Transfer accuracy of 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets

By

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ABSTRACT

Objectives: To evaluate the transfer accuracy of custom orthodontic brackets using 3D printed transfer trays in a fully digital workflow.

Methods and Materials: Twenty-one participants who were treated with LightForce (LightForce, Burlington, MA, USA) brackets were bonded using 3D printed transfer trays. Intraoral scans (iTero, Align Technology, San Jose, CA, USA) were taken after brackets were bonded. The virtual bracket setup was compared to post-bonding scans using digital model superimpositions. Discrepancies in bracket position were assessed, and one-sided t-tests were used to determine if the mean transfer discrepancies were within clinically acceptable limits of 0.5 mm in linear dimensions and 2° for angular dimensions.

Results: The mean bracket position differences were 0.21 mm, 0.39 mm and 0.38 mm for mesiodistal, buccolingual, and occlusogingival directions, respectively. The frequency of bracket positions within 0.5 mm ranged from 73% to 95%. Mean bracket position differences were 1.69°, 1.09° and 1.70° for torque, tip, and rotation, respectively. The frequency of bracket positions within 2° ranged from 69% to 84%. P-values ranged from 0.00 to 0.694. The mean differences were statistically significant ($p<0.05$) and within clinically acceptable limits for all teeth in mesiodistal and tip dimensions.

Conclusion: 3D printed transfer trays have high transfer accuracy in many dimensions. Bracket position discrepancies in angular dimensions are more frequent than in linear dimensions. A digital workflow using virtually planned bracket positions and 3D printed transfer trays, as judged from this study, may be implemented with clinical confidence in indirect bonding of orthodontic bracket.

KEY TERMS
Indirect Bonding; Computer-aided design/Computer-aided manufacturing (CAD/CAM); 3D Printing; Transfer Trays

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CHAPTER 1: INTRODUCTION

Indirect bonding was first introduced by Silverman in 1972 and it has since gained popularity in clinical practice during the years to follow (Silverman et al., 1972)

The advantages of indirect bonding techniques include improved accuracy in bracket position with limited chairside time (Kalange, 2004; Nawrocka & Lukomska-Szymanska, 2020). Indirect bonding can be used in cases with severe malocclusion, crowding, and rotations to achieve more accurate bracket placement which would otherwise be difficult to achieve with traditional direct bonding methods (Nawrocka & Lukomska-Szymanska, 2020). While several studies have shown that indirect bonding techniques can improve the overall precision of bracket placement (Kulkarni & Goyal, 2022; Patano et al., 2023), neither direct nor indirect methods are able to guarantee ideal clinical placement. This means that repositioning or brackets and adjustments may be necessary in both techniques in order to achieve optimal clinical results (Sabbagh et al., 2022)

Inaccurately positioned brackets result in poorly positioned teeth. This in turn necessitates bracket repositioning and more arch wire adjustments. As a result, this can lead to an increase in treatment time or a compromised final occlusion for the patients. Carlson and Johnson noted that with both direct and indirect bonding techniques, there are generally four elements required to accurately position brackets: (1) base adaptation, (2) rotational position, (3) vertical position, and (4) slot angulation. Poor bracket positioning can make the most customized prescription ineffective (Carlson & Johnson, 2001)

Facilitated by advances in intraoral scanning, 3D printing, and virtual treatment planning, digital methods for indirect bonding have been developed (Christensen & Cope, 2018; Layman, 2019; Spitz et al., 2018). In digital indirect bonding, software is used to digitally position brackets on virtual models of the teeth. A transfer tray or jig can be designed virtually and directly 3D printed with no physical transfer model as an intermediary.

It has been suggested that digitally planned indirect bonding and transfer trays may be more accurate than traditional manually planned indirect bonding methods (De Oliveira et al., 2019). However, accurate clinical execution of the virtually planned bracket position is critical in this technique to achieve the digitally simulated alignment (Sabbagh et al., 2022)

As we continue to move toward a fullydigital workflow, the latest advancements have led to the first complete 3D printed bracket system featuring customized brackets, known as LightForce (LightForce, Burlington, MA, USA). This bracket system is designed and printed *de novo* based on the digital setup and planning with the LightForce planning software. This bracket system allows for a customized base and slot prescription tailormade to the desired clinical movements of each tooth. With each case, 3D printed indirect bonding transfer trays are fabricated to transfer the custom brackets to the patient's dentition (Waldman et al., 2023).

KEY TERMS

Indirect Bonding; Computer-aided design/Computer-aided manufacturing (CAD/CAM); 3D Printing; Transfer Trays

CHAPTER 2: REVIEW OF THE LITERATURE

2.1 HISTORY

The earliest record of moving teeth began with people being told to apply constant pressure with their finger to reposition a tooth. Several removable appliances were developed during the nineteenth century. While these appliances were revolutionary during their time, they had their drawbacks such as providing poor root control (Kulkarni & Goyal, 2022). Edward Angle's standard edgewise appliance was then developed which combatted these issues by providing control to the teeth in all three dimensions. The major drawback of this appliance was that it was time consuming as multiple bends were required in the arch wire in order to properly position the teeth (Kulkarni & Goyal, 2022)

This led to the development of the straight wire technique by Lawrence Andrews in the 1970s, which provided control over tooth movement in each dimension while also reducing the number of overall bends required (Andrews, 1979; McLaughlin & Bennett, 1989). The straight wire technique depends greatly on the accuracy of bracket placement (Aboujaoude et al., 2022)

A technique aimed to improve the accuracy of bracket placement is indirect bonding (Silverman et al., 1972). Indirect bonding has gained popularity for the many advantages it affords the clinician, including reduced clinical chair time, increased patient comfort, and better visibility for bracket placement. Bracket positioning can be done at the clinician's convenience in advance of the patient's arrival. It allows the orthodontist to carefully position the brackets in a dry, easily accessible field with unlimited working time, away from patient-related factors. A number of studies have suggested that indirect bonding thus improves the accuracy of bracket placement (Aboujaoude et al., 2022; Hodge et al., 2004; Israel et al., 2011; Kalange, 2007; Shpack et al., 2007).

2.2 TRADITIONAL INDIRECT BONDING AND TRANSFER TRAYS

With traditional indirect bonding methods, brackets are first positioned on plaster models of the patient's dentition. Transfer trays are then fabricated via laboratory processes, which allow the brackets to be transferred to the teeth. This technique has been shown to reduce variability from clinical challenges such as limited visibility, excessive salivary flow or complex dental morphology (Fiorillo et al., 2023). However, extra laboratory processes may introduce errors related to the technical procedures or the experience of the operator. In addition, operator experience has an influence on the correctness and accuracy of bonding procedures (De Oliveira et al., 2019)

2.3 INDIRECT BONDING MATERIALS

Historically, there have been many different materials used for transfer trays. Moin and Dogon used a transfer tray fabricated from polyether materials in the late 1970s (Moin & Dogon, 1977) while Thomas demonstrated the use of a thermoplastic sheet adapted over a working model using a vacuum former shortly after (Thomas, 1979). Other authors have used transparent materials which would enable light-cured resins to be used instead of self-curing resins during the bonding process (Kulkarni & Goyal, 2022). In 1993, Hickham developed a dual-tray transfer method which used a chemically cured composite (Hickham, 1993) while other authors later demonstrated the use of materials such as reprosil vinyl polysiloxane and glue gun materials to fabricated custom trays (Kulkarni & Goyal, 2022). Hot glue transfer trays have also been discussed as a transfer tray material in other studies (Nojima et al., 2015).

Along with variability in bracket materials, transfer tray properties vary significantly. Silicone trays and 3D printed trays showed higher accuracy compared to vacuum-formed trays. The use of 3D printed trays may suggest an increase in treatment efficiency due to higher precision in implementing the digital setup and treatment plan (Sabbagh et al., 2022).

One study noted that exclusive use of soft materials, such as thermoplastic ethylene-vinyl acetate copolymer in the form of a stick (hot glue) or in thermoforming sheets, can lead to poor fitting transfer trays which results in imprecise bracket positioning and bond failures (Nojima et al., 2015).

Materials with excessive retention between the brackets and the tray may be undesirable as the retention adds excessive force to the brackets during removal. On the contrary, reduced bracket-tray retention may result in bracket displacement from the tray. Flexibility to the tray to facilitate removal while maintaining retention is highly important (Nojima et al., 2015).

Another valuable factor to consider in the success of indirect bonding is the use of a clear tray. This allows visual confirmation of the appropriate fit of the tray along with bracket position, while also allowing the use of light curable bonding materials. During tray removal, bond strength is tested, and light-curing materials provide higher initial bond strength than their self-curing counterparts (Nojima et al., 2015)

2.4 3D SCANNING AND DIGITAL TRANSFER TRAYS

Computer-aided systems are increasing in popularity in many areas of dentistry such as restorative dentistry, prosthodontics, surgery and orthodontics. Three-dimensional CAD/CAM technology allows for a movement toward a completely digital workflow starting from the impression to the final bonding steps. It is believed that the movement toward digital workflows will replace traditional methods (Czolgosz et al., 2021)

With the advancements in computer technology, indirect bonding techniques have been enhanced. Three-dimensional CAD/CAM methods have provided a useful means of fabrication of indirect bonding trays which may help reduce some of the challenges that come with traditional indirect bonding methods (Fiorillo et al., 2023).

In preparation for CAD/CAM-assisted indirect bonding, teeth are scanned using an intraoral scanner, which results in digital 3D images of the patient's dentition. These 3D images are then used for digital planning of bracket position. Once the brackets are virtually placed at the desired position, customized transfer trays for indirect bonding are fabricated. The brackets are then manually placed into wells in the transfer trays. The trays are then used to position the brackets on the teeth in the position simulated in the computer software (Pamukçu & Özsoy, 2016).

This digital bonding method is thought to optimize bracket position and limit the number of manufacturing stages (Czolgosz et al., 2021).

2.5 ADVANTAGES AND DISADVANTAGES OF INDIRECT BONDING

2.5.1 Advantages

1. Reduced bonding time chairside (Nawrocka & Lukomska-Szymanska, 2020).
2. More predictable and precise than direct bonding (Patano et al., 2023).
3. Fewer bracket placement errors than direct bonding (Patano et al., 2023).

4. Increased patient comfort due to shorter bonding appointments, and reduction in contamination risk from saliva (Pamukçu & Özsoy, 2016).
5. Office staff and assistants can be used to a greater extent (Zachrisson & Brobakken, 1978).
6. Bracket positioning can be viewed in all dimensions on a model prior to placement which aids in better treatment results (Kulkarni & Goyal, 2022).
7. Little need for compensation bends (Nojima et al., 2015).
8. Reduced physical and mental stress as the indirect clinical procedure is simpler than direct bonding (Nojima et al., 2015).

2.5.2 Disadvantages

1. There is an additional laboratory procedure and cost associated with the indirect bonding technique (Pamukçu & Özsoy, 2016)
2. It is difficult to remove excessive adhesive flash around bracket bases, which can increase risk of gingival inflammation and decalcification. This in turn may lead to increased incidence of bracket debonding (Zachrisson & Brobakken, 1978).

In 1982, a clinical study by Aguirre noted that the time required for indirect bonding was significantly longer than the time required for direct bonding when the laboratory procedures are being considered as well (Aguirre et al., 1982). While the clinical chairside time for indirect bonding cases is shorter, authors such as Bozelli commented on the importance of considering total time including laboratory procedures when comparing direct bonding to indirect bonding practices (Bozelli et al., 2013).

