect on a specific point in three dimensional space.[39] Accuracy of the scan was affected if certain surfaces had uneven light dispersion. For this reason, spraying an opaque powder coating of titanium dioxide was necessary to overcome this by providing even light dispersion.[47]

The CEREC® Bluecam system was the 4th generation of intra-oral scanners introduced in 2009. Images were captured by visible blue light released from an LED blue diode light source, utilizing single image acquisition. CEREC® AC Omnicam was introduced in 2012, using continuous image (video) capturing where sequential data acquisition produced a 3D model.

While the Bluecam is usually used for single tooth restoration or quadrant scans; the Omnicam can be utilized for single tooth restorations, quadrant, or even full arch scans to produce accurate 3D images with natural colors. The Omnicam has a powder free scanning process which is beneficial when scanning larger areas in the moist environment of the mouth.[48]

Clinically, the operator positions the scanner intraorally and directs the camera towards the working area. The camera head must be a few millimeters away from the tooth surface or slightly touching it. The operator then slides the scanner head over the teeth in a single direction gently, constructing the 3D model from the successively captured data. The scanning process can be stopped and continued at any time by the operator. A more recent feature called shake detection can confirm that images are only captured when the scanner is being moved in a steady motion.[42]

Once scanning is complete, the virtual cast can be viewed and manipulated on the monitor, a virtual die is defined, and the finish line is identified. The software then recommends an ideal design for the restoration and allows the operator to modify it utilizing the software's tools. Once the restoration design is approved, the dentist chooses the appropriate block of ceramic or composite resin material of the desired color and mounts it in the milling machine to fabricate the restoration. Throughout the design phase, color-coded instruments determine the thickness of the restorative material, the interproximal contacts, and occlusal contacts. Occlusal contacts are based on the articulation achieved using a virtual interocclusal record [49].

The dentist can either scan the preparation intra-orally and mill the restoration chairside in a single visit, or send the scan to the dental laboratory via CEREC® Connect® to design and fabricate the restoration[48]. The CEREC® intraoral scanner is indicated for single full coverage restorations, veneers, inlays, onlays, and implant-supported fixed dental prostheses, where the implant abutment or attached scan body can be scanned[42,50].

CEREC® is a closed system in which the digital data is exported as a proprietary format file that is only compatible with Sirona-supported milling units like CEREC MC and CEREC In-Lab. CEREC MC is a chairside milling machine which allows for single-visit restorations to be fabricated. In the past, CEREC MC did not allow milling fixed dental prostheses using high-strength ceramic blocks, so those restorations had to be fabricated through CEREC In-Lab. With recent CEREC MC X and CEREC MC XL in combination with CEREC® AC Omnicam offer a broader range of restorative solutions including fixed dental prostheses and zirconia restorations.[47]

1.2.2 Accuracy of Intraoral Scanning Systems

1.2.2.1 Quadrant and full arch scans

Ender et al.[51] compared the precision of quadrant digital and conventional impression techniques. Eight intraoral scanning systems (Lava True Definition, Lava Chairside, iTero, Trios, Trios Color, Bluecam 4.0, Bluecam 4.2, Omnicam) were used. Digital impressions had comparable precision to conventional impression techniques, newer systems such as True Definition, Trios, and Trios Color had higher precision than the older systems such as iTero, Bluecam, or Lava Chairside, proving the constant improvement of intra-oral scanners. When the same authors assessed the precision of digital and conventional full arch scans using seven intra-oral scanning systems (Lava True Definition, Lava Chairside, iTero, Trios, Trios Color, Bluecam, Omnicam), they found that PVS conventional impression technique had the highest precision while Alginate conventional impression had the lowest. However, digital scanning systems resided in between those two extremes, significantly lower than the highly precise PVS impressions, and not as predictable as the quadrants digital impression.[52] Patzelt et al.[53] compared the accuracy of full arch scans using iTero, CEREC AC Bluecam, Lava COS and Zfx Intrascan. The highest accuracy was recorded by the Lava COS IO scanner, while CEREC AC Bluecam was found to be the least accurate. This was explained as a result of the different technologies used in the scanning systems.

When assessing the trueness of digital full arch impressions compared to convensional impression techniques in clinical use, Kuhr et al.[54] found that conventional full arch polyether impressions are still more accurate than full arch digital impressions using intra-oral scanners (CEREC Omnicam, 3M True Definition, TRIOS). That being said, conclusive information on full arch scans is lacking. Goracci et al.[55] conducted a systematic review concerning the accuracy, reliability and efficiency of intra-oral scanners for full arch digital impressions. Eight clinical studies for full arch digital impressions were found, only four of which assessed validity, repeatability and reproducibility of full arch impressions using iTero and Lava intraoral scanners. One of the reviewed studies found that iTero scanner was less accurate intra-orally than when it was used extra-orally, indicating the effect of the intraoral environment on the quality of the scan. Moreover, models scanned with bench scanner were more accurate than those acquired with the iTero scanner.[56] They concluded that sampling in most studies was neither enough nor representative of population and further research is needed in the area of full arch scans.[55]

1.2.2.2 Fixed Prosthodontics

The marginal fit of crowns fabricated using intra-oral scanners compared with those fabricated from conventional PVS impressions was compared by Ng et al.[57] They found that the digital impression method produced crowns with improved margin fit in comparison to the conventional technique. Another clinical study by Zarauz et al.[58] was conducted to assess the fit of all-ceramic crowns fabricated using digital impressions compared to those fabricated using conventional impression techniques. They stated that the fit of the crowns was significantly influenced by the impression technique used, with higher values of internal and marginal misfit found in crowns fabricated using the conventional workflow. As a result, all-ceramic crowns fabricated using intra-oral scanners are deemed to have clinically acceptable internal and marginal fit. Boeddinghaus et al.[59] compared the marginal fit of crowns fabricated using three different intra-oral scanners: CEREC Omnicam, Trios, and Lava True Definition, and one conventional impression technique. They found the mean marginal gap to be 88 µm using Lava True Definition; 112 µm using TRIOS; 113 µm using conventional impressions, and 149 µm using Omnicam.

1.2.2.3 Removable Partial Dentures

The steps required in making a cast framework for partial dentures using CAD/CAM technology and rapid prototyping (RP) include: taking a digital impression with an intra-oral scanner, designing and determining the path of insertion of the framework virtually, and then producing the metal frameworks using RP.[60] Prototyping technology used in fabricating cast frameworks offers the advantage of eliminating the need for designing in wax, hence reducing errors associated with that and improving the quality of the final removable prostheses.[61, 62] Furthermore, the path of insertion can be determined virtually with rapid identification of the retentive areas, reducing the working time. Several techniques like stereolithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), selective deposition modeling

(SDM), 3D printing, and direct inkjet printing have been the interest of clinical research to validate their use in fabricating cast denture frameworks by rapid prototyping techniques.[63] However, most of the available literature is based on case reports, and further clinical research is still required.

1.2.2.4 Complete Dentures

The available research suggests that a combination of manual and digital steps is still required for the fabricating of digital complete dentures.[64] Conventional impressions of the edentulous jaws are still required, as complete intraoral scanning of an edentulous ridge is still not possible due to the need for recording the dynamic movement of the muscles and oral structures, and the moist mucosal tissues.[65]

1.2.2.5 Patients' Related Outcomes

Joda et al.[66] compared patients' satisfaction and working time using intra-oral scanners to conventional polyether impressions in a cross-over study. They found the mean convenience level for the intra-oral scanning to be 78.6, compared to 53.6 for the polyether impression technique. The working time for the digital technique was 14.8 minutes compared to 17.9 minutes for the conventional impression. Based on these results, digital scanning appears to be preferable. Another similar cross-over study by Schepke et al.[67] used the CEREC Omnicam and compared it to the polyether conventional impression technique (6 minutes and 39 seconds versus 12 minutes and 13 seconds). Over 80% of participants preferred the digital technique over the conventional one. Moreover, intraoral scanning took significantly less working time in comparison to the conventional technique. Gjelvold et al.[68] included dentists' assessments of both techniques and found the conventional impression technique to be more challenging compared to the digital impression technique.

1.2.2.6 Implant Dentistry

The accuracy of scanning implants for the fabrication of single-unit, multiple-unit, or full arch restorations has also been studied. Lin et al.[69] described a digital pathway for making a digital impression of a single implant using a scan body and an intraoral digital scanner for the fabrication of custom zirconia abutments and crowns in the esthetic zone. They found this to be an efficient method, being simple and less time consuming, while achieving clinically acceptable and predictable results. Flugge et al.[70] evaluated the accuracy of implant impressions for three different intra-oral scanners on two partially edentulous models with different implant numbers and distributions. They compared the results to those from a laboratory scanner, and found the intra-oral scanners to be significantly less precise than the laboratory scanner, with precision decreasing as the distance between the scan bodies increased.

Clinical studies conducted by Gherlone et al.[71, 72] assessed the fit of a full arch implant-supported framework fabricated from scans using an intra-oral scanner versus those made using conventional polyether impressions. All definitive prosthesis revealed a very accurate fit using the Sheffield test and radiographic assessment. There were no significant differences found between the two groups in regard to the amount of bone loss around the implants. The digital group was significantly more efficient according to the total time needed to fabricate the prostheses. On the other hand, Andriessen et al.[73] found that the distance and angulation errors were too great to produce well-fitting prostheses on two implants in an edentulous mandible using intra-oral scanners. They concluded that these unreliable results were due to the gingival tissue between the implants providing poor reference landmarks during the intra-oral scan.

Gimenez et al. conducted several in-vitro studies assessing the effect of different angulations, depths, and distance between implants in an edentulous maxilla on the accuracy of intra-oral scanners. They found that different angulations and depth of the implants did not influence the accuracy, however the length of the scanned section had an adverse effect. One study showed that experienced operators showed better results compared to novice operators, while another showed no significant difference.[74-77] Vandeweghe et al.[78] compared the accuracy of four intra-oral scanners when scanning six implants in an edentulous mandible. They found that the 3M True Definition scanner and the Trios Scanner were the most accurate, while the Lava COS scanner was not suitable to use in a completely edentulous jaw.

