Accuracy of Composite Attachment Position with Four Different Indirect Bonding Techniques

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THESIS
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This thesis is dedicated to all the educators in my family who instilled in me the pursuit of knowledge from day one.

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LIST OF ABBREVIATIONS

ABO-OGS	American Board of Orthodontics Objective Grading System
B/L	Buccal-Lingual
BJP	Binder Jetting Processing
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CAT	Clear Aligner Therapy
CLIP	Continuous Light Interface Processing
DLP	Digital Light Processing
FFF	Fused Filament Fabrication
I/G	Incisal-Gingival
IDB	Indirect Bonding
IPR	Interproximal Reduction
M/D	Mesial-Distal
PVS	Polyvinyl Siloxane
SLA	Stereolithography Apparatus
VSE	Vinylsiloxanether

SUMMARY

A key feature of doctor-provided clear aligner orthodontic therapy (CAT) is the utilization of composite resin attachments as additional surfaces of engagement to assist with tooth movement. Composite attachments are placed onto the patients' teeth using indirect bonding (IDB). Despite the widespread use of IDB for composite attachments in CAT, there is a paucity of research on this topic. One technique variation used clinically involves sectioning transfer trays into smaller pieces as to make tray removal from the mouth easier and decrease attachment debonding upon tray removal. Although considered by some to be useful, this strategy has never before been validated for achieving accurate attachment positions. This *in vitro* study is concerned with elucidating the effect of tray sectioning on IDB accuracy.

Twenty 3D printed dental models without attachments were bonded with composite resin attachments using thermoformed plastic template trays fabricated from physical reference models. Four different indirect bonding techniques were employed (n=5): 1) whole arch (Whole), 2) whole arch, buccal segment only (Halves), 3) sextants (Thirds), and 4) sextants, buccal segment only (Sixths). After bonding, scans of the bonded models were imported into software for 3D superimposition with the reference digital model.

In general, all IDB techniques studied achieved clinically acceptable and similar attachment positions in the buccal-lingual, mesial-distal, incisal-gingival dimensions, and in tip. We observed a trend of incisal and lingual attachment positional bias, and negligible mesial-distal bias. Attachment tip was the least accurate positional measurement in this study.

I. INTRODUCTION

1.1 Background

Clear Aligner Therapy (CAT) has become a very popular orthodontic technique since the Invisalign® system was first made available to the public in 1999. According to Align Technology, over 6 million cases have been treated with the Invisalign® system. Over the years, competing products such as ClearCorrect™ (ClearCorrect, LLC, Round Rock, TX), SureSmile® Aligners (Dentsply Sirona, York, PA) and 3M™ Clarity™ Aligners (The 3M Company, Maplewood, MN) have entered the marketplace. With advances in (CAD/CAM) technology and workflow, some doctors are even producing in-office clear aligners. It is clear that CAT has become a mainstay in orthodontics and has the potential to increase in popularity.

A key feature of doctor-provided CAT options such as Invisalign® and ClearCorrect™ is the utilization of composite resin attachments. Composite attachments in CAT are somewhat analogous to orthodontic brackets in traditional orthodontic treatment in that they act as handles upon which an active orthodontic force is applied to achieve dental movement. Their proposed benefits include enhancement of aligner retention[1], and of improved local and global dental movements[2–5]. They are not a feature of direct-to-consumer products such as SmileDirectClub™ (SmileDirectClub, Nashville, TN), Candid™ (Candid Co., Brooklyn, NY), and Orthly® (Orthly, Inc., Philadelphia, PA). Composite attachments are placed onto the patients' teeth using indirect bonding techniques (IDB). IDB in a general sense is a process by which orthodontic appliances are transferred to patients' dentition from an idealized extra-oral setup using trays, jigs, or other transfer devices. In the context of CAT attachments, IDB describes the transferring of unpolymerized resin attachments from a template/mold onto tooth surfaces, followed by resin polymerization. The body of literature regarding IDB in the context of bonding traditional orthodontic brackets has been growing ever since the technique was first proposed in the 1970s.[6] There are a number of technique variations that have been practiced in clinical orthodontics regarding IDB of CAT attachments based on expert opinion; however, these techniques have been disseminated mainly through word-of-mouth, personal communication, or online mediums and have been implemented without any scientific proof. Despite the widespread use of composite attachments in CAT, there is a paucity of research regarding how accurate different IDB techniques are in achieving accurate attachment position.

The aim of this study is to three-dimensionally (3D) evaluate the deviation of attachment position from the ideal position using four IDB technique variations.

1.2 Specific Aims

The purpose of this *in vitro* study is to elucidate the effects of different IDB tray sectioning strategies on the accuracy of resin attachment position. Clinicians often utilize sectioned IDB template trays for resin attachment bonding for reasons related to ease of tray removal and improving bond success, and reducing difficulty with dental isolation. For instance, the lingual portions of a tray may be removed if there are only buccal surface resin attachments, or the tray may be cut into sextants because the clinician plans to bond a limited number of teeth at one time. In this study, we measured the deviation of resin attachment positions from the original digital template positions after utilizing different IDB techniques. The template trays were split into buccal and lingual parts, and also sectioned into sextants. Four tray-sectioning variations were studied: 1) Whole arch (Whole), 2) Whole arch, buccal segment only (Halves), 3) Sextants (Thirds), and 4) Sextants, buccal segment only (Sixths). The deviations from the ideal positions in terms of the buccal-lingual (B/L), mesial-distal (M/D), and incisal-gingival (I/G) dimensions, and tip angulation were investigated.

1.3 Null Hypothesis

There is no mean difference of attachment position in 3D on the buccal-lingual, mesial-distal, incisal-gingival and tip, among the attachment orientation, tooth type and bonding techniques.

II. LITERATURE REVIEW

To the author's knowledge, there is no published article to date on the comparison of accuracy of any composite attachment IDB method or variations thereof. This is the first study that utilizes three-dimensional software analysis to study the accuracy of composite attachment indirect bonding (IDB) technique variations. It provides a starting point for the orthodontic community to evaluate the similarities and differences between IDB of composite attachments and traditional orthodontic brackets. This study also contributes to the contemporary orthodontic knowledge in that it explores the effect of different IDB technique variations which clinicians employ, and yet have not been well studied. With CAT becoming an increasingly popular modality of orthodontic treatment, and with composite attachments being a prominent feature of doctor-provided CAT, it is important to study how accuracy of composite attachment position could be affected by the different techniques of the available IDB practices.

2.1 Indirect Bonding of Orthodontic Appliances

Indirect bonding in a general sense is a technique in which a replica of the dentition is used to place orthodontic appliances in an ideal fashion extra-orally followed by the transfer of the ideal setup of brackets/unpolymerized resin attachments onto the dentition in a clinical procedure using a transfer tray/template or other appliances. It is an alternative to direct bonding, when brackets are placed and cured directly onto teeth clinically. There has been a number of articles studying IDB ever since the technique was first proposed in 1972.[6] The articles have focused on adhesive selection and bond success/failure, bracket setup strategies, tray design and clinical techniques, achieved accuracy, and other such topics.[7] This review section will cover a number of articles with different purposes but will primarily focus on technique accuracy as it relates to variations in tray design. Zero articles in the review studied composite attachments. Due to a paucity of literature related to resin attachments, the literature review in this section was based solely on the extensive studies of IDB for orthodontic brackets.

An 1982 study[8] by Aguirre et al. found that single-layer polyvinyl siloxane (PVS) IDB performed better with upper and lower canine angulation and upper canine vertical placement than direct bonding technique. However, the study's design was called into question and further investigation took place.

Koo et al.[9] used a light-body PVS and outer 0.5 millimeter (mm) thermoform shell in their study and found that IDB from second premolar to second premolar resulted in deviations of 0.31 mm in height, 0.18 mm in M/D position, and 2.43° in tip. Their photography-based *in vitro* study compared IDB to the direct bonding of brackets and concluded that IDB performed equally to direct bonding in M/D position and tip, and better than the direct bonding in vertical position, but that neither IDB nor direct bonding achieved ideal bracket placement.

An *in vivo* split-mouth study comparing a single thermoform layer IDB technique to direct bonding from canine to canine by Hodge et al. agreed that IDB achieved statistically similar results to direct bonding.[10] This photography-based study found that the mean error for the IDB group was 0.20 mm to the gingival, 0.05 mm to the distal and 0.02mm tilted to the mesial (the authors in this study converted the angular error into the linear distance of the chord of the arc of the angular difference).

Few investigators have studied IDB accuracy among different tray set-ups. In an *in vitro* photography-and-grid based study covering first molar to first molar, Castilla et al.[11] found that double-PVS, PVS-putty, and PVS-thermoform groups were highly accurate, and significantly more accurate than the single- or double-thermoform groups in I/G discrepancy, especially in anterior teeth. Single-thermoform performed the worst overall with mean differences of significance ranging from 0.11 mm to 0.49mm; this technique also had the greatest number of mean deviations exceeding 0.13 mm between working and experimental models.

Wendl, et al.[12] studied the accuracy of a novel IDB transfer device with steel wire extensions to hold brackets in place, which used air pistons to push brackets onto teeth. This *in vitro* study used a 3D laser scanner and 3D software analysis and found that the device produced mean deviations of 0.15 mm, 0.17 mm, and 0.19 mm along x, y and z axes, respectively. The authors concluded that this was “an extremely accurate transfer” technique.

Kim et al.[13] published an *in vitro* study utilizing individual CAD/CAM transfer jigs and 3D software analysis and found that mean linear deviations ranged from 0.05 mm to 0.19 mm, with the vertical dimension being the least accurate; while mean angular deviations ranged from 1.1 to 3.36°, with torque being the least accurate, rotation being the most accurate, and tip in between.

Another jig-based IDB study published by Schubert et al.[14] found that the Quick Modul System® for bonding lingual brackets produced mean linear errors from 0.10 to 0.13mm and mean angular errors from 2.20 to 3.21°. This study was unique in that it was an *in vivo* study, which utilized an intraoral scanner to capture achieved bracket positions.

An *in vivo* study utilizing cone beam computed tomography (CBCT) scans of patients after IDB using a PVS putty transfer tray concluded that the technique was highly accurate.[15] Mean deviations for linear measurements ranged from -0.012 mm (distal bias on incisors) to -0.492mm (lingual bias on premolars); and those for angular measurements ranged from -0.040° (distal rotation on premolars) to 0.405° (mesial rotation on molars). Overall, there was a modest directional bias of deviations toward the buccal and the gingival in this study.

According to a review by Kalange and Thomas, most modern transfer trays for IDB of brackets are based on either a dual-layer clear tray (soft inner, hard outer) or a single-layer full PVS tray design.[7] Existing studies pertaining to the accuracy of IDB did not always adhere to this trend, and therefore there was much heterogeneity among study designs. Transfer appliance design varied widely and included single- and double- layer trays of PVS or thermoform material or a combination of both; single-tooth jigs, and a whole-arch metal transfer device with air pistons. There were also other major differences among studies, such as *in vitro* or *in vivo* designs, 2D measurements based on photographic methods or 3D measurements from digital casts obtained from desktop scanners or intraoral scanners, or CBCT machines. Some studies bonded the brackets onto models or dentitions with malocclusion while others bonded the brackets onto those with well-aligned setups.

Due to the varieties of design and techniques in the studies above, there is no one standard for clinical significance with regards of IDB accuracy. Several papers have cited the American Board of Orthodontics Objective Grading System (ABO-OGS)[16] to establish their cutoff values[15,13,11], but their reasoning and interpretations varied. Grünheid et al.[15] selected 0.5 mm and 2° as cutoffs because 0.5 mm deviations in alignment and marginal ridge categories resulted in point deductions and because 2° in tip of an average molar resulted in marginal ridge discrepancies of 0.5 mm. Kim et al. set their cutoffs as 0.5 mm based on the ABO-OGS, and 1° based on a study, which found that laypeople and prosthodontists could perceive 1° of asymmetry in esthetics.[13] Castilla et al. set 0.13 mm as a linear difference cutoff and suggested that errors greater than or equal to 0.25 mm were clinical significant. The authors reasoned that if two adjacent brackets were 0.13mm off in opposite directions, the significance threshold would be reached.[11] Based on the literature, linear deviations ranged between 0.13 mm to 0.5 mm and angular deviations between 1 and 2° were deemed clinically significant in the context of IDB of orthodontic brackets.

Despite study differences, overall, there is a general impression in the literature about IDB accuracy. IDB of traditional orthodontic appliances appears to be at least as accurate as direct bonding[9,10] and generally delivers clinically acceptable results,[9–11,13,15] depending on the thresholds used. Studies overall have shown that for linear measurements, IDB tends to have weakness along the vertical axis[9–11,13,15];there is a suggestion that there is a tendency for B/L error,[12,15] as well. Mean angular errors in the reviewed studies were less approximately 3-3.5° or less. One study suggested that stiffer transfer trays such as those incorporating PVS performed better than thinner, less rigid trays based on thermoform material.[11] To date, there are no published systematic reviews or meta-analyses on the subject of IDB, so one should be guarded in making strong conclusions regarding its accuracy.

2.2 Clear Aligner Composite Attachments

Composite attachments are resin objects of various sizes and geometries that are bonded onto tooth surfaces to enhance the expression of planned tooth movements. They provide additional surfaces upon which sequential clear aligners can engage to move teeth towards the desired outcome.

Attachments have been used in situations such as space closure, incisor torque, premolar/molar distalization, dental derotation, intrusion, extrusion, expansion; and in malocclusions such as open bite, deep bite, and cross bite.[17,2,18–20,5]

Most literature on the subject of CAT studies the Invisalign® system specifically, and findings may not be applicable to other CAT systems. This section of the review will therefore cover studies mostly utilizing Invisalign® attachments but will discuss clear aligner composite attachments in a general sense.

2.2.1 Effectiveness of Attachments

The effect of attachments on tooth movement from a clinical standpoint remains somewhat unclear. In a systematic review,[2] Rossini concluded that all attachments, whether ellipsoid or rectangular, improved orthodontic tooth movement. However, when evaluating the reviewed articles in depth, the situation appears more complex. Simon et al. reported that the presence of attachments (horizontal ellipsoid for incisors, optimized for premolars, horizontal beveled gingival for molars) did not significantly affect efficacy of incisor torque, premolar derotation, and molar distalization; however, factors such as poor patient compliance, overall planned correction and velocity of correction per tray affected their results.[18] Kravitz et al. found that use of vertical ellipsoid attachments only and interproximal reduction (IPR) only did not significantly improve canine rotation.[17] They did not study the effect of coincident use of attachments and IPR; however, they noted that the highest achieved mean accuracy was from IPR and not attachments. Djeu et al. supported the use of attachments for premolar derotation but did not specify a particular attachment design or strategy for use in a treatment-outcome assessment.[21] In a more recent systematic review,[5] the authors suggested that attachments may be effective in supporting rotation, extrusion of maxillary incisors and overbite control and may be limited in efficacy in arch expansion and extraction space closure. However, it was noted that the findings should be interpreted with caution since there was high heterogeneity among included studies.