Czolgosz and others used a randomized controlled clinical trial to compare bonding time, bonding failures and cost efficiency of CAD/CAM indirect bonding with that of traditional direct bonding (Czolgosz et al., 2021). They noted that clinical chair time was significantly shorter when using CAD/CAM indirect bonding when compared to traditional direct bonding. Specifically, they noted that the chair time required for CAD/CAM indirect bonding was 4 minutes shorter per half mouth than the chair time for direct bonding. Overall, they found that indirect bonding was 12 minutes and 52 seconds for half of the mouth while direct bonding required 16 minutes and 47 seconds (Czolgosz et al., 2021). Other authors reported similar findings such as Bozelli who reported 13 minutes and 8 seconds for a full-mouth indirect bonding procedure (Bozelli et al., 2013). Aguirre and others demonstrated that 24 minutes and 30 seconds of chair time was required for indirect bonding of a full-mouth while 42 minutes and 18 seconds would be required when using direct bonding techniques (Aguirre et al., 1982)

When comparing total time, (clinical chair time plus digital bracket placement), the CAD/CAM indirect bonding procedure was significantly longer than that spent when using the direct bonding technique (Aguirre et al., 1982). Previous studies by Bozelli and Aguirre reported similar findings. Bozelli and others found that indirect laboratory procedures using plaster casts took approximately 30 minutes of total time. Digital bracket placement took approximately 15 minutes per half mouth as reported by Czolgosz and others. These studies were consistent in the conclusion that total time is longer for computer-aided and traditional indirect bonding techniques when compared to direct bonding (Czolgosz et al., 2021).

Immediate debonding is an important concept to consider when comparing different bonding methods. These events are characterized by debonding during the actual bonding procedure (Czolgosz et al., 2021), typically upon removal of the transfer tray or shortly thereafter. Cooper and others studied this and noted that out of 1090 brackets bonded using indirect bonding techniques, 15 brackets debonded within the first 24 hours (Cooper & Sorenson, 1993). The failures were attributed mostly to moisture contamination during the bonding process, along with excessive pressure placed on the tray (Cooper & Sorenson, 1993).

Czolgosz reported that computer-aided indirect bonding showed more bonding failures compared to traditional direct bonding. It was found that a bond failure of 5.1 per cent occurred immediately after indirect bonding procedures (Czolgosz et al., 2021). Another study by Penning and others found increased bonding failures with customized brackets bonded with indirect bonding techniques (Penning et al., 2017)

Indirect bonding failures have also been attributed to causes outside of the alternate bonding technique. For example, Czolgosz and others reported that too short of a light-curing time may be a cause of increased failure rates. Overcured indirect bonding trays can also impact the transparency of the transfer jigs, which may impact the exposure of bonding materials to the light (Czolgosz et al., 2021).

2.6 3D BRACKET MATERIALS

Ceramic brackets provide an aesthetic option to fixed appliances in adolescents and adults. The introduction of 3D printing technology provides the option for orthodontic offices to print brackets in-house. The brackets are fabricated through an additive manufacturing method based on adding layers to create the appliance. This method provides an alternative to the challenges often associated with subtractive techniques. The majority of ceramic brackets are based on alumina of monocrystalline or polycrystalline structures. While the advent of ceramic brackets provides aesthetic advantages along with their inherent strength, it is important to be aware of the brittle nature of ceramic materials. As bracket wings fracture, orthodontic treatment and enamel integrity may be compromised as brackets are removed and replaced. One study reported that 3D printed zirconia brackets showed increased fracture toughness properties when compared to polycrystalline alumina brackets. Zirconia may therefore be considered as a possible candidate for customized aesthetics brackets with a higher resistance to wing fracture (Polychronis et al., 2023).

2.7 LIGHTFORCE

2.7.1 LightForce Overview

With advancements in technology, LightForce was developed as the first complete 3D printed bracket system featuring polycrystalline alumina brackets which are fully customized to the patient's dentition. Each bracket is designed virtually with a custom base along with a custom slot prescription. The brackets are 3D printed along with custom 3D printed transfer trays for the placement of brackets on the teeth (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

LightForce's 3D printed, custom brackets, indirect bonding trays and digital planning software are advertised to optimize efficiency in orthodontic treatment. The system claims to provide the ability for practitioners to offer shorter treatment times along with fewer appointments without any compromise on treatment result when compared to conventional bracket systems. One article by Waldman and others reported that LightForce cases had 30% shorter treatment times and required 30% fewer appointments than cases treated with conventional brackets. LightForce also reports 50-70% fewer repositioning appointments and wire adjustment procedures, which limits the number of detailing bends and thus chairside doctor time as well (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

LightForce offers a so-called LightPlan software, which is a cloud based virtual treatment planning software that provides clinicians the opportunity to have 3-dimensional control over tooth movement. The software enables the planning and development of brackets with specific slot dimensions and custom bases along with 3D printed indirect bonding transfer trays. LightForce can be prescribed in three different slot sizes, .018", .020", 0.22", and a number of bidimensional combinations which may be useful for sensitive anchorage requirements and extraction cases. The initial indirect bonding transfer trays come in sextants, along with individual jigs for second molars. The transfer trays also include digitally designed custom bite turbos where necessary (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

The individualized approach of LightForce enables specific tooth movements to be made which would otherwise be difficult with traditional pre-adjusted brackets and a standard prescription. Waldman and others reported the advantages of full customization of brackets in cases where a patient is missing a lateral incisor and being treated with canine substitution. (Waldman et al., 2023). The custom bracket base allows for changes in vertical position of the bracket on the tooth to create an ideal smile arc without altering the torque delivery (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

2.7.2 LightForce Indirect Bonding

LightForce claims to have eliminated or reduced many of the problems associated with traditional indirect bonding such as technical issues with laboratory setups along with improper bonding technique. The indirect bonding transfer trays are fabricated using the same digital file as the brackets, which may limit discrepancies in the process resulting in an improved fit of the brackets in the tray and accurate positioning of the brackets on the teeth. The improved accuracy ultimately results in greater bond strength. When practitioners receive the transfer trays from the company, they come pre-loaded with the LightForce bracket ready for the chairside bonding procedure. Each case also comes with backup brackets that are preloaded in individual jigs (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

2.7.3 Clinical Bonding Technique

It is recommended that appropriate isolation is used throughout the bonding procedure. Pumice prophylaxis, followed by etching and priming is completed for each tooth to be bonded. LightForce recommends a universal primer followed by a filled flowable composite resin or traditional adhesive paste to be used for bonding. A small amount of adhesive is recommended which provides accurate and intimate contact with the bracket and tooth while still ensuring that the bonding material is engaged into the mechanical undercuts of the bracket. Typically, posterior sextants are bonded first, followed by anterior sextants. Bite turbos are bonded last. LightForce recommends an initial cure with gentle pressure applied to the trays. The transfer trays are then removed, and a final cure is given. After the brackets are bonded, the wells of the bite turbos are filled with composite and bonded in the same fashion as the brackets (Waldman & Bonebreak-Jackson, 2023).

2.7.4 LightForce Philosophy and Claimed Effectiveness

The principles and effectiveness of LightForce are based on the accuracy of the indirect bonding system. Leveling and alignment of the dentition are influenced by the accuracy of bond, the fit of the custom bracket bases to the teeth, and the effectiveness of digitally planned bite turbos, which open the bite and reduce force of occlusion. The customization of the appliance facilitates longer activation periods with nickel titanium archwires which allow for longer periods of time between appointments. With greater effectiveness in the leveling and alignment, LightForce claims to allow earlier administration of rectangular or square nickel-titanium wires, which may initiate correction in the 3rd order positioning. Efficiency in treatment is also gained by reducing the need for direct bonding of second molars later in treatment or bracket repositioning appointments. Furthermore, the finishing stages of LightForce is said to be reduced as a direct result of custom prescriptions and bases, which limit the need for wire bending. It is suggested that digital planning of marginal ridge position may also improve the occlusal fit of the dentition and reduce the need for extensive settling with inter-arch elastics (Waldman et al., 2023; Waldman & Bonebreak-Jackson, 2023).

2.8 IMPORTANCE OF ACCURACY IN ORTHODONTICS

Removable appliances that were developed during the nineteenth century had drawbacks such as providing poor root control (Kulkarni & Goyal, 2022). Edward Angle's appliance was then developed which provided control to the teeth in all three dimensions. However, it required multiple bends to properly position the teeth making it time consuming (Kulkarni & Goyal, 2022)

The straight wire appliance was then developed by Lawrence Andrews, which provided control over tooth movement in each dimension while also reducing the number of overall bends required (Meyer & Nelson, 1978). The straight wire technique depends greatly on the accuracy of bracket placement. Meyer and Nelson demonstrated in their study that vertical bracket error in position of 3 mm on a premolar resulted in 15-degree torque variation and a 0.04 mm variation in the first order. It was also noted that vertical bracket displacement on teeth with greater buccal curvature will result in greater torque and in-out alteration than teeth with less buccal curvature. Furthermore, the mandibular first premolar generally has the greatest buccal curvature of any tooth. Meyer and Nelson also found that error in tooth position may be more significant when brackets with built in tip are poorly placed (Meyer & Nelson, 1978).

As orthodontics transitioned from predominantly banding to bonding, there was a push toward improving the accuracy of bracket placement. The success of treatment with orthodontics is dependent on the reliability and accuracy of the appliance bonded to the teeth. Furthermore, failure in bonding along with bracket replacement can slow down treatment progress along with added costs in both clinical time and materials (Czolgosz et al., 2021).

2.9 CLINICAL RELEVANCE

Time management and finding areas to save time is crucial for busy orthodontic practices. Reducing clinical chair time during bonding procedures may allow an orthodontist to see more patients in a day. Furthermore, clinical procedures such as bonding using indirect techniques may allow greater distribution of work and delegation of procedures to dental assistants where legally permissible, which frees up time for the orthodontist while still maintaining high accuracy of bracket placement (Czolgosz et al., 2021).

Simply stated, the indirect bonding technique should satisfy two requirements: (1) provide high accuracy in bracket placement, and (2) be simple in its execution. Attention to detail is required for the successes of this technique (Czolgosz et al., 2021).

2.10 PREVIOUS STUDIES

With the advent of indirect bonding, a few studies have investigated the transfer accuracy of laboratory-fabricated trays and a variety of bracket systems. Aboujadoude and others compared the accuracy of placement between direct and indirect bonding techniques in the maxillary arch using two different bracket systems, conventional twin brackets and self-ligating brackets (Aboujaoude et al., 2022). This study concluded that differences between bonding techniques were significant only for maxillary lateral incisors with regards to angulation, along with upper right canine and second premolar with regards to mesiodistal centering. The authors also concluded that self-ligating brackets had a greater deviation range compared to conventional brackets (Aboujaoude et al., 2022).

Another study by Bachour and others published in 2022 tested the accuracy of 3D printed trays for indirect bonding of orthodontic brackets. This study looked at twenty-three patients and a total of 363 brackets to compare digital bracket setups with scans taken immediately after bonding. Superimpositions revealed that the mean bracket position differences were 0.10 mm, 0.10 mm, and 0.18 mm for mesiodistal, buccolingual, and occlusogingival measurements, respectively. These values suggest that linear measurements are all within clinically acceptable limits of 0.5mm and 2 degrees. These limits were selected as clinically relevant because they represent accepted professional standards. The American Board of Orthodontics deducts points for teeth that deviate 0.5 mm or more from proper alignment or alignment of marginal ridges (Casko et al., 1998). A crown-tip positioning error of 2 degrees causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar. On the contrary, measurements of torque, tip and rotation were 2.55 degrees, 2.01 degrees and 2.47 degrees respectively, which are outside the clinically acceptable norms. This study concluded that indirect bonding using 3D printed trays provides high positional accuracy in linear dimensions; however, torque, tip, and rotation may lack the same degree of accuracy (Bachour et al., 2022)

CHAPTER 3: PURPOSE AND NULL HYPOTHESIS

One of the latest developments in a digital workflow in orthodontics includes initial intraoral scanning, digital planning and bracket design, customization of the bracket system and 3D printed brackets and transfer trays, aimed to improve clinical efficiency and reduce treatment times with orthodontic fixed appliances. In order to achieve the digitally simulated alignment, accurate clinical execution of the virtually planned bracket position is crucial.