1.2.3 Virtual Occlusal Indicators

Occlusal contacts can be identified and quantified by assessing the virtual contacts obtained from virtual records. So, it is of crucial importance to be able to accurately align the digitized images of the dental arches so that they accurately reproduce the patient's occlusion.[7] Virtual occlusal contacts provide three-dimensional quantitative records of occlusal contacts, which can be compared sequentially to identify changes in occlusion over time and assess occlusal function. The area, location, and orientation of an identified contact can be calculated and displayed for evaluation.[4, 7] Another advantage of the digital system is that the analysis is consistent over time once the record is digitized.[31]

Multiple methodologies have been suggested to allow virtual representations of the patient's occlusion. Virtual dental arches are acquired by scanning dental casts, impressions, or by scanning the arches intra-orally. Interocclusal records taken in maximal intercuspal position (MIP), or any other position, can be scanned and digitized as well. The virtual casts can be aligned manually or by using the scanned interocclusal records. The main advantage of manually aligning the virtual casts is that an interocclusal record is not necessary. However, aligning the virtual casts manually requires marking the teeth and recording contact locations as a reference, which could be more time consuming than taking an interocclusal record. When the scanned interocclusal record is used to align the virtual casts, cusp indents on the virtual interocclusal record are aligned to the corresponding cusps of the virtual casts, ultimately aligning the maxillary and mandibular virtual casts to each other. Once the virtual casts are aligned, virtual contacts can be calculated as regions on opposing virtual surfaces that are within a specified distance from each other. Occlusal contacts can also be measured directly on the scanned interocclusal record, with virtual contacts being any points on the opposing surfaces of the scanned interocclusal record that are within a specified distance from each other.[7]

Delong et al[4] studied these three-dimensional scanning methods and found that they provide accurate, quantitative measures of occlusal contacts when compared to transillumination as the gold standard. They concluded that transillumination, scanned interocclusal records, and virtual cast methods showed similar contact results. Although when using the scanned interocclusal record method one worries about the effects of scanning objects with perforations and translucent regions where the teeth contact, it is reassuring to know that all the contacts are being measured with the upper and lower jaws in the same occlusal relationship and under the same bite force. Movements caused by the teeth contacting each other are recorded to some extent using the interocclusal record method, but are not recorded in any way when using the virtual cast method. Therefore, the virtual interocclusal record can be considered the better method of these three for identifying contacts in clinical studies, with outcomes dependent on occlusal contact locations.[4]

In addition to the various limitations correlated with different indicators, it has been suggested that the thickness of any interocclusal material could result in over-detection of the occlusal contact area and bite force, especially in the posterior region near the hinge axis.[5] The thickness of the material could also provoke a proprioceptive response that causes the jaw to deflect on closing. Therefore, there is a concern that the tooth contacts measured do not accurately represent the contacts in the patient's mouth when there is no indicator present. The thickness of an indicator may alter the occlusal marking, even if the patient does not perceive the excessive thickness.[3, 5, 79] Thicker and stiffer indicators have been shown to alter muscle activity of the anterior temporalis and the superficial masseter during biting, which indicates the possibility of different tooth contact measurements and occlusion parameters. Forrester et al[5] found that T-Scan sensors (96 μm) and articulating paper (202 μm) had significantly greater effects on the bite, were less comfortable, rougher, and tougher, when compared to Accufilm (24 μm) and articulating silk (60 μm). This concern applies to all the previously discussed occlusal indicator tools and methods, since a finite thickness is placed between the occluding teeth during the process of recording.

A completely digital alternative is available that does not require having anything placed between the teeth to take an occlusal record. Intraoral scans of complete arches are supplemented with buccal scans of occluding posterior teeth in the intercuspal position (virtual interocclusal records), which are used to position and align the opposing virtual dentitions. The software usually implements an initial approximate alignment followed by a least-squares computational fit, often accompanied by measurements of the iterative closest points between them.[80] Theoretically, the virtual casts, when aligned using the virtual interocclusal records, should allow identification and quantification of virtual occlusal contacts. Although the virtual records attained from this method are currently being used to fabricate single and multiunit restorations that must be in the correct occlusal scheme, there is little evidence in the literature on the accuracy or reproducibility of this process. Solaberrieta et al[6] attempted to validate this virtual procedure of locating the relative position of the digital casts and to verify the occlusal contact points obtained using this technique. They compared the virtual occlusal contact points to the contacts obtained with articulating paper on mounted casts on an articulator. They concluded that virtual occlusion is a valid procedure for the location of the mandibular cast and that contacts observed in the virtual environment were significantly more accurate than those of the physical ones, provided more objective and meaningful data. That being said, this study used an industrial three-dimensional scanner to digitize the casts and to obtain their virtual interocclusal records and, therefore, the results cannot be applied to intra-oral scanning.

Stavness et al.[81] used an intra-oral scanner to digitize maxillary and mandibular casts, and an industrial three-dimensional scanner to obtain the virtual interocclusal records. They found that digital simulation utilizing virtual interocclusal records can closely replicate the occlusal contacts and primary movements of mounted casts on a semi-adjustable articulator.

Solaberrieta et al.[82, 83] determined that intra-oral virtual occlusal recording is a valid procedure for locating a mandibular cast on a virtual articulator. Virtual contacts were compared to contacts identified on the casts using articulating ribbon and shimstock foil. An industrial three-dimensional scanner and intra-oral scanners (Lava Cos and Trios 3Shape) were used. They concluded that the best combination for virtual occlusal records consisted of two lateral and frontal sections, or a combination of left and right lateral occlusal records. The best results were found when the distance between the sections was maximized.

Iwaki et al.[84] assessed the dimensional accuracy of optical bite registration using an intra-oral scanner (CEREC Bluecam) compared to that of a conventional physical method (silicone bite registration material) in-vitro. This was done by comparing the distances and angles between specified reference points on the casts when the digital bite registration and the physical method were utilized before and after preparation of teeth on the models. They found that optical bite registration was more effective in single posterior restorations when compared to the conventional method, however, for multiple preparations, the optical method showed significantly more discrepancies.

The accuracy of an intra-oral scanner (CEREC Omnicam) in reproducing the occlusal contacts of a cast was assessed by Arslan et al.[85] They compared the accuracy of virtually indicated occlusal contacts to those identified with articulating paper on the models being scanned. The variables assessed included full arch versus half arch digital impressions, prepared abutment teeth versus sound teeth, and buccal bite scans taken on the ipsilateral side versus the contralateral side. The comparison was done by superimposing the screenshot images of the virtual casts to the screenshot images of the casts with the indicated occlusal contacts. The highest percentages of virtual occlusal contacts identical to the casts were seen in the nonprepared full-arch digital impressions. There was no significant difference found between full-arch impressions taken with or without prepared abutment teeth, regardless of the location of the buccal bite scans. The half-arch digital impressions showed significantly lower percentages of identical contacts when compared to the full-arch digital impressions when abutment teeth were prepared. They recommended taking a full-arch digital impression when there is no posterior antagonist contact following tooth preparations.

1.3 Literature Review Summary

There is no universally accepted gold standard for identifying occlusal contacts. Combinations of patient feedback and an occlusal examination serve as a clinician's most reliable method for identifying occlusal contacts. The accuracy of most occlusal contact marking indicators is not supported by evidence in the literature, yet it remains to be assumed accurate by most dental practitioners. None of the inter-occlusal recording methods reviewed can be more than supplementary documentation devices, as no proven reliability or diagnostic validity is offered, and their efficacy is not supported by research.[3, 4, 32] Several of the most commonly used occlusal indicators lack clinical accuracy and rely entirely on subjective interpretation. Therefore, there is a clinical need for an accurate, and reproducible occlusal indicator standard. The new digital impression instruments have diagnostic potential, but have yet to be validated.[15, 32] There are various considerations that play a role in the capability of an occlusal indicator to accurately, reliably, and validly mark occlusal contact. Therefore, the selection and utilization of any indicator requires cautious consideration, interpretation, and clinical judgement.[3, 5]

Intra-oral scanning systems are now being widely used in clinical practice, playing an important role in completely digitizing the process of CAD/CAM prosthetic reconstructions. While conventional impression techniques and materials are well established and known for their high accuracy, intra-oral scanning has the advantages of reducing working time, saving materials, and improving work efficiency. Nevertheless, intra-oral scanners require the dentist to acquire specific skills in order to obtain high quality. Digital dentistry is a constantly evolving field as technology advances and research progresses.

Intra-oral scanners produce virtual casts and allow for virtual articulation to be used in fabrication of prostheses. Virtual casts are articulated together using a virtual interocclusal record taken using an intra-oral scanner. There is a paucity of literature on the accuracy of this process, and limited recommendations on the most effective method to achieve accurate registration.

Therefore, two questions remain: a) do the virtual interocclusal records taken with intraoral scanners accurately align the digitized images of dental arches so that they accurately reproduce the patient's occlusion? and b) does the location of the virtual interocclusal record affect the virtual occlusal contacts produced?

1.4 Study Rationale

With the rapid advancements in digital dentistry and CAD/CAM technology, virtual images of dental arches are being used more frequently. Multiple methodologies have been suggested to allow virtual representations of the patient's occlusion, using extra-oral scanners to digitize casts, impressions, or interocclusal records. A completely digital alternative is available, in which intraoral scans of complete arches are supplemented with buccal bite scans of occluding posterior teeth in the intercuspal position (virtual interocclusal records) to position and align the opposing virtual dentitions. There have been multiple studies assessing the accuracy and reliability of quadrant and full arch scans taken using intra-oral scanners, but there is little evidence in the literature on the accuracy or reproducibility of the bite registration procedure. In addition, for the majority of intra-oral scanners there are no details for how their software algorithm uses the virtual interocclusal records to articulate the virtual cast. The clinical recommendations providing suggested techniques and locations to take virtual interocclusal records are not supported with published scientific evidence. This missing information inspired the current study.

1.5 Aims

The aims of this study were:

- To assess if virtual interocclusal records taken at different locations on the arch have an effect on the alignment of virtual casts.
- To assess whether quadrant scans and full arch scans have an effect on the alignment of virtual casts when articulated using virtual interocclusal records.

1.6 Hypotheses

The null hypotheses of the study were:

- H_{o1}: The use of virtual interocclusal records taken at different locations on the arch does not affect alignment (assessed by the presence or absence of occlusal contacts) of virtual casts.
- H_{o2}: The use of virtual interocclusal records results in no difference between the alignment (assessed by the presence or absence of occlusal contacts) of full arch scans and quadrant scans.

Chapter 2: Materials and Methods

2.1 Master Models

The master models were fabricated and used in a previous study.[57] Maxillary and mandibular zirconia master models were fabricated from full-arch scans of prepared acrylic typodonts. The digital file of the typodont arches were replicated by milling solid 25mm thickness Wieland translucent yttria-stabilized zirconia blocks (Wieland Dental, Schwenninger, Germany). The complete arches were stained for gingival and tooth color followed by glazing (Figures 1 and 2). The use of one piece zirconia ceramic casts allows for controlled and standardized evaluation of occlusal contacts.