Numerous investigators have studied composite resin attachments *in vitro*. Dasy et al. found that beveled attachments significantly enhanced aligner retention while vertical ellipsoid attachment did not.[1] Hennessy and Al-Awadhi suggested that precision half-ellipsoid attachments used alone or in pairs theoretically should offer better control of rotations and root angulation.[3] This contention corresponded with a 3D finite element analysis, which concluded that the Optimized Root Control Attachments (a pair of half-ellipsoid attachments used to generate a couple on a tooth crown) helped to achieve the biomechanical force systems needed for bodily movement and prevention of undesirable tipping on a premolar.[22] Simon et al. found that optimized rotation attachments increased initial premolar rotation moment from 1.2 to 8.8 Nm. They interpreted this value as being within the orthodontic force range and concluded that planned premolar derotation should be supported with attachments.[19]

Wheeler[4] notes that the fast pace in CAT innovation often leads to research regarding CAT being case studies. Materials, protocols and attachment designs have changed over different generations of Invisalign®,[3] and some findings may therefore become outdated. Clinical studies often included previous generations of CAT, and showed limited efficacy of aligners. More recent non-clinical research show that CAT attachments are promising in terms of their biomechanical benefits but it remains to be seen whether these advantages will translate to clinical results. Nonetheless, clinicians are still avidly using attachments in their CAT treatment plans and therefore more research should be done regarding composite attachments.

2.2.2. How Attachments are Designed and Bonded

Composite attachments are bonded using indirect bonding technique (IDB). Composite attachment IDB uses a single-layer transparent thermoform template tray filled with unpolymerized resin in wells of the desired shape to transfer attachments onto tooth surfaces for polymerization. The fabrication of the template tray utilizes CAD/CAM technology. 3D digital scans of dental arches, alginate/PVS impressions or dental models are imported into specialized CAD Software and the operators/technicians then place attachments as desired digitally. The models are then 3D printed, and served as the templates upon which a thermoform transfer tray can be fabricated. After the template tray is trimmed and processed, the patient's teeth are prepared for bonding, and the template tray wells are filled with unpolymerized composite resin. The trays are seated onto patient's teeth, the composite resin attachments are polymerized, and then the template tray is removed to complete the bonding procedure.

Although composite attachments are attached using IDB, there is a paucity of research on the accuracy of the achieved attachment position and orientation. Current attachment placement protocols vary and are mostly based on expert opinion. Variations in techniques may involve sectioning strategies, application of separating mediums, material selection, composite flash removal, and tray adaptation and removal. A popular technique is to section the template tray. Operators can segment the template tray at points where there are no attachments (i.e. anterior and posterior segments) and/or split the tray (i.e, buccal and lingual aspects) before bonding for an easier removal process. Anecdotally, intraoral tray removal can be challenging after attachment polymerization. As to alleviate patient discomfort and clinician frustration, and possibly decrease attachment bond failure, some have advised tray sectioning. However, there have not been any studies on if tray sectioning affects bonding accuracy.

2.3 Intraoral Scanners

The use of intraoral scanners for study casts has been extensively validated. In a study comparing an intraoral scanner (TRIOS® Color Pod) to two desktop scanners and a CBCT machine, Wesemann[23] found that the intraoral scanner achieved comparable accuracy to the desktop scanners with regard to intermolar width, intercanine width, and arch length. The author used the following cutoffs to grade technique accuracy: less than 30 micrometers (µm), "excellent," less than 140 µm "very good," less than 250 µm "acceptable," and above 250 µm "insufficient." The Trios® scanner produced mean deviations ranging from 27 to 50 µm and was rated "very good to excellent", which was better than the R700® ("very good") and inferior to the R900® desktop scanner which was the most accurate in the study (excellent, mean deviations of 12-17 µm). These techniques were all better than scanning of a plaster model or an impression on the Promax® 3D Mid CBCT machine (rated as "acceptable", and "insufficient", respectively). The mean deviation values in this study for the Trios® scanner were similar to those of the LAVA® COS and iTero® scanners as reported by other studies. The authors concluded that intraoral scanners could be a useful alternative for desktop scanners for orthodontic applications.

A study based on 3D digital scans of dry skulls made with CBCT and iTero® scanners found that the iTero® scanner generated digital models that were more accurate than those generated by CBCT and achieved nearly one-to-one agreement with caliper measurements.[24]

Ender and Mehl[25] reported an *in vitro* study that digital impressions from different scanners, Cerec® Omnicam, Cerec® Bluecam, iTero®, and LAVA® COS, were less true and precise than conventional vinylsiloxanether (VSE) impressions, but were at least as true and precise as alginate impressions, if not better. The mean trueness of the digital scanners were 29.4 (Cerec®), 32.4 (iTero®), 37.3 (Omnicam®) and 44.9 (LAVA®) µm. The mean precision values of the digital scanners were 19.5 (Cerec®), 35.5 (Omnicam®), 36.4 (iTero®) and 63.0 (LAVA®) µm. For comparison, the VSE pour-up trueness and precision were 13.0 and 12.3 µm, respectively and alginate trueness and precision were 37.3 and 59.6 µm, respectively.

In a later *in vivo* study, the same group of investigators[26] evaluated the same scanners as above against conventional impression methods but also included the True Definition® Scanner, Trios®, and Trios® Color. However, only precision was evaluated in this study due to the nature of the clinical study design. They found that the digital scanners achieved statistically similar levels of precision to each other and that aside from the LAVA® scanner, were more precise than the alginate impressions. The Omnicam®, True Definition® Scanner, Trios® and Trios® color were even as precise as VSE digitized after pour-up but less precise than the conventional one and directly digitized VSE one. For comparison, the mean precisions were 17.7 (conventional VSE), 18.3 (Directly digitized VSE), 36.7 (VSE digitized after pour-up), 42.9 (Trios® Color), 47.5

(Trios®), 48.6 (Omnicam®) 56.4 (Cerec®), 59.7 (True Definition®), 68.1 (iTero®), 82.2 (LAVA®), and 162.2 (Alginate) µm. It seems that precision of conventional and digital impressions decreases slightly in the intraoral environment.

Based on existing literature, it appears that while intraoral scanners such as iTero® and Trios® are not as accurate as conventional high accuracy impressions or the highest-performing desktop scanners, they do achieve a comparable level of accuracy which is certainly higher than those from alginate impressions and CBCT scans. It also appears that intraoral scanners perform slightly better extra-orally, as in the case of most impression techniques.

2.4 3D Printing

3D Printing, sometimes called Rapid Prototyping or Additive Manufacturing, experienced its commercial beginnings in 1986. Many 3D printing options utilize light polymerization of resins in order to form the desired object, but powdered resins and other materials can be manipulated chemically or thermally for printing as well. Some techniques that have been used in medical and dental applications include Stereolithography Apparatus (SLA), Digital Light Processing (DLP), Continuous Liquid Interface Production (CLIP), Fused Filament Fabrication (FFF), Binder Jetting Process (BJP) and MultiJet or PolyJet. According to Stansbury and Idacavage, SLA printers can produce layers of 50 to 200 µm, down to 10 µm; CLIP can produce layers in the "10s" of µm; and PolyJet can produce layers of 20 µm.[27] According to ISO 5725-1[28], there are two components of "accuracy": trueness and precision. "Trueness" is the closeness of a mean of a set of measurements to the actual value, and "precision" is the closeness of agreement of the measurements among each other within a set.

In a study comparing SLA and Polyjet printers,[29] investigators found that the Polyjet technique was more true but that the SLA technique was more precise. Based on 3D digital superimpositions, mean deviation in precision was 23 µm for Polyjet and 46 µm for SLA, whereas mean deviation for trueness was 66 µm for Polyjet and 109 µm for SLA. Because of acceptable dimensional errors, it was concluded that 3D printed replicas of digital models were suitable for diagnosis and treatment planning.

Another study investigated the performance of the DLP, PolyJet and BJP techniques. This study measured printed replicas with calipers and compared them to measurements of a physical reference cast. They found that the DLP and Polyjet techniques produced models with high agreement of crown height and width to the reference. The BJP technique, however only had high agreement in crown width but poorer agreement in reference crown height compared to the other two techniques (mean deviation of 0.25 mm). Aside from BJP crown height, all mean differences were between 0.02 to 0.08 mm in linear deviation, and therefore the authors concluded that 3D printed dental replicas were acceptable in terms of accuracy for orthodontic uses.[30]

Kim et al.[31] in addition to the DLP and Polyjet, also included the SLA and FFF techniques in their study. They found that "the trueness of overall tooth measurements was highest for the PolyJet technique, followed by the SLA, DLP, and FFF techniques, with mean RMS values of 78, 107, 143, and 188 mm, respectively." This study was unique in that it quantified precision and not just trueness. In terms of precision, Polyjet performed the best (69 µm of mean RMS difference) followed by DLP (74 µm), FFF (89 µm), and finally SLA (176 µm). The authors noted that since they calculated values using RMS instead of positive or negative measurements, their values were not directly comparable to those of other studies. Overall, this study showed that Polyjet was the most accurate technique and SLA was the least precise of the specific printers investigated even though it was the second truest technique.

One study on CLIP[32] revealed that this technique could print objects such as cylinders with diameters of 50 µm and that this printer could print at a speed of 1000 mm/hour if resolution is sacrificed. The Carbon printer is one that uses the CLIP process.

One recent study[33] found that SLA printed models possessed transverse shrinkage based on the design of the dental model base, and that this was not seen with the Polyjet printing. The authors discussed that post-print curing may have contributed to this shrinkage, but also noted that overall, both the SLA and Polyjet produced accurate models. Brown et al.[34] compared models printed from intraoral scans with the DLP and Polyjet printers against stone models produced from alginate impressions of the same subjects. They found that there was high agreement between all models and all measurements regardless of techniques except for crown height between the DLP and stone models (mean difference of 0.29 mm). Most other mean differences in the study were below 0.13 mm.

One group of investigators[35] studying printed models using BJP technique found that 3D printed models were not comparable to stone models as differences exceeded their cutoff for clinical significance of 0.5 mm. However, it was important to note that they used a printer (ZPrinter® 450) that has a minimum feature size of 150 to 200 μm, which is poorer than the resolution of more accurate printers on the market. Thus, one should be cautioned against drawing conclusions on the inaccuracy of other printers or printing techniques.

A systematic review on digital study models which included 17 studies concluded that the use of digital models for measurements in lieu of plaster casts for manual measurements is valid because absolute mean differences were small and deemed clinically insignificant.[36] Overall, a review of the literature suggested that most 3D printed models were accurate and valid for orthodontic uses. Polyjet consistently performed well based on published studies, and DLP and SLA also performed satisfactorily, but may have some weaknesses in the transverse or vertical dimension. FFF and BJP were not well studied in the orthodontic literature but may be less accurate than other techniques. Just one study investigated and validated the CLIP technique. Some printing techniques and some printers within those technique categories were more accurate than others, so it was important to note technical specifications and capabilities when evaluating 3D printing.

III. MATERIALS AND METHODS

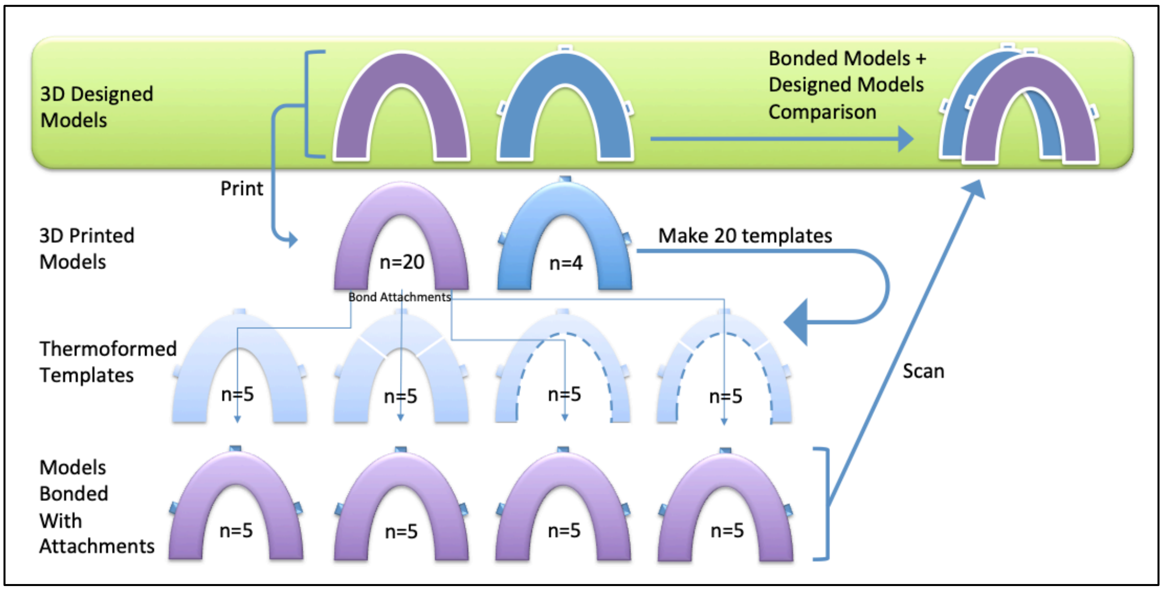

Figure 1. Schematic diagram of experimental design. Models with attachments were designed digitally and printed for fabrication of the template trays in four experimental groups. Models without attachments were also printed for the attachment bonding procedure. 3D scans were obtained after bonding and imported into 3D software for measurements of attachment positional deviation.

3.1 Designing and Printing of Casts and Production of Template Trays

The maxillary arch of a dental model (M-PVR-860 with Edentulous # 5, # 20 and Endodontic # 3 and # 8, Columbia Dentoform Company, Long Island City, NY) with a well-aligned setup was scanned with the iTero® Element scanner. The .stl file was exported through OrthoCAD® (Align Technology, San Jose, CA). The .stl file was imported into Meshmixer® 3D (Autodesk, Inc., San Rafael, CA) for reference model design. Because tooth UR4 was missing, a mirror image of the existing UL4 tooth was merged to the arch to fill the edentulous space. The third molars were trimmed such that the mesial half of the crown was intact and the distal half was trimmed off with a bevel toward the model base as to reduce undercuts and allow for a pivot area for thermoform tray removal. Four attachments per sextant were placed on all plastic teeth except 3rd molars and canines for a total of twelve attachments per arch. The rectangular attachments were 3.0 x 1.5 x 1.5 mm in dimension with a taper at the gingival aspect to reduce the severity of undercuts. Half the attachments were placed horizontally (second molars, second premolars, lateral incisors bilaterally), and half were placed vertically (first molars, first premolars, central incisors bilaterally). The attachments were placed in the center of the crown part with neutral torque and rotation, with an offset of approximately 0.75 mm and oriented either along the long axis of the crown or perpendicular to it depending on the tooth. The modified model was saved in .stl format for reference as well as printing of template models. In addition, a version of the digital models without attachments was saved for the printing of bonding models.

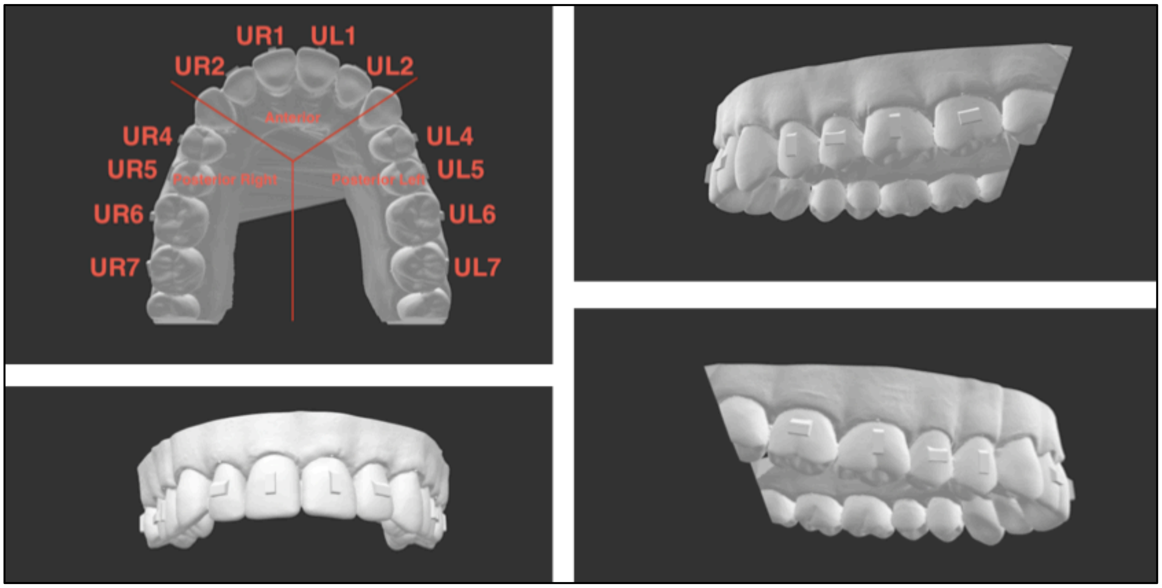

Figure 2. Multi-view composite of reference digital cast with attachments. The occlusal, anterior, posterior left and posterior right views are shown.