3.1 PURPOSE

Assess the transfer accuracy of bracket position and evaluate *in vivo* any discrepancies between the digitally planned setup with the actual clinical bracket position immediately after indirect bonding.

3.2 NULL HYPOTHESIS

There is no significant difference between the bracket position simulated in the digitally planned setup and the actual clinical bracket position after transfer of the simulated bracket position to the dentition for customized 3D printed LightForce brackets.

CHAPTER 4: MATERIALS AND METHODS

4.1 ETHICS APPROVAL

This clinical study was approved by the Health and Research Ethics Board (HREB) at the University of Manitoba on November 22, 2024 (Ethics # HS26185 (H2023:305) along with the Provincial Health Research Privacy Committee (PHRPC) on September 3, 2024 (PHRPC No. P2023-107). Each study participant provided written consent and for participants who were minors, a parent or legal guardian provided consent on their behalf.

4.2 STUDY SAMPLE

4.2.1 Participants

The study participants were 20 patients, 12 male and 8 female, who sought orthodontic treatment in the private practice setting from two separate clinical practices. The first site is an orthodontic office in Warrenton, Virginia, USA (Griffin & Errera Orthodontics). The second site is an orthodontic office in Winnipeg, Manitoba, Canada (Dr. Dumore & Team). Patients were screened by practitioners based on inclusion and exclusion criteria. Patients were not recruited specifically for this study. The patients who were already planned for orthodontic treatment with LightForce (LightForce, Burlington, MA) bracket systems qualified as participants if they provided consent.

4.2.1 Inclusion Criteria

Inclusion criteria were fully erupted permanent dentitions, along with mild to severe crowding or spacing. Both extraction and non-extraction cases were included in the study.

4.2.2 Exclusion Criteria

Exclusion criteria were fixed prosthesis, craniofacial anomalies, severe dental anomalies such as microdontia, hypodontia, and severe attrition.

4.3 BRACKET POSITIONING AND TRANSFER TRAY FABRICATION

All patients had intraoral scans taken using an iTero Element scanner (Align Technology, San Jose, CA, USA) as part of their initial diagnostic records prior to starting treatment. Virtual models were created from the intraoral scans and uploaded to the LightForce planning software, LightPlan (Lightforce, Burlington, MA, USA), where brackets were digitally positioned on the virtual models. Slot size was determined by provider preference. Both of the clinics in this study used .020” bracket slot size. The models with digitally positioned brackets were referred to as the “virtual setup.”

The virtual setup on the LightPlan software was then sent for fabrication of the brackets and the indirect bonding trays, known as the LightTray (Lightforce, Burlington, MA, USA). The brackets were 3D printed using polycrystalline alumina material. The transfer trays were also 3D printed. LightTrays were fabricated in sections: upper right, upper anterior, upper left, lower right, lower anterior and lower left. The brackets were manually installed by the manufacturer into their respective wells and were provided to the end user ready for use. At that point they were then quality checked by a technician and distributed to their respective office

4.4 BONDING PROCEDURE

A total of 433 brackets were bonded to maxillary and mandibular incisors, canines, premolars and molars. Clinical staff followed dental bonding procedures as recommended by the manufacturers of the dental materials.

1. Polish with prophylaxis polisher plain pumice to prepare for bonding
2. Etch (30 seconds) with 35% phosphoric acid Opal Etch (Ultradent Products Inc, South Jordan, UT), 40% phosphoric acid Henry Schein Etching Gel (Henry Schein Inc, Melville, NY), or 37% phosphoric acid Reliance Liquid Etchant (Reliance Orthodontics Products Inc, Itasca, IL)
3. Rinse thoroughly with water and dry (5 seconds per tooth for liquid etchant, 10 seconds per tooth for gel etchant)
4. 3M™ Unitek Transbond™ XT Light Cure Orthodontic Adhesive Primer (Solventum, St. Paul, MN, USA) or Assure Plus All Surface Bonding Resin (Reliance Orthodontics Products Inc, Itasca, IL) were used following manufacturer’s directions.
5. 3M™ Transbond™ XT Light Cure Adhesive (Solventum, St. Paul, MN, USA) was used to bond the brackets.
6. Each transfer tray was placed intraorally with light pressure applied on the occlusal surface.
7. Initial light curing for 5 seconds per tooth, followed by removal of the transfer tray and final cure for each tooth.

Immediately after bonding, a new intraoral scan was taken using the iTero Element scanner to generate a new digital model with the final bracket position (Figure 4.1). This digital model is referred to as the post-bonding model and was used to compare the final bracket position with the planned bracket position on the virtual setup.

Figure 4.1. Post-bonding intraoral scan of the dentition. Intraoral scan taken with iTero Element scanner.

4.5 SUPERIMPOSITIONS/DATA ACQUISITION

The virtual setup and post-bonding model for each patient was compared using superimpositions through best-fit methods with a custom software (Voyager Dental, Eden Prairie, MN, USA). Brackets and soft tissue were removed from the post-bonding model during the superimposition process, which ensured that the superimposition was based solely on tooth features (Figure 4.2). Superimpositions were completed for sextants (upper right, upper anterior, upper left, lower right, lower anterior and lower left) to mimic indirect bonding trays (Figure 4.3). Once each superimposition was complete, a new file was created with both the virtual setup model and the post-bonding model.

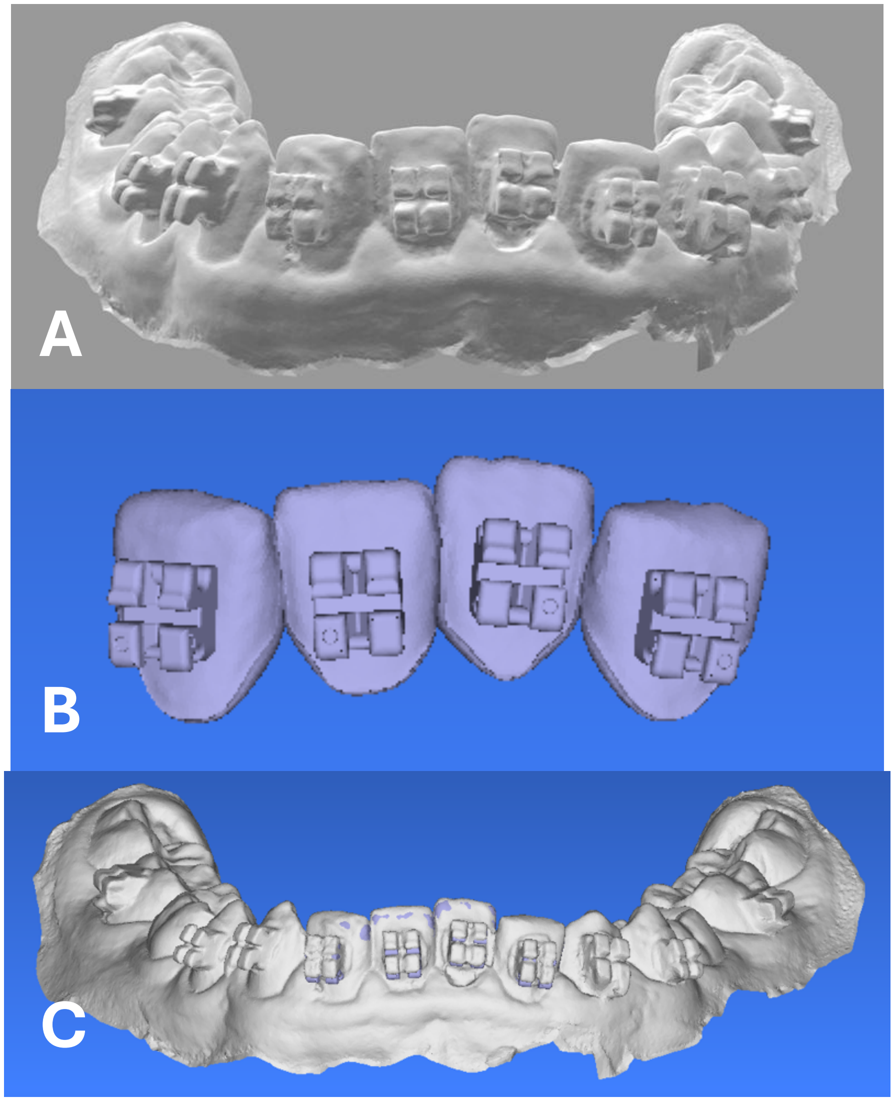

Figure 4.2. Digital models and superimposition. (A) Post-bonding model. (B) Virtual setup with digitally planned bracket position. (C) Superimposed best-fit digital setup model (purple) and post bonding model (white)

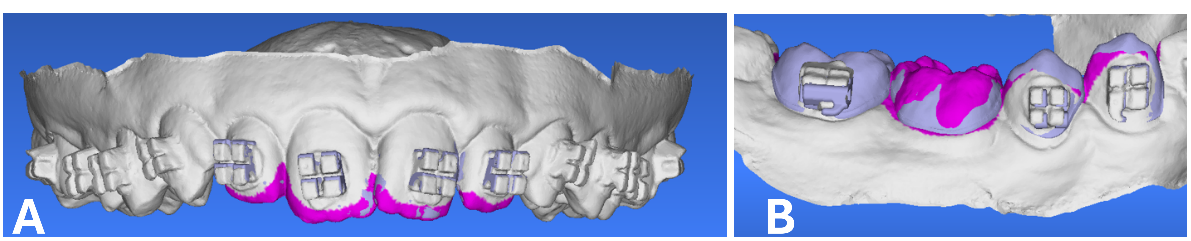

Figure 4.3 . Superimposition of digitally planned bracket position and post-bonding model. Digitally planned bracket position (purple) and post-bonding model (white) in upper anterior (A) and lower right posterior (B). Highlighted fuchsia structure represents tooth structure used for superimposition.

The bracket positions between the virtual setup and the post-bonding model were compared as follows: four datum points were assigned to each bracket in the upper right, lower right, upper left, and lower left corners of the bracket slot (Figure 4.4). An XYZ coordinate system was created based on these datum points.

Figure 4.4. Bracket coordinate system generation. Four datam points placed in each corners of the bracket slot (upper right, lower right, upper left, lower left).

For each bracket pairing (i.e., same bracket in virtual setup and post-bonding model), the software computed the positional discrepancies with respect to six dimensions of tooth movement. The six dimensions included three linear measurements (mesiodistal, buccolingual, and occlusogingival translation), and three angular measurements (tip, torque, and rotation). The measurement values expressed the magnitude of the discrepancy. During this comparison, the virtual setup was considered the reference model, while the post-bonding model was considered the comparison.

When assessing the discrepancy measurements between the reference model and the comparison, absolute values were used to eliminate risk that the summation of positive and negative values would negate each other. Following earlier studies (Bachour et al., 2022) clinically acceptable transfer error limits were set to 0.5 mm for linear measurements (mesiodistal, buccolingual, occlusogingival) and 2 degrees for angular measurements (rotation, tip, torque) based on the standards determined by the American Board of Orthodontics. For their assessment, clinicians are penalized when teeth deviate 0.5 mm or more from proper alignment of marginal ridges. A crown tip error of 2 degrees causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar (Bachour et al., 2022).

4.6 STATISTICAL ANALYSIS

Left-right differences in absolute measurements were assessed and revealed an equal distribution of values between each analogous tooth type. In other words, for each dimension, the left-right differences were not significant. Therefore, contralateral tooth pairings were grouped together for subsequent tests. Maxillary and mandibular teeth were assessed independently. If either tooth from the pair was missing, left-right differences could not be computed. A total of 206 pairs of analogous teeth were assessed.

Descriptive statistics were calculated for each tooth type and each dimension. One-sided t-tests were used with absolute values in each dimension to assess if the mean transfer discrepancies were within the clinically acceptable limits. P-values of less than 0.05 indicated that the differences between the digital setup and post-bonding bracket position were within these limits

Mean differences +/- standard deviations for each tooth type and each dimension were calculated. The frequency of bonding bracket errors being within the acceptable limits were also calculated. In this assessment, measurements were given as absolute counts as well as proportions.

