Transfer Accuracy of 3D-Printed Trays for Indirect Bonding of Orthodontic Brackets: 
A Clinical Study

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Dedication

I dedicate this work to:

To my late grandfather Salam, who encouraged my commitment to education and motivated my interest in this profession.

And to my late grandfather Elias, who inspired me to work with conscience and trusted in me to make a difference in the lives of others.
Abstract

Aim: To evaluate the transfer accuracy of 3D-printed indirect bonding trays constructed using a fully digital workflow in a clinical setting.

Methods: Twenty-three consecutive patients had their incisors, canines, and premolars bonded using a fully digital indirect bonding method and 3D-printed transfer trays. Intraoral scans were taken to capture the final bracket positioning on the teeth following bonding. Digital models of the post-bonding scans were superimposed on those of the corresponding virtual bracket setups, and bracket positioning differences were quantified. A total of 363 brackets were evaluated. One tailed t-tests were used to determine whether bracket positioning differences were within limits of 0.5 mm in the mesio-distal, bucco-lingual, and occluso-gingival dimensions, and within 2° for torque, tip, and rotation.

Results: Mean bracket positioning differences were 0.10 mm, 0.10 mm, and 0.18 mm for mesio-distal, bucco-lingual, and occluso-gingival measurements, respectively. For the linear dimensions, frequencies of bracket positioning error within the 0.5-mm limit ranged from 96.4–100%. Mean differences were significantly within the acceptable range for these dimensions. Mean differences were 2.55°, 2.01°, and 2.47° for torque, tip, and rotation, respectively. For the angular measurements, frequencies within the 2°-limit ranged from 46.0–57.0%. The mean differences for the angular dimensions were outside the acceptable limit; however, this may have been due to limitations of the scan data.

Conclusions: Indirect bonding using 3D-printed trays transfers the planned bracket position from the digital setup to the patient’s dentition with a high positional accuracy in the mesio-distal, bucco-lingual, and occluso-gingival dimensions. Questions remain regarding the transfer accuracy in the angular dimensions.
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Introduction

Orthodontists constantly explore ways to make treatment more comfortable, effective, and efficient. Since the introduction of preadjusted appliances in the 1970’s, clinicians have sought ways to improve the accuracy of bracket placement in order to align teeth efficiently with a straight wire and to minimize the need for wire bending and bracket re-positioning later in treatment.\textsuperscript{2,3}

There are two main techniques used for placing orthodontic brackets on the patient’s dentition: direct bonding and indirect bonding. In the direct bonding method, brackets are placed directly onto the patient’s teeth. In the indirect bonding method, brackets are first positioned on a model of the patient’s dentition. Then, a custom tray capturing the bracket position is fabricated and used to transfer the appliances to the teeth.\textsuperscript{4,5}

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.\textsuperscript{4–7} 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.\textsuperscript{5,8} Some have suggested that indirect bonding thus improves the accuracy of bracket placement.\textsuperscript{6,7,9–13}
Since its introduction in 1972, the indirect bonding method has seen many variations and improvements in practice. In traditional indirect bonding methods, brackets are manually placed on a stone or resin model of the patient’s dentition, and trays are created in a laboratory setting using silicone-based and/or vacuum-formed materials. More recently, facilitated by advances in intraoral scanning, 3D printing, and virtual treatment planning, a digital method for indirect bonding has been developed. In digital indirect bonding, software is used to digitally position brackets on virtual models of the teeth. A transfer tray or jig based on the digital setup can be designed virtually and directly 3D-printed using biocompatible resin. Brackets can then be placed in the trays and used for bonding. Advantages to this entirely digital workflow include computer-aided bracket placement, minimization of human error in tray fabrication, and reduced number of manufacturing stages.

In order to perform their intended function, indirect bonding devices must reliably transfer the planned bracket position to the patient’s dentition. Transfer errors resulting from tray properties, bonding technique, contaminants, or interferences could impede efficient levelling and alignment and negate the efficiencies gained by indirect bonding. While traditional indirect bonding methods have been found to reliably transfer brackets to their intended positions on the dentition in vivo, little is known regarding the transfer accuracy of digital methods during clinical application. For this reason, the present study aimed to measure the positional accuracy of a digital indirect bonding technique using 3D-printed transfer trays in vivo.
Review of the Literature

Bracket Positioning: Importance and Implications

The standard edgewise appliance, developed by Edward Angle in the mid-1920’s, was the first to use an orthodontic bracket with a horizontal slot. In the standard edgewise system, the same bracket with a uniform slot and base was used for each tooth in the arch. Because each tooth type has a unique morphology, the use of standard edgewise appliances required numerous compensatory bends in the archwire to achieve ideal alignment of the dentition—a technique-sensitive, error-prone, and time-consuming process.