2.2 Occlusal Adjustments

The master casts were hand articulated and mounted in maximum intercuspal position (MIP) using a semi adjustable Denar 330 articulator (Whipmix Corp., USA). Occlusal adjustments were made using a zirconia adjusting, finishing and polishing system (Brasseler, USA) to achieve bilaterally distributed sites of close proximity (SCP) in MIP on a minimum of three teeth in each sextant. Occlusal contacts were marked using 21 µm thick articulating film (Accufilm II, Parkell Prod Inc., USA) and confirmed using 12.7 µm thick occlusal registration shim stock strips (Artus Corp., USA).[83, 84]

Figure 1 - Maxillary master model

Figure 2 - Mandibular master model

2.3 Confirming and Identifying Sites of Close Proximity and Sites of Clearance

Sites of Close Proximity (SCP) and Sites of Clearance (SC) were confirmed and anatomically identified by the transillumination of three interocclusal impressions following a modified version of a method described by Owens et al.[23] The interocclusal impressions were made from the mounted models in MIP using a vinyl siloxane bite registration material (Futar D, Kettenbach GmbH & Co., Germany). Calibrated molds were made from the same mix by injecting samples of the material on a glass plate and seating a calibrated sphere of a known diameter (12 mm) through the material until setting (Bearings Canada Inc, Canada). Each interocclusal impression and its corresponding calibrated mold were placed on a V500 photo scanner (Seiko Epson Corporation, Japan), in addition to a flat circular metal shim of a known external and internal diameter, 19.177 mm and 12.700 mm respectively (Acklands Grainger, Canada). The three objects were scanned into a Tag Image File Format (TIFF) – (Figure 3)

The images were uploaded on ImageJ 1.50i[86] which enabled the analysis of the TIFF colour-image. The calibration sphere had a known diameter and perforated the bite registration material where it touched the glass plate on which the record was made. Pixel values in the image radiating from the perforation point reflected the increasing thickness of the bite registration material in accord with the spherical surface responsible for the impression. The profile analysis tool in ImageJ provided a graphical plot and a data file comparing pixel intensities with image distances expressed in pixels from a specified point. The pixel distances were then scaled to represent actual distances by using the circular shim with a known diameter as a scaling factor.

The threshold adjustment tool in ImageJ permitted the selection of a narrow, circular band of pixels surrounding the perforation point. This selection was then fitted with concentric circles using an ImageJ plugin tool. The tool also provided the coordinates of the circles' center which allows specification of the starting point for any radiating lines needed for the profile analysis. ImageJ therefore provided an exportable data file describing the pixel intensity along a straight line expressed in metric units from the bite registration perforation. Since the exported data represented transilluminated image pixel values proportional to changes in the bite registration thickness expressed linearly from the perforation in a plane tangential to the spherical surface, a conversion formula* described below was used to describe the actual thickness of the bite registration material based on the pixel values up to those at which the image density becomes saturated under transillumination.

*Record thickness = R - $\sqrt{(R^2 - r^2)}$

R = radius of calibrated sphere

r = distance from the perforation

The measurement, scale setting and calibration, pixel intensity, and thresholding tools on ImageJ 1.50i [86] in addition to photo editing tools on Adobe Photoshop CC (Adobe System Inc., USA) were then used to identify all regions in the impressions with a thickness ≤100 µm, and image superimposition was performed to identify their dental anatomic location. (Figures 4-6)

In addition, the interocclusal impressions were visually examined on a flatbed lightbox to identify areas with perforations or near perforations in the bite registration material.

Figure 3 - Scan of interocclusal impression, calibrated mold, and metal shim.