CHAPTER 5: RESULTS

5.1 LINEAR AND ANGULAR DISCREPANCIES IN BRACKET POSITION

A total of 433 brackets were bonded and evaluated for transfer accuracy. Differences between post-bonding and virtual setup bracket positions are shown in Table 5.1. The differences in linear bracket position ranged from 0.168 to 0.506 mm for upper teeth and from 0.175 to 0.485 mm for lower teeth. For angular dimensions, the discrepancies in bracket position ranged from 1.226 to 2.048 degrees for upper teeth and from 0.88 to 2.117 degrees for lower teeth.

Table 5.1. Differences between post-bonding and virtual setup bracket positions. [1,2,3,4]

		Dimension					
Tooth Type	n	Mesiodistal (mm)	Buccolingual (mm)	Occlusogingival (mm)	Rotation (°)	Tip (°)	Torque (°)
Incisor							
Upper	80	0.168 ± 0.147*	0.334 ± 0.200*	0.239 ± 0.167*	1.868 ± 1.738	1.158 ± 0.948*	1.626 ± 1.387*
Lower	75	0.175 ± 0.134*	0.413 ± 0.222*	0.409 ± 0.217*	2.117 ± 1.995	1.289 ± 1.194*	1.663 ± 1.401*
Canine							
Upper	38	0.243 ± 0.177*	0.506 ± 0.434	0.347 ± 0.258*	1.403 ± 1.166*	1.211 ± 1.210*	1.750 ± 1.277
Lower	39	0.215 ± 0.116*	0.423 ± 0.279*	0.419 ± 0.256*	1.780 ± 1.635	0.974 ± 0.915*	1.687 ± 1.700
Premolar							
Upper	61	0.256 ± 0.222*	0.437 ± 0.243*	0.343 ± 0.229*	1.65 ±1.481*	1.017 ± 0.950*	2.048 ± 1.764
Lower	69	0.207 ± 0.140*	0.463 ± 0.344	0.485 ± 0.296	1.65 ± 1.774*	0.880 ± 0.789*	1.662 ± 1.583*
Molar							
Upper	32	0.222 ± 0.153*	0.205 ± 0.262*	0.408 ± 0.289*	1.226 ± 0.827*	1.287 ± 0.943*	1.461 ± 1.322*
Lower	39	0.273 ± 0.179*	0.219 ± 0.152*	0.460 ± 0.275	1.252 ± 0.950*	0.839 ± 0.844*	1.711 ± 1.182

[1] n is the number of teeth assessed in each respective category
[2] Results are presented as mean and standard deviation of bracket discrepancies
[3] Limits are set as 0.5 mm for linear measurements and 2° for angular measurements
[4] Asterisks (*) indicates statistically significant values ($p<0.05$)

When all tooth types were combined, deviations for linear measurements were 0.212 mm, 0.386 mm and 0.380 mm for mesiodistal, buccolingual, and occlusogingival measurements, respectively. Overall deviations for angular measurements were 1.694 degrees, 1.085 degrees and 1.709 degrees for rotation, tip, and torque measurements, respectively.

When assessing incisor position, the lower incisor consistently had a greater value in discrepancy for all dimensions when compared to its upper counterpart. With respect to the specific dimensions of occlusogingival displacement and rotation, lower teeth consistently had a greater magnitude of discrepancy when compared to their upper counterparts for all teeth. There were no other clear patterns present in the data.

5.2 STATISTICAL SIGNIFICANCE

P-values of post-bonding bracket position compared to virtual bracket setup within clinically acceptable limits in linear and angular dimensions are shown in Table 5.2. The p-values ranged from 0.00 to 0.6936. One sided t-tests where values were below 0.05 reached statistical significance and indicated that the brackets were transferred within the set clinically acceptable limits. Mesiodistal and tip dimensions had p-values that were below 0.05 for all tooth types indicating that for these dimensions, brackets were transferred within the acceptable limits of 0.5 mm and 2 degrees respectively. Box and whisker plots for linear discrepancies between virtual and actual bracket position for each tooth type are shown in Figure 5.1. On average, the discrepancy between virtual and actual bracket position was least in the mesiodistal dimension. Box and whisker plots for angular discrepancies between virtual and actual bracket position for each tooth type are shown in Figure 5.2. In general, the discrepancy between virtual and actual bracket position was least in the tip dimension.

Table 5.2. P-values of post-bonding bracket position compared to virtual bracket setup within clinically acceptable limits in linear and angular dimensions. [1,2]

	Dimensions					
Tooth Type	Mesiodistal	Buccolingual	Occlusogingival	Rotation	Tip	Torque
Incisor						
Upper	0	0.0000	0.0000	0.2486	0.0000	0.0091
Lower	0	0.0006	0.0003	0.6936	0.0000	0.0203
Canine						
Upper	0	0.5326	0.0004	0.0016	0.0001	0.1173
Lower	0	0.0465	0.0274	0.2028	0.0000	0.1284
Premolar						
Upper	0	0.0234	0.0000	0.0351	0.0000	0.5844
Lower	0	0.1869	0.3400	0.0522	0.0000	0.0403
Molar						
Upper	0	0.0000	0.0397	0.0000	0.0001	0.0140
Lower	0	0.0000	0.1864	0.0000	0.0000	0.0677

[1] p-values are rounded to four decimal places
[2] Values below 0.05 indicate that the difference is within clinically acceptable limits while values above 0.05 indicate that the difference is outside of clinically acceptable limits

Notably, upper molars had a p-value below 0.05 for all dimensions indicating that discrepancies in all dimensions were within clinically acceptable limits. In contrast, p-values above 0.05 indicated that the discrepancies did not reach statistical significance. Rotation and torque had the greatest number of tooth types that did not reach statistical significance. Furthermore, lower premolars had the greatest number of p-values above 0.05 with respect to buccolingual, occlusogingival and rotational bracket position changes. This indicates that lower premolars had deviations in final bracket position that did not reach statistical significance and may not necessarily be transferred within the clinically acceptable limits set.

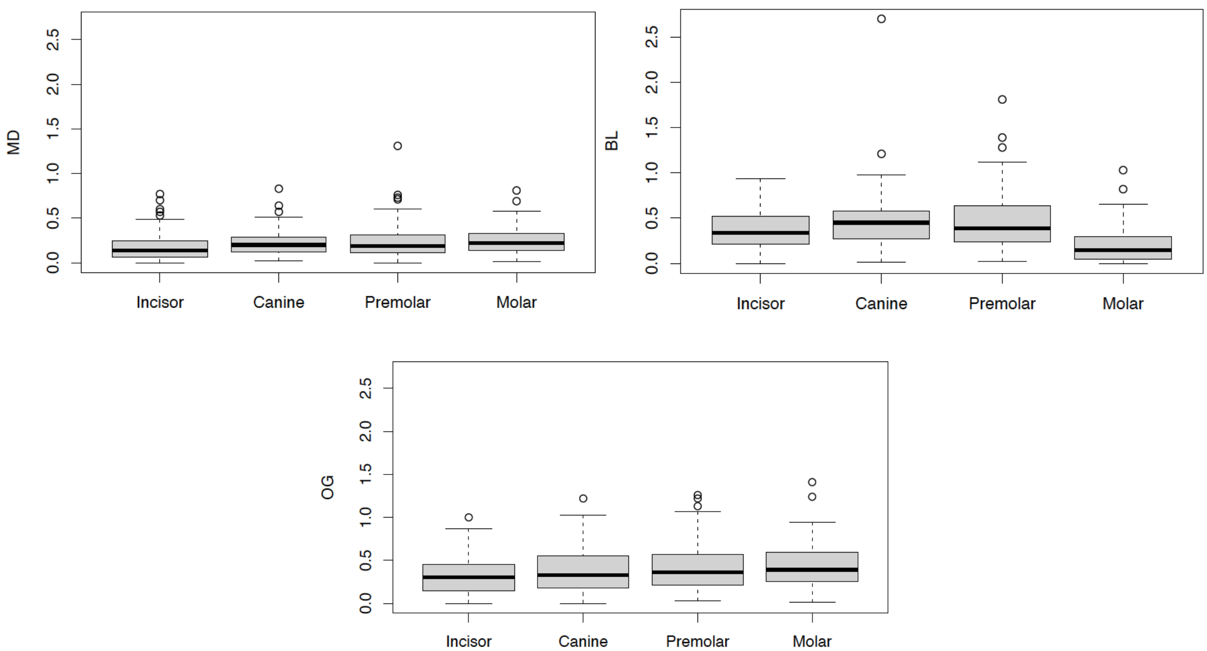

Figure 5.1. **Box and whisker plots for discrepancies between virtual and actual bracket position for four tooth types in linear dimensions.** The centerline represents the median. The upper and lower borders of the box represent the third and first quartile respectively (interquartile range). Vertical lines mark the largest and smallest observed data values within 1.5 times the interquartile range. Values beyond these bounds are outliers.

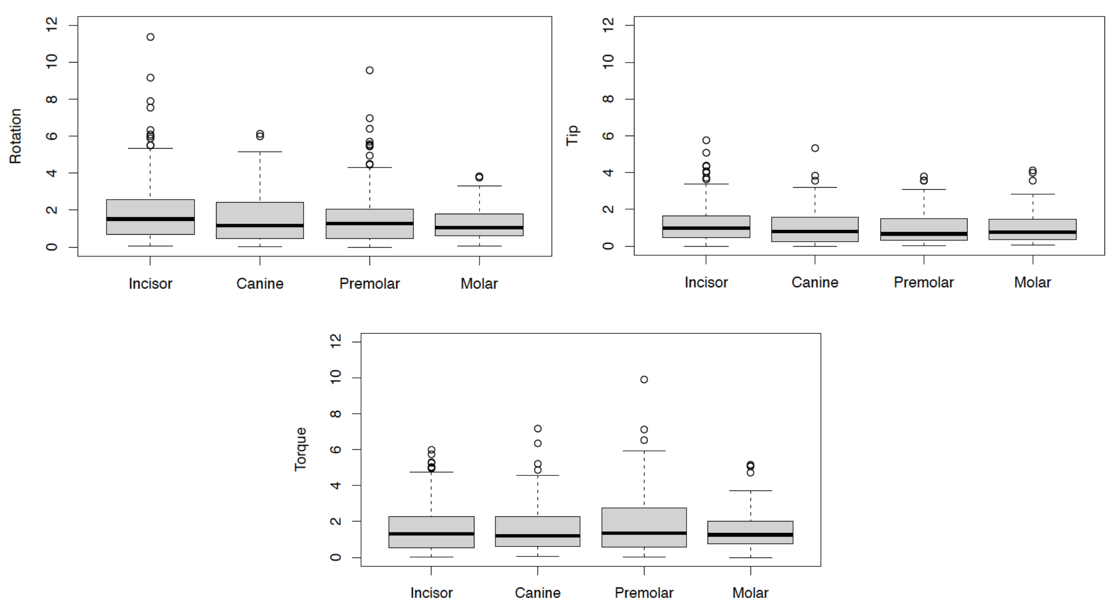

Figure 5.2. **Box and whisker plots for discrepancies between virtual and actual bracket position for four tooth types in the angular dimensions.** The centerline represents the median. The upper and lower borders of the box represent the third and first quartile respectively (interquartile range). Vertical lines mark the largest and smallest observed data values within 1.5 times the interquartile range. Values beyond these bounds are outliers.

5.3 FREQUENCIES OF BRACKET POSITION WITHIN SET LIMITS

Frequency of post-bonding bracket positions within clinically acceptable limits in linear and angular dimensions are shown in Table 5.3. The frequency of brackets on the post-bonding models within clinically acceptable limits in linear position ranged from 57.9 to 97.5% in the upper arch and from 59 to 97.4% in the lower arch. For angular dimensions, the frequency of brackets on the post-bonding models within clinically acceptable limits ranged from 57.4 to 87.5 % in the upper arch and from 61.3 to 92.3% in the lower arch. Upper incisors had the highest frequency of brackets within acceptable limits with 97.5% in the mesiodistal dimension while lower premolars had the lowest frequency of brackets within acceptable limits with 53.6% in the occlusal gingival dimensions.