In the early 1970’s, Lawrence Andrews developed and introduced the straight-wire appliance, which consisted of tooth-specific brackets with built-in torque, tip, and in-out compensations. The concept behind the pre-adjusted appliance was that, because variation was built into the brackets, fewer modifications to the wire would be necessary to achieve proper alignment with a straight wire. For the desired built-in features to be properly transferred from the brackets to the teeth, the brackets must be positioned optimally in the center of the clinical crown, in line with the facial axis of the clinical crown (the long axis of the tooth’s clinical crown). Although many modifications have been made to Andrews’ original straight-wire appliance throughout the years, the pre-adjusted appliances utilized today still largely rely on the premise of ideal bracket placement to achieve ideal tooth alignment.
Accurate bracket placement is critical for effective and efficient orthodontic treatment with preadjusted orthodontic appliances. Placing brackets in the ideal position at the initiation of treatment minimizes the costly and time-consuming process of repositioning brackets partway through treatment and bending archwires to correct marginal ridge discrepancies, rotations, and root parallelism.\textsuperscript{3,24} Correct bracket placement in all dimensions is particularly important because the same bracket prescription can lead to variable expression depending on where it is bonded on the tooth. A positioning error in one dimension can have a detrimental effect on the tooth’s position in other dimensions; for example, a vertical error in bracket position can result in alterations in both the torque and buccal-lingual position of the tooth.\textsuperscript{25} Finally, because brackets work simultaneously through the wire, one poorly positioned bracket will influence adjacent brackets, and this effect will be compounded if more than one bracket is misplaced, impeding efficient finishing of the case.\textsuperscript{22} It follows that optimal bracket placement from the onset of treatment thus results in more streamlined treatment for the clinician and patient.

\textit{Direct and Indirect Bonding}

Bracket positioning can be completed using either direct or indirect bonding methods. Direct bonding involves the placement of brackets by the clinician directly onto the tooth surface. Direct bonding relies on the clinician’s ability to adequately visualize the correct mesio-distal position, vertical position, and slot angulation of the bracket on each tooth while working within the confines of the mouth.\textsuperscript{3} Indirect bonding, first introduced by Silverman \textit{et al.} in 1972, involves the positioning of brackets on a model of the dentition, and the subsequent transfer of these brackets to the patient’s teeth using a custom tray or
jig.\textsuperscript{14} Although indirect bonding has several advantages and has grown in popularity in recent years, direct bonding is still the method used by most orthodontists.\textsuperscript{19}

There are various methods and materials used for indirect bonding. In traditional indirect bonding, brackets are manually placed on stone or resin models of the patient’s dentition, and a transfer tray is created using silicone materials, vacuum-formed thermoplastic sheets, or a combination of materials.\textsuperscript{9,14–18,26–28} These trays are then used to transfer the brackets to the patient’s teeth during the bonding procedure.

More recently, however, technological advances have given rise to digital techniques for indirect bonding.\textsuperscript{19–21,29–32} Advances in intraoral scanning, virtual treatment planning, computer-aided design and computer-aided manufacturing (CAD/CAM), 3D printing, and biocompatible resin materials have made way for digital transformation of a decades-old technique. In digital indirect bonding, software is used to virtually position brackets on digital models of the patient’s dentition created from intraoral scans. Most software offers the ability to rotate the model 360 degrees and to visualize a tooth from various perspectives simultaneously while positioning brackets. Many also provide computer-aided measurements to guide bracket placement, as well as a predicted alignment of the teeth with the given bracket selection.\textsuperscript{19}

After the brackets have been digitally positioned, two main options exist for tray fabrication. One technique involves 3D printing of the model with brackets, known as the bracket transfer model, followed by fabrication of a traditional indirect bonding tray.
using silicone-based or vacuum-formed materials.\textsuperscript{30,33} This differs from traditional methods that require physical brackets to be positioned on a model, but it still requires a laboratory step for tray fabrication. Another contemporary technique gaining popularity involves digitally designing and directly 3D printing a transfer tray or jig based on the virtual model using biocompatible resin, with no physical printed bracket transfer model as an intermediary.\textsuperscript{19,31,34} This technique is fully digital up until the step of tray printing and does not require use of a wet laboratory. The printing step can be outsourced to a dental laboratory or completed in-house in offices that have a 3D printer. In both digital methods described, after the trays have been fabricated, physical brackets can then be placed in their respective wells in the printed trays, which are used to transfer the brackets to the patient’s dentition during bonding. Digital indirect bonding offers several unique advantages. In addition to offering a fully digital workflow and computer-aided bracket placement, digital methods minimize human error in tray fabrication, reduce the number of manufacturing stages and materials needed, and can be turned around quickly in-house.\textsuperscript{19–21}

\textit{Indirect Bonding: Advantages, Drawbacks, and Considerations}

There are advantages and disadvantages to both direct and indirect bonding, and many studies have been conducted to compare them.\textsuperscript{6,7,40,10,12,13,35–39} Most studies have evaluated traditional forms of indirect bonding.

Traditional indirect bonding has been found to require shorter clinical chair time for the orthodontist compared to direct bonding, resulting in a quicker and more comfortable
appointment for the patient and efficient use of valuable doctor time in the clinic.\textsuperscript{6,7,38} However, almost all studies found that this comes with the drawback of increased time spent on laboratory steps: producing models, positioning brackets, and fabricating trays.\textsuperscript{6,7}