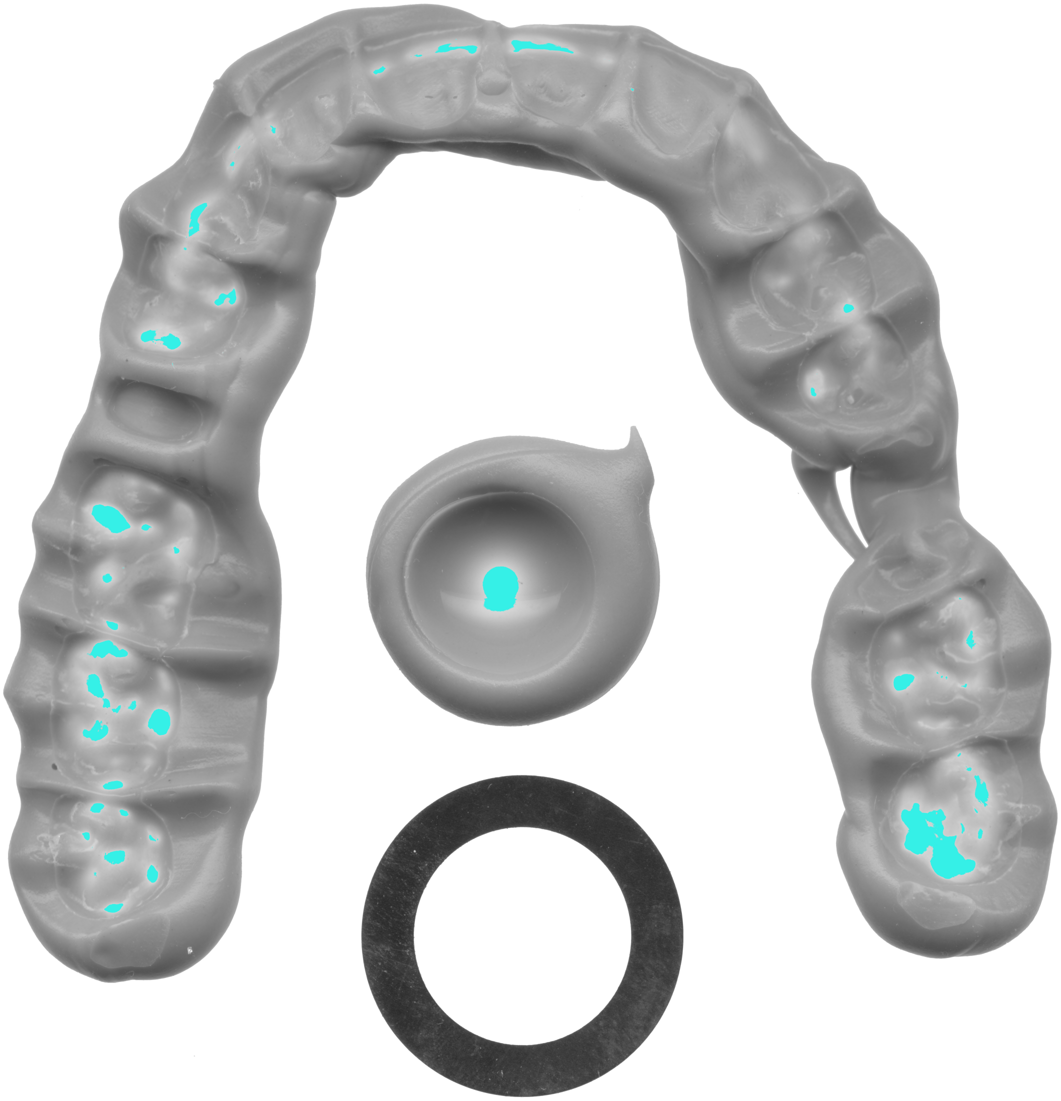


Figure 4 – Transilluminated interocclusal record #1

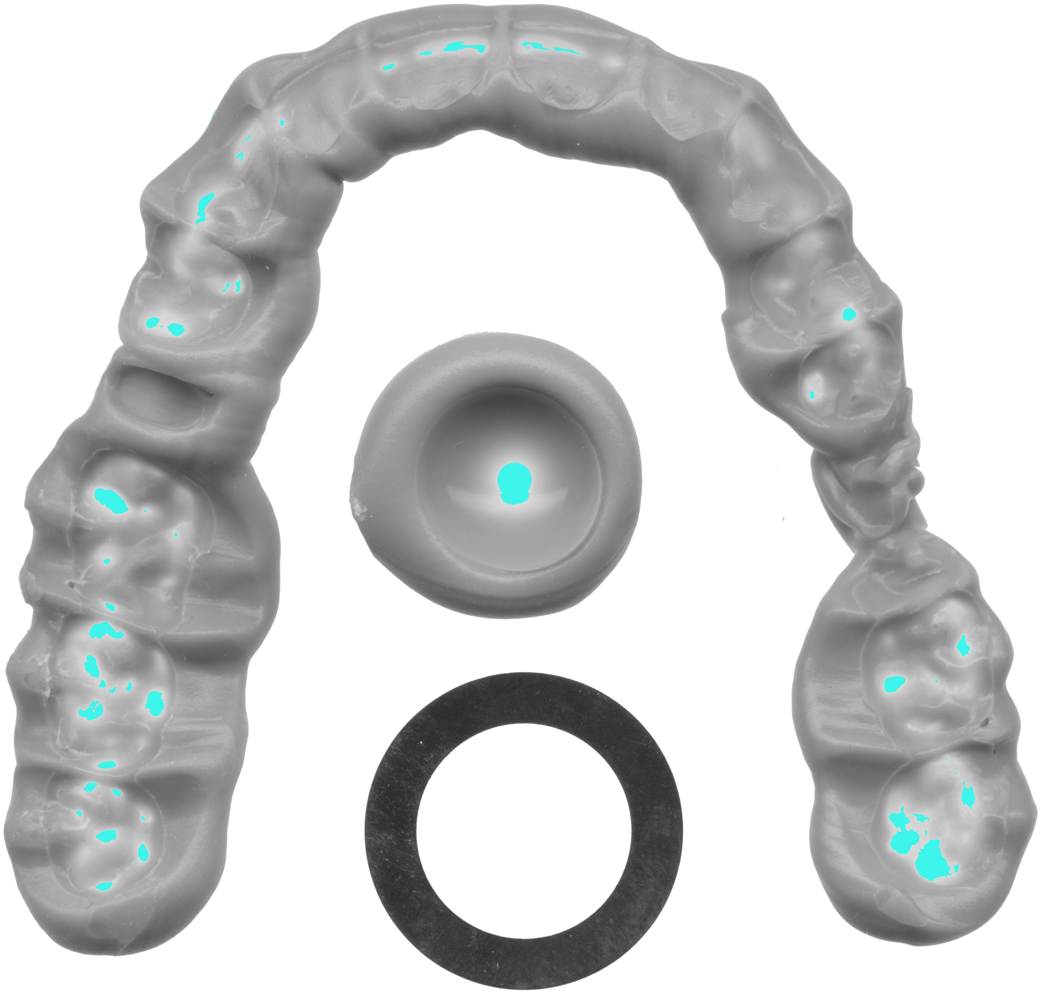


Figure 5 - Transilluminated interocclusal record #2

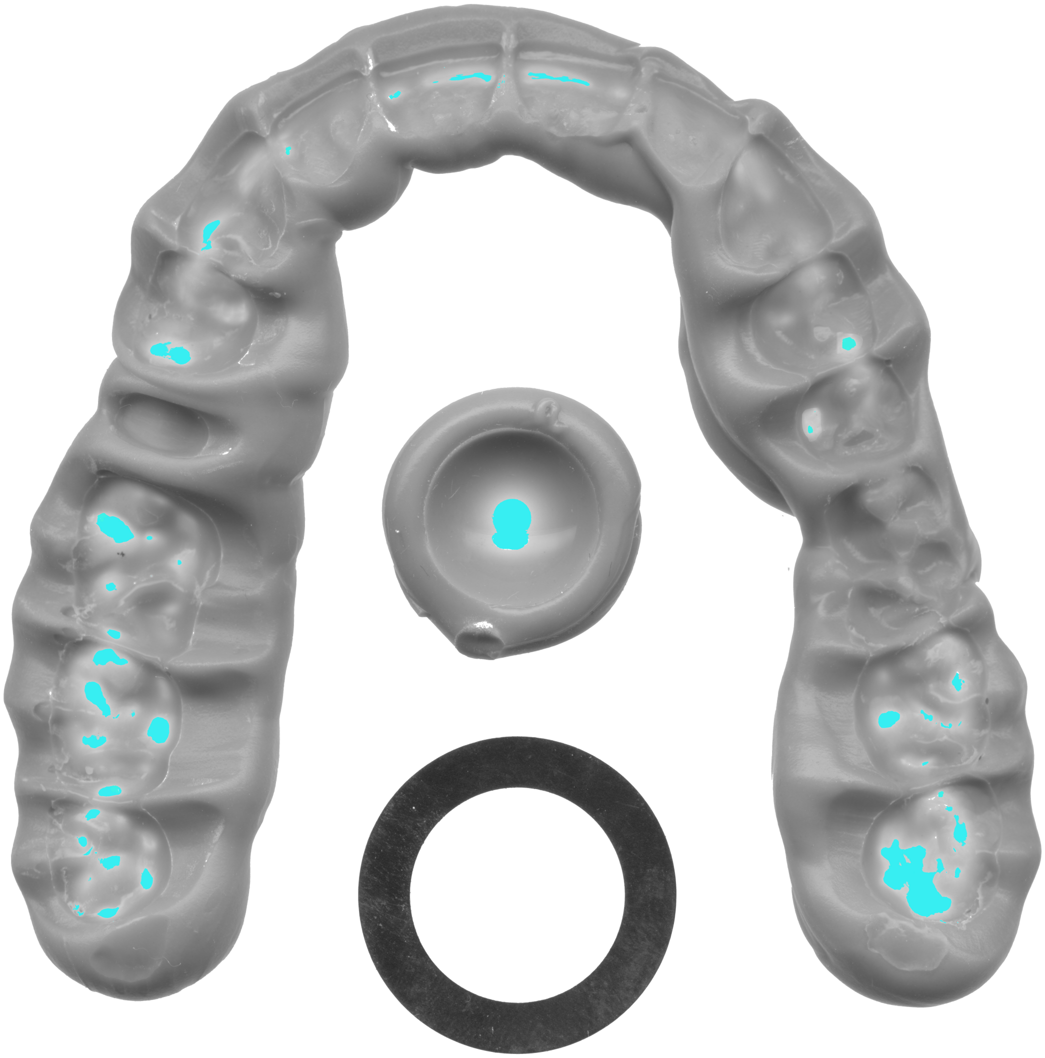


Figure 6 - Transilluminated interocclusal record #3

2.4 Selecting Sites of Close Proximity

Three SCP were selected in each sextant of the maxillary arch (Master SCP). The SCP were only selected if the site met all of the following criteria:

- Holds 12.7 µm thick occlusal registration shim stock strips when models are in MIP.
- Visibly shows perforations or near perforations on all three interocclusal impressions.
- Appears as an area with a thickness ≤100 µm under transillumination.

2.5 Selecting Sites of Clearance

Three SC were selected in each sextant of the maxillary arch (Master SC). The SC were only selected if the site met all of the following criteria:

- Does not hold 12.7 µm thick occlusal registration shim stock strips when models are in MIP.
- Visibly shows no perforations or near perforations on all three interocclusal impressions.
- Appears as an area with a thickness >100 µm under transillumination.

2.6 Virtual casts

The maxillary and mandibular mounted models were digitized using a CEREC® Omnicam intra-oral scanner (Dentsply Sirona, USA). The following scans were taken according to the manufacturer's protocols:

- Upper full arch scan (UFA)
- Lower full arch scan (LFA)
- Upper right quadrant scan (URQ)
- Lower right quadrant scan (LRQ)

2.7 Articulation of virtual casts

With the upper and lower full arch or quadrant scans remaining constant, several virtual interocclusal records (buccal bite scans) were taken to articulate the virtual casts. The full arch scans (UFA and LFA) were virtually articulated using the following virtual interocclusal records.

- Anterior bite scan from canine to canine (to produce articulated casts AB1 and AB2)
- Posterior left bite scan from molars to bicuspids (to produce articulated casts LB1 and LB2)
- Posterior right bite scan from molars to bicuspids (to produce articulated casts RB1 and RB2)

Every bite scan was identically repeated once under the same conditions.

The right quadrant scans (URQ and LRQ) were virtually articulated using the following virtual interocclusal records.

- Canine bite scan (to produce articulated casts CB1 and CB2)
- Molar bite scan (to produce articulated casts MB1 and MB2)
- Quadrant bite scan from molars to the midline (QB1 and QB2)

Every bite scan was identically repeated once under the same conditions.

This produced a total of 6 full arch articulated virtual casts and 6 quadrant articulated virtual casts. The Omnicam software produced images of the virtual casts with colour coded markings identifying sites of close proximity ≤100 μm and perforations. (Figures 7 – 18)

According to the manufacturer, red represents 100 µm of contact or greater; yellow represents 50 to 100 µm of contact; green represents 0 to 50 µm of contact; dark blue represents 0 to 50 µm of occlusal clearance; royal blue represents 50 to 100 µm of occlusal clearance; and light blue represents 100 µm of occlusal clearance.

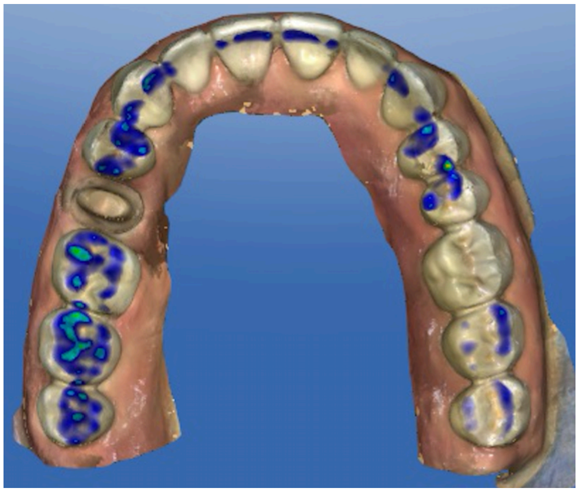


Figure 9 – AB1 (IO Scanner)

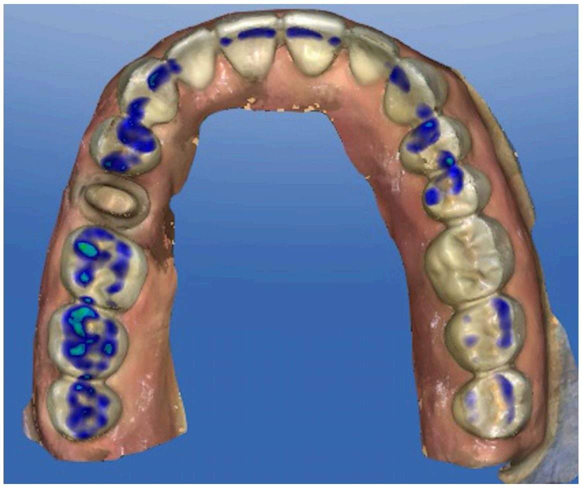


Figure 10 – AB2 (IO Scanner)

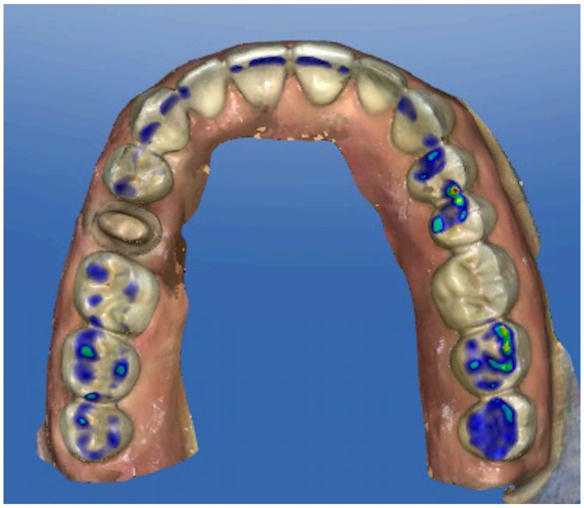


Figure 7 – LB1 (IO Scanner)

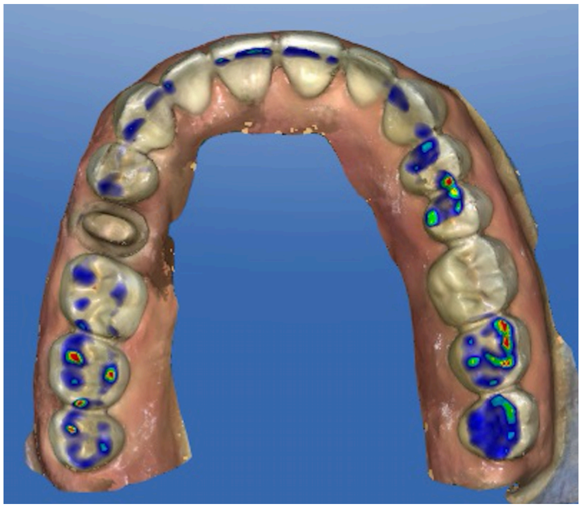


Figure 8 – LB2 (IO Scanner)

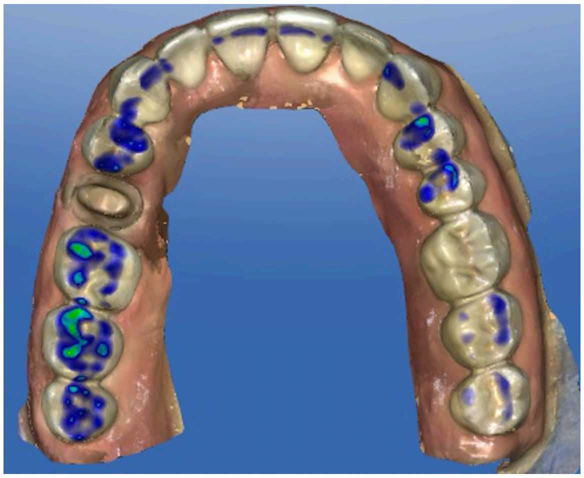


Figure 14 – RB1 (IO Scanner)

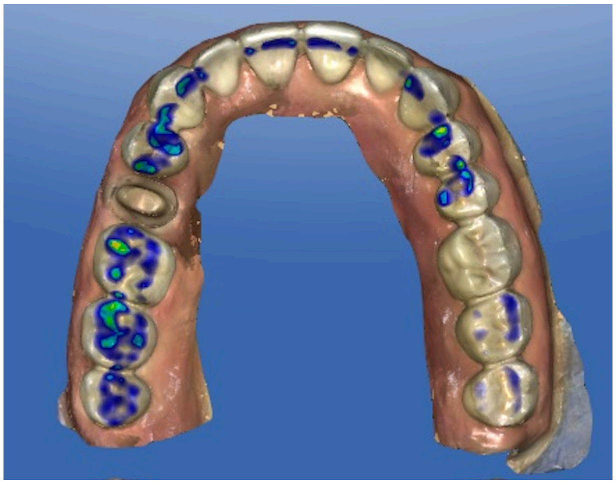


Figure 13 – RB2 (IO Scanner)