Table 5.3. Frequency of post-bonding bracket positions within clinically acceptable limits in linear and angular dimensions.[1,2,3]

		Dimension					
Tooth Type	n	Mesiodistal	Buccolingual	Occlusogingival	Rotation	Tip	Torque
Incisor							
Upper	80	97.5	77.5	93.8	70.0	80.0	72.5
Lower	75	96.0	64.0	69.3	61.3	81.3	69.3
Canine							
Upper	38	92.1	57.9	73.7	71.1	76.3	57.9
Lower	39	97.4	61.5	61.5	69.2	89.7	71.8
Premolar							
Upper	61	90.2	62.3	83.6	75.4	83.6	57.4
Lower	69	97.1	60.9	53.6	73.9	88.4	72.5
Molar							
Upper	32	93.8	84.4	71.9	87.5	81.2	78.1
Lower	39	89.7	94.9	59.0	74.4	92.3	71.8

[1] n is the number of teeth assessed in each respective category
[2] Frequency is reported as percentage
[3] Limits are set as 0.5 mm for linear measurements and 2° for angular measurements

CHAPTER 6: DISCUSSION

The developments in a digital workflow in orthodontics includes aims to improve clinical efficiency and reduce treatment times with orthodontic fixed appliances. In order to achieve the digitally simulated alignment, accurate clinical execution of the virtually planned bracket position is crucial.

6.1 TRANSFER ACCURACY OF BRACKETS

6.1.1 Comparison Of Anterior and Posterior Dentition

The comparison between the digitally planned setup and the actual bracket position immediately after bonding showed a high transfer accuracy of brackets in all dimensions except rotation in upper and lower incisors, whereas the accuracy was generally lower in the posterior dentition. The high degree of accuracy in the anterior dentition could be attributed to better access and moisture control when compared to posterior teeth. This idea is supported by studies into the accuracy of posterior tooth bracket position with CAD/CAM developed indirect bonding jigs, which suggest that challenges in the posterior dentition may be due to difficulties with visibility, moisture control, and patient management (Kim et al., 2018). Other factors that may impact bracket transfer accuracy in posterior teeth are cusp height and morphology variations. These features may influence the fit of transfer jigs and thus, the precise transfer of brackets to the teeth. This idea has been supported in the literature by researchers who suggest cusp reduction before jig fabrication may increase the accuracy of the bracket position (Kim et al., 2018). Both upper and lower canine final bracket position were outside of clinically acceptable limits for torque which may be due to previously discussed factors. In addition, maxillary canines showed some of the largest discrepancies in the buccolingual dimension.

6.1.2 Comparison Of Maxillary and Mandibular Dentition

The upper premolars showed a high transfer accuracy in all dimensions with the exception of torque while lower premolars showed a high transfer accuracy in only the mesiodistal, tip, and torque dimensions. When comparing maxillary and mandibular arches, the upper molars showed high accuracy of bracket positions in all dimensions, while the lower molars showed a high accuracy in all dimensions with the exception of the occlusogingival dimension and torque. Overall, teeth in the upper arch had more frequently brackets that were transferred within clinically acceptable limits when compared to their lower counterparts. These findings support the previously discussed notion that access and visibility may play an important role in transfer bracket accuracy using indirect bonding methods (Kim et al., 2018).

6.1.3 Comparison Of Linear and Angular Dimensions

A comparison of linear and angular dimensions yielded fewer discrepancies in the linear dimensions than in the angular dimensions. Furthermore, in this study, rotation and torque had the greatest number of bracket deviations outside of clinically acceptable limits. These findings are consistent with previous findings of very small positional discrepancies (approximately one-tenth of a millimeter) in occlusogingival, mesiodistal, and buccolingual measurements, which suggest that a high transfer accuracy in the linear dimensions can achieved with 3D printed indirect bonding trays (Bachour et al., 2022). However, similar to the present findings, previous reports suggest a poorer transfer accuracy in angular dimensions (Bachour et al., 2022) which may exceed the clinically acceptable limits in some patients.

It is of note that this pattern of positional discrepancies is similar to conventional indirect bonding techniques. Studies into conventional indirect bonding transfer accuracy show that bracket deviations were higher in angular dimensions, when compared to linear dimensions (Niu et al., 2021). Of the angular dimensions, torque had the greatest amount of deviation, while vertical deviations toward the gingival direction were the greatest discrepancies seen in linear dimensions (Niu et al., 2021). Similarly, Koch and others found transfer accuracy of linear measurements were higher than that of angular measurements (98.3% and 86.7%, respectively) when CAD/CAM based indirect bonding trays were used (Koch et al., 2022). A recent systematic review noted that while indirect bonding is fairly accurate, the highest transfer error was reported in the buccolingual direction at the incisors, and torque and tip in the premolars for angular measurements (Campobasso et al., 2023).

In this study, a high frequency of final bracket position within the acceptable limits were seen in the mesiodistal dimension of all teeth. When reviewing specific tooth types, premolars had a low frequency of bracket positions within acceptable limits and had a fairly large range of mean errors, which suggests that the transfer accuracy was lower in these posterior teeth. No other clear patterns were noted.

6.2 STUDY LIMITATIONS

6.2.1 Intraoral Scanners

The present results may have been influenced by challenges faced while capturing the post-bonding intraoral scans. In some cases, detail of the bracket slots were not captured clearly

(Figure 6.1). One study concluded that the iTero Scanner had the highest reproducibility and accuracy in clinical settings when compared to other intraoral scanners (Costa et al., 2022). Despite the high accuracy and precision of iTero scanners, there are many factors that may have impacted scan accuracy such as possible scan distortion of the orthodontic brackets. One study evaluated the effects of orthodontic brackets bonded to tooth surfaces on intraoral scans and assessed the range of distortion around the brackets (Kang et al., 2021). These researchers concluded that the cross-sections of the superimposed intraoral scans showed deviations of around 0.40 mm in the horizontal section and 0.35 mm in the vertical section around the brackets (Kang et al., 2021). Other factors that may impact the clarity and accuracy of intraoral scans could be attributed to scattered reflection of light rays caused by different materials found intraorally. This idea is supported by researchers who noted that reflection of light rays by metal surfaces may impact scan accuracy of iTero scanners as they operate by the principle of light emission (Kang et al., 2021). Another study affirmed this idea by suggesting that metallic restorations resulted in considerable artifacts in 3D surface models (Nabha et al., 2014). While these findings may provide information that is comparable to metal brackets, there is little information regarding the impact of materials such as polycrystalline alumina brackets, which are used in the LightForce bracket system. These studies suggest that while scanners are accurate enough to complete superimpositions on tooth structure, the analysis of bracket position may be challenging due to the inability of the scanner to record details of an orthodontic bracket, irrespective of the bracket material.

Figure 6.1. Quality comparison of mandibular incisors of the same brackets on one patient. (A) Post-bonding intraoral scan. (B) Digital model with virtually positioned brackets.

6.2.2 Superimposition Software

In this current study, challenges in capturing clear scans of the brackets resulted in further difficulty while placing datum points on the Voyager software. Bracket slots were chosen for placement of the four datum points as the slot was easily identifiable in both the virtual setups and post-bonding scans. The four datum points were then used to create a coordinate system for each tooth, and coordinate systems were compared between the two scans. Due to discrepancies capturing detail of the bracket, a multiplanar appearance resulted in some of the post-bonding scans. In contrast, brackets on the virtual setup were clear; datum point targets and their corresponding coordinate systems were easily identifiable and reproducible. Surface differences may have created an illusion that the coordinate systems had greater discrepancies than they actually did. Similar findings were reported in a study by Bachour et al. who assessed superimpositions from intraoral iTero scans on 022” slot Victory Series brackets (3M Unitek, Monrovia, CA) and 018” slot Mini-Master Series brackets (American Orthodontics, Sheboygan, WI). Researchers proposed that multiplanar post bonding scans may have a considerable impact on angular dimensions such as tip, torque and rotation (Bachour et al., 2022).

6.2.3 Bonding Procedure

Another possible reason for discrepancies in angular dimensions, rotation and torque, may be due to variations in adhesive application at the bracket interface. This notion is supported by researchers who found that the that lack of consistency in resin application may contribute to angular transfer errors (Niu et al., 2021). Linear transfer errors in the vertical dimension may be due to improper seating of the indirect bonding transfer jig (Figure 6.2). Displacement of a bracket toward the occlusal direction may suggest incomplete seating of a transfer jig (Niu et al., 2021), while displacement in a gingival direction may indicate increased force during seating of a transfer jig (Castilla et al., 2014).

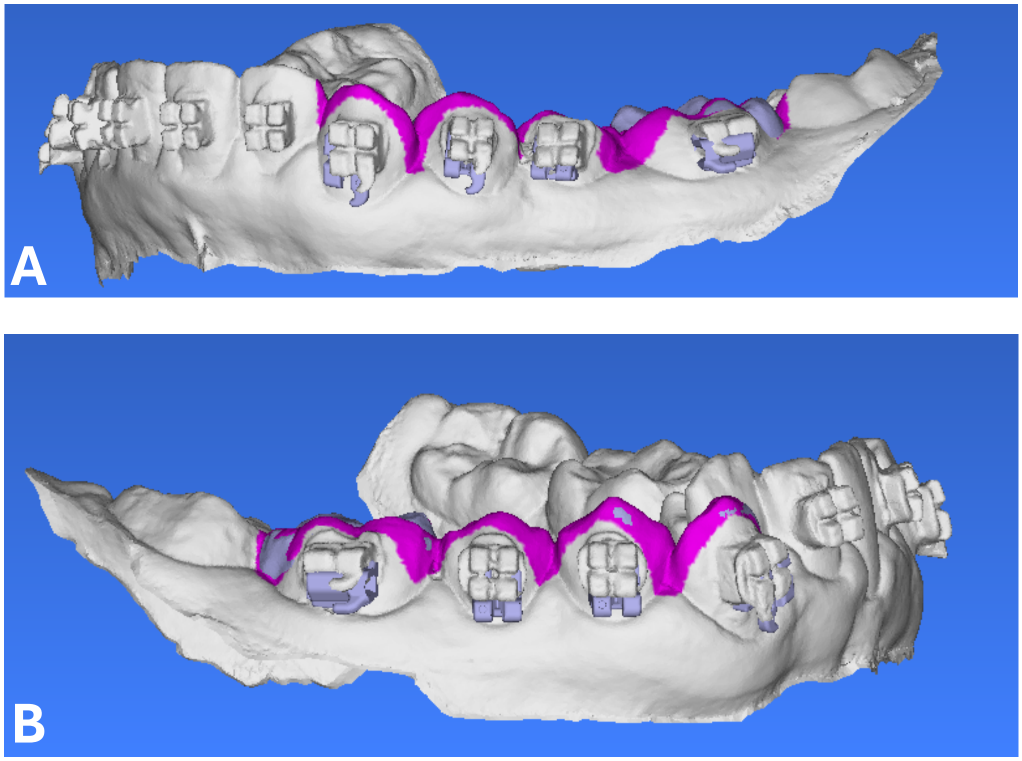

Figure 6.2 . Superimposition of digitally planned bracket position and post-bonding model showing linear transfer errors in the vertical dimension. Superimposition of virtual setup (purple) and post bonding model (white) in lower left posterior (A) and lower right posterior (B). Highlighted fuchsia structure represents tooth structure used for superimposition

6.2.4 Transfer Tray Characteristics and Properties

Another consideration to rationalise inaccuracies in bracket position in this current study could be the rigidity of the transfer trays used. One study suggests that low rigidity in an indirect bonding tray may result not only in inaccurate bracket position transfer, but also in an increased number of bond failures due to poor adaptation (Castilla et al., 2014). Using this information, one may conclude that greater adaptation leads to improved angular dimension transfer accuracy. On the contrary, it is important to note that high rigidity in transfer tray material may present challenges with removing the tray such as an increased risk of debonding brackets (Bachour et al., 2022). In either case the rigidity of the 3D printed transfer tray may have an impact on both the discrepancies with bracket transfer and immediate debonding of brackets. 3D printed indirect bonding trays have been found to have similar accuracy to that of conventional methods for bracket placement (Shin et al., 2021), while others have reported that 3D indirect bonding trays having a higher accuracy than other methods such as double vacuum formed trays (Niu et al., 2021). A systematic review by Sabbagh et al. concluded that silicone trays and 3D printed trays showed higher accuracy compared to vacuum-formed trays (Sabbagh et al., 2022).