The time requirement for digital forms of indirect bonding has been compared with direct bonding and with traditional indirect bonding methods.\textsuperscript{40,41} Czolgosz \textit{et al.} performed a split-mouth randomized controlled trial evaluating the chair time and overall time for indirect bonding using 3D-printed CAD/CAM trays compared to direct bonding.\textsuperscript{40} They found that clinical chair time was significantly reduced by four minutes per half-mouth when using the CAD/CAM trays. However, the total time, including the time spent on digital bracket placement, was 11.5 minutes longer per half-mouth compared to direct bonding. Plattner \textit{et al.} compared the time required to produce digital and traditional (laboratory) indirect bonding trays.\textsuperscript{41} Although the total production time for digital indirect bonding trays was found to be greater, much of this time was considered “passive” time required for model printing and processing, which could vary based on the type of printer used. The “active” working time for digital indirect bonding was reduced compared to traditional methods. Virtual bracket positioning was found to require only 13.5\% of the time needed for bracket positioning on a plaster model. The authors concluded that, when considering the active working time and personnel costs for producing traditional transfer trays, the digital planning and production of 3D-printed trays was time-efficient.
Another potential advantage of indirect bonding compared to direct bonding is accuracy of bracket positioning. Some have suggested higher precision of bracket placement using the indirect technique, a claim that has been supported by several studies evaluating traditional indirect bonding methods.\textsuperscript{6,7,10–13} It has been argued that bracket position can be better visualized during indirect bonding, as the models can be rotated and the dentition viewed from more perspectives than would be possible while working intraorally.\textsuperscript{4,5} The ability to visualize models of the teeth up close—or even magnified on a computer screen in the case of digital methods—can also facilitate bracket positioning. In digital bracket placement, computer-aided axis definition, measurements, and predicted outcomes could also enhance precision.\textsuperscript{32} Additionally, because bracket positioning is completed outside of the mouth in indirect bonding, clinical influences that complicate direct bonding, such as moisture control, patient-related factors, and time constraints can be minimized or eliminated.\textsuperscript{5,8} Taken together, these features are thought to facilitate more “ideal” or accurate bracket placement when indirect bonding.

It should be noted that most studies evaluating accuracy of bracket placement between direct and indirect methods have been \textit{in vitro} studies. Historically, the majority have used photographic methods to compare bracket position to a pre-determined “ideal” position at the center of the clinical crown.\textsuperscript{6,10,12} While many of these studies show modest placement advantages on individual teeth using indirect bonding,\textsuperscript{6,7,10–13} questions remain regarding the clinical significance of these improvements. In a clinical study, Yildrim \textit{et al.} found that the indirect bonding method results in better leveling of marginal ridges.\textsuperscript{7} Clinical and practice-based studies comparing clinical endpoints have
found no significant difference in total treatment time, number of appointments, and additional wire-bending and bracket repositioning between patients bonded with direct and traditional indirect methods.\textsuperscript{7,37}

Despite its advantages in chair time reduction, patient comfort, and ease of bracket placement, indirect bonding is still used by a minority of orthodontists.\textsuperscript{19} One reason clinicians may hesitate to adopt this technique is the fear of bond failures. Bond failure, or the unintentional detachment of a bracket following bonding, can compromise clinical efficiency and patient satisfaction, and is a reasonable concern.\textsuperscript{39} However, the literature has consistently shown the bond failure rate for indirect bonding to be comparable to that of direct bonding,\textsuperscript{6,10,13,37,38} and the bond strengths to be similar to those of direct techniques.\textsuperscript{36,42} Another common criticism of indirect bonding is the inability to easily remove excess adhesive prior to curing, raising hygiene concerns. However, the literature has shown no significant difference in the oral hygiene status, including plaque buildup and the presence of white spot lesions, in patients bonded with either technique.\textsuperscript{6,7}

Finally, indirect bonding requires the investment of additional time, materials, and labor in preparation for the chairside procedure.\textsuperscript{6,7,38,40} It also requires the coordination of timely and orderly model acquisition, bracket positioning, and tray fabrication in a busy schedule. Thus, in order to successfully integrate indirect bonding, an office must have good systems in place. Digital indirect bonding with direct 3D printing simplifies this workflow.\textsuperscript{19}
Indirect Bonding: Transfer Accuracy

Perhaps the most important consideration in indirect bonding is the ability of the transfer devices to reliably transfer the planned bracket position to the dentition. In evaluating traditional and novel techniques, it is paramount to answer the question: How well do the indirect bonding trays deliver the bracket positions to the teeth? Sources of transfer error during indirect bonding could include soft tissue interferences, incomplete or improper tray seating, excess adhesive on the bracket base, or technical errors in tray fabrication.8

Historically, studies have relied on 2D or photographic methods to determine transfer accuracy.26,43 However, advancements in 3D imaging, digital intraoral scanning, and 3D superimposition strategies have provided new tools to compare bracket positioning with six degrees of freedom. Several recent studies have utilized 3D superimpositions to evaluate bracket transfer accuracy.8,27,28,33,34,44–48 Although the methods vary by study, the same general approach is employed: two sets of digital models are produced from digital intraoral or cone-beam computed tomography (CBCT) scans of models or dentition. Typically, one model represents the “setup”, or planned position of the brackets, and the other represents the position of the brackets on the teeth or models following indirect bonding. The models are then digitally superimposed using best-fit methods, and differences in bracket positions are measured.

Various studies have examined the transfer accuracy of traditional indirect bonding methods.8,26–28,43 Most of these have been in vitro studies. Wendl et al. found reasonable transfer accuracy using a custom traditional indirect bonding jig in a laboratory setting.43
Castilla et al. compared the *in vitro* transfer accuracy of five traditional indirect bonding tray types using photographic methods. They found that silicone-based trays had consistently high transfer accuracy compared to purely vacuum-formed trays. Schmid et al. and Mohlhenrich et al. both performed *in vitro* studies to evaluate different types of traditional indirect bonding trays, using 3D superimposition of scanned models to assess transfer accuracy. Schmid et al. found polyvinylsiloxane (PVS) trays to have slightly higher transfer accuracy than vacuum-formed trays, with clinically acceptable transfer errors of 98.5–100% in the linear dimensions (mesio-distal, bucco-lingual, and occluso-gingival), and 80.6–90.3% in the angular dimensions (torque, tip, and rotation) for the PVS trays. Mohlhenrich et al. found that different types of traditional transfer trays, as well as the presence of bracket hooks, resulted in variable transfer accuracy, as measured by maximum linear and angular deviations. In 2016, Grünheid et al. performed the first *in vivo* study to measure the transfer accuracy of PVS trays using superimposed CBCT scans of the setup models and the bonded dentition. They found final bracket positions to be significantly within the acceptable limits in all six dimensions, with the lowest transfer accuracy for torque (80.2% within acceptable range), and the highest transfer accuracy in the mesiodistal and buccolingual dimensions (98.5% within acceptable range).