Approximately 15 template models and 40 bonding models were generously provided by a commercial dental lab (Sculpture Studios, Cary, NC) using the Carbon M1 printer (Model 102222, software v1.18-564.50) in the proprietary DRP® 10 Resin. After printing, the lab performed a 3-stage alcohol wash, two simple rinses and a final 15-minute agitated wash, followed by a three-minute UV polymerization per side for all models.

All models were visually inspected for quality control and ultimately 10 of the template models and 25 of the bonding models were used in the study. From the template models, the template trays were thermoformed using the Drufomat Scan (Dentsply International Raintree Essix, Sarasota, FL) and 0.5 mm thick Essix A+® (Dentsply International Raintree Essix, Sarasota, FL) material according to manufacturer instructions. A thin application of cooking spray (PAM® Original, Conagra Brands, Inc., Chicago, IL) was used as a separating medium. If model fracture occurred during removal of the template tray, no more template trays were thermoformed from that broken model. No more than 5 template trays were thermoformed from each template model to reduce errors of measurement due to model abrasion. The template trays were trimmed and scalloped at the gingival margin. Five trays were left intact, five trays were split into buccal and lingual halves, five trays were segmented into sextants and five trays were segmented and split into buccal and lingual halves. A vent hole for excess resin flash was made with a dental explorer from the intaglio surface out in the approximate middle facial of each attachment well to allow for excessive composite to extrude out when seating the template trays on the models.

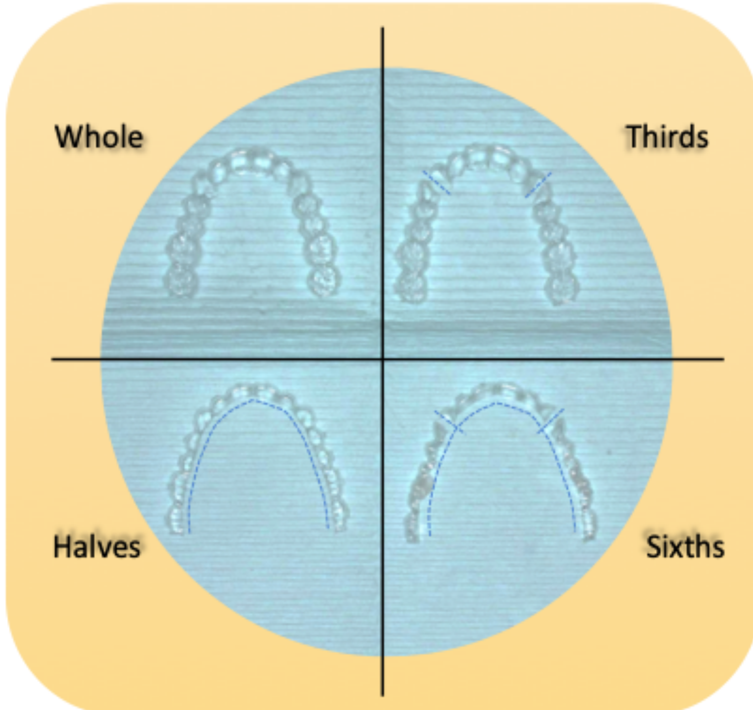

Figure 3. Depiction of tray sectioning in the four bonding techniques studied

3.2 Bonding of Attachments and Digitization of Bonded Models

Each template tray was used once to place composite attachments onto the bonding models. The cooking spray oil was applied with a microbrush to intaglio surfaces of attachment wells and the excess was removed with a cotton pellet. Flow Tain™ (Reliance Orthodontic Products Inc., Ithasca, IL) was loaded into each well of each segment of the attachment template tray. The bonding took place at a dental chair unit with the assistant operator (T.N.) sitting to the virtual patient's left and the bonding operator (Z.C.) to the virtual patient's right. The template tray was seated onto the bonding models with a cotton roll and firm digital pressure on the occlusal surface by the assistant operator. College pliers were used by the bonding operator to adapt the tray to each tooth incisally and gingivally, excess composite from the vent hole was wiped away with a microbrush, followed by composite resin polymerization for 20 seconds using a hand-held generic LED light curing unit (manufacture unknown). The path of attachment bonding started from the distal to the midline on upper left quadrant, then the midline to the distal on upper right quadrant. The assistant operator rotated the dental arch in such a way as to simulate a patient's head rotating to orient the attachments being bonded towards the bonding operator. After bonding, a high speed handpiece with a round bur (#2) was used to remove the polymerized excess composite from the vent holes to prevent interlocking between the attachments and the template trays. The template trays were removed from the bonding models using a scalpel as needed to score/cut the template trays for ease of tray removal.

Figure 4. Image of the bonding procedure

Because of poor bonding results in the anterior segment of the Sixths group, the IDB procedure for 5 additional bonding models was repeated. In the second set of Sixths group casts, the posterior segments had poor bonding results. Therefore, we decided to analyze posterior attachments only on the first round of the Sixths group casts, and anterior attachments only on the second round of Sixths casts to maximize the number of attachments that could be analyzed.

All the bonding models after placement of all attachments were scanned using iTERO® Element intraoral scanner and exported into .stl format through OrthoCAD®.

3.3 Selection Criteria for Attachments to be Measured

Prior to performing measurements, each digital model was inspected per attachment site. If the corners of an attachment were clear enough and were without evidence of damage such that at least one diagonal reference line could be drawn, the attachment was included for measurements. The first reference line considered was from distal gingival to mesial incisal, but if either of these two corners was damaged or unclear, the alternate reference line (mesial gingival to distal incisal) was used. If there was damage to the attachments such that no accurate diagonal reference line could be drawn, the attachment was excluded from the measurement. Examples of exclusion criteria include: 2 chipped corners along the shorter leg of the attachment, 3 or more chipped corners, or no attachment at all. We logged whether the default or alternative reference line was to be used for measurements, and also logged excluded attachments.

3.4 Measurements Recorded and Measurement Technique

To complete the measurement process, 3D Slicer® analysis software with Q3DC and CMFReg extensions was used.

In 3D Slicer (The Slicer Community), the original digital reference model was landmarked. Using the CMFReg extension tool, a set of 16 anterior fiducial Landmarks and 32 posterior landmarks were placed for fiducial superimposition. The 16 anterior landmarks were the cingulum of all anterior teeth from canine to canine, the cusp tip of the canines, and the mesial and distal incisal angles of the incisors. The 32 posterior landmarks were all buccal and lingual cusp tips from first premolars to the mesial half of third molars and the cusp tip and cingulum of canines.

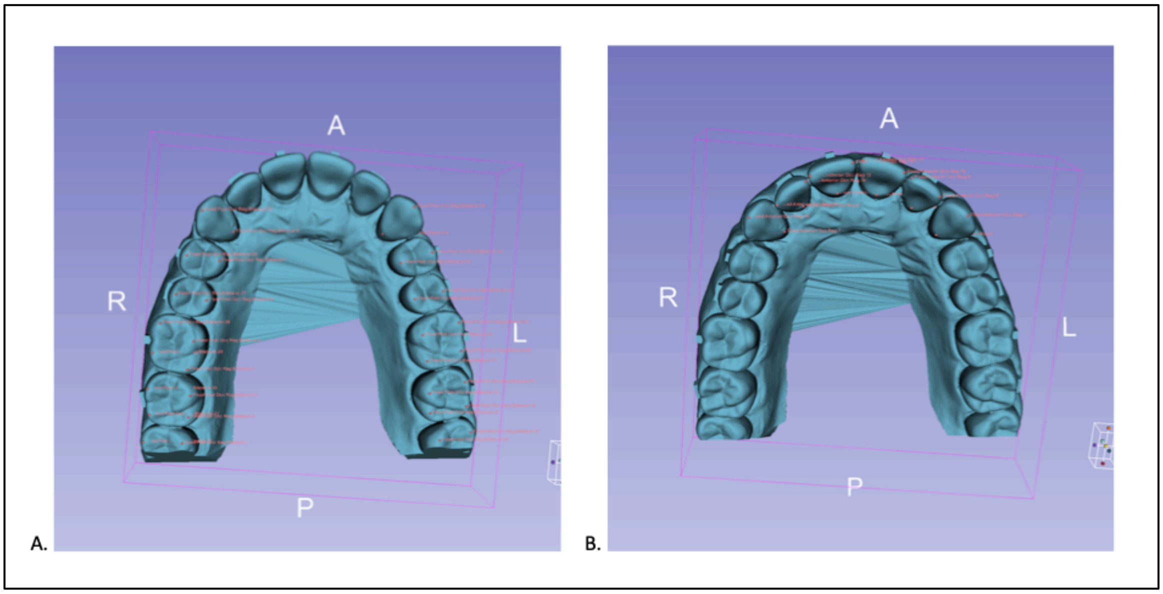

Figure 5. Depiction of A.) 32 posterior fiducial landmarks and B.) 16 anterior fiducial landmarks

Then using the Q3DC extension, all reference model attachments were landmarked on their four corners. Lastly, 12 different reference views, one for each attachment, were saved such that each attachment was oriented orthogonally to the XYZ axes in its respective view. In 3D Slicer, the XYZ system was described in anatomical terms, and the objects existed in a 3D box.

There were Superior-Inferior, Left-Right, and Anterior-Posterior dimensions with 6 walls (S, I, L, R, A, P). Anterior attachments were oriented orthogonally to the anterior wall of the box, Posterior left attachments to the left wall, and posterior right attachments to the right wall. The 12 saved reference views allowed for the measurement of deviation from the ideal attachment position in three dimensions after superimposition.

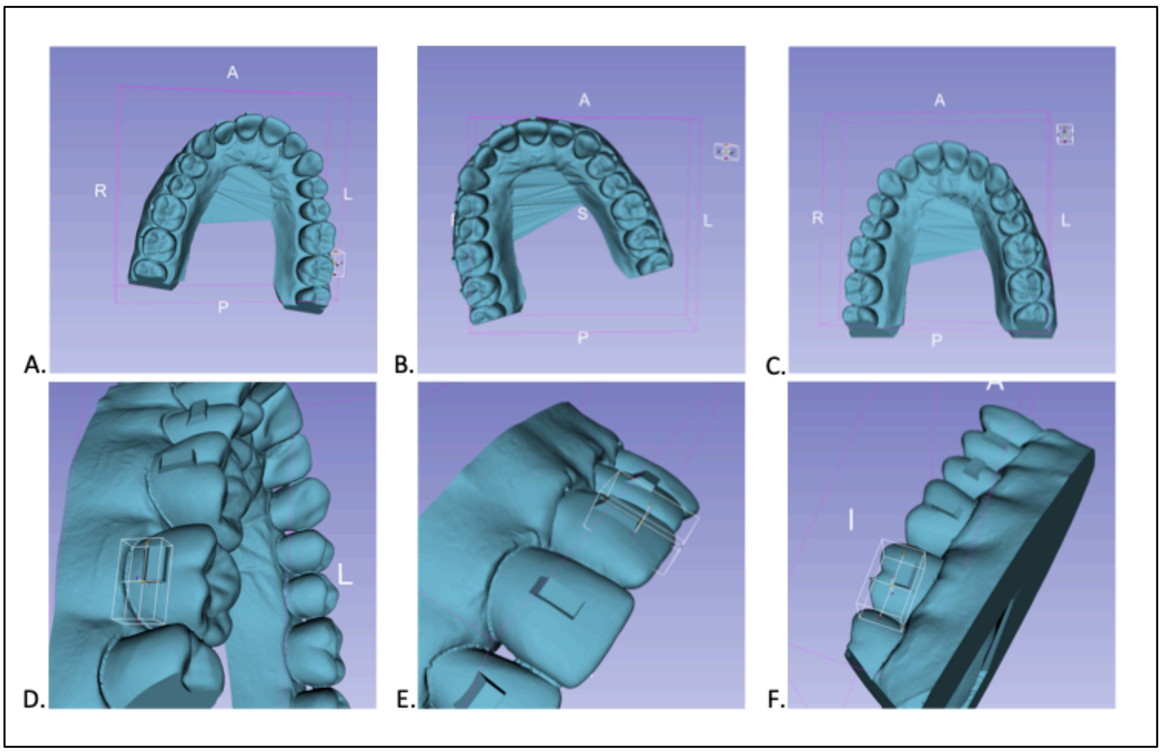

Figure 6. A-C: Depiction of orthogonal orientation of UR7, UL1 and UR7 attachments to the global coordinate system, respectively D-F: Detail of orthogonal orientation of UR7, UL1 and UL7, respectively, using a reference box tool that is orthogonal to the global coordinate system.

The digitized experimental models were landmarked in the same way for anterior and posterior fiducials and for the designated diagonal corners as determined during the inclusion/exclusion step.

CMFReg was used to superimpose the reference and test models. Posterior fiducial superimposition was completed for posterior attachment measurements and anterior fiducial superimposition was then completed for anterior attachment measurements. As each attachment was measured, the superimposed models were oriented according to the attachment's corresponding reference view as described above.

Q3DC tool was used to calculate the midpoint of the reference diagonals of test attachment and their distance in all three dimensions (I/G, M/D, B/L) away from the midpoint of the reference attachment in mm. A positive linear distance indicated gingival, mesial, and buccal biases. Then, the angular (tip) difference between the corresponding diagonal reference lines was calculated in degrees. A positive angular value indicated increased mesial tip, which meant a deviation that corresponded to a tooth with more distal root angulation than the reference, if the gingival point of the reference lines represented the root apex.

All measurements were recorded on a Microsoft Excel spreadsheet. Each attachment was labeled for the cast it was from, the Bonding Technique Group (Whole, Halves, Thirds, Sixths), Attachment Orientation (Vertical, Horizontal), and Tooth Type (Upper Right Molar, Upper Right Premolar, Upper Right Incisor, Upper Left Incisor, Upper Left Premolar, Upper Left Molar).