6.2.5 Practitioner Experience

A potential limitation to this study is the lack of standardization of practitioners completing the indirect bonding procedure clinically. Multiple practitioners were involved in the initial scan, the actual indirect bonding procedure, and the post-bonding scan. The indirect bonding tray design along with a practitioner's professional experience has a significant influence on positioning accuracy when indirect bonding techniques are used (Sabbagh et al., 2024). The clinical execution of indirect bonding systems are highly technique sensitive and other factors such as practitioner experience may impact the accuracy of bracket transfer (Sabbagh et al., 2024). While indirect bonding has been shown to be fairly accurate in many dimensions (Sabbagh et al., 2022), standardization of the technique and use of an experienced clinician may provide a clearer assessment of accuracy in different dimensions.

6.3 NULL HYPOTHESIS TESTING

The Null hypothesis states: There is no significant difference between the bracket position simulated in the digitally planned setup and the actual clinical bracket position after transfer of the simulated bracket position to the dentition for customized 3D printed LightForce brackets.

Based on results discussed in Chapter IV, the Null hypotheses is rejected: there was a statistically significant difference between the bracket position of the digitally planned LightPlan setup and the actual clinical bracket position of the 3D printed transfer trays for customized 3D printed LightForce brackets in several dimensions; however, in many cases it was not clinically significant. When all tooth types were combined, the mean discrepancies for linear measurements were 0.212 mm, 0.386 mm and 0.380 mm for mesiodistal, buccolingual, and occlusogingival measurements, respectively. The mean discrepancies for angular measurements were 1.694 degrees, 1.085 degrees and 1.709 degrees for rotation, tip, and torque measurements, respectively. Of note, all these mean values lie within the limits considered clinically acceptable by professional standards, suggesting that the transfer accuracy of brackets with the LightForce system is generally high. It can, therefore, be concluded, that 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets can achieve bracket placement accuracy sufficient for clinical application and equivalent or potentially superior to conventional indirect bonding methods. As the technology progresses, it is anticipated that transfer accuracy of indirect bonding will continue to improve even more.

CHAPTER 7: CONCLUSIONS

Based on results of this study, the following conclusions can be reached:

1. LightForce custom brackets positioned virtually in a fully digital workflow and bonded using 3D printed transfer trays showed a high level of positional accuracy in most dimensions.
2. Positional discrepancies in angular positions tend to be more frequent than discrepancies in linear positions; however, the magnitude may not be clinically relevant.
3. Discrepancies in transfer accuracy tended to be greater in the posterior dentition than in the anterior dentition.
4. A digital workflow using virtually planned bracket positions and 3D printed transfer trays for orthodontic bracket bonding, as judged from this study, may be implemented with clinical confidence.

CHAPTER 8: RECOMMENDATIONS

8.1 RECOMMENDATIONS FOR METHODOLOGY

A single experienced practitioner taking all pre- and post-bonding scans may provide improved accuracy and consistency in scans, specifically when trying to capture bracket slot details. While detail of tooth structure was captured with a high degree of clarity, components of the bracket were not. The software used in this study for superimpositions, Voyager, was able to create superimpositions with ease based on the tooth structure. The comparison of coordinate systems for each of the bracket position was not nearly as straightforward. Attention to detail on capturing slot accuracy would allow for improved accuracy in scans for better assessment in bracket position, especially in the angular dimensions. Furthermore, a single experienced practitioner completing all the indirect bonding procedures would reduce the margin of error that comes from different skill level and experience. The varying skill level in the direct bonding procedure may have implications on the results that are more likely due to practitioner error rather than errors in the actual indirect bonding system.

8.2 FUTURE RESEARCH

In future studies, it may be valuable to explore a relationship between accuracy of bracket placement and need for compensatory bends, repositioning of brackets and subsequently the overall treatment time. Researchers have suggested that while indirect bonding is more time and cost-consuming overall than direct bonding due to the laboratory process required, there is a notable reduction in clinical chair time (Sabbagh et al., 2022). This idea could be studied further as it relates to a completely digital workflow with customized brackets such as LightForce. In future studies it may also be advantageous to assess the degree of crowding, access and other factors on their impact of transfer accuracy. Another possible study could look at practitioners' experience with indirect bonding systems and how that impacts the accuracy of bonding in linear and angular dimensions.

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CHAPTER 9: APPENDIX

9.1 ETHICS APPROVAL

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University of Manitoba | Research Ethics and Compliance

HEALTH RESEARCH ETHICS BOARD (HREB)
CERTIFICATE OF FINAL APPROVAL FOR NEW STUDIES
Delegated Review

PRINCIPAL INVESTIGATOR: Dr. Stella Korowski	**INSTITUTION/DEPARTMENT:** University of Manitoba/Preventive Dental Sciences	**ETHICS #:** HS26185 (H2023:305)
APPROVAL DATE: November 22, 2023	**EXPIRY DATE:** November 22, 2024	
STUDENT PRINCIPAL INVESTIGATOR SUPERVISOR (If applicable): Dr. Fabio Pinheiro		

PROTOCOL NUMBER:	**PROJECT OR PROTOCOL TITLE:** Precision of indirect bonding using 3D printed trays for custom-made 3D printed orthodontic brackets
SPONSORING AGENCIES AND/OR COORDINATING GROUPS:	

Submission Date of Investigator Documents: October 24, 2023 and November 15, 2023	**HREB Receipt Date of Documents:** October 30, 2023 and November 16, 2023

THE FOLLOWING ARE APPROVED FOR USE:

Document Name	Version (if applicable)	Date
Protocol:		
Protocol (undated) along with proposal as outlined in the revised University of Manitoba Bannatyne Campus Research Research Ethics Board Submission Form and Letter of Response dated November 15, 2023		submitted October30, 2023
Consent and Assent Form(s):		
Other:		
Master List		November 14, 2023
Data Collection/Capture Sheet		November 14, 2023

CERTIFICATION
The above-named research study/project has been reviewed in a ***delegated manner*** by the University of Manitoba (UM) Health Research Board (HREB) and was found to be acceptable on ethical grounds for research involving human participants. The study/project and documents listed above was granted final approval by the Chair or Acting Chair, UM HREB.

HREB ATTESTATION
The University of Manitoba (UM) Research Board (HREB) is organized and operates according to Health Canada/ICH Good Clinical Practices, Tri-Council Policy Statement 2, and the applicable laws and regulations of Manitoba. In respect to clinical trials, the HREB complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations of Canada and carries out its functions in a manner consistent with Good Clinical Practices.

QUALITY ASSURANCE
The University of Manitoba Research Quality Management Office may request to review research documentation from this research study/project to demonstrate compliance with this approved protocol and the University of Manitoba Policy on the Ethics of Research Involving Humans.

A unit of the office of the Vice-President (Research and International)
https://umanitoba.ca/research/opportunities-support/ethics-compliance/ethics/bannatyne

- 1 -

9.2 PROVINCIAL HEALTH RESEARCH PRIVACY COMMITTEE APPROVAL

Provincial Health Research Privacy Committee (PHRPC)
Certificate of Final Approval for New Studies

PHRPC No. P2023-107
file number to be quoted on all correspondence

September 3, 2024

Application date: November 14, 2023
Submission received: November 16, 2023
Approval date: September 3, 2024
Researcher name: Stella Korowski (student)
Project title: Precision of indirect bonding using 3D printed trays for custom-made 3D printed orthodontic brackets.

The Provincial Health Research Privacy Committee (PHRPC) has considered and ***approved*** your request for **use** of Personal Health Information for the purposes of the above-named project as described in the application form and supporting documents only. The security provisions set out within the submission meet the minimum criteria for PHRPC approval.

Note: Additional considerations surrounding access and disclosure of the requested information, including the requirement for a Data Sharing Agreement, will be provided by the applicable data trustee(s) as part of the institutional impact review of the submitted project. Data trustee approval is required prior to work commencing on the project.

Please also note that this project has received approval from the Committee for Harmonized Health Impact, Privacy and Ethics Review (CHIPER).

Any significant changes to the proposed study design must be reported to the Chair/PHRPC for consideration in advance of initiating the project.

Also, please be reminded that any manuscripts and/or presentation materials resulting from this study do not require submission to PHRPC*, but may need to be sent to the Personal Health Information trustee(s) for review. Please consult with the applicable trustee(s) to determine their requirements.
**Prior to January 1, 2022, manuscripts and presentation materials were required to be submitted to HIPC.*

If you have any questions or concerns, please do not hesitate to contact the RITHIM Program Officer (PHRPC Lead) at PHRPC@researchmb.ca.

Yours truly,

[redacted]

Chair, Provincial Health Research Privacy Committee

PLEASE ALWAYS USE THE MOST RECENT VERSION OF PHRPC FORMS FROM THE PHRPC WEBSITE
- see 'Forms & Guides' at https://www.rithim.ca/phrpc-submission-information

V. May 10, 2023

9.3 JOURNAL ARTICLE SUBMISSION

Transfer accuracy of 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets

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ABSTRACT

Objectives: To evaluate the transfer accuracy of custom orthodontic brackets using 3D printed transfer trays in a fully digital workflow.

Methods and Materials: Twenty-one participants who were bonded with LightForce brackets (LightForce, Burlington, MA, USA) using 3D printed transfer trays. Intraoral scans (iTero, Align Technology, San Jose, CA, USA) were taken after the brackets were bonded. The virtual bracket setup was compared to post-bonding scans using digital model superimpositions. Discrepancies in bracket position were assessed, and one-sided t-tests were used to determine if the mean transfer discrepancies were within clinically acceptable limits of 0.5 mm in linear dimensions and 2° in angular dimensions.

Results: The mean bracket position discrepancies were 0.21 mm, 0.39 mm and 0.38 mm for mesiodistal, buccolingual, and occlusogingival directions, respectively. The frequency of bracket positions within 0.5 mm ranged from 73% to 95%. Mean bracket position discrepancies were 1.69°, 1.09° and 1.70° for torque, tip, and rotation, respectively. The frequency of bracket positions within 2° ranged from 69% to 84%. P-values ranged from 0.00 to 0.694. The mean discrepancies were statistically significant ($P<0.05$) and within clinically acceptable limits for all teeth in mesiodistal and tip dimensions.

Conclusion: 3D printed transfer trays have high transfer accuracy in many dimensions. Bracket position discrepancies in angular dimensions are more frequent than in linear dimensions. A digital workflow using virtually planned bracket positions and 3D printed transfer trays, as judged from this study, may be implemented with clinical confidence in indirect bonding of orthodontic brackets.

KEY TERMS

Indirect Bonding; Computer-aided design/Computer-aided manufacturing (CAD/CAM); 3D Printing; Transfer Trays

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FUNDING

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INTRODUCTION

Indirect bonding was first introduced by Silverman in 1972 and has since gained popularity in clinical practice.[1] The advantages of indirect bonding techniques include improved accuracy in bracket position with limited chairside time.[2,3] Indirect bonding can be used in cases with severe malocclusion, crowding, and rotations to achieve more accurate bracket placement, which would otherwise be difficult to achieve with traditional direct bonding methods.[3]

Facilitated by advances in intraoral scanning, 3D printing, and virtual treatment planning, digital methods for indirect bonding have been developed.[4–6] In digital indirect bonding, software is used to digitally position brackets on virtual models of the teeth. A transfer tray or jig can be designed virtually and directly 3D printed with no physical transfer model as an intermediary.