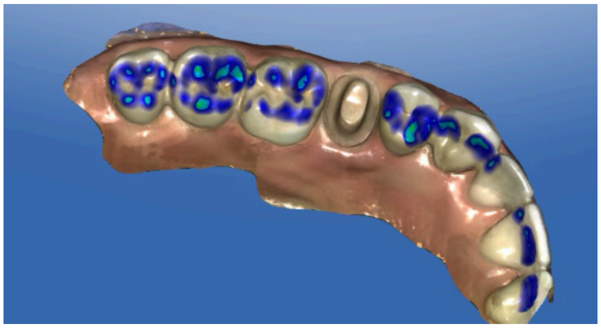


Figure 11 - CB1 (IO Scanner)

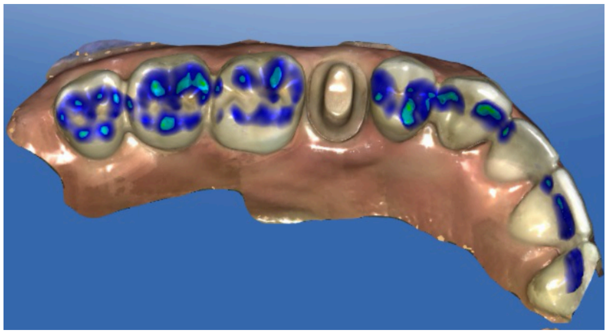


Figure 12 - CB2 (IO Scanner)

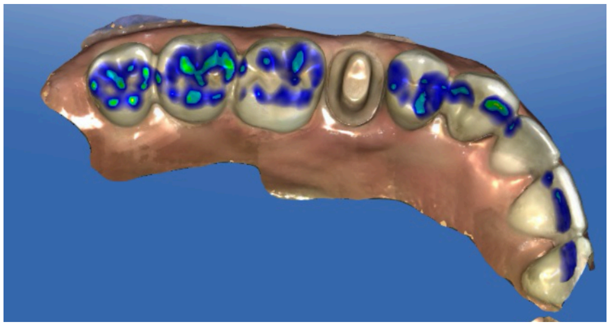


Figure 15 – MB1 (IO Scanner)

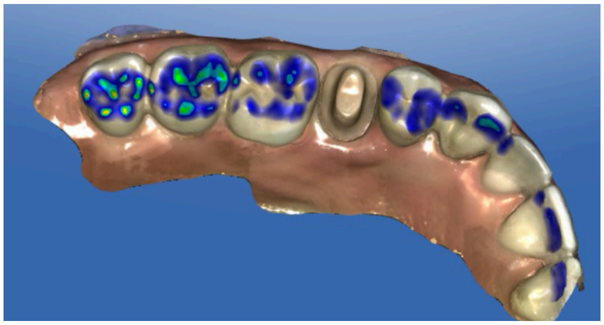


Figure 16 – MB2 (IO Scanner)

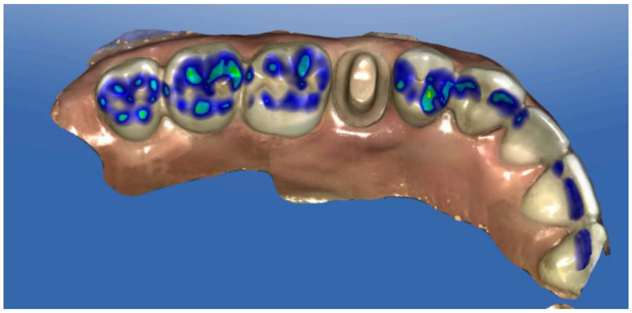


Figure 18 – QB1 (IO Scanner)

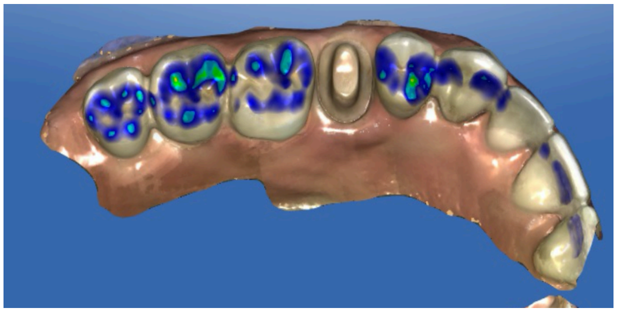


Figure 17 – QB2 (IO Scanner)

2.8 Independent Confirmation of Virtual Sites of Close Proximity

The 12 articulated virtual cast files were sent to a dental lab (The Aurum Group, Calgary, Canada) via the Sirona Connect Portal (Dentsply Sirona, USA) and converted into Standard Tessellation Language (STL) file format. CloudCompare V2.7 (http://www.cloudcompare.org) was utilized to measure the mesh separations (distance between points on the virtual casts) and perforations between the articulated virtual casts. By setting thresholds for the program's distance map settings, all distances ≤100 μm and perforations were identified. Green represents areas with 0 to 100 μm of occlusal clearance and blue represents areas of mesh perforation. (Figures 19-30)

2.9 Comparison and Statistical Analysis

The Master SCP and SC were examined on the color coded virtual casts produced by the intra-oral scanner, and on the color coded virtual casts produced after interpretation using the independent software. Master SCP and SC were marked as either:

- Negative: clearance >100 μm
- Positive (clearance): clearance ≤100 μm
- Positive (perforation): perforations of the virtual casts

True positive (TP), true negative (TN), false positive (FP), and false negative (FN) calculations were identified for each virtually articulated cast, and the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were determined similar to what was demonstrated by Delong et al.[87] and Solaberrieta et al.[82, 83]

Sensitivity means the probability the test will show positive if a contact exists = TP / (TP+FN)

Specificity means the probability the test will show negative if there is no contact = TN / (TN+FP)

PPV means the probability a contact truly exists when the test is positive = TP / (TP+FP)

NPV means the probability a contact is truly not present when the test is negative = TN / (TN+FN)

Pearson's r Correlation Coefficient was used to estimate the concordance between the repeated virtual interocclusal records taken of the same site as demonstrated by Stavness et al.[81]

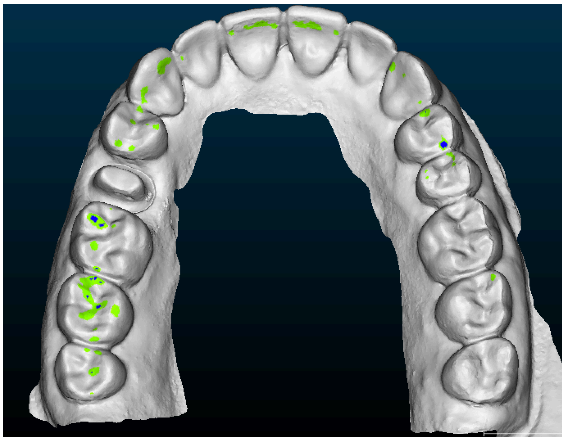


Figure 23 – AB1 (CC Software)

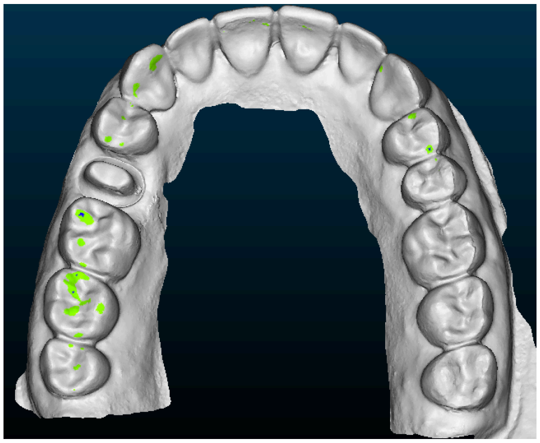


Figure 24 – AB2 (CC Software)

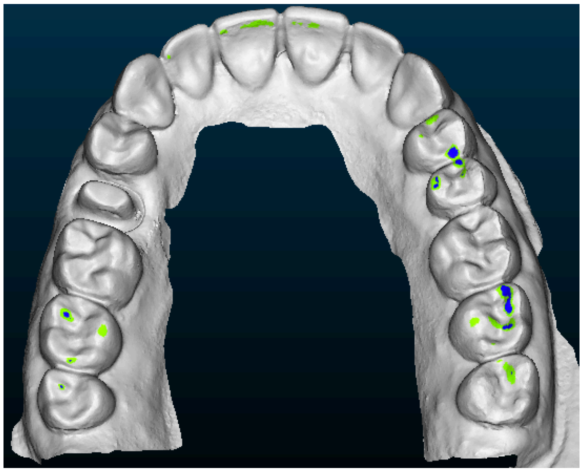


Figure 19 – LB1 (CC Software)

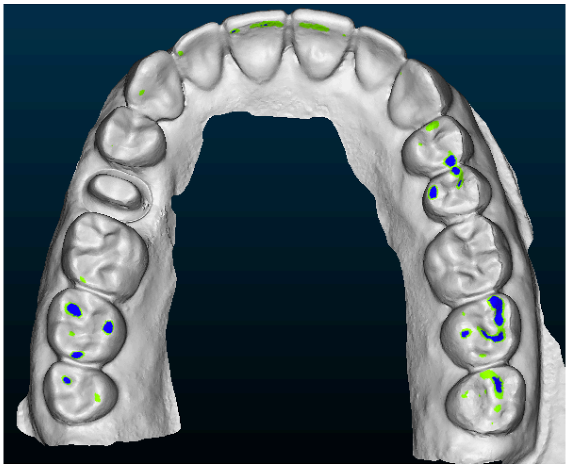


Figure 20 – LB2 (CC Software)

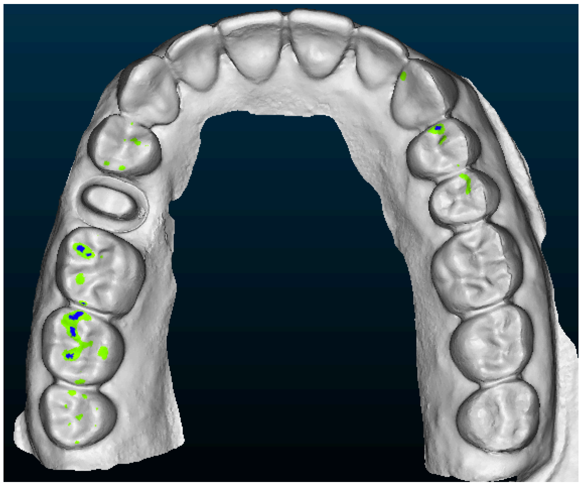


Figure 22 – RB1 (CC Software)