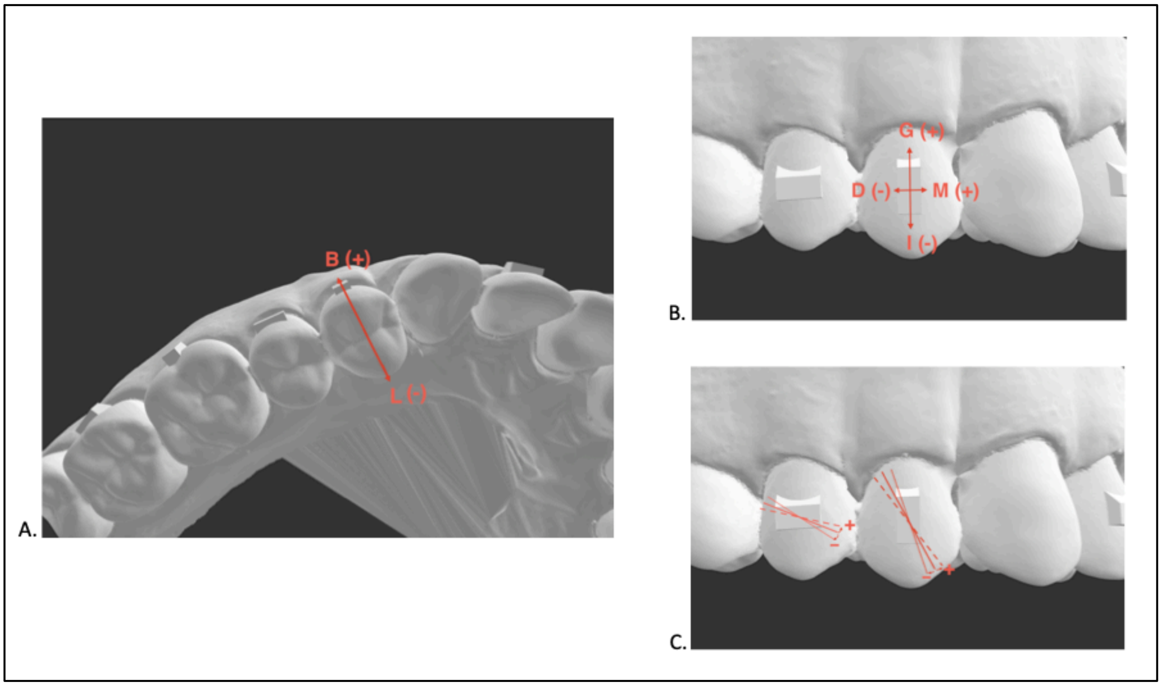

Figure 7. A-C: Depiction of the sign (+/-) conventions used in this experiment

A.) Buccal-lingual dimension B.) Mesial-distal and incisal-gingival dimensions C.) Tip

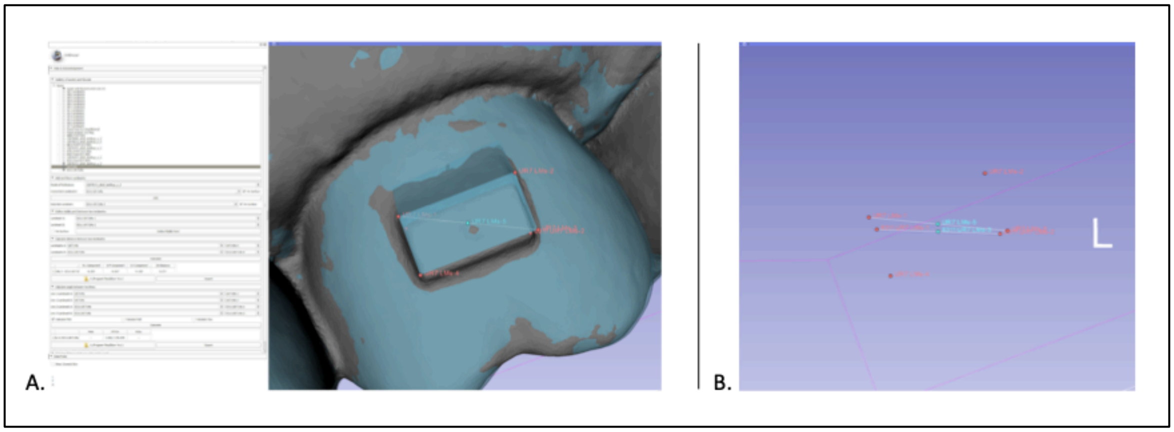

Figure 8. A-B: Depiction of performing 3D Slicer measurements on an attachment A.) with models visible and B.) Landmarks visible only

<u>3.5 Verification of 3D Printer and Scanner Accuracy</u>

The gold standard intra-arch cast measurements and intra-operator reliability for 3D software measurements was determined by performing intra-arch measures on the original digital template model 5 times using 3D Slicer and calculating the means and standard deviation (S.D.). The gold standard inter-incisal, inter-canine, and inter-molar distances were 29.63 mm, 42.21 mm, and 51.25 mm with S.D. of 0.05 mm, 0.02 mm, and 0.05 mm, respectively. The reference measurements were established and the low S.D. indicated the operator was reliable in the 3D intra-arch measurements.

To verify the accuracy of the Carbon® printer, 5 template models were randomly selected for intra-arch measurements. Using the Carrera Precision 6-inch digital caliper, one of these 5 models was measured a total of 5 times for all intra-arch distances to determine caliper reference distances for this cast to the nearest 0.01 mm, and also intra-operator caliper reliability. The other 4 models were measured once each for inter-incisor, inter-premolar and inter-molar distances. The mean inter-incisal, inter-canine, and inter-molar distances for the single cast repeated measurement using digital calipers were 29.46 mm, 42.62 mm, and 51.34 mm with S.D. of 0.05 mm, 0.09 mm, and 0.10 mm, respectively. The small S.D. indicated the operator was reliable in caliper measurements. The mean inter-incisal, inter-canine, and inter-molar distances across the 5 casts were 29.51 mm, 42.54 mm, and 51.39 mm with S.D. of 0.06 mm, 0.11 mm, and 0.15 mm, respectively. The mean measured distances were 0.57%, 0.78%, and 0.27% away from the digital reference distances, respectively. The low percentage deviation and low S.D. indicated the Carbon® printer was accurately reproducible in inter-arch dimensions.

To verify the accuracy of the iTero® scanner, the same cast used for caliper intra-operator reliability was scanned 5 times. The resulting scans were measured for all intra-arch distances. The mean inter-incisal, inter-canine, and inter-molar distances of the 5 scans were 29.52 mm, 42.12 mm, and 51.24 mm with S.D. of 0.07 mm, 0.02 mm, and 0.05 mm, respectively. The mean measured distances were 0.20%, 1.12%, and 0.19% away from the caliper reference distance of this cast. The low percentage deviation and low S.D. indicated the iTero® scanner was accurate in inter-arch dimensions. Additionally, the 5 repeated scans were superimposed in GeoMagic software (3D Systems, Morrisville, NC) to generate a “heat map” to evaluate dimensional deviations among the scans. The global registration analysis found that the average distance among the casts was 0.015 mm, S.D.= 0.025 mm. The heat map indicated minute deviation from the anterior teeth back to first molars, and some minor deviation patches at the second and third molars. The small average deviation and small S.D. of the heat map indicated that the iTero scanner is also accurate from a global registration perspective.

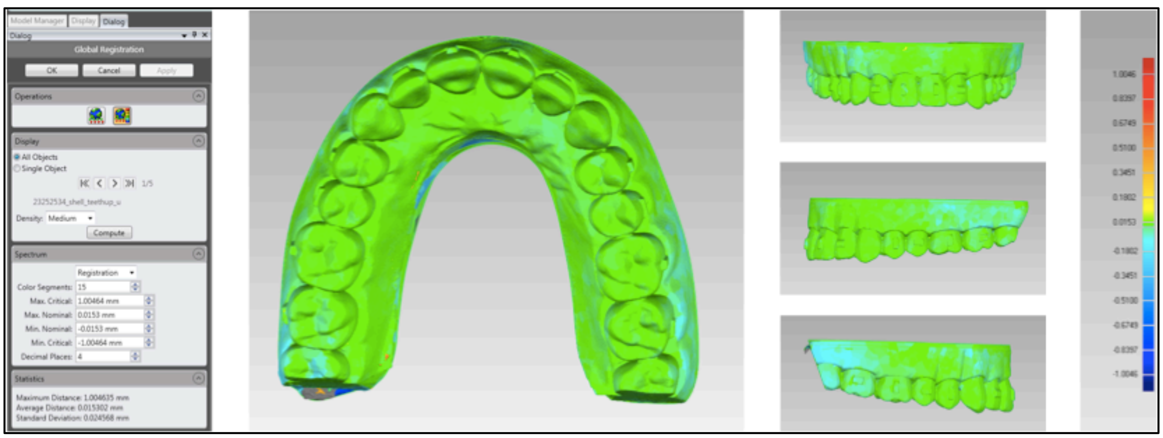

Figure 9. Multi-view composite of GEOMAGIC superimpositions of 5 iTero scans of the same cast

<u>3.6 ICC Intra-/Inter- Reliability Testing</u>

The intra class correlation coefficients (ICC) were determined for each of the study variables as an indicator of consistency on the study method.

To determine the intra-reliability measurements, one investigator (Z.C.) assessed five casts twice on UR7 B/L, UR7 M/D, UR7 I/G and UR7 Tip.

The correlation coefficients on the study variables: UR7 B/L, UR7 M/D, UR7 I/G and UR7 Tip, for the intra reliability were approximately 0.80 and higher, indicating a good degree of intra-reliability for the principal investigator on the study method.

To determine the inter-reliability measurements, two investigators (Z.C. and R.M.) assessed five casts once on UR7 B-L, UR7 M/D, UR7 I/G and UR7 Tip.

The correlation coefficients on the study variables: UR7 B/L, UR7 I/G and UR7 Tip, for the inter reliability were approximately 0.80 and higher, indicating a good degree of inter-reliability between two investigators on the study method, except for the variable UR7 M/D that indicated correlation coefficient of only approximately 0.70.

On the same casts, the same inter- and intra- reliability coefficients were determined for measurements on UL1, but they failed to reach an acceptable value (<0.8). Therefore we excluded all anterior attachments from the statistical analysis.

3.7 Statistical Analysis

The mean differences among the levels in each of the three factors, orientation of attachment, bonding technique group and tooth type on the four studied variables B/L discrepancy, M/D discrepancy, I/G discrepancy and tip discrepancy, were investigated using ANOVA. Depending on whether the assumption of equal variances were violated, the post hoc Games Howell test was the choice for the multiple comparison test if the violation was indicated. Independent Student t-test was used to evaluate the difference between pairs.

Statistical significance was set at 5%.

The statistical analysis was performed using SPSS v. 25.0. (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.)

3.8 IRB

This study did not use human or animal subjects and therefore was IRB exempt.

IV. RESULTS

4.1 Results

The statistical analysis was performed using absolute values to study deviation of the four dependent variables in an absolute sense. All reported differences of statistical significance in this study were calculated with absolute values. However, due to the nature of the research topic, directional bias is of interest in the study. Therefore, we also reported calculated means using +/- signs to describe any directional bias of the four dependent variables. Reporting on directional bias followed analysis with absolute values. Unless otherwise specified, the means reported were calculated with absolute values. At times, means calculated with absolute values were described with phrases such as “in an absolute sense” for the sake of clarity.

Means calculated using +/- signs were reported with phrases such as “in terms of directionality” or “had a bias towards.”

The following were the statistically significant mean differences found on each variable.

4.1.1 Buccal-Lingual Discrepancy

The main effect among the levels of bonding technique group in the presence of orientation of attachment, and tooth type showed statistically significant mean differences, p-value = 0.034.

One-way ANOVA among levels of bonding technique group did not show statistically significant mean differences, p-value = 0.068. This result did approach, but did not reach, significance.

The main effect among the levels of tooth type in the presence of orientation of attachment, and bonding technique group showed statistically significant mean differences, p-value < 0.001.

One-way ANOVA among levels of tooth type showed statistically significant mean differences between upper left molars and upper right molars, between upper left molars and upper right premolars, between upper left premolars and upper right premolars (p-values = 0.047, < 0.001, and < 0.001, respectively).

Mean B/L discrepancy of upper right premolars (0.099 mm, S.D. = 0.073 mm) was lower than those of upper left molars (0.204 mm, S.D. = 0.089 mm) and upper left premolars (0.194 mm, S.D. = 0.059 mm); (Table I).

Mean B/L discrepancy of upper left molars was higher than those of upper right molars (0.144 mm, S.D. = 0.101) and upper right premolars. The mean discrepancy of upper left premolars was higher than the one of upper right premolars (0.099 mm, S.D. = 0.073 mm).

TABLE I. ABSOLUTE VALUES OF MEAN AND STANDARD DEVIATION OF BUCCAL-LINGUAL DISCREPANCY BY TOOTH TYPE

Tooth Type	n	B/L Discrepancy (mm) ± SD
Upper Left Molar	37	0.204 ± 0.089 [a, b]
Upper Left Premolar	33	0.194 ± 0.059 [c]
Upper Right Molar	35	0.144 ± 0.111 [a]
Upper Right Premolar	37	0.099 ± 0.073 [b, c]
[a] $p=0.047$, [b] $p<0.001$, [c] $p<0.001$		

Overall, B/L deviation values on the left side were greater than those of the right side in an absolute sense.

When evaluating directional bias, overall, mean value of B/L discrepancy across all attachments was -0.150 mm, S.D = 0.106 mm, indicating a lingual directional bias.

The mean values of B/L discrepancy for upper right premolars (-0.078 mm, S.D. = 0.095 mm) and upper right molars (-0.137 mm, S.D. = 0. 111mm) were less negative compared to those of upper left molars (-0.195 mm, S.D. = 0.106 mm) and upper left premolars (-0.194 mm, S.D. = 0.059 mm); (Table II).

All tooth types had a lingual bias, but more so on the left side teeth.

TABLE II. MEAN AND STANDARD DEVIATION OF BUCCAL-LINGUAL DIRECTIONAL BIAS BY TOOTH TYPE

Tooth Type	n	B/L Directional Bias (mm) ± SD
Upper Left Molar	37	-0.195 ± 0.106
Upper Left Premolar	33	-0.194 ± 0.059
Upper Right Molar	35	-0.137 ± 0.101
Upper Right Premolar	37	-0.078 ± 0.073
All	142	-0.150 ± 0.106
(-) sign denotes lingual direction		

4.1.2 Mesial-Distal Discrepancy

The main effect among the levels of bonding technique group in the presence of orientation of attachment, and tooth type showed statistically significant mean differences, p-value = 0.006.

One-way ANOVA among levels of bonding technique group showed statistically significant mean M/D discrepancy differences between Whole and Thirds groups, between Halves and Thirds groups, and between Thirds and Sixths groups, p-values= 0.016; 0.044 and 0.008, respectively. The mean of Whole group (0.077 mm, S.D. = 0.062 mm) was higher than that of

Thirds group (0.039 mm, S.D. = 0.034mm). The mean of Halves group (0.072 mm, S.D. = 0.065 mm) was higher than that of Thirds group. The mean of Sixths group (0.100 mm, S.D. = 0.107 mm) was higher than that of Thirds group (Table III).

Thirds group had less mean value of M/D discrepancy than all other bonding technique groups in an absolute sense.

TABLE III. ABSOLUTE VALUES OF MEAN AND STANDARD DEVIATION OF MESIAL-DISTAL DISCREPANCY BY BONDING TECHNIQUE

Bonding Technique	n	M/D Discrepancy (mm) ± SD
Whole	32	0.077 ± 0.062 [a]
Halves	36	0.072 ± 0.065 [b]
Thirds	36	0.039 ± 0.034 [a, b, c]
Sixths	38	0.100 ± 0.107 [c]
[a] p=0.016, [b] p=0.044, [c] p=0.008		

When evaluating directional bias, overall mean value of M/D deviation across all attachments was 0.007 mm, S.D. = 0.105 mm, indicating mesial directional bias.