As we continue to move toward a fully digital workflow, the latest advancements have led to the first complete 3D printed bracket system featuring customized brackets, known as LightForce (LightForce, Burlington, MA, USA). This bracket system is designed and printed *de novo* based on the digital setup and planning with the LightForce planning software. This bracket system allows for a customized base and slot prescription tailormade to the desired clinical movements of each tooth. With each case, 3D printed indirect bonding transfer trays are fabricated to transfer the custom brackets to the patient's dentition.[7,8] Since accurate clinical execution of the virtually planned bracket position is critical in this technique to achieve the digitally simulated alignment,[9] the present study aimed to assess the transfer accuracy of bracket position and evaluate *in vivo* any discrepancies between the digitally planned setup with the actual clinical bracket position immediately after bonding.

MATERIALS AND METHODS

This clinical study was approved by the Health and Research Ethics Board at the University of Manitoba. The study participants were 20 patients, 12 male and 8 female, who sought orthodontic treatment from two separate specialty orthodontic clinical practices in the USA and Canada. Patients were not recruited specifically for this study. The patients who were already planned for orthodontic treatment with LightForce bracket systems qualified as participants if they provided consent. Inclusion criteria were fully erupted permanent dentitions with mild to severe crowding or spacing. Both extraction and non-extraction cases were included in the study. Exclusion criteria were fixed prosthesis, craniofacial anomalies, and severe dental anomalies such as microdontia, hypodontia, hypoplasia, enamel defects, and severe attrition.

All patients had intraoral scans taken using an iTero Element scanner (Align Technology, San Jose, CA, USA) as part of their initial diagnostic records prior to starting treatment. Virtual models were created from the intraoral scans and uploaded to the LightPlan planning software (Lightforce, Burlington, MA, USA), where brackets were digitally positioned on the virtual models. Both of the clinical practices in this study used .020" bracket slot size. The models with digitally positioned brackets were referred to as the 'virtual setup.' The virtual setup on the LightPlan software was then sent for fabrication of the brackets and the indirect bonding trays, known as the LightTray (Lightforce, Burlington, MA, USA). The brackets were 3D printed using polycrystalline alumina material. The transfer trays were also 3D printed. LightTrays were fabricated in sections: upper right, upper anterior, upper left, lower right, lower anterior, and lower left. The brackets were manually installed by the manufacturer into their respective wells in the trays, which were provided to the end user ready for use.

The study participants' maxillary and mandibular incisors, canines, premolars and molars were bonded with the LightForce bracket system using LightTray indirect bonding trays. Clinical staff followed dental bonding procedures as recommended by the manufacturers of the dental materials. The teeth were polished with plain pumice in preparation for bonding. They were then etched, rinsed thoroughly with water, and dried. A primer was used following manufacturer's directions and 3M™ Transbond™ XT Light Cure Adhesive (Solventum, St. Paul, MN, USA) was used to bond each bracket. Each transfer tray was placed with light pressure applied on the occlusal surface. The brackets were initially light cured for 5 seconds per tooth, the transfer tray removed, and final cure for each tooth was then completed for each sextant. Immediately after bonding, a new intraoral scan was taken using the iTero Element scanner to generate a new digital model with the final bracket position (Figure 1). This digital model is referred to as the 'post-bonding model' and was used to compare the final bracket position with the planned bracket position on the virtual setup.

The virtual setup and post-bonding model for each patient was compared using superimpositions through best-fit methods using a custom software (Voyager Dental, Eden Prairie, MN, USA). Brackets and soft tissue were removed from the post-bonding model during the superimposition process, which ensured that the superimposition was based solely on tooth features (Figure 2). Superimpositions were completed for sextants (upper right, upper anterior, upper left, lower right, lower anterior and lower left) to mimic indirect bonding trays (Figure 3).

The bracket positions between the virtual setup and the post-bonding model were compared as follows: four datum points were assigned to each bracket in the upper right, lower right, upper left, and lower left corners of the bracket slot (Figure 4). An XYZ coordinate system was created based on these datum points. For each bracket pairing (i.e., same bracket in virtual setup and post-bonding model), the software computed the positional discrepancies with respect to six dimensions of tooth movement. The six dimensions included three linear measurements (mesiodistal, buccolingual, and occlusogingival translation), and three angular measurements (tip, torque, and rotation). The measurement values expressed the magnitude of the discrepancy. During this comparison, the virtual setup was considered the reference model, while the post-bonding model was considered the comparison.

When assessing the discrepancy measurements between the reference model and the comparison, absolute values were used to eliminate risk that the summation of positive and negative values would negate each other. Following earlier studies,[10] clinically acceptable transfer error limits were set to 0.5 mm for linear measurements (mesiodistal, buccolingual, occlusogingival) and 2 degrees for angular measurements (rotation, tip, torque) based on the standards determined by the American Board of Orthodontics. For their assessment, clinicians are penalized when teeth deviate 0.5 mm or more from proper alignment of marginal ridges. A crown tip error of 2 degrees causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar.[10]

Statistical Analysis

Left-right differences in absolute measurements were assessed and revealed an equal distribution of values between each analogous tooth type. Therefore, contralateral tooth pairings were grouped together for subsequent tests. Maxillary and mandibular teeth were assessed independently. Descriptive statistics were calculated for each tooth type and each dimension. One-sided t-tests were used with absolute values in each dimension to assess if the mean transfer discrepancies were within the clinically acceptable limits. P-values of less than 0.05 indicated that the differences between the digital setup and post-bonding bracket position were within these limits.

RESULTS

A total of 433 brackets were bonded and evaluated for transfer accuracy. Differences between post-bonding and virtual setup bracket positions are shown in Table 1. The discrepancies in linear bracket position ranged from 0.168 to 0.506 mm for upper teeth and from 0.175 to 0.485 mm for lower teeth. For angular dimensions, the discrepancies in bracket position ranged from 1.226 to 2.048 degrees for upper teeth and from 0.88 to 2.117 degrees for lower teeth.

One-sided t-tests where P-values were below 0.05 reached statistical significance and indicated that the brackets were transferred within the set clinically acceptable limits. Mesiodistal and tip dimensions had P-values that were below 0.05 for all tooth types indicating that for these dimensions, brackets were transferred within the acceptable limits of 0.5 mm and 2 degrees. Notably, upper molars had a P-value below 0.05 for all dimensions indicating that discrepancies in all dimensions were within clinically acceptable limits. In contrast, lower premolars had the greatest number of P-values above 0.05 with respect to buccolingual, occlusogingival and rotational bracket position changes.

Frequency of post-bonding bracket positions within clinically acceptable limits in linear and angular dimensions are shown in Table 2. The frequency of brackets on the post-bonding models within clinically acceptable limits in linear position ranged from 57.9 to 97.5% in the upper arch and from 59 to 97.4% in the lower arch. For angular dimensions, the frequency of brackets on the post-bonding models within clinically acceptable limits ranged from 57.4 to

87.5% in the upper arch and from 61.3 to 92.3% in the lower arch. Upper incisors had the highest frequency of brackets within acceptable limits with 97.5% in the mesiodistal dimension while lower premolars had the lowest frequency of brackets within acceptable limits with 53.6% in the occlusogingival dimension.

DISCUSSION

The comparison between the digitally planned setup and the actual bracket position immediately after bonding showed a high transfer accuracy of brackets in all dimensions except rotation in upper and lower incisors. In contrast, the accuracy was generally lower in the posterior dentition. The high degree of accuracy in the anterior dentition could be attributed to better access and moisture control when compared to posterior teeth. This idea is supported by studies into the accuracy of posterior tooth bracket position with CAD/CAM developed indirect bonding jigs, which suggest that challenges in the posterior dentition may be due to difficulties with visibility, moisture control, and patient management.[11] Other factors that may impact bracket transfer accuracy in posterior teeth are cusp height and morphology variations. This idea has been supported in the literature by researchers who suggest cusp reduction before jig fabrication may increase the accuracy of the bracket position.[11]

When comparing maxillary and mandibular arches, the upper molars showed high accuracy of bracket positions in all dimensions, while the lower molars showed a high accuracy in all dimensions with the exception of the occlusogingival dimension and torque. Overall, teeth in the upper arch had more frequently brackets that were transferred within clinically acceptable limits when compared to their lower counterparts. These findings support the previously discussed notion that access and visibility may play an important role in transfer bracket accuracy using indirect bonding methods.[11]

A comparison of linear and angular dimensions yielded fewer discrepancies in the linear dimensions than in the angular dimensions. These findings are consistent with previous findings of very small positional discrepancies (approximately one-tenth of a millimeter) in occlusogingival, mesiodistal, and buccolingual measurements, which suggest that a high transfer accuracy in the linear dimensions can achieved with 3D printed indirect bonding trays.[10] However, similar to the present findings, previous reports suggest a poorer transfer accuracy in angular dimensions,[10] which may exceed the clinically acceptable limits in some patients.

It is of note that this pattern of positional discrepancies is similar to conventional indirect bonding techniques. Studies into conventional indirect bonding transfer accuracy show that bracket deviations were higher in angular dimensions, when compared to linear dimensions.[12] Of the angular dimensions, torque had the greatest amount of deviation, while vertical deviations toward the gingival direction were the greatest discrepancies seen in linear dimensions.[12] Similarly, Koch and others found transfer accuracy of linear measurements were higher than that of angular measurements (98.3% and 86.7%, respectively) when CAD/CAM based indirect bonding trays were used.[13]

The present results may have been influenced by challenges faced while capturing the post-bonding intraoral scans. In some cases, detail of the bracket slots was not captured clearly (Figure 5). Despite the high accuracy and precision of iTero scanners,[14] there are other factors that may have impacted scan accuracy in this study, such as possible scan distortion of the orthodontic brackets.[15] Another factor that may impact the clarity and accuracy of intraoral scans could be attributed to scattered reflection of light rays caused by different materials found intraorally. This idea is supported by researchers who noted that reflection of light rays by metal surfaces may impact scan accuracy of iTero scanners as they operate by the principle of light emission.[15]

Due to discrepancies capturing detail of the bracket, a multiplanar appearance resulted in some of the post-bonding scans. In contrast, brackets on the virtual setup were clear; datum point targets and their corresponding coordinate systems were easily identifiable and reproducible. Surface differences may have created an illusion that the coordinate systems had greater discrepancies than they actually did. Similar findings were reported in a study by Bachour et al. who suggested that multiplanar post-bonding scans may have a considerable impact on angular dimensions such as tip, torque and rotation.[10]

Another possible reason for discrepancies in angular dimensions, rotation and torque, may be due to variations in adhesive application at the bracket interface.[12] Linear transfer errors in the vertical dimension may be due to improper seating of the indirect bonding transfer jig (Figure 6). Displacement of a bracket toward the occlusal direction may suggest incomplete seating of a transfer jig,[12] while displacement in a gingival direction may indicate increased force during seating of a transfer jig.[16]

The present results suggest that there was a statistically significant difference between the bracket position of the digitally planned LightPlan setup and the actual clinical bracket position of the 3D printed transfer trays for customized 3D printed LightForce brackets in several dimensions; however, in many cases it was not clinically significant. When all tooth types were combined, the mean discrepancies for linear measurements were 0.212 mm, 0.386 mm and 0.380 mm for mesiodistal, buccolingual, and occlusogingival measurements, respectively. The mean discrepancies for angular measurements were 1.694 degrees, 1.085 degrees and 1.709 degrees for rotation, tip, and torque measurements, respectively. Of note, all these mean values lie within the limits considered clinically acceptable by professional standards, suggesting that the transfer accuracy of brackets with the LightForce system is generally high. It can, therefore, be concluded, that 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets can achieve bracket placement accuracy sufficient for clinical application and equivalent or potentially superior to conventional indirect bonding methods. As technology progresses, it is anticipated that the transfer accuracy of indirect bonding will continue to improve even more.