More recently, several studies have been conducted to test the transfer accuracy of digital indirect bonding techniques. Similarly, nearly all have been *in vitro* studies. In 2018, Kim et al. performed an *in vitro* study on scanned plaster models to evaluate the transfer accuracy of 3D-printed transfer jigs (not trays) in posterior teeth with different
cusp heights.\cite{44} They found that the jigs had excellent transfer accuracy in the linear dimensions, but subpar transfer accuracy in the angular dimensions, with over half the brackets failing to fall within acceptable range for torque, tip, and rotation. Several investigations have studied directly 3D-printed transfer trays \textit{in vitro}. Pottier \textit{et al.} found 3D-printed transfer trays to have good transfer accuracy (89–100\% and 79–100\% within acceptable range in the linear and angular dimensions, respectively), but to be significantly less accurate than silicone trays.\cite{46} Duarte reported acceptable transfer accuracy of 3D-printed trays tested on printed models using two different bracket systems.\cite{45} In 2020, Niu \textit{et al.} performed an \textit{in vitro} study comparing the transfer accuracy of two types of digital transfer trays: a directly 3D-printed tray, and a vacuum-formed tray fabricated off a 3D-printed model.\cite{33} They report that the 3D-printed trays had a lower mean mesio-distal transfer error, and a higher prevalence of rotational error as compared to the vacuum-formed trays. The 3D-printed trays had high transfer accuracy in the linear dimensions (95.4–100\% within acceptable range), but lower accuracy in the angular dimensions (50.9\%–85.2\% within acceptable range).

While several \textit{in-vitro} studies have shed light on the transfer accuracy of digital indirect bonding devices, little is known about the transfer accuracy of these methods in live patients. To date, only two \textit{in-vivo} studies with this aim have been conducted, both using 3D superimpositions in their analysis of bracket position.\cite{34,47} In 2020, Xue \textit{et al.} studied the transfer accuracy of a custom 3D-printed guided bonding device (jig).\cite{34} The acceptable range of error was defined as 0.5 mm for linear and 2° for angular dimensions. The transfer error for all brackets was within the acceptable range for all three linear
dimensions as well as rotation and angulation. They found 15% of brackets with torque deviations outside of acceptable limits. Only one study has evaluated the transfer accuracy of 3D-printed indirect bonding trays in vivo, comparing it to that of traditional PVS trays. In 2021, Chaudhary et al. found that the 3D-printed trays were more accurate than the PVS trays in the mesio-distal and bucco-lingual dimensions for most tooth types, as well as in the angular dimensions. For the 3D-printed trays, they report transfer errors all falling within acceptable range (defined as 0.25 mm or 1°) for all dimensions, with the exception of 9 transfer errors outside of acceptable range in the vertical dimension only. The authors report mean errors in the linear dimensions ranging from 0.000–0.078 mm, and mean errors in the angular dimensions ranging from 0.000–0.032°, concluding that the 3D-printed trays are highly reliable.

While the digital indirect bonding procedure offers many advantages, the success of this technique hinges largely on its ability to transfer the planned bracket position reliably to the dentition. Despite the fact that 3D-printed indirect bonding trays are being used by many clinicians in practice today, there is a paucity of research on their ability to transfer bracket position reliably to the dentition. It is important to determine the transfer accuracy of 3D-printed indirect bonding trays, as transfer errors in bracket position could negate the efficiencies gained by digital indirect bonding.

The present study aimed to determine the reliability of indirect bonding with 3D-printed transfer trays by measuring the discrepancy between virtually planned and bonded
bracket positions with respect to six degrees of freedom. The findings would inform evidence-based practice using this technique.
Aims and Hypotheses

The general aim of this study was to evaluate the transfer accuracy of a fully digital indirect bonding technique for orthodontic brackets using 3D-printed trays in vivo.

The specific aims of this study were:

1. To evaluate the reliability of 3D-printed indirect bonding trays in transferring brackets to their intended positions by measuring the discrepancies between planned and actual bracket positions with respect to six degrees of freedom, and to determine whether the discrepancies fall within acceptable limits of error.
2. To determine whether specific tooth types or positions in the dental arch more frequently result in bracket transfer error.
3. To determine the frequency of directional biases in either direction along the six axes as a result of transfer.

Hypothesis

The following hypotheses were tested:

1. The 3D-printed indirect bonding trays reliably transfer the intended bracket position to the dentition, with positional discrepancies falling within the clinically acceptably limits of 0.5 mm in the linear dimensions and 2° in the angular dimensions.
2. The frequency of bracket transfer error is the same for all tooth types.
3. There is no directional bias of bracket placement error in any given dimension.
Methods

The protocol for this prospective clinical trial was approved by the Institutional Review Board at the University of Minnesota (Study #00009952). The patients were informed about the study procedures both orally and with written information packets. Each patient provided written informed consent before initiation of the study. In the case of minors, a parent or legal guardian provided consent; the minor provided assent.