Across the bonding techniques, mean values of M/D discrepancy were all positive aside from Thirds group (-0.0004 mm, S.D. = 0.052 mm). Whole (0.005 mm, S.D. = 0.100mm), Halves (0.012 mm, S.D. = 0.097 mm), and Sixths (0.010 mm, S.D. = 0.147 mm) groups had a mesial directional bias (Table IV).

TABLE IV. MEAN AND STANDARD DEVIATION OF MESIAL-DISTAL DIRECTIONAL BIAS BY BONDING TECHNIQUE

Bonding Technique	n	M/D Directional Bias (mm) ± SD
Whole	32	+0.005 ± 0.100
Halves	36	+0.012 ± 0.097
Thirds	36	-0.0004 ± 0.052
Sixths	38	+0.010 ± 0.147
All	142	+0.007 ± 0.105
(-) sign denotes distal direction		

4.1.3 Incisal-Gingival Discrepancy

There was statistically significant mean interaction between orientation of attachment and tooth type, p-value = 0.024.

The main effect among the levels of bonding technique group in the presence of orientation of attachment, and tooth type showed statistically significant mean differences, p-value = 0.015.

One-way ANOVA among levels of bonding technique group showed statistically significant mean differences only between Halves and Sixths groups, p-value = 0.037.

The mean I/G discrepancy of Halves group (0.081 mm, S.D. = 0.054 mm) was higher than that of Sixths group (0.050 mm, S.D. = 0.043mm) in an absolute sense. Whole group mean value (0.080 mm, S.D. = 0.055 mm) and also that of the Thirds group (0.063mm, S.D. = 0.039 mm) did not show any significant difference (Table V).

TABLE V. ABSOLUTE MEAN AND STANDARD DEVIATION OF INCISAL-GINGIVAL DISCREPANCY BY BONDING TECHNIQUE

Bonding Technique	n	I/G Discrepancy (mm) ± SD
Whole	32	0.080 ± 0.055
Halves	36	0.081 ± 0.054 [a]
Thirds	36	0.063 ± 0.039
Sixths	38	0.050 ± 0.043 [a]
[a] p=0.037		

When evaluating directional bias, overall mean value of I/G discrepancy across all attachments was -0.051 mm, S.D. = 0.067 mm, indicating incisal directional bias.

For I/G directional bias across bonding techniques, mean values of all technique group I/G discrepancies were negative, indicating incisal directional bias.

The mean value of Whole group (-0.077 mm, S.D. = 0.060 mm) and Halves group (-0.074 mm, S.D. = 0.064 mm) were more negative than the ones of Thirds group (-0.038 mm, S.D. = 0.064mm) and Sixths group (-0.020 mm, S.D. = -0.063mm);(Table VI).

The mean for Sixths group was the least negative or most gingival and most accurate among all technique groups in a directional sense, followed by the mean for Thirds group.

TABLE VI. MEAN AND STANDARD DEVIATION OF INCISAL-GINGIVAL DIRECTIONAL BIAS BY BONDING TECHNIQUE

Bonding Technique	n	I/G Directional Bias (mm) ± SD
Whole	32	-0.077 ± 0.060
Halves	36	-0.074 ± 0.064
Thirds	36	-0.038 ± 0.064
Sixths	38	-0.020 ± 0.063
All	142	-0.051 ± 0.067
(-) sign denotes incisal direction		

4.1.4 Tip Discrepancy

The main effect between the levels of orientation of attachment in the presence of bonding technique group and tooth type showed statistically significant mean differences, p-value < 0.001.

The mean of the horizontal attachments (1.505 °, S.D. = 1.236°) was lower than the mean of vertical attachments (3.574°, S.D. = 1.198°) in an absolute sense (Table VII).

TABLE VII. ABSOLUTE VALUE OF MEAN AND STANDARD DEVIATION OF ATTACHMENT TIP DISCREPANCY BY ATTACHMENT ORIENTATION

Attachment Orientation	n	Tip Discrepancy (°) ± SD
Horizontal	70	1.505 ± 1.236 [a]
Vertical	72	3.574 ± 1.198 [a]
[a] p<0.001		

The main effect among the levels of tooth type in the presence of orientation of attachment, and bonding technique group showed statistically significant mean differences, p-value = 0.002.

One-way ANOVA among levels of tooth type did not show statistically significant mean differences of tip discrepancy between the tooth type levels.

When evaluating for directional bias, the mean of the horizontal attachments (1.170°, S.D. = 1.560°) is positive indicating positive attachment angular bias and the mean for the vertical attachments was negative (-3.242°, S.D. = 1.931°), indicating mesial root attachment angular bias (Table VIII).

Across all attachments, the mean tip discrepancy was -1.067 degrees, S.D. = 2.823 degrees, indicating mesial root angular bias.

TABLE VIII. MEAN AND STANDARD DEVIATION OF ATTACHMENT ANGULAR BIAS BY ATTACHMENT ORIENTATION

Attachment Orientation	**n**	**Tip Angular Bias (°) ± SD**
Horizontal	70	1.170 ± 1.560
Vertical	72	-3.242 ± 1.931
All	142	-1.067± 2.823
(-) sign denotes that occlusal aspect of attachment reference line was too occlusal to that of the ideal		

V. DISCUSSION

5.1 Clinical Significance Threshold

Other studies[11,13,15] have cited the ABO-OGS[16] for their clinical significance values based on the measurement thresholds at which a case receives point deductions. Because this study evaluated the accuracy of CAT attachment placement with IDB techniques that were different from those of traditional brackets and wires IDB studies, the cutoff threshold of clinical significance was set to follow guidelines from the market leader of clear aligners. Previously proposed clinical significance thresholds may have validity, but were based on assumptions about the orthodontic treatment rendered and the appliances used in the studies. Other studies reported that a 0.5 mm I/G discrepancy in position for bracket and wire orthodontics could lead to a 0.5 mm marginal ridge discrepancy, or that a 2° bracket error could translate to a 2° excess root tip, not withstanding the “slop” between wires and brackets. However, no published study has reported what predictably happens to a tooth when a composite resin attachment has a 0.5mm I/G discrepancy or a 2° angular discrepancy. For this experiment, the established clinical significance cutoff value was set at 0.25 mm for linear measurements and a 1° cutoff for angular measurements. This was based on the values reported from Invisalign protocol that the maximum staging per tray was 0.25 mm per aligner and 1° lingual root movement per aligner.[20] No root tip staging per tray was reported.

5.2 Discrepancy of Composite Attachments in Buccal-Lingual Dimension

Across all attachments, there was a lingual directional bias of 0.150 mm. A lingual bias could be due to polymerization shrinkage of the composite resin, or over-seating of the template. Flow-Tain® is categorized as a flowable composite resin. Average flowable composite polymerization shrinkage was 5% volumetrically according to a review.[37] This would translate to about 1.7% shrinkage in one dimension for a square object. To quantify polymerization shrinkage in this experiment linearly, 5 horizontal and 5 vertical attachments from iTero cast scans were measured for length of the long and short legs of the attachment. We found that on average across these 10 attachments, there was a 0.239 mm or 7.95% shrinkage for the long leg, and 0.193 mm or 12.84% shrinkage for the short leg compared to the reference value of 3.0 mm and 1.5 mm, respectively. It is important to note that this shrinkage may be cumulative from printing shrinkage and bonding shrinkage as measured at attachment corners. We did not have a standard reference for B/L thickness for attachments because the buccal surfaces of teeth were not perfectly flat, but this dimension was estimated at 0.75 mm. Assuming around 10% dimensional shrinkage for B/L thickness based on the shrinkage on the other two dimensions, about 0.075 mm, or half, of B/L discrepancy may be accounted for by polymerization shrinkage. Although overseating of the trays in the B/L dimension was mitigated by using college pliers to apply seating pressure incisally and gingivally to the attachments and not directly on top of them, the template trays may possess a degree of elasticity that could result in some overseating.

Using absolute value analysis, left molars and premolars had more B/L deviation than right molars and premolars (around 0.200 mm compared to 0.140 mm or less). The directionality across all tooth types was lingual. Of all tooth types, upper right premolars had the least lingual attachment positioning, followed by the upper right molars. That is, all left side attachments tended to be situated more lingually than those of the right side. It is possible that due to the dexterity of the right-handed operator that the template tray was seated more securely for left side attachments than those on the right.

Neither the mean deviations across all tooth types nor the difference in mean among tooth types reached clinical significance for the B/L dimension. It appears that IDB is accurate in achieving accurate B/L position across all posterior teeth.

In this study, bonding technique did not affect B/L discrepancy based on the results of this experiment. Schubert et al.[14] found that the B/L absolute discrepancy was 0.13mm for their IDB method. Their study utilized single tooth bonding jigs for bonding lingual brackets and they did not report directional bias. This B/L discrepancy value was slightly lower than the mean values for left side attachments, about equal to that of the right molars, and greater than that of the right premolars. Based on the clinical significance cutoff of our present study, neither our study nor theirs detected IDB B/L deviations that reached clinical significance.

Grünheid et al.[15] reported a modest buccal directional bias when studying the IDB of brackets intraorally using a PVS putty tray, and reported that it happened in about 80% of brackets, but did not quantify the degree to which these brackets were buccally placed. This buccal tendency was the opposite of what the present study found. Nearly all attachments measured had a lingual deviation. Although our results differed in direction, the discussion presented by Grünheid et al. provided a possible explanation on what causes lingual displacement in IDB. They noted that a minority of their brackets did have a lingual deviation and hypothesized that the custom composite base for the brackets may have broken off or thinned during IDB processing.[15] For this study, we did not have a custom composite base for the attachments, but if overseating of the tray had occurred, too much composite resin would have extruded from the vent hole, and in essence could cause a deficiency in B/L thickness, leading to a lingually biased measurement. It is unclear whether this phenomenon happened in our experiment and to what degree it would affect the results.

5.3 Discrepancy of Composite Attachments in Mesial-Distal Dimension

The means of the M/D discrepancy of all tooth types with directional bias in mind were within approximately 50 µm to zero, suggesting that tooth position in the arch does not affect M/D discrepancy in a clinically significant way. Overall mean M/D directional bias across all teeth was 7 µm to the mesial, which is essentially zero and suggests that IDB is accurate in M/D positioning across all posterior teeth.

M/D discrepancy was affected by bonding technique based on the results of this study. The Thirds group had significantly less absolute M/D discrepancy than other bonding groups. This is an interesting finding because one would expect the Whole group to perform similarly well due

to more tray rigidity. Perhaps there is a benefit to sectioning trays into sextants in that any issues with tray fit over the anterior teeth do not affect M/D deviation as long as the sextant was kept reasonably rigid, as when both the buccal and lingual aspects of the tray were present. The Sixths group had greater M/D discrepancy even though there was no anterior tray engagement, possibly because sextant rigidity was decreased in this technique.
The Whole and Halves group performed similarly with mean M/D discrepancy, which was anticipated because they were techniques involving continuous archs. Although not significantly different than the Whole and Halves groups, it is interesting to note that the Sixths group had the highest mean deviation and widest standard deviation. Because the Sixth technique was the most sectioned tray technique, it would not be surprising that this technique would be less accurate due to more freedom of tray movement. Perhaps smaller tray sections led to a wider envelope of M/D errors.

The difference between the worst and best M/D mean deviations among the tooth types was less than 7 µm, and the worst mean deviation of the bonding techniques did not exceed 100 µm. Therefore, it appears that with regards to M/D discrepancy, all four techniques were accurate and equivalent to each other in a clinical sense.

Koo et al.[9] reported 0.18 mm of M/D absolute deviation when studying IDB using a light PVS/thin thermoform dual layer transfer tray, and a plot of deviations in the + and – directions did not show a clear directional bias across all brackets. Hodge et al.[10] reported a 0.05 mm distal bias when studying IDB using a thermoform transfer tray. Schubert et al. reported 0.12

mm of M/D absolute deviation when studying IDB using single-tooth transfer jigs for lingual brackets. Grünheid et al.[15] reported a 98.53% clinical accuracy in the M/D dimension and no notable directional bias when studying IDB of brackets using a PVS putty tray. Depending on the tooth type, in our study the mean absolute deviation ranged from around 0.04 mm to 0.10 mm. These values are on the lower end of reported M/D deviations in the reported literature. Interestingly, our values were the most similar to the study of Hodge et al., which used a single layer clear thermoform transfer tray to bond brackets, which the tray design was most similar to that of our study. Overall, our results did not show a strong bias towards the mesial or distal, and this was in agreement with previous IDB studies.

5.4 Discrepancy of Composite Attachments in Incisal-Gingival Dimension

Across all attachments, there was an incisal directional bias of approximately 0.05 mm, showing that IDB was accurate in I/G positioning.

I/G discrepancy was affected by the bonding technique based on the results of the experiment. The Sixths technique produced the most gingival attachment positions, followed by the Thirds group. The Whole and Halves groups produced similar mean I/G deviations. Although there was only statistically significant difference between the Sixths and Halves group, it appeared that as templates became more sectioned, there may be less resistance to inhibit seating of the template towards the gingival. In this case, more freedom to seat the tray may have actually produced better I/G positioning. The Sixths group had the least mean I/G discrepancy (0.050 mm), followed by the Thirds group (0.063 mm).

All bonding techniques achieved a mean I/G deviation of approximately 0.080 mm or less in an absolute sense. The directionality of the deviation was incisal across all bonding techniques. The difference between the best performing and worst performing bonding technique was approximately 30 µm. Therefore, the results suggest that with regards to I/G discrepancy, all four techniques were accurate and equivalent to each other in a clinical sense.

Previous literature reporting I/G discrepancy in have mean I/G discrepancy in absolute terms ranging from 0.1 mm[14] to 0.3 mm[9], and mostly around 0.2 mm[10,11,13]. Hodge et al.[10] reports a 0.2 mm incisal bias, which was in agreement with our results in direction, but was much greater in magnitude that what we found. Grünheid et al. found that their IDB technique resulted in gingival bias 60.29% of the time.[15] Although the bias was modest, their finding was in contrast to that of our study. They speculated that the elasticity of the PVS putty trays was enough such that the trays distorted under pressure and allowed facial and gingival sliding of the trays. Perhaps the combination of tray elasticity and applied pressure was different in our experiment such that we did not see this distortion or sliding. Castilla et al.[11] reported that I/G was the least accurate dimension, and particularly in single- and double-thermoform tray techniques which had about 0.2 mm I/G deviation across all teeth and 0.3 mm deviation for anterior teeth specifically. Castilla et al. cited the thinning of thermoform material over the anterior crowns as a reason for poorer tray adaptation and inferior I/G positions. Our study showed less than half magnitude of deviation, but did not include anterior teeth in the analysis. It was unclear whether tray material thinning in the anterior would cause greater mean I/G errors in our experimental set up. Castilla et al. also reported that right side attachments tended to have more I/G discrepancy than left side ones, and stated that thinner tray materials may be sensitive to differences in digital pressure. Operator handedness in our experiment appeared to have an effect only on the B/L dimension, but not on the I/G dimension.

5.5 Discrepancy of Composite Attachments in Tip

It was found that horizontal attachments had lower mean deviation in an absolute sense, approximately 1.5°, than vertical attachments which had a mean deviation of about 3.5°. The difference was about 2°, which exceeded the clinical significance cutoff for this experiment. It was not clear why horizontal attachment deviations would be greater. It would seem that attachments of vertical orientation did not achieve clinically satisfactory tip with IDB. However this result should also be interpreted with additional consideration.