CONCLUSIONS

Based on results of this study, the following conclusions can be reached:

1. LightForce custom brackets positioned virtually in a fully digital workflow and bonded using 3D printed transfer trays showed a high level of positional accuracy in most dimensions.
2. Positional discrepancies in angular positions tend to be more frequent than discrepancies in linear positions; however, the magnitude may not be clinically relevant.
3. Discrepancies in transfer accuracy tended to be greater in the posterior dentition than in the anterior dentition.
4. A digital workflow using virtually planned bracket positions and 3D printed transfer trays for orthodontic bracket bonding, as judged from this study, may be implemented with clinical confidence.

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Table 1. Differences between post-bonding and virtual setup bracket positions.[1,2,3,4]

		Dimension					
Tooth Type	n	Mesiodistal (mm)	Buccolingual (mm)	Occlusogingival (mm)	Rotation (°)	Tip (°)	Torque (°)
Incisor							
Upper	80	0.168 ± 0.147*	0.334 ± 0.200*	0.239 ± 0.167*	1.868 ± 1.738	1.158 ± 0.948*	1.626 ± 1.387*
Lower	75	0.175 ± 0.134*	0.413 ± 0.222*	0.409 ± 0.217*	2.117 ± 1.995	1.289 ± 1.194*	1.663 ± 1.401*
Canine							
Upper	38	0.243 ± 0.177*	0.506 ± 0.434	0.347 ± 0.258*	1.403 ± 1.166*	1.211 ± 1.210*	1.750 ± 1.277
Lower	39	0.215 ± 0.116*	0.423 ± 0.279*	0.419 ± 0.256*	1.780 ± 1.635	0.974 ± 0.915*	1.687 ± 1.700
Premolar							
Upper	61	0.256 ± 0.222*	0.437 ± 0.243*	0.343 ± 0.229*	1.65 ±1.481*	1.017 ± 0.950*	2.048 ± 1.764
Lower	69	0.207 ± 0.140*	0.463 ± 0.344	0.485 ± 0.296	1.65 ± 1.774*	0.880 ± 0.789*	1.662 ± 1.583*
Molar							
Upper	32	0.222 ± 0.153*	0.205 ± 0.262*	0.408 ± 0.289*	1.226 ± 0.827*	1.287 ± 0.943*	1.461 ± 1.322*
Lower	39	0.273 ± 0.179*	0.219 ± 0.152*	0.460 ± 0.275	1.252 ± 0.950*	0.839 ± 0.844*	1.711 ± 1.182

[1] n is the number of teeth assessed in each respective category
[2] Results are presented as mean and standard deviation of bracket discrepancies
[3] Limits are set as 0.5 mm for linear measurements and 2° for angular measurements
[4] Asterisk (*) indicates statistically significant values ($P<0.05$)

Table 2. Frequency of post-bonding bracket positions within clinically acceptable limits in linear and angular dimensions.[1,2,3]

Tooth Type	n	Mesiodistal	Buccolingual	Occlusogingival	Rotation	Tip	Torque
		Dimension					
Incisor							
Upper	80	97.5	77.5	93.8	70.0	80.0	72.5
Lower	75	96.0	64.0	69.3	61.3	81.3	69.3
Canine							
Upper	38	92.1	57.9	73.7	71.1	76.3	57.9
Lower	39	97.4	61.5	61.5	69.2	89.7	71.8
Premolar							
Upper	61	90.2	62.3	83.6	75.4	83.6	57.4
Lower	69	97.1	60.9	53.6	73.9	88.4	72.5
Molar							
Upper	32	93.8	84.4	71.9	87.5	81.2	78.1
Lower	39	89.7	94.9	59.0	74.4	92.3	71.8

[1] n is the number of teeth assessed in each respective category
[2] Frequency is reported as percentage
[3] Limits are set as 0.5 mm for linear measurements and 2° for angular measurements

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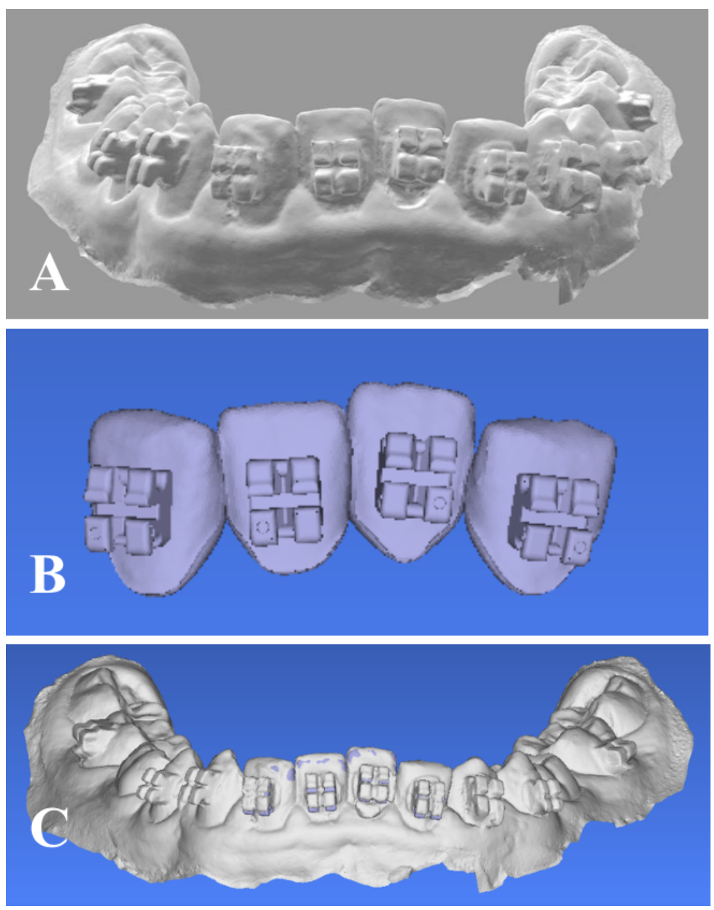

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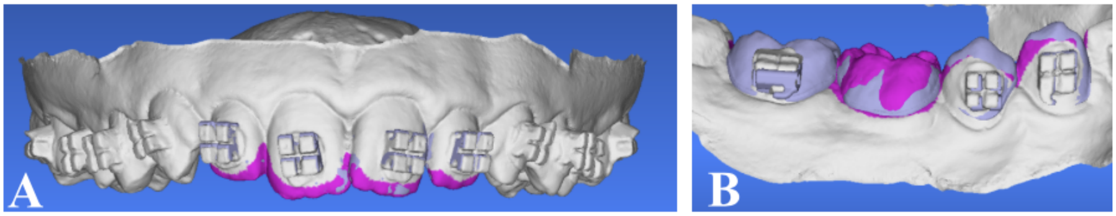

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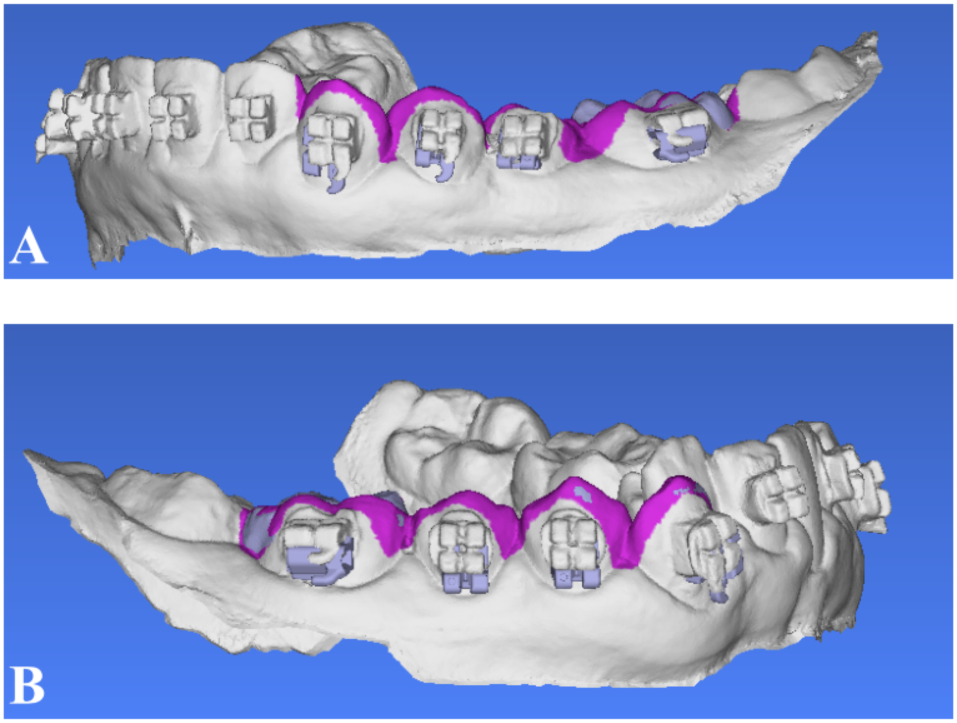

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Digital Dentistry Journal

Transfer accuracy of 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets

--Manuscript Draft--

Manuscript Number:	DDJ-D-25-00075
Full Title:	Transfer accuracy of 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets
Article Type:	Full Length Article
Keywords:	Indirect Bonding; Computer-aided design/Computer-aided manufacturing (CAD/CAM); 3D Printing; Transfer Trays
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Abstract:	Objectives To evaluate the transfer accuracy of custom orthodontic brackets using 3D printed transfer trays in a fully digital workflow. Methods and Materials Twenty-one participants who were bonded with LightForce brackets (LightForce, Burlington, MA, USA) using 3D printed transfer trays. Intraoral scans (iTero, Align Technology, San Jose, CA, USA) were taken after the brackets were bonded. The virtual bracket setup was compared to post-bonding scans using digital model superimpositions. Discrepancies in bracket position were assessed, and one-sided t-tests were used to determine if the mean transfer discrepancies were within clinically acceptable limits of 0.5 mm in linear dimensions and 2° in angular dimensions. Results The mean bracket position discrepancies were 0.21 mm, 0.39 mm and 0.38 mm for mesiodistal, buccolingual, and occlusogingival directions, respectively. The frequency of bracket positions within 0.5 mm ranged from 73% to 95%. Mean bracket position discrepancies were 1.69°, 1.09° and 1.70° for torque, tip, and rotation, respectively. The frequency of bracket positions within 2° ranged from 69% to 84%. P-values ranged from 0.00 to 0.694. The mean discrepancies were statistically significant ($P<0.05$) and within clinically acceptable limits for all teeth in mesiodistal and tip dimensions.

	Conclusion 3D printed transfer trays have high transfer accuracy in many dimensions. Bracket position discrepancies in angular dimensions are more frequent than in linear dimensions. A digital workflow using virtually planned bracket positions and 3D printed transfer trays, as judged from this study, may be implemented with clinical confidence in indirect bonding of orthodontic brackets.
Additional Information:	
Question	**Response**
To complete your submission you must select a statement which best reflects the availability of your research data/code. IMPORTANT: this statement will be published alongside your article. If you have selected "Other", the explanation text will be published verbatim in your article (online and in the PDF). (If you have not shared data/code and wish to do so, you can still return to Attach Files. Sharing or referencing research data and code helps other researchers to evaluate your findings, and increases trust in your article. Find a list of supported data repositories in Author Resources, including the free-to-use multidisciplinary open Mendeley Data Repository.)	The data that has been used is confidential.

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Transfer accuracy of 3D printed trays for indirect bonding of custom 3D printed orthodontic brackets

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We have received the above referenced manuscript you submitted to Digital Dentistry Journal.

It has been assigned the following manuscript number: **DDJ-D-25-00075**.

Thank you for submitting your work to this journal.

Kind regards,

Digital Dentistry Journal