Subjects and Sample Size

Consecutive patients who sought orthodontic treatment at the University of Minnesota Faculty and Graduate Orthodontic Clinics, met the inclusion criteria, and were willing to participate in the study were enrolled. All patients required preadjusted edgewise appliances per their treatment needs and accepted to have metal brackets bonded. Inclusion criteria were English-speaking adults and children (12 years and older) in the permanent dentition presenting with mild to moderate crowding or spacing. Exclusion criteria were patients under 12 years of age, prosthetic restorations extending on the facial surfaces of teeth, primary or mixed dentition, and patients with craniofacial anomalies.

The subjects consisted of 23 consecutive new patients (16 female, 7 male). The age of the subjects ranged from 12 to 31 years of age. Of the 23 subjects, 22 were treated without extraction of permanent teeth, and one subject underwent extraction of four bicuspids prior to initiation of treatment.
A sample size calculation was used to determine the proper sample size. Mean differences and standard deviations of the accuracy of measurements were estimated according to Grünheid et al. A sample size of 72 brackets provided 80% power to identify means to be statistically significantly different from 0.5 mm or 2° using one-sample t-tests at a significance level of 5%. Over-recruitment was performed to account for potential sample attrition.

The incisors, canines, and bicuspid of both dental arches were bonded. Molars were excluded to minimize potential error associated with moisture control and tray seating in the posterior region. Within the dental arches of eligible subjects, specific teeth were excluded from bonding if they had restorations on the facial surface or were partially erupted. A total of 410 brackets were initially included in the study. 19 brackets were later excluded due to bond failures, and 28 brackets were excluded due to scan errors. The remaining 363 brackets were evaluated for transfer accuracy.

**Digital Bracket Positioning**

Intraoral scans of each subject were taken as a part of initial diagnostic records using an iTero Element scanner (Align Technology, San Jose, California). The average time from scan acquisition to bonding date was two weeks. Digital stereolithography (.STL) models were generated from the scans and used for digital bracket placement. OrthoAnalyzer (3Shape, Copenhagen, Denmark) software version 1.7.1.3 was used for digital bracket positioning. The pre-treatment model of each patient was uploaded into OrthoAnalyzer. The desired preadjusted edgewise twin brackets were then selected from the virtual
bracket library and positioned on the patient’s pre-treatment models by the treating orthodontist (Fig 1). The bracket systems used in this study were based on provider preference and included Victory Series, .022” slot, MBT prescription (3M Unitek, Monrovia, CA) and Mini-Master Series, .018” slot, MBT prescription (American Orthodontics, Sheboygan, WI). The resultant digital models of the dentition with the virtually placed brackets, referred to as the “digital setup,” were exported in .STL format for subsequent analysis.

**Figure 1:** Screen capture of OrthoAnalyzer software showing digital bracket placement. In this image, the upper left lateral incisor is selected for bracket positioning. The three images in the lower right allow the selected tooth to be viewed simultaneously from a facial, side, and occlusal view. Software-generated measurements of the bracket position relative to anatomical landmarks of the tooth are also shown.
Fabrication of 3D-Printed Transfer Trays and Bracket Installation

The digital setup was exported into Appliance Designer software (3Shape, Copenhagen, Denmark). Any undercuts under bracket hooks were virtually blocked out on the digital models, and the indirect bonding transfer trays were digitally designed.

The indirect bonding trays were then directly 3D-printed on a Carbon digital light synthesis printer (Carbon, Redwood City, CA) using Fotodent IBT 385 nm biocompatible resin (Dreve Dentamid GmbH, Unna, Germany) and processed according to manufacturer instructions. Each arch was sectioned in half at the midline, resulting in quadrant trays. Physical brackets were manually installed in their respective wells in the trays in preparation for bonding and the trays were then tried onto 3D-printed resin models of the dentition to ensure proper fit (Fig 2).

Figure 2: 3D-printed indirect bonding trays. a: Intaglio view of upper arch indirect bonding quadrant trays with brackets installed. b: Indirect bonding tray tried onto 3D-printed resin model of upper arch.
Clinical Bonding Procedure

All clinical bonding procedures were completed by a single operator. The teeth to be bonded were polished with fluoride-free pumice, rinsed with water, and dried. Isolation was achieved using cheek retractors. The buccal surfaces were etched using 37% phosphoric acid (3M Unitek, Monrovia, CA) for 20 seconds, rinsed, and dried until frosty white. A thin layer of Assure Plus primer adhesive (Reliance Orthodontic Products, Itasca, IL) was applied to the buccal surface of each tooth and lightly dried. A small amount of Transbond XT light-curing bracket adhesive (3M Unitek, Monrovia, CA) was applied to the base of each bracket. Each quadrant tray was carefully positioned over the teeth and the correct positioning was visually confirmed. The trays were fully seated using light finger pressure on the occlusal surface. The adhesive was then light-cured for 40 seconds per tooth, i.e., 10 seconds from each direction (mesial, distal, occlusal, and gingival). The trays were carefully removed from the teeth with the aid of a scaler. Excess cement was removed from around the brackets with a scaler or carbide bur on a slow-speed handpiece as needed. Any bond failures as a result of transfer were recorded, and new brackets were bonded directly without the use of transfer trays.