Overall, across all attachments, the mean tip discrepancy had a bias of approximately 1.0° in the negative direction. This deviation was right at the cutoff for clinical significance in this experiment. However, angular measurements were very sensitive to attachment dimensional changes from shrinkage or land marking error. From the earlier exploration of attachment shrinkage, the average dimension of a bonded attachment was 1.307 x 2.761 mm as opposed to 1.5 x 3.0 mm. Based on trigonometry, the acute angle of a right triangle with legs of the above dimensions would be 25.332° and 26.565°, a difference of over 1°. Small dimensional changes of attachments alone were sufficient to produce a difference exceeding our clinical significance threshold. Shrinkage along may account for the overall 1 ° deviation across all attachments.

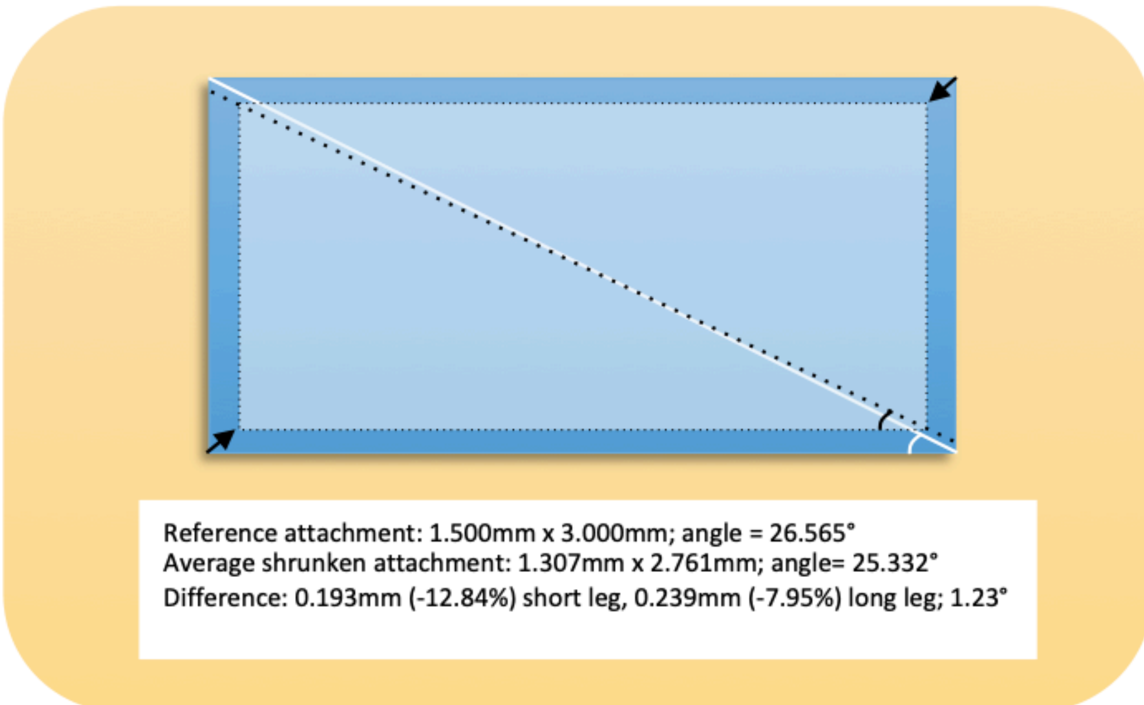

Figure 10. Depiction of the effect attachment shrinkage has on angular measurements

The finding that horizontal attachments tended to have positive tip discrepancy and that vertical attachments tended to have negative tip likely has to do with shrinkage that affected the short leg of attachments at a greater percentage than the long leg. If operators identified landmarks in such a way that the landmarks converged along the short leg of the attachment toward the long axis of the attachment face, it would explain why vertical attachments had negative tip and horizontal attachments had positive tip when using the reference line of distal-gingival to mesial-incisal attachment corners.

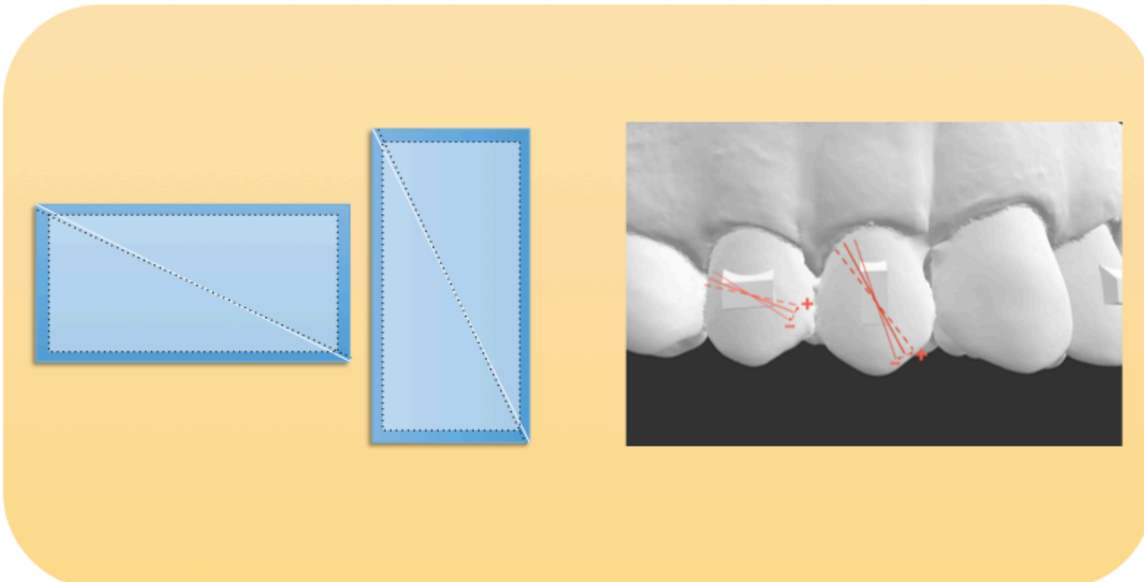

Figure 11. Depiction of the differential effect on tip from shrinkage based on orientation on a horizontal and vertical attachment on the upper right posterior. The tip sign convention reference figure is juxtaposed. Horizontal attachments measure more (+) tip and vertical attachments measure more (-) tip. White- ideal reference line; black- experimental reference line.

The tip discrepancy was not affected by tooth type, nor was it affected by bonding technique based on the statistical results.

Overall, the results suggested that IDB was consistent in reproducing tip across all posterior teeth and that all four techniques performed equally well with regards to tip. The orientation of the attachment seemed to affect its resultant tip, but angular sensitivity to dimensional or landmark differences could have affected the results.

Reported mean tip deviations in the IDB literature range from 1.3°[8] and 1.5°[13] to 2.43°[9] and 3.21°[14]. Our horizontal attachment tip deviation fell on the low end of this range and our vertical attachment tip deviation fell just above the high end of the range. Kim et al. noted that in their study, angular deviations (including tip, torque and rotation), were more likely to exceed clinical significance thresholds than linear deviations.[13] This was the case for our study as well, although it is important to note that their cutoffs were 1°and 0.5 mm. None of the mean linear deviations in B/L, M/D and I/G dimensions exceeded clinical significance cutoffs in the present study, but the angular deviations did.

5.6 Limitations

5.6.1 Comparability to Existing Literature

Although we compared our findings in the 3 dental dimensions and in tip to available previous studies, method heterogeneity may limit the usefulness of such comparisons. To our knowledge, this present study is the first one to study IDB of composite attachments, and the only one to study the effects of tray sectioning strategies for IDB in general, not just for composite attachments. Although there were studies which used a single layer thermoform material as a transfer tray, these studies evaluated bonding orthodontic brackets which were different from composite attachments in several regards. For instance, composite attachments tend to be smaller and less massive than brackets. They are also not preformed, unlike brackets. They can also be in very different orientations, unlike brackets used for straight wire technique. Although there were other studies that used 3D superimposition analysis, the software used and methodologies varied greatly. One study used 4 different software programs to complete 3D measurements.[13] Other studies used software programs that were inaccessible to the author of the present study.[15] At times during the literature review, it was unclear how measurements were completed for certain studies. Cast design and .stl exporting aside, our study used just a single open-source software and plug-ins to complete 3D measurements, which comes with the advantage of accessibility but may come with the disadvantages of less user-friendliness and lack of customization for orthodontic purposes. The research community has not explored much in the way of the IDB of composite attachments, nor has it established best practices in how to measure IDB accuracy in 3D.

Only one study[14] has used an intraoral scanner for scanning casts after bonding. Other studies have used alginate impressions[10], photographs[8–12], CBCT reconstructions[15], or desktop scanners[12,13] to take record of the post bond situation. Although the existing literature validated the use of intraoral scanners such as the iTero as a substitute for desktop scanners, this study internally verified the accuracy of the iTero scanner as a scanner which is accurate in scanning dental arches extra-orally, with minor posterior transverse discrepancies.

This study is the among the first studies to used 3D printed models as bonding models; aside from the study of Kim et al.[13], other studies bonded onto stone casts[9,11], extracted teeth[12], or live patient dentition[8,10,14,15]. Although the use of 3D printed models for orthodontic purposes has been validated, this study also took measurements to validate the accuracy of the Carbon printer, which to our knowledge has only been validated by one non-orthodontic study.[32]

5.6.2 Superimpositions

Due to low reliability of measurements, we had to exclude all anterior attachments from our statistical analysis in this experiment. Therefore, the results of the study were limited to posterior attachments, and this is a main limitation of the study. In this experiment, we were only able to achieve acceptable reliability for posterior attachments and not for anterior attachments. We validated that the printing and scanning was accurate in this study, and narrowed the source of errors down to measurement method. Landmarking of attachments did not likely affect the reliability of anterior attachment measurements because the landmarking was sufficient to achieve reliable posterior measurements. Therefore we speculated that poor anterior measurement reliability was because the superimposition method was good for posterior teeth, but was not satisfactory for anterior teeth. This ultimately led us to drop all anterior attachments from analysis. Visually, posterior superimpositions were better matched than anterior ones. Anterior superimpositions at times were not matched in the I/G dimension, or had a cant difference as viewed from the front.

We postulated that since there were twice as many fiducial landmarks that were spread out over a greater 3D span for posterior superimpositions compared to anterior superimpositions, the quality was lower for the anteriors. Furthermore, posterior cusp tips were less ambiguous than anterior landmarks such incisal corners and cingulums, which tended to be rounded and ill-defined.

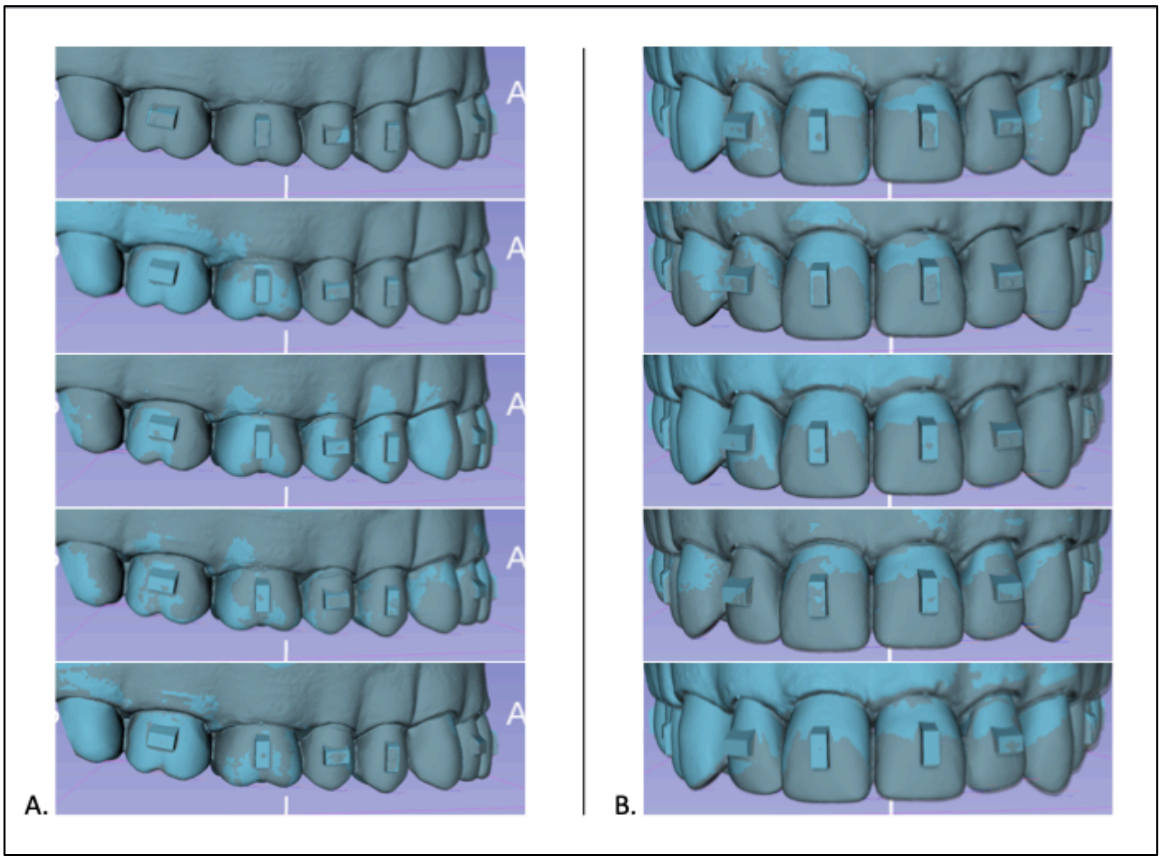

Figure 12. A and B: Quality of A.) anterior and B.) posterior superimpositions across 5 experimental casts onto the reference cast

If we were to use the same experimental casts for re-measurement, we could try to use other landmarks such as the lowest point of buccal and gingival margins for a single superimposition that could encompass both anterior and posterior landmarks. The difficulty with this strategy is that resin overflow obscured some of the gingival margins. One could attempt to scale away the excess resin, but there could be damage done to the cast since the resin chemically bonds to the cast material. Excess resin would be easier to remove, had there been a separating medium applied to the gingival margins prior to bonding. Alternately, if we had to redesign the cast for another version of the experiment, unambiguous protrusions could be made on the cast either away from the bonding surfaces such as lower on the gingival, or simply on the teeth as done in a study by Kim et al.[31] Of course, incorporating artificial gingival protrusions or dental protrusions would be challenging if the study were eventually transitioned to an *in vivo* one. Dental landmarks are natural and readily accessible, but in the case of the present *in vitro* study, they did not allow us to achieve good superimpositions using the fiducial landmarks method.

5.6.3 Shrinkage, Loss of Detail, and Effects on Measurements

As previously discussed, we found that there was dimensional shrinkage of the attachments, and demonstrated that this dimensional shrinkage could affect angular measurement. Throughout the experiment, we noticed that there was a certain amount of roundedness in the appearance of attachments on digital casts. Whether the loss of detail was from template model printing, template tray fabrication, polymerization shrinkage of flowable resin, or scanning, the landmarking of the attachments could be a challenge. Because edges and corners were rounded, and because the centroid point was calculated as the midline of two attachment corner landmarks, the calculated centroid was almost invariably below the facial surface of the attachment. This could have contributed to some degrees of the lingual bias of attachment positioning in the experiment. There was an option in 3D Slicer to project the centroid onto the surface of the model, but this was not done for consistency's sake, since the extrusion hole was placed at about the middle point of the attachment face. At this site, sometimes there would be a bump or a dimple on the surface of the attachment depending on how much composite was removed with the round bur to remove any composite that would lock the template tray to the attachment. If we were to repeat the experiment, perhaps the vent hole could be at a slightly different site so the centroid could be projected to the surface of the attachment to be more accurate on the B/L dimension.