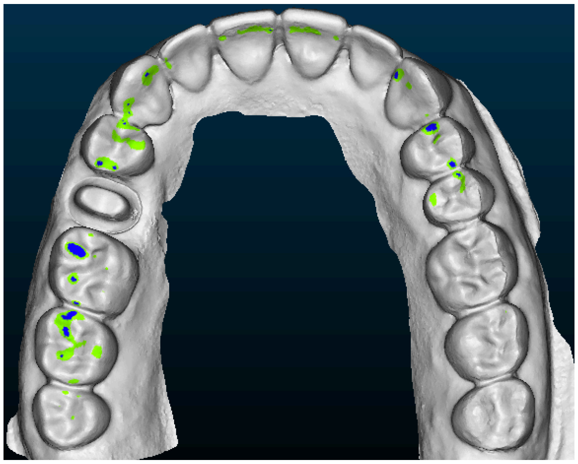


Figure 21 – RB2 (CC Software)

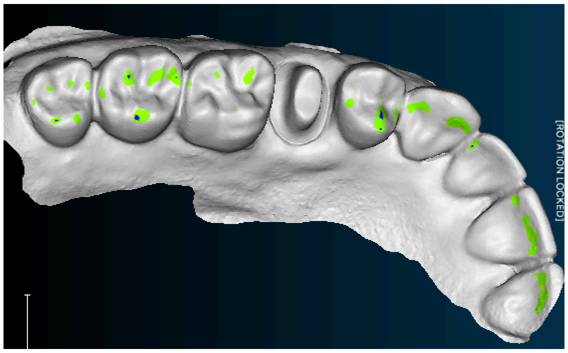


Figure 30 – CB1 (CC Software)

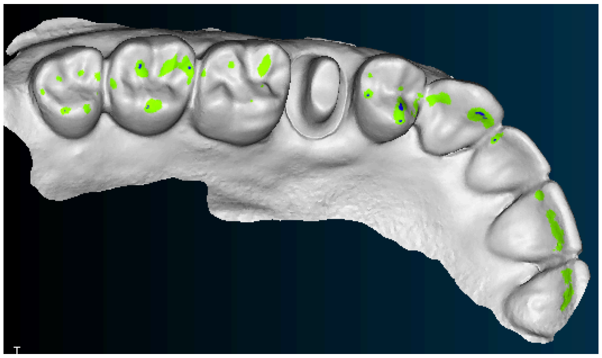


Figure 29 – CB2 (CC Software)

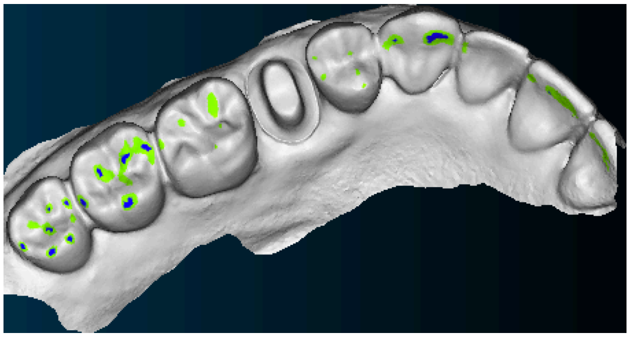


Figure 28 – MB1 (CC Software)

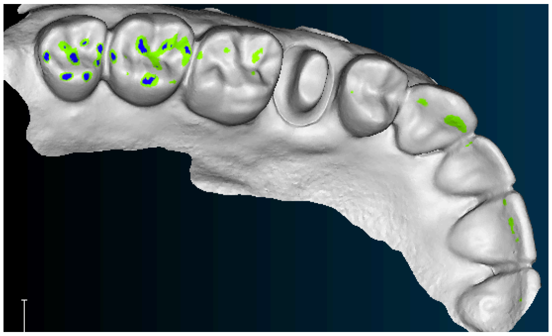


Figure 27 – MB2 (CC Software)

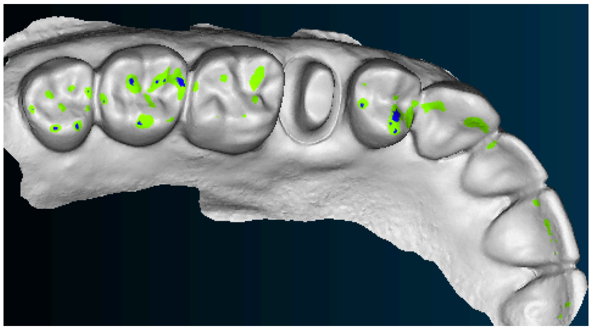


Figure 25 – QB1 (CC Software)

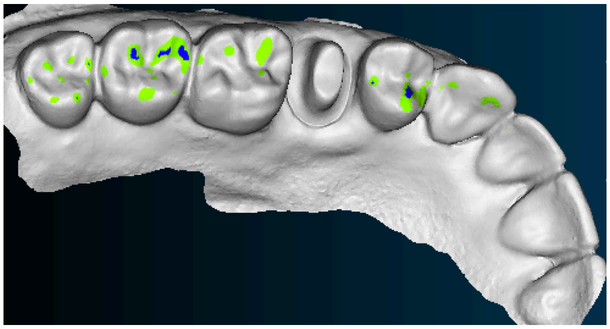


Figure 26 – QB2 (CC Software)

Chapter 3: Results

3.1 Master Sites of Close Proximity

The Master SCP chosen based on the set criteria were as follows (Figure 31):

- SCP 1: #18 – central groove
- SCP 2: #17 – mesiobuccal marginal ridge
- SCP 3: #14 – distopalatal marginal ridge
- SCP 4: #13 – distal aspect of cusp
- SCP 5: #11 – incisal third of mesial marginal ridge
- SCP 6: #21 – incisal third
- SCP 7: #25 – palatal cusp
- SCP 8: #27 – mesiopalatal cusp on the oblique line
- SCP 9: #28 – distopalatal cusp

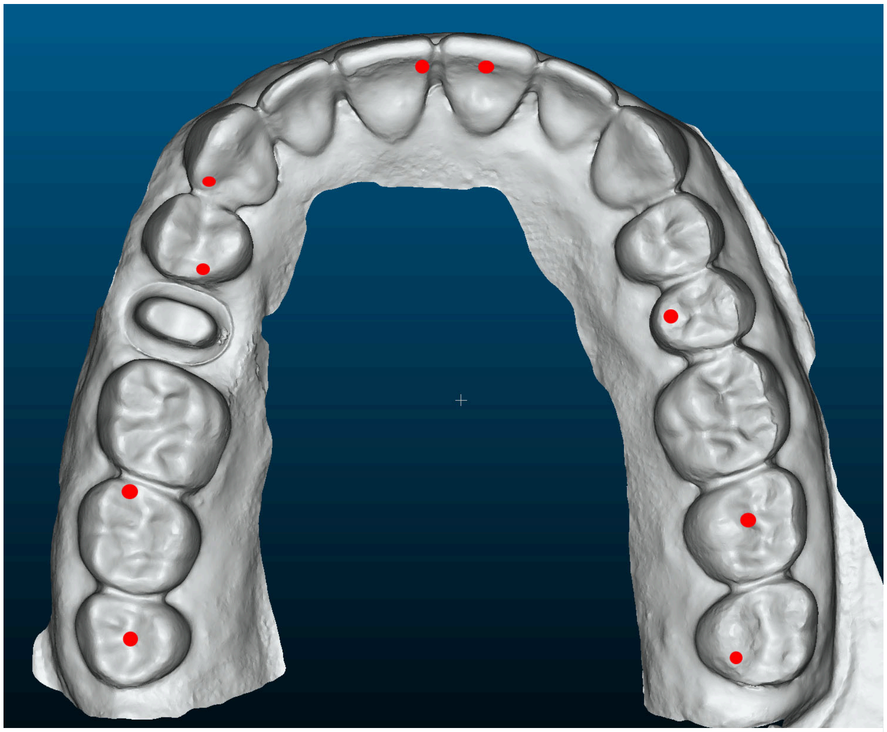


Figure 31 – Master Sites of Close Proximity

3.2 Master Sites of Clearance

The Master SC chosen based on the set criteria were as follows (Figure 32):

- SC 1: #17 – mesiopalatal cusp
- SC 2: #16 – distopalatal cusp
- SC 3: #14 – distal inclination of palatal cusp
- SC 4: #12 – mesioincisal region
- SC 5: #22 – distoincisal region
- SC 6: #23 – distal marginal ridge
- SC 7: #24 – palatal cusp
- SC 8: #27 – mesial marginal ridge
- SC 9: #28 – mesiopalatal cusp

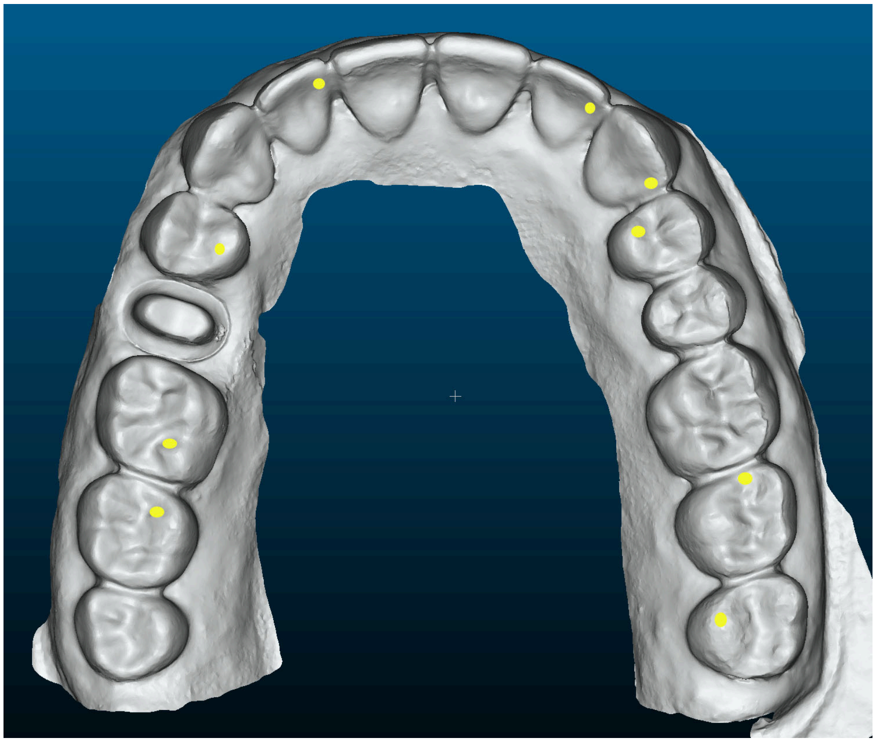


Figure 32 – Master Sites of Clearance

3.3 Comparing Sites of Close Proximity and Sites of Clearance

A total of 12 virtual articulated casts were made using different virtual interocclusal records (buccal bite scans). The bite scans articulated the same full arch or quadrants scans.