Scanning Final Bonded Bracket Positions In Vivo

Following bonding, an intraoral scan was taken using the iTero Element scanner (Align Technology, San Jose, CA) to capture the final position of the brackets bonded to the teeth (Fig 3). The resulting digital model, referred to as the “post-bonding model,” was exported in .STL format and used for comparison to the digital setup.
Superimposition of Digital Models

For each dental arch, two analogous digital models were superimposed to assess bracket placement accuracy. The first was the digital setup model representing the planned position of the brackets. The second was the post-bonding model capturing the final position of the brackets bonded to the patient’s teeth. The model superimpositions and bracket position analysis were completed using the software VisionX Compare (VisionX, Edina, MN).

To prepare the models for superimposition, the pair of corresponding STL files of digital setup and post-bonding models for each arch were imported into the VisionX Compare software. To ensure that superimposition was based only on tooth-surface features, soft tissue, brackets, and bonding material around the brackets were eliminated from the post-bonding models in preparation for superimposition (Fig 4). Since there was no tooth movement between initial scan acquisition and bonding, tooth structure was considered stable for superimposition.
Initial model registration was completed using a 6-point match based on the buccal cusp tips of the bicuspid and canine. An Iterative Closest Point (ICP) matching algorithm was then employed to achieve surface feature-based, best-fit superimposition of the post-bonding model on the digital setup model, which was considered the reference. The process is summarized in Fig 4.

**Figure 4:** Digital models and superimposition. a: Digital setup model of dentition with virtually positioned brackets. b: Prepared post-bonding model; highlighted fuchsia structure represents tooth surface to be used for superimposition. c: Superimposed best-fit digital setup model (grey) and post-bonding model (green).
**Analysis of Bracket Positional Differences**

After the tooth surfaces were overlayed, the displacement in corresponding bracket position between the digital setup and post-bonding models could be measured. The software allowed the capability to toggle between the two models so that each could be viewed alone, or both models viewed simultaneously without changing their overlayed position in space. The bracket identification process was completed for each model viewed separately, with the corresponding best-fit model hidden.

To assign the position of each bracket in space, four consistent datums were manually identified on the surface of each bracket in the upper left, lower left, upper right, and lower right corners of the bracket base between the tie wings (Fig 5). An X-Y-Z coordinate system defining each bracket’s position in space was automatically created based on these datums. This process was completed for each bracket on the digital setup and post-bonding models. Once complete, the superimposed models and respective coordinate systems could be viewed in overlay (Fig 5). In some cases, artifact, contamination (i.e., saliva), or the quality of the post-bonding scan prohibited the identification of the landmark datums. When landmarks could not be identified, such brackets were noted but discarded from analysis due to “scan error.”
For each corresponding bracket pair in the digital setup and post-bonding models, measured differences with respect to six dimensions of tooth movement, including mesio-distal (MD), bucco-lingual (BL), and occluso-gingival (OG) translation, as well as torque, tip, rotation were calculated in reference to the bracket coordinate systems.

Although the software computes the positional discrepancies in each dimension automatically, a brief description of its methodology is of note. To calculate the difference in bracket position in a given dimension, the digital setup model was considered the “reference”, and the post-bonding model was considered the “comparison.” For translational changes in the linear dimensions for a given axis (mesio-distal, bucco-lingual, or occluso-gingival), the comparison bracket axis origin is projected onto the reference bracket axis, and the distance along the axis is reported. To determine
the angular changes, the software computes Euler angle displacement between the comparison and reference coordinate systems, in the order of rotation first, tip second, and torque last.

The reported differences described both the magnitude and direction of the discrepancy. The direction of each discrepancy was designated by the sign of the value, either positive or negative. Table 1 lists the discrepancy measurements and definitions for positive and negative values for each dimension measured. The directions describe the post-bonding position in reference to the digital setup position. For example, a positive mesio-distal discrepancy measure indicates that the bonded bracket was positioned mesially relative to the corresponding bracket in the digital setup.

**Table 1: Directionality of Bonding Error**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measure Type</th>
<th>Positive (+)</th>
<th>Negative (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesio-distal</td>
<td>Linear (mm)</td>
<td>Mesial translation</td>
<td>Distal translation</td>
</tr>
<tr>
<td>Bucco-lingual</td>
<td>Linear (mm)</td>
<td>Buccal translation</td>
<td>Lingual translation</td>
</tr>
<tr>
<td>Occluso-gingival</td>
<td>Linear (mm)</td>
<td>Occlusal translation</td>
<td>Gingival translation</td>
</tr>
<tr>
<td>Torque</td>
<td>Angular (degrees)</td>
<td>Buccal crown torque</td>
<td>Lingual crown torque</td>
</tr>
<tr>
<td>Tip</td>
<td>Angular (degrees)</td>
<td>Mesial crown tip</td>
<td>Distal crown tip</td>
</tr>
<tr>
<td>Rotation</td>
<td>Angular (degrees)</td>
<td>Mesial-in</td>
<td>Mesial-out</td>
</tr>
</tbody>
</table>

*Repeatability*

The same operator re-measured a total of 65 brackets from 7 randomly selected arch pairs after a wash-out period of two weeks. Repeatability was assessed as the difference of
measurements on replicate samples using the method described by Bland and Altman. The biases were computed as the average of the differences for each dimension.

Statistical Analysis

In order to eliminate the possibility that summation of positive and negative discrepancy values would negate one another and give the illusion of accuracy, absolute values of each individual discrepancy were calculated.

The mean values and standard deviations for each dimension were calculated for the composite sample, as well as for each tooth type (incisors, canines, and premolars). Discrepancy values for each dimension were compared independently for maxillary and mandibular arches, and between teeth right and left of the midline using two-sample t-tests ($\alpha = 0.05$). Right/left comparison demonstrated equal distribution of values for each dimension, so right and left analogous tooth types within each arch were thus combined for further analysis.