5.6.4 Difference from Clinical Situation

This experiment used a model with well-aligned dentition as the bonding subject. Orthodontic patients generally have some degree of malocclusion. Other studies have bonded onto malocclusion states *in vitro*[9,13] and i*n vivo*[8,10,14,15], so the results from these investigations may yield more clinically useful information. Furthermore, the attachments in this study were bonded onto printed resin models and not real teeth. Because the experiment was *in vitro*, the isolation, attachment handling and access for clinician might not represent chair-side situation. Grünheid et al.[15] reported that in their *in vivo* study, there was a tendency of reduced accuracy in posterior teeth, for which they cited intraoral access as an explanation. Since there was no previous study investigating the differences of bonding techniques on the accuracy of resin attachment position, our controlled, extra-oral experimental design needed to be set up as such. In the present study, we had attachments on 4 adjacent teeth in each sextant, and our sections never included fewer than 4 teeth. A clinical case may require or allow for different segmentation spans or strategies, which could give researchers additional considerations to think about when designing composite attachment IDB studies.

5.7 Future Research

Investigators in the future may wish to use the current study as a preliminary study for an *in vivo* experiment for patients with malocclusions. Because one of the potential benefits of sectioning trays is prevention of attachment debonding, an *in vivo* study could actually study the rate of bond failure of the IDB procedure. Most of the significant findings in our study did not reach clinical significance thresholds, but an *in vivo* study might render different results.

VI. CONCLUSIONS

- IDB was highly accurate in the mesial-distal dimension for posterior attachments.
- IDB created a clinically insignificant degree of incisal bias in the Incisal-gingival dimension for posterior attachments.
- IDB accuracy was marginally acceptable for posterior attachment tip in a clinical sense, and attachment orientation may affect tip deviation to a clinically significant degree.
- Trays sectioned into relatively rigid sextants which preserve both buccal and lingual tray aspects may improve mesial-distal posterior attachment positions due to not engaging anterior teeth.
- Trays which are sectioned into smaller pieces may result in more gingivally positioned attachments due to fewer occlusal stops and greater flexibility.
- In general, all IDB techniques studied achieved clinically acceptable and similar attachment positions in the B/L, M/D, I/G, dimensions, and in tip.

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VIII. APPENDIX

TABLE IX. ATTACHMENT MEASUREMENTS, RAW DATA

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Posterior Left	thirds	8899	UL7	1	-0.356	-0.069	-0.145	1.258
Vertical	Posterior Left	thirds	8899	UL6	1	-0.311	-0.034	-0.09	-4.832
Horizontal	Posterior Left	thirds	8899	UL5	1	-0.305	-0.034	-0.087	0.252
Vertical	Posterior Left	thirds	8899	UL4	1	-0.231	-0.081	-0.169	-1.955
Horizontal	Anterior	thirds	8899	UL2	1	-0.112	-0.055	-0.026	1.467
Vertical	Anterior	thirds	8899	UL1	n/a	n/a	n/a	n/a	n/a
Vertical	Anterior	thirds	8899	UR1	1	-0.218	-0.047	-0.011	-2.623
Horizontal	Anterior	thirds	8899	UR2	1	-0.126	0.121	-0.09	-0.884
Vertical	Posterior Right	thirds	8899	UR4	1	-0.114	-0.004	-0.061	-4.416
Horizontal	Posterior Right	thirds	8899	UR5	1	-0.151	-0.021	0.032	-1.767
Vertical	Posterior Right	thirds	8899	UR6	1	-0.16	0.034	-0.035	-5.457
Horizontal	Posterior Right	thirds	8899	UR7	1	-0.277	0.027	-0.071	0.04
Horizontal	Posterior Left	thirds	8886	UL7	1	-0.075	0.059	-0.044	0.266
Vertical	Posterior Left	thirds	8886	UL6	1	-0.085	0.049	-0.09	-2.928

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Posterior Left	thirds	8886	UL5	1	-0.102	-0.04	-0.073	0.507
Vertical	Posterior Left	thirds	8886	UL4	1	-0.139	0.019	-0.067	-3.06
Horizontal	Anterior	thirds	8886	UL2	1	-0.07	0.007	0.043	-0.09
Vertical	Anterior	thirds	8886	UL1	1	-0.157	-0.038	0.025	-3.148
Vertical	Anterior	thirds	8886	UR1	1	-0.067	0.034	-0.008	-2.264
Horizontal	Anterior	thirds	8886	UR2	1	-0.127	0.054	-0.083	1.611
Vertical	Posterior Right	thirds	8886	UR4	1	-0.062	-0.014	-0.029	-4.447
Horizontal	Posterior Right	thirds	8886	UR5	1	-0.067	-0.026	0.036	0.225
Vertical	Posterior Right	thirds	8886	UR6	1	-0.164	0.007	0.057	-3.69
Horizontal	Posterior Right	thirds	8886	UR7	1	-0.112	-0.013	-0.13	3.867
Horizontal	Posterior Left	whole	8427	UL7	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Left	whole	8427	UL6	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	whole	8427	UL5	1	-0.232	0.062	-0.112	0.965
Vertical	Posterior Left	whole	8427	UL4	1	n/a	n/a	n/a	n/a
Horizontal	Anterior	whole	8427	UL2	2	-0.004	-0.095	-0.22	-0.523
Vertical	Anterior	whole	8427	UL1	1	-0.074	-0.059	-0.275	-3.215
Vertical	Anterior	whole	8427	UR1	1	-0.175	0.122	-0.216	-2.999
Horizontal	Anterior	whole	8427	UR2	2	-0.204	0.047	-0.079	-3.065

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Posterior Right	whole	8427	UR4	1	0.05	0.014	-0.023	-2.111
Horizontal	Posterior Right	whole	8427	UR5	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Right	whole	8427	UR6	1	0.04	0.069	-0.04	-2.497
Horizontal	Posterior Right	whole	8427	UR7	1	0.023	0.164	-0.069	0.859
Horizontal	Posterior Left	halves	8815	UL7	1	-0.127	0.121	-0.106	1.833
Vertical	Posterior Left	halves	8815	UL6	1	-0.186	0.031	-0.124	-4.501
Horizontal	Posterior Left	halves	8815	UL5	1	-0.187	0.016	-0.046	-0.225
Vertical	Posterior Left	halves	8815	UL4	1	-0.226	0.038	-0.137	-3.174
Horizontal	Anterior	halves	8815	UL2	1	-0.128	-0.027	-0.128	-1.158
Vertical	Anterior	halves	8815	UL1	1	-0.18	-0.044	-0.246	-2.625
Vertical	Anterior	halves	8815	UR1	1	-0.143	0.04	-0.306	-2.493
Horizontal	Anterior	halves	8815	UR2	1	-0.107	0.019	-0.14	3.597
Vertical	Posterior Right	halves	8815	UR4	1	-0.076	-0.024	-0.047	-3.712
Horizontal	Posterior Right	halves	8815	UR5	1	-0.004	-0.043	-0.008	1.852
Vertical	Posterior Right	halves	8815	UR6	1	-0.094	0.018	-0.049	-2.652
Horizontal	Posterior Right	halves	8815	UR7	1	-0.102	0.068	-0.114	4.223
Horizontal	Posterior Left	whole	8311	UL7	1	-0.284	-0.03	-0.066	2.371

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Posterior Left	whole	8311	UL6	1	-0.223	-0.035	-0.101	-5.778
Horizontal	Posterior Left	whole	8311	UL5	1	-0.235	0.028	-0.062	-0.382
Vertical	Posterior Left	whole	8311	UL4	1	-0.275	0.04	-0.086	-2.635
Horizontal	Anterior	whole	8311	UL2	1	-0.097	-0.064	-0.063	-1.576
Vertical	Anterior	whole	8311	UL1	1	-0.07	-0.001	-0.159	-4.485
Vertical	Anterior	whole	8311	UR1	1	-0.063	0.087	-0.249	-1.743
Horizontal	Anterior	whole	8311	UR2	2	0.04	0.275	-0.132	-1.369
Vertical	Posterior Right	whole	8311	UR4	1	-0.005	-0.045	0.044	-3.65
Horizontal	Posterior Right	whole	8311	UR5	2	-0.013	-0.034	-0.04	0.037
Vertical	Posterior Right	whole	8311	UR6	1	-0.08	0.068	-0.038	-2.293
Horizontal	Posterior Right	whole	8311	UR7	1	-0.118	0.059	-0.148	4.92
Horizontal	Posterior Left	whole	8472	UL7	1	-0.268	-0.015	-0.145	3.798
Vertical	Posterior Left	whole	8472	UL6	1	-0.227	-0.009	-0.074	-3.619
Horizontal	Posterior Left	whole	8472	UL5	1	-0.234	0.027	-0.075	0.143
Vertical	Posterior Left	whole	8472	UL4	n/a	n/a	n/a	n/a	n/a
Horizontal	Anterior	whole	8472	UL2	2	-0.174	-0.119	-0.145	-1.128
Vertical	Anterior	whole	8472	UL1	1	-0.195	-0.054	-0.25	-2.178
Vertical	Anterior	whole	8472	UR1	1	-0.109	0.089	-0.352	-1.61

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Anterior	whole	8472	UR2	1	-0.128	0.014	-0.359	1.1
Vertical	Posterior Right	whole	8472	UR4	2	-0.017	-0.016	-0.175	1.742
Horizontal	Posterior Right	whole	8472	UR5	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Right	whole	8472	UR6	1	-0.039	-0.066	-0.061	-3.722
Horizontal	Posterior Right	whole	8472	UR7	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	halves	8845	UL7	1	-0.282	0.103	-0.153	2.875
Vertical	Posterior Left	halves	8845	UL6	1	-0.342	0.308	-0.141	-5.308
Horizontal	Posterior Left	halves	8845	UL5	1	-0.272	0.059	-0.221	1.325
Vertical	Posterior Left	halves	8845	UL4	n/a	n/a	n/a	n/a	n/a
Horizontal	Anterior	halves	8845	UL2	1	-0.105	0.034	-0.137	1.813
Vertical	Anterior	halves	8845	UL1	1	-0.085	0.015	-0.185	-2.86
Vertical	Anterior	halves	8845	UR1	1	-0.057	0.002	-0.179	-2.787
Horizontal	Anterior	halves	8845	UR2	1	-0.07	0.055	-0.149	3.567
Vertical	Posterior Right	halves	8845	UR4	1	0.069	0.045	-0.136	-3.632
Horizontal	Posterior Right	halves	8845	UR5	1	0.06	0.004	-0.062	1.145
Vertical	Posterior Right	halves	8845	UR6	1	-0.087	0.067	-0.031	-3.659
Horizontal	Posterior Right	halves	8845	UR7	1	-0.047	0.052	-0.108	1.425

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Posterior Left	halves	8791	UL7	1	-0.252	-0.207	-0.054	0.48
Vertical	Posterior Left	halves	8791	UL6	1	-0.199	-0.177	0.012	-5.17
Horizontal	Posterior Left	halves	8791	UL5	n/a	n/a			
Vertical	Posterior Left	halves	8791	UL4	1	-0.135	-0.0143	-0.05	-4.578
Horizontal	Anterior	halves	8791	UL2	n/a	n/a			
Vertical	Anterior	halves	8791	UL1	1	0.162	-0.139	-0.135	-4.107
Vertical	Anterior	halves	8791	UR1	1	-0.192	-0.114	-0.206	-3.266
Horizontal	Anterior	halves	8791	UR2	1	-0.123	-0.104	-0.101	1.469
Vertical	Posterior Right	halves	8791	UR4	1	-0.228	0.082	-0.12	-3.181
Horizontal	Posterior Right	halves	8791	UR5	2	-0.239	0.022	-0.078	-0.931
Vertical	Posterior Right	halves	8791	UR6	1	-0.281	0.047	-0.139	-3.633
Horizontal	Posterior Right	halves	8791	UR7	1	-0.296	-0.063	-0.117	4.041
Horizontal	Posterior Left	thirds	8929	UL7	1	-0.366	-0.076	-0.076	2.324
Vertical	Posterior Left	thirds	8929	UL6	1	-0.315	-0.1	-0.044	-4.12
Horizontal	Posterior Left	thirds	8929	UL5	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Left	thirds	8929	UL4	1	-0.29	-0.064	-0.097	-2.335
Horizontal	Anterior	thirds	8929	UL2	1	-0.127	-0.037	-0.056	0.294

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Anterior	thirds	8929	UL1	2	-0.096	-0.052	-0.067	4.189
Vertical	Anterior	thirds	8929	UR1	1	-0.178	0.098	-0.142	-2.693
Horizontal	Anterior	thirds	8929	UR2	2	-0.197	0.11	-0.097	-2.127
Vertical	Posterior Right	thirds	8929	UR4	1	-0.17	0	0.01	-4.739
Horizontal	Posterior Right	thirds	8929	UR5	1	-0.147	-0.015	-0.004	2.894
Vertical	Posterior Right	thirds	8929	UR6	1	-0.261	-0.011	-0.065	-2.97
Horizontal	Posterior Right	thirds	8929	UR7	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	whole	8353	UL7	1	-0.16	0.185	-0.067	1.282
Vertical	Posterior Left	whole	8353	UL6	1	-0.183	0.219	-0.029	-4.895
Horizontal	Posterior Left	whole	8353	UL5	1	-0.136	0.135	-0.026	0.292
Vertical	Posterior Left	whole	8353	UL4	1	-0.142	0.193	-0.095	-4.346
Horizontal	Anterior	whole	8353	UL2	1	0.064	-0.017	-0.203	0.474
Vertical	Anterior	whole	8353	UL1		n/a	n/a	n/a	n/a
Vertical	Anterior	whole	8353	UR1	1	-0.054	0.091	-0.105	-2.768
Horizontal	Anterior	whole	8353	UR2	2	-0.116	0.101	-0.097	-1.007
Vertical	Posterior Right	whole	8353	UR4	1	-0.007	0.022	-0.023	-3.447
Horizontal	Posterior Right	whole	8353	UR5	1	0.075	-0.026	-0.046	0.538
Vertical	Posterior Right	whole	8353	UR6	1	-0.069	-0.011	-0.043	-3.346

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Posterior Right	whole	8353	UR7	2	-0.126	0.029	-0.027	-0.443
Horizontal	Posterior Left	thirds	8861	UL7	1	-0.1	-0.032	-0.042	0.075
Vertical	Posterior Left	thirds	8861	UL6	1	-0.109	-0.009	0.036	-5.392
Horizontal	Posterior Left	thirds	8861	UL5	1	-0.148	-0.012	0.056	-2.15
Vertical	Posterior Left	thirds	8861	UL4	1	-0.219	-0.045	0.067	-3.586
Horizontal	Anterior	thirds	8861	UL2	1	-0.045	0.006	-0.05	1.211
Vertical	Anterior	thirds	8861	UL1	1	-0.087	0.01	-0.04	-3.341
Vertical	Anterior	thirds	8861	UR1	n/a	n/a	n/a	n/a	n/a
Horizontal	Anterior	thirds	8861	UR2	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Right	thirds	8861	UR4	1	-0.077	0.07	0.085	-2.54
Horizontal	Posterior Right	thirds	8861	UR5	1	0.033	0.001	0.027	-1.664
Vertical	Posterior Right	thirds	8861	UR6	2	0.012	0.134	0.046	3.797
Horizontal	Posterior Right	thirds	8861	UR7	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	halves	8801	UL7	1	-0.128	-0.152	-0.08	1.556
Vertical	Posterior Left	halves	8801	UL6	1	-0.217	-0.106	-0.116	-2.272
Horizontal	Posterior Left	halves	8801	UL5	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Left	halves	8801	UL4	1	-0.246	-0.15	-0.183	-3.02