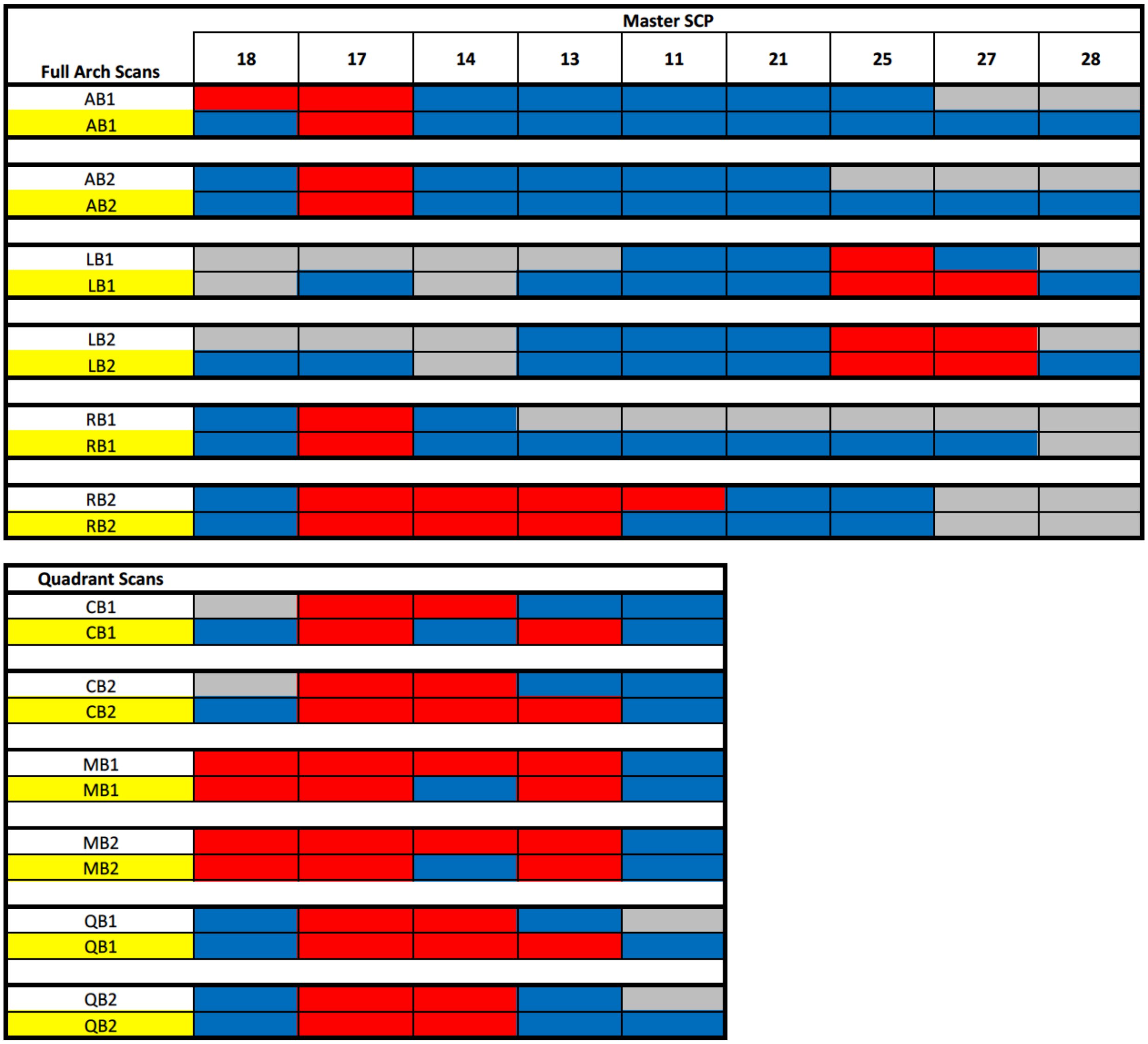
The analysis of SCP is visually displayed in **Table 1**, showing a change in the location of the positive clearances and positive perforations depending on the location of the virtual interocclusal record.

The analysis of SCP and SC combined is visually displayed in **Table 2**. The true positive, true negative, false positive, and false negative contacts were calculated for each virtually articulated cast, and the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) are summarized in **Table 3** and **Table 4**. The CEREC software displayed contacts showed higher sensitivity and NPV (92.86% and 84.21% respectively) when compared to the contacts displayed on the independent CloudCompare software (69.05% and 70.45% respectively). However, the intra-oral scanner software had lower specificity and PPV (41.03% and 62.90% respectively) compared to the CloudCompare software (79.49% and 78.38% respectively). Quadrant scans showed higher sensitivity when compared to full arch scans.

Pearson's r Correlation Coefficient was used to estimate the concordance between the repeated virtual interocclusal record taken of the same site. Results are summarized in **Table 5**. Repeated bite scans taken for articulating quadrant virtual casts showed higher correlation (0.97) when compared to repeated bite scans taken for articulating full arch virtual casts (0.81). Also, repeated bite scans displayed using the intra-oral scanner software showed higher correlation

(0.96) compared to the independent software (0.81). The correlation appears to be acceptable in all categories, keeping in mind the small sample size of repetitions.

Table 1 – Sites of Close Proximity Analysis



Full Arch Scans	Master SCP 18	17	14	13	11	21	25	27	28
AB1	🟥	🟥	🟦	🟦	🟦	🟦	🟦	▨	▨
🟨 AB1	🟦	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦
AB2	🟦	🟥	🟦	🟦	🟦	🟦	▨	▨	▨
🟨 AB2	🟦	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦
LB1	▨	▨	▨	▨	🟦	🟦	🟥	🟦	▨
🟨 LB1	▨	🟦	▨	🟦	🟦	🟦	🟥	🟥	🟦
LB2	▨	▨	▨	🟦	🟦	🟦	🟥	🟥	▨
🟨 LB2	🟦	🟦	▨	🟦	🟦	🟦	🟥	🟥	🟦
RB1	🟦	🟥	🟦	▨	▨	▨	▨	▨	▨
🟨 RB1	🟦	🟥	🟦	🟦	🟦	🟦	🟦	🟦	▨
RB2	🟦	🟥	🟥	🟥	🟥	🟦	🟦	▨	▨
🟨 RB2	🟦	🟥	🟥	🟥	🟦	🟦	🟦	▨	▨

Quadrant Scans					
CB1	▨	🟥	🟥	🟦	🟦
🟨 CB1	🟦	🟥	🟦	🟥	🟦
CB2	▨	🟥	🟥	🟦	🟦
🟨 CB2	🟦	🟥	🟥	🟥	🟦
MB1	🟥	🟥	🟥	🟥	🟦
🟨 MB1	🟥	🟥	🟦	🟥	🟦
MB2	🟥	🟥	🟥	🟥	🟦
🟨 MB2	🟥	🟥	🟦	🟥	🟦
QB1	🟦	🟥	🟥	🟦	▨
🟨 QB1	🟦	🟥	🟥	🟥	🟦
QB2	🟦	🟥	🟥	🟦	▨
🟨 QB2	🟦	🟥	🟥	🟦	🟦

Legend	
Positive Clearance	🟦 ≤100µm
Positive Perforation	🟥
Negative	▨ >100µm
Omnicam Output	🟨
CloudCompare Output	⬜

AB	Anterior Bite Scan
LB	Left Bite Scan
RB	Right Bite Scan
CB	Right Canine Bite Scan
MB	Right Molar Bite Scan
QB	Full Right Quadrant Bite Scan

Table 2 – Sites of Close Proximity and Sites of Clearance Analysis

Full Arch Scans	Master SCP									Master SC								
	18	17	14	13	11	21	25	27	28	17	16	14	12	22	23	24	27	28
AB1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0
AB1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0
AB2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
AB2	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0
LB1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	0
LB1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
LB2	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1
LB2	1	1	0	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
RB1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RB1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0
RB2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0
RB2	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	1	0	0

Quadrant Scans									
CB1	0	1	1	1	1	0	0	0	0
CB1	1	1	1	1	1	1	1	1	0
CB2	0	1	1	1	1	0	0	0	0
CB2	1	1	1	1	1	1	1	1	0
MB1	1	1	1	1	1	0	0	0	0
MB1	1	1	1	1	1	1	1	1	0
MB2	1	1	1	1	1	1	0	0	0
MB2	1	1	1	1	1	1	1	1	0
QB1	1	1	1	1	0	1	0	0	0
QB1	1	1	1	1	1	1	1	1	0
QB2	1	1	1	1	0	1	0	0	0
QB2	1	1	1	1	1	1	1	1	0

Legend		
Positive Clearance	🟩	≤100µm
Positive Perforation	🟩	
Negative	▨	>100µm
Omnicam Output	🟨	
CloudCompare Output	⬜	

AB	Anterior Bite Scan
LB	Left Bite Scan
RB	Right Bite Scan
CB	Right Canine Bite Scan
MB	Right Molar Bite Scan
QB	Full Right Quadrant Bite Scan

Table 3 – CEREC Software Output Analysis

CEREC Software Output

	True positive	False positive	False negative	True negative	Sensitivity	Specificity	PPV	NPV
AB1	9	5	0	4	100.00	44.44	64.29	100.00
AB2	9	5	0	4	100.00	44.44	64.29	100.00
LB1	7	4	2	5	77.78	55.56	63.64	71.43
LB2	8	4	1	5	88.89	55.56	66.67	83.33
RB1	8	5	1	4	88.89	44.44	61.54	80.00
RB2	7	5	2	4	77.78	44.44	58.33	66.67
Total Full Arch	**48**	**28**	**6**	**26**	**88.89**	**48.15**	**63.16**	**81.25**
CB1	5	3	0	1	100.00	25.00	62.50	100.00
CB2	5	3	0	1	100.00	25.00	62.50	100.00
MB1	5	3	0	1	100.00	25.00	62.50	100.00
MB2	5	3	0	1	100.00	25.00	62.50	100.00
QB1	5	2	0	2	100.00	50.00	71.43	100.00
QB2	5	3	0	1	100.00	25.00	62.50	100.00
Total Quadrant	**30**	**18**	**0**	**6**	**100.00**	**25.00**	**62.50**	**100.00**
Total	**78**	**46**	**6**	**32**	**92.86**	**41.03**	**62.90**	**84.21**

Table 4 – CloudCompare Software Output Analysis

CloudCompare Software Output

	True positive	False positive	False negative	True negative	Sensitivity	Specificity	PPV	NPV
AB1	7	1	2	8	77.78	88.89	87.50	80.00
AB2	6	0	3	9	66.67	100.00	100.00	75.00
LB1	4	2	5	7	44.44	77.78	66.67	58.33
LB2	5	3	4	6	55.56	66.67	62.50	60.00
RB1	3	0	6	9	33.33	100.00	100.00	60.00
RB2	7	1	2	8	77.78	88.89	87.50	80.00
Full Arch Total	**32**	**8**	**22**	**46**	**59.26**	**85.19**	**80.00**	**67.65**
CB1	4	0	1	4	80.00	100.00	100.00	80.00
CB2	4	0	1	4	80.00	100.00	100.00	80.00
MB1	5	0	0	4	100.00	100.00	100.00	100.00
MB2	5	1	0	3	100.00	75.00	83.33	100.00
QB1	4	1	1	3	80.00	75.00	80.00	75.00
QB2	4	2	1	2	80.00	50.00	66.67	66.67
Quadrant Total	**26**	**8**	**4**	**16**	**86.67**	**66.67**	**76.47**	**80.00**
Total	**58**	**16**	**26**	**62**	**69.05**	**79.49**	**78.38**	**70.45**

Table 5 – Repeated Bite Scans Analysis

Correlation Coefficient	
AB	0.79
AB	1
LB	0.79
LB	0.89
RB	0.50
RB	0.88
CB	1
CB	1
MB	0.79
MB	1
QB	1
QB	1

Legend	
CloudCompare Output	⬜
Omnicam Output	🟨

Chapter 4: Discussion

The importance of predictably examining, recording, storing, and transferring information regarding occlusion is crucial in restorative dentistry. Traditionally, dental casts mounted on an articulator were used to assess the occlusion, and transfer that information to a dental laboratory for the fabrication of a restoration or prosthesis to the desired occlusal design. With the advancements in digital dentistry, intra-oral scanners allow for virtual casts and articulation to be used in the fabrication of prostheses. There is evidence available to suggest that the accuracy of intra-oral scanners is comparable to that of conventional impressions when taking quadrant scans[51] and acceptable with full arch scans, although further verifications are required[55].