The data was approximately normally distributed as determined by visual inspection. One-tailed t-tests were performed on the absolute value of the discrepancy measurements in each dimension to determine whether the mean transfer error was statistically within the selected limits of 0.5 mm for linear measurements, and $2^\circ$ for angular measurements. P-values of less than 0.05 indicated differences within the limits of 0.5 mm for linear measurements and $2^\circ$ for angular measurements. These tests were performed on the
pooled sample, on grouped tooth types (incisors, canines, and premolars), and on arch-specific tooth types (upper incisors, lower incisors, etc.).

These threshold values of 0.5 mm and 2° were used because they represent accepted professional standards. The American Board of Orthodontics Cast-Radiograph Evaluation (CR-Eval, formerly Objective Grading System, OGS) deducts points for teeth that deviate 0.5 mm or more from proper alignment or alignment of marginal ridges.\(^5^0\)

The angular threshold was set because a crown-tip positioning error of 2° causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar. Several studies have used these thresholds when evaluating tooth and bracket discrepancies in superimposed models.\(^8,33,34,46,5^1\)

Frequency statistics were calculated to further characterize the reliability of the indirect bonding method in transferring brackets as intended to the dentition, as well as to reveal any directional biases in bracket transfer. The frequency of bracket position discrepancies for each tooth type falling within and outside of the acceptable thresholds was calculated for the whole sample, for each tooth type, and for each tooth type within a given arch. The frequency of directional errors was calculated for the whole sample and for each tooth type.

All statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, North Carolina) with the level of statistical significance set to \(\alpha = 0.05\).
Results

Repeatability

Repeatability assessments are reported in Table 2. Bland-Altman analyses of agreement between measurements of individual bracket positions performed at two time points yielded mean differences ranging from -0.002 to 0.006 for linear measurements, and from -0.087° to 0.409° for angular measurements. Plots are shown in Fig 6. All brackets recorded as “scan failures” due to inadequacy of the scan for landmark identification were consistently re-identified as such in the repeat trials.

Table 2: Bland-Altman Analyses Performed to Assess Repeatability for Each Dimension of Tooth Movement

<table>
<thead>
<tr>
<th>Dimension</th>
<th>n</th>
<th>Mean</th>
<th>Lower 95% CL for Mean</th>
<th>Upper 95% CL for Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesio-distal (mm)</td>
<td>65</td>
<td>-0.002</td>
<td>-0.009</td>
<td>0.004</td>
</tr>
<tr>
<td>Bucco-lingual (mm)</td>
<td>65</td>
<td>0.006</td>
<td>-0.002</td>
<td>0.013</td>
</tr>
<tr>
<td>Occluso-gingival (mm)</td>
<td>65</td>
<td>-0.002</td>
<td>-0.011</td>
<td>0.006</td>
</tr>
<tr>
<td>Torque (°)</td>
<td>65</td>
<td>0.409</td>
<td>-0.049</td>
<td>0.867</td>
</tr>
<tr>
<td>Tip (°)</td>
<td>65</td>
<td>-0.087</td>
<td>-0.512</td>
<td>0.337</td>
</tr>
<tr>
<td>Rotation (°)</td>
<td>65</td>
<td>-0.103</td>
<td>-0.641</td>
<td>0.435</td>
</tr>
</tbody>
</table>

n indicates number of brackets used for analysis. CL: confidence level.
Figure 6: Bland-Altman plots of agreement to assess repeatability for each dimension of tooth movement. The difference between the original and repeat measurements (mm or degrees) are plotted against the mean of the original and repeat measurements for each bracket pair. Each circle represents one bracket pair. 95% of measurement differences lie between the limits indicated by the top and bottom dashed lines.
Bracket Failures

Of the 410 brackets used in indirect bonding, 19 failed to adhere to the teeth during the bonding procedure, resulting in a bond failure rate of 4.63%. In nearly all bond failure cases, the bracket remained in the transfer tray following removal, and the cured adhesive remained on the dentition.

Transfer Error Descriptive Statistics

The means and standard deviations of the linear and angular bracket position differences for the overall sample, as well as for each tooth type (incisors, canines, premolars) and tooth type by arch are shown in Table 3. Box-and-whisker plots characterizing the distribution of means for each tooth type in each of the six dimensions are shown in Figure 7. For the composite sample, the mean value and standard deviation for linear transfer error was $0.10 \pm 0.08$ mm, $0.10 \pm 0.07$ mm, and $0.18 \pm 0.14$ mm for the MD, BL, and OG dimensions, respectively. The mean angular transfer error for the total sample was $2.55 \pm 1.98^\circ$, $2.01 \pm 1.66^\circ$, and $2.47 \pm 2.09^\circ$ for torque, tip, and rotation, respectively.