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Anterior	halves	8801	UL2	1	0.077	-0.003	-0.116	1.051
Vertical	Anterior	halves	8801	UL1	1	-0.039	-0.023	-0.228	-4.059
Vertical	Anterior	halves	8801	UR1	1	-0.056	0.053	-0.295	-4.085
Horizontal	Anterior	halves	8801	UR2	1	-0.133	0.142	-0.177	0.439
Vertical	Posterior Right	halves	8801	UR4	1	-0.03	-0.034	-0.123	-3.621
Horizontal	Posterior Right	halves	8801	UR5	1	0.091	-0.042	-0.066	-0.268
Vertical	Posterior Right	halves	8801	UR6	1	0.046	0.014	-0.079	-3.535
Horizontal	Posterior Right	halves	8801	UR7	1	-0.015	0.033	-0.046	1.532
Horizontal	Posterior Left	whole	8388	UL7	1	0.057	-0.113	-0.175	3.096
Vertical	Posterior Left	whole	8388	UL6	1	-0.044	-0.07	-0.121	-4.683
Horizontal	Posterior Left	whole	8388	UL5	1	-0.12	-0.146	-0.095	0.248
Vertical	Posterior Left	whole	8388	UL4	1	-0.163	-0.137	-0.186	-4.085
Horizontal	Anterior	whole	8388	UL2	1	-0.08	-0.083	-0.117	0.908
Vertical	Anterior	whole	8388	UL1	n/a	n/a	n/a	n/a	n/a
Vertical	Anterior	whole	8388	UR1	1	-0.083	0.105	-0.133	-0.514
Horizontal	Anterior	whole	8388	UR2	1	-0.118	0.158	-0.091	-0.342
Vertical	Posterior Right	whole	8388	UR4	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Right	whole	8388	UR5	2	-0.144	-0.17	0.011	-1.895

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Posterior Right	whole	8388	UR6	1	-0.1	-0.151	-0.04	-3.142
Horizontal	Posterior Right	whole	8388	UR7	1	-0.057	-0.086	-0.226	3.03
Horizontal	Posterior Left	halves	8835	UL7	1	-0.262	-0.021	-0.038	1.364
Vertical	Posterior Left	halves	8835	UL6	1	-0.255	-0.024	-0.024	-4.969
Horizontal	Posterior Left	halves	8835	UL5	1	-0.211	-0.02	0.034	0.192
Vertical	Posterior Left	halves	8835	UL4	1	-0.222	0.036	0.009	-3.89
Horizontal	Anterior	halves	8835	UL2	1	-0.056	-0.117	-0.095	2.181
Vertical	Anterior	halves	8835	UL1	1	-0.033	-0.118	-0.129	-1.895
Vertical	Anterior	halves	8835	UR1	1	-0.099	0.189	-0.099	-2.419
Horizontal	Anterior	halves	8835	UR2	n/a	n/a	n/a	n/a	n/a
Vertical	Posterior Right	halves	8835	UR4	2	-0.02	0.107	0.005	2.906
Horizontal	Posterior Right	halves	8835	UR5	1	-0.05	0.122	0.064	0.477
Vertical	Posterior Right	halves	8835	UR6	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Right	halves	8835	UR7	1	-0.195	0.109	0.006	2.327
Horizontal	Posterior Left	thirds	8909	UL7	1	-0.334	0.003	-0.056	1.401
Vertical	Posterior Left	thirds	8909	UL6	1	-0.248	0.006	-0.048	-4.434
Horizontal	Posterior Left	thirds	8909	UL5	n/a	n/a	n/a	n/a	n/a

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Posterior Left	thirds	8909	UL4	1	-0.24	0.044	-0.135	-4.012
Horizontal	Anterior	thirds	8909	UL2	1	0.034	-0.107	-0.174	-2.418
Vertical	Anterior	thirds	8909	UL1	2	0.024	-0.021	-0.176	-3.649
Vertical	Anterior	thirds	8909	UR1	1	-0.009	0.119	-0.162	-1.559
Horizontal	Anterior	thirds	8909	UR2	1	-0.077	0.106	-0.225	3.993
Vertical	Posterior Right	thirds	8909	UR4	1	-0.058	0.12	-0.016	-3.503
Horizontal	Posterior Right	thirds	8909	UR5	1	-0.119	0.02	-0.038	0.361
Vertical	Posterior Right	thirds	8909	UR6	1	-0.223	0.081	0	-1.967
Horizontal	Posterior Right	thirds	8909	UR7	1	-0.226	0.012	-0.097	3.019
Horizontal	Anterior	sixths	8501	UL2	1	-0.039	-0.049	-0.173	2.484
Vertical	Anterior	sixths	8501	UL1	1	-0.074	-0.046	-0.259	-3.03
Vertical	Anterior	sixths	8501	UR1	1	-0.087	0.091	-0.181	-2.736
Horizontal	Anterior	sixths	8501	UR2	1	-0.096	0.1	-0.073	-0.685
Horizontal	Anterior	sixths	8521	UL2	n/a	n/a	n/a	n/a	n/a
Vertical	Anterior	sixths	8521	UL1	n/a	n/a	n/a	n/a	n/a
Vertical	Anterior	sixths	8521	UR1	1	-0.086	0.093	-0.107	-2.768
Horizontal	Anterior	sixths	8521	UR2	1	-0.074	0.02	-0.165	-0.282
Horizontal	Anterior	sixths	8568	UL2	1	-0.103	0.125	-0.022	2.956
Vertical	Anterior	sixths	8568	UL1	1	-0.154	0.121	-0.095	-3.38
Vertical	Anterior	sixths	8568	UR1	1	-0.066	-0.056	-0.15	-4.516

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Anterior	sixths	8568	UR2	1	-0.113	0.023	-0.109	-0.692
Horizontal	Anterior	sixths	8591	UL2	1	-0.062	0.064	-0.008	0.996
Vertical	Anterior	sixths	8591	UL1	1	-0.121	0.005	-0.032	-2.986
Vertical	Anterior	sixths	8591	UR1	1	-0.118	0.013	-0.061	-2.924
Horizontal	Anterior	sixths	8591	UR2	2	-0.137	0.139	-0.125	-3.142
Horizontal	Anterior	sixths	8625	UL2	1	-0.122	0.003	-0.079	2.883
Vertical	Anterior	sixths	8625	UL1	n/a	n/a	n/a	n/a	n/a
Vertical	Anterior	sixths	8625	UR1	2	-0.159	-0.02	-0.176	3.734
Horizontal	Anterior	sixths	8625	UR2	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	sixths	450	UL7	1	-0.186	0.059	-0.059	1.169
Vertical	Posterior Left	sixths	450	UL6	1	-0.186	-0.007	-0.114	-2.358
Horizontal	Posterior Left	sixths	450	UL5	1	-0.164	-0.029	-0.034	0.668
Vertical	Posterior Left	sixths	450	UL4	1	-0.18	-0.092	-0.12	-1.196
Vertical	Posterior Right	sixths	450	UR4	1	-0.08	0.042	-0.011	-5.258
Horizontal	Posterior Right	sixths	450	UR5	1	-0.023	0.103	-0.052	1.118
Vertical	Posterior Right	sixths	450	UR6	1	-0.097	0.239	-0.028	-5.76
Horizontal	Posterior Right	sixths	450	UR7	1	-0.031	0.253	-0.057	0.431
Horizontal	Posterior Left	sixths	1139	UL7	1	-0.219	0.147	-0.045	2.452

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Vertical	Posterior Left	sixths	1139	UL6	1	-0.269	0.139	-0.015	-2.923
Horizontal	Posterior Left	sixths	1139	UL5	1	-0.251	0.068	0.04	-0.26
Vertical	Posterior Left	sixths	1139	UL4	1	-0.27	0.07	0.075	-2.926
Vertical	Posterior Right	sixths	1139	UR4	1	-0.249	0.003	0.106	-5.078
Horizontal	Posterior Right	sixths	1139	UR5	1	-0.168	0.009	0.056	-0.602
Vertical	Posterior Right	sixths	1139	UR6	1	-0.295	0.048	-0.001	-1.519
Horizontal	Posterior Right	sixths	1139	UR7	1	-0.39	0.031	-0.059	3.175
Horizontal	Posterior Left	sixths	1671	UL7	1	-0.089	0.065	-0.049	4.02
Vertical	Posterior Left	sixths	1671	UL6	1	-0.16	0.007	-0.121	-2.684
Horizontal	Posterior Left	sixths	1671	UL5	1	-0.11	-0.62	-0.003	1.48
Vertical	Posterior Left	sixths	1671	UL4	1	-0.135	-0.07	-0.006	-4.101
Vertical	Posterior Right	sixths	1671	UR4	1	-0.124	-0.023	0.023	-4.987
Horizontal	Posterior Right	sixths	1671	UR5	1	-0.183	0.009	-0.06	-1.123
Vertical	Posterior Right	sixths	1671	UR6	1	-0.171	0.077	-0.071	-6.609
Horizontal	Posterior Right	sixths	1671	UR7	1	-0.227	0.157	-0.048	2.086

Table IX (continued).

Orientation	Sextant	Technique	Model #	Tooth	Ref. Line	B/L Discrep.	M/D Discrep.	I/G Discrep.	Tip discrep.
Horizontal	Posterior Left	sixths	2167	UL7	1	0.1	0.059	-0.009	0.723
Vertical	Posterior Left	sixths	2167	UL6	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Left	sixths	2167	UL5	1	-0.1	-0.076	-0.014	2.939
Vertical	Posterior Left	sixths	2167	UL4	1	-0.147	-0.181	0.055	3.512
Vertical	Posterior Right	sixths	2167	UR4	1	-0.082	-0.208	0.181	-0.362
Horizontal	Posterior Right	sixths	2167	UR5	1	-0.124	-0.088	0.002	2.256
Vertical	Posterior Right	sixths	2167	UR6	n/a	n/a	n/a	n/a	n/a
Horizontal	Posterior Right	sixths	2167	UR7	1	-0.063	0.033	-0.008	1.757
Horizontal	Posterior Left	sixths	6977	UL7	1	-0.176	-0.055	0	0.841
Vertical	Posterior Left	sixths	6977	UL6	1	-0.164	-0.076	-0.002	-2.321
Horizontal	Posterior Left	sixths	6977	UL5	1	-0.162	-0.108	0.024	0.227
Vertical	Posterior Left	sixths	6977	UL4	1	-0.172	-0.085	-0.043	-2.249
Vertical	Posterior Right	sixths	6977	UR4	1	-0.223	0.09	-0.072	-3.386
Horizontal	Posterior Right	sixths	6977	UR5	1	-0.22	0.096	-0.021	0.269
Vertical	Posterior Right	sixths	6977	UR6	1	-0.267	0.102	-0.134	-2.519
Horizontal	Posterior	sixths	6977	UR7	1	-0.255	0.176	-0.079	3.3

	Right								
					n/a indicates that attachment was excluded from analysis				
					key: 1= default reference line, 2=alternate reference line				

TABLE X. INTER- AND INTRA- RELIABILITY TESTING, RAW DATA

Cast	UR7 B-L	UR7 M-D	UR7 I-G	UR7 Tip	UL1 B-L	UL1 M-D	UL1 I-G	UL1 Tip
8311.1	-0.118	0.059	-0.148	4.92	-0.07	-0.001	-0.159	-4.485
8427.1	0.023	0.164	-0.069	0.859	-0.074	-0.059	-0.275	-3.215
8791.1	-0.296	-0.063	-0.117	4.041	0.162	-0.139	-0.135	-4.107
8815.1	-0.102	0.068	-0.114	4.223	-0.18	-0.044	-0.246	-2.625
8886.1	-0.112	-0.013	-0.13	3.867	-0.157	-0.038	0.025	-3.148
8311.2	-0.191	0.124	-0.088	4.54	-0.099	0.09	-0.204	-2.148
8427.2	-0.025	0.091	-0.062	0.77	-0.055	0.071	-0.223	-3.361
8791.2	-0.212	0.007	-0.091	3.964	-0.101	0.064	-0.21	-0.767
8815.2	-0.129	0.141	-0.076	4.121	-0.092	0.042	-0.166	-1.384
8886.2	-0.128	-0.061	-0.16	1.085	-0.078	0.031	-0.232	-2.591
8311.3	-0.16	0.109	-0.169	4.4	-0.07	-0.133	-0.023	-2.879
8427.3	-0.022	0.102	-0.053	-1.935	0.061	0.04	-0.059	-3.167
8791.3	-0.302	-0.031	-0.163	3.353	-0.12	-0.032	-0.12	-1.733
8815.3	0	0	-0.125	3.945	-0.232	-0.013	-0.043	-2.734
8886.3	-0.059	0.101	-0.192	-0.174	-0.086	0.072	-0.019	-2.196
where 0.1 means ZC first measurement, 0.2 ZC re measure and 0.3 RM inter-op measurement								

TABLE XI. VERIFICATION OF 3D PRINTING AND SCANNING ACCURACY

Cast Label ID	Cast Number	Inter-incisor	Inter-premolar	Inter-molar
4	1	29.53	42.49	51.22
12	2	29.59	42.41	51.28
13	3	29.43	42.55	51.54
15	4	29.47	42.53	51.36
17	5	29.53	42.7	51.54
	mean	29.51	42.536	51.388
	S.D.	0.06164414	0.106207344	0.147377067
Measurement of 3D Printing Accuracy with Calipers				

Cast Number	Inter-incisor	Inter-premolar	Inter-molar
1	29.53	42.49	51.22
1	29.41	42.58	51.46
1	29.42	42.67	51.42
1	29.45	42.74	51.29
1	29.5	42.6	51.31
mean	29.462	42.616	51.34
S.D.	0.051672043	0.094498677	0.098234414
Interoperator Reliability with Caliper Measurement			

Cast File ID	Scan Number	inter-incisor	inter-premolar	inter-molar
2822	1	29.45	42.11	51.28
2534	2	29.45	42.15	51.14
2223	3	29.57	42.11	51.25
1699	4	29.6	42.12	51.23
2325	5	29.54	42.1	51.27
	mean	29.522	42.118	51.234
	S.D.	0.069065187	0.019235384	0.055946403
Measurement of 3D Scanning Accuracy with 3D Software				

Attempt	inter-incisor	inter-premolar	inter-molar
1	29.6	42.21	51.29
2	29.61	42.2	51.28
3	29.61	42.22	51.19
4	29.71	42.18	51.29
5	29.64	42.23	51.19
mean	29.634	42.208	51.248
S.D.	0.04505521	0.019235384	0.053103672
Interoperator Reliability with 3D Software Measurement and Determination of Gold Standard Distances			

Definition of Inter-Arch Distances	
Inter- incisor	Distal of lateral incisor to distal of lateral incisor contacts measured from labial
Inter- canine	Canine to canine cusp tip
Inter- premola	2nd premolar to 2nd premolar central fossa
Inter- molar	2nd molar to 2nd molar central fossa

TABLE XII. MEASUREMENT OF ATTACHMENT SHRINKAGE

Short Leg	Long Leg	
1.233	2.709	
1.328	2.811	
1.355	2.645	
1.298	2.869	
1.257	2.778	
1.341	2.781	
1.238	2.781	
1.35	2.79	
1.258	2.752	
1.415	2.698	
1.3073	2.7614	mean
-0.1927	-0.2386	mm diff from ideal
-0.128466667	-0.079533333	% diff from ideal
Measured the attachments on 1139 total of 10 (5 vert and 5 horiz) to determine polymerization shrinkage		

IX. VITA

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