This study aimed to assess another aspect of intra-oral scanning accuracy, that of the virtual occlusion obtained after articulating virtual casts together using virtual interocclusal records taken using an intra-oral scanner. Few studies have assessed virtual interocclusal records, and coordinate measuring machine scanners were mostly used.[6, 81, 83] The few studies that have assessed virtual interocclusal records taken using intra-oral scanners have found that this procedure is accurate if used in particular situations.[82, 84, 85]

Techniques for measuring occlusal contacts or sites of close proximity are not precise and there is no agreed upon gold standard. Transilluminated interocclusal impressions have been shown to be superior to other conventional techniques.[4, 7, 32] Occlusal contacts and sites of close proximity (SCP) have been defined by various authors as material thickness of the transilluminated interocclusal record ranging from less than 30 μm to as much as 350 μm.[81] For this study, SCP were defined and determined where material thickness was ≤100 μm, and confirmed on three different transilluminated interocclusal records, in addition to visual inspection for perforation or near perforation, and physical confirmation using shimstock foil. This allowed for selecting 3 SCP in each sextant with confidence, overcoming, to some extent, the limitation of not having a universal gold standard for identifying and quantifying occlusal contacts. Multiple thresholds for SCP have been used by authors, ranging from 50 µm - 350 µm. 100 µm was the threshold used in this study to allow for comparison and consistency with the results generated using the intra-oral scanner software. Three sites of clearance were selected in each sextant using similar methodology, except with the criteria reversed. This allowed for comparing the occlusal contacts displayed on the virtual casts from the intra-oral scanner's software and the independent software, to 9 known SCP and 9 known SC.

Scanning of the models and stitching of the scanned segments using video capture introduces an error that could affect the final results.[53] Straga[88] has shown that the less captures used for digitization, the more accurate the occlusal contact determination is. To reduce the consequences of these errors and standardize them among all the samples, a single maxillary and mandibular full arch scan, and a single maxillary and mandibular right quadrant scan were taken, to which different bite scans were used to produce twelve virtually articulated samples. Therefore, the only variable factor amongst the different samples was the bite scan, which allowed for better comparison.

The CEREC® Omnicam software produces a color-coded occlusal contact display after articulating the virtual casts. The similarities between the colors made interpretation challenging. It was very difficult to differentiate between royal blue and dark blue. However, this is not likely to have had any effect on the results due to the set definition of SCP being anything ≤100 µm.

Inter-occlusal perforations are a phenomenon that does not, and cannot, exist in conventional casts, models, or dentitions. They only exist in virtual casts and have been integrated into the software algorithms to allow for positioning of the upper and lower virtual casts into occlusion. That being said, they must introduce an error when attempting to accurately replicate an existing occlusion, due to the fact that they cannot truly exist in our physical world. In this study, when a left bite scan was taken, more perforations are present on the teeth in the left quadrants, and increased clearance is observed between the teeth in the right quadrants. The same is seen when a right bite scan is taken, but vice versa.

Virtual casts are oriented in three planes (x,y,z). Therefore, the above observation can be thought of as a 'tilting' of the virtual casts, on one or more planes, towards the section where the virtual interocclusal record was taken. This leads to more contacts (and perforations) being present in the section closest to the virtual interocclusal record, and more contacts missed on the sections farthest from it. This is clearly observed in the full arch scans, but is minimized in the quadrant scans (although still present). This can be attributed to the fact that the teeth in the quadrant scans are all closer in range to where the virtual interocclusal record was taken. Based on these findings, it is recommended that multiple virtual interocclusal records be taken when attempting to articulate full arch scans. This was also suggested by other authors, who advocated for taking multiple buccal scans, as far apart as possible.[84, 85] This may reduce the "tilting effect" observed with a single virtual interocclusal record. In cases where the software does not allow for multiple virtual interocclusal records, such as in with CEREC® Omnicam restorative software used for this study (although multiple bite scans are possible when using the orthodontic software), the virtual interocclusal record should be taken as close as possible to the area of interest (tooth preparation or implant). If full arch scans are taken for diagnostic or record purposes (and there is no specific area of interest), virtual interocclusal records taken in the anterior region (cuspid to cuspid) produce more accurate reproduction of the occlusal contacts (higher sensitivity), compared to left or right bite scans, based on the results of this study.

It is important to consider the clinical consequence of inter-occlusal perforations in the virtual casts on the final restorations. Since perforations do not exist outside of the virtual world, a restoration designed and fabricated based on the occlusion of virtual casts that have perforated each other will theoretically always be light or out of occlusion once in a patient's mouth. This is a common finding many clinicians have encountered since they started using CAD/CAM technology, and this very well might be the explanation. Although it may seem advantageous to have restorations light or out of occlusion due to the reduced need for adjustments, this should not be what we strive for. Restorations are made to restore function, and adequate occlusal contacts are necessary. This problem can be confronted by introducing collision resolution to the software algorithms in order to simulate naturally occurring dental collision, as demonstrated by Stavness et al.[81]

The contacts displayed using the CEREC® software showed higher sensitivity and NPV (92.86% and 84.21% respectively) when compared to the contacts displayed on the independent CloudCompare software (69.05% and 70.45 respectively). Thus, the intra-oral scanner software identified more of the master SCP. Areas it displayed to be greater than 100 µm apart are also more likely to be true negative (SC). The high sensitivity of the intra-oral scanner software's occlusion display is encouraging as it will likely lead to restorations that require less occlusal adjustments.

However, the intra-oral scanner software had lower specificity and PPV (41.03% and 62.90% respectively) compared to the CloudCompare software (79.49% and 78.38% respectively). A possible explanation for these findings is that the intra-oral scanner software's distance thresholds for the color coding are larger than described, leading to more areas being categorized as contacts or near contacts. If this were true, it would have the advantage of allowing the production of restorations that require less occlusal adjustments, but increases the likelihood of restorations being out of occlusion. The risk of restorations being made out of occlusion increases even more when the perforation of virtual casts is accounted for, as mentioned previously.

Solaberrieta et al.[82] has shown that knowing the deviation of the best-fit operation or algorithm is useful in order to account for the cumulative error that is produced. That being said, the intra-oral scanner algorithm used in this study is known only to the manufacturer. On the other hand, CloudCompare's approach for measuring distances is known, which is why it was used as an independent platform. The software uses available mesh-vertices as points, and then measures the distance between a point-cloud and the closest opposing mesh-face. One virtual cast is used as the reference mesh, and the other as the one for comparison.[80] It is important to bear in mind that the intra-oral scanner software and the CloudCompare software use different algorithms, and this may contribute to the differences observed.

Quadrant scans showed higher sensitivity when compared to full arch scans. This means that contacts (or SCP) are more likely to be identified in quadrant scans, which can be attributed to a reduced 'tilting effect', as explained previously. This differs from the findings of Arslan et al.[85], who reported that half-arch digital impressions showed significantly lower percentages of identical contacts when compared to the full-arch digital impressions. That being said, in their study, two posterior fixed dental prosthesis abutments were prepared, which significantly reduces the occlusal contacts observed on a quadrant scan. Iwaki et al.[84] also found that for multiple preparations, the virtual interocclusal records showed significantly larger discrepancies. In this study, there was only one tooth-bound prepared abutment tooth in the quadrant scans.

Quadrant scans also showed higher NPV compared to full arch scans, which means that areas displayed to be more than 100 μm apart are more likely to truly be SC. Surprisingly, full arch scans displayed higher specificity than quadrant scans, which implies that full arch scans were better in identifying SC. There was no significant difference in PPV between quadrant and full arch scans.

Repeated bite scans taken for articulating quadrant virtual casts showed higher correlation (0.97) when compared to repeated bite scans taken for articulating full arch virtual casts (0.81). Also, repeated bite scans displayed using the intra-oral scanner software showed higher correlation (0.96) compared to the independent software (0.81). Although the correlation appears to be acceptable in all categories, keeping in mind the small sample size of repetitions.

However, one should keep in mind that this experiment was conducted in-vitro on one set of articulated zirconia ceramic casts, which does not simulate the biological environment of the oral cavity or the physiological intrusion of natural teeth with bite force. Extra-oral scanning was shown to produce virtual images with higher resolution and accuracy when compared to intra-oral scanning.[88] The small sample size (number of different scans) is also a limitation since small differences can amplify into significant changes of the numeric results. This analytic approach utilized is commonly used to verify predictive accuracy, which is clinically relevant. Nevertheless, clinical investigations with larger sample sizes are necessary to allow for a more comprehensive understanding of virtual jaw relationship records and articulation.

Chapter 5: Conclusion

The following conclusions can be made:

- There is a significant difference in occlusal contacts obtained from bite scans of different segments of the opposing dental arches, therefore H_{o1} can be rejected. This difference is more obvious in full arch scans, in which a "tilting effect" towards the site of the bite scan can be observed.
- Occlusal contacts obtained from bite scans taken for quadrant virtual arches exhibited higher sensitivity when compared to those obtained from bite scans taken for full virtual arches, therefore H_{o2} can be rejected.
- Repeated bite scans taken for quadrant virtual arches also exhibited higher correlation and were more reproducible when compared to those taken for full virtual arches.

The following clinical recommendations can be made:

- Quadrant scans should be used in single unit cases to achieve the most accurate occlusal representation.
- Multiple virtual interocclusal records should be taken when attempting to articulate full arch scans to reduce the "tilting effect" towards a single virtual interocclusal record.
- In cases where the software does not allow for multiple virtual interocclusal records, the single virtual interocclusal record should be taken as close as possible to the area of interest (tooth preparation or implant).

- If full arch scans are taken with no specified site of interest (for diagnostic or record purposes), virtual interocclusal records are to be taken in the anterior region (cuspid to cuspid) to produce more accurate reproduction of the majority of occlusal contacts.

The following topics are recommended for further investigation:

- In-vivo studies with larger sample sizes are necessary to allow for a more comprehensive understanding of virtual jaw relationship records and articulation.
- Virtual simulation of dental collisions when articulating virtual casts to resolve the “tilt effect” and the inaccuracy of perforations.

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