When comparing the discrepancy between upper and lower teeth within a given linear dimension, there was consistently a greater magnitude of error in the BL dimension for the lower arch compared to the upper arch in all tooth types. No other clear patterns were noted.
Table 3: Differences Between Post-Bonding Bracket Position and Digital Setup

<table>
<thead>
<tr>
<th>Tooth Type</th>
<th>n</th>
<th>MD (mm)</th>
<th>BL (mm)</th>
<th>OG (mm)</th>
<th>Torque (°)</th>
<th>Tip (°)</th>
<th>Rotation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incisor</td>
<td>150</td>
<td>0.087 ± 0.074*</td>
<td>0.083 ± 0.059*</td>
<td>0.179 ± 0.136*</td>
<td>2.493 ± 1.790</td>
<td>1.961 ± 1.724</td>
<td>2.393 ± 1.908</td>
</tr>
<tr>
<td>U Incisor</td>
<td>72</td>
<td>0.095 ± 0.075*</td>
<td>0.071 ± 0.053*</td>
<td>0.165 ± 0.138*</td>
<td>2.273 ± 1.559</td>
<td>1.750 ± 1.818</td>
<td>1.902 ± 1.623</td>
</tr>
<tr>
<td>L Incisor</td>
<td>78</td>
<td>0.080 ± 0.072*</td>
<td>0.094 ± 0.062*</td>
<td>0.193 ± 0.134*</td>
<td>2.696 ± 1.968</td>
<td>2.155 ± 1.621</td>
<td>2.847 ± 2.044</td>
</tr>
<tr>
<td>Canine</td>
<td>74</td>
<td>0.103 ± 0.076*</td>
<td>0.100 ± 0.079*</td>
<td>0.180 ± 0.134*</td>
<td>2.154 ± 1.469</td>
<td>1.780 ± 1.304</td>
<td>2.692 ± 2.203</td>
</tr>
<tr>
<td>U Canine</td>
<td>38</td>
<td>0.117 ± 0.082*</td>
<td>0.081 ± 0.064*</td>
<td>0.175 ± 0.147*</td>
<td>2.028 ± 1.486</td>
<td>1.522 ± 1.164*</td>
<td>2.989 ± 2.246</td>
</tr>
<tr>
<td>L Canine</td>
<td>36</td>
<td>0.087 ± 0.067*</td>
<td>0.121 ± 0.089*</td>
<td>0.185 ± 0.120*</td>
<td>2.286 ± 1.460</td>
<td>2.052 ± 1.401</td>
<td>2.378 ± 2.144</td>
</tr>
<tr>
<td>Premolar</td>
<td>139</td>
<td>0.116 ± 0.089*</td>
<td>0.114 ± 0.083*</td>
<td>0.182 ± 0.149*</td>
<td>2.824 ± 2.359</td>
<td>2.182 ± 1.741</td>
<td>2.439 ± 2.218</td>
</tr>
<tr>
<td>U Premolar</td>
<td>69</td>
<td>0.142 ± 0.094*</td>
<td>0.094 ± 0.067*</td>
<td>0.182 ± 0.134*</td>
<td>2.472 ± 1.974</td>
<td>1.777 ± 1.390</td>
<td>2.733 ± 2.268</td>
</tr>
<tr>
<td>L Premolar</td>
<td>70</td>
<td>0.091 ± 0.077*</td>
<td>0.133 ± 0.092*</td>
<td>0.182 ± 0.164*</td>
<td>3.171 ± 2.654</td>
<td>2.582 ± 1.958</td>
<td>2.148 ± 2.144</td>
</tr>
<tr>
<td>Total</td>
<td>363</td>
<td>0.101 ± 0.081*</td>
<td>0.098 ± 0.074*</td>
<td>0.181 ± 0.140*</td>
<td>2.550 ± 1.984</td>
<td>2.009 ± 1.657</td>
<td>2.471 ± 2.089</td>
</tr>
</tbody>
</table>

Results are mean values ± standard deviations. All values are absolute values. n indicates number of each tooth type used for analysis. MD: mesio-distal, BL: bucco-lingual, OG: occluso-gingival. Asterisks * indicate P < 0.05, indicating a transferred bracket position within the selected limits of 0.5 mm for linear measurements and 2° for angular measurements.
Figure 7: Box-and-whisker plots of discrepancy values between planned and actual bracket positions for the 3 tooth types in 6 dimensions. The center line denotes the median. The upper and lower borders of the box represent the third quartile (75th percentile) and the first quartile (25th percentile), respectively. The vertical lines extending up and down from the box mark the third quartile plus 1.5 times the interquartile range, and the first quartile minus 1.5 times the interquartile range, respectively. Values beyond these bounds are outliers, marked by dots.
Significance of Transfer Error

The asterisks in Table 3 denote a mean bracket position difference within the selected limits of acceptability. All one-sided t-tests reached statistical significance (P < 0.05) for all linear dimensions in all tooth types, indicating that the brackets were transferred with acceptable translational error in the MD, BL, and OG dimensions, regardless of tooth type or arch. All one-sided t-tests did not reach statistical significance (P > 0.05) for all angular dimensions in all tooth types except maxillary canine tip. This suggests that, aside from maxillary canine tip, the difference in the torque, tip, and rotation of the final brackets was outside of the acceptable range of 2°.

Frequency of Transfer Error Within Acceptable Range

The frequencies of bracket position falling within the selected range of 0.5 mm for linear measures and 2° for angular measures is shown in Table 4 and illustrated graphically in Fig 8. For the linear dimensions, frequencies within 0.5 mm were high, ranging from 96.4–100% overall. For the angular measurements, frequencies within the limit of 2° ranged from 46.0–52.1%. Overall, the transfer accuracy was highest for MD and BL bracket placement (both 100%), and lowest for torque (46.0%).

Frequency of Directional Bias

The frequencies of directional bias result from indirect bonding are shown in Table 5. In the bucco-lingual dimension, the bonded bracket position was biased toward the buccal in 67.5% of the brackets.
<table>
<thead>
<tr>
<th>Tooth Type</th>
<th>n</th>
<th>MD</th>
<th>BL</th>
<th>OG</th>
<th>Torque</th>
<th>Tip</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incisor</td>
<td>150</td>
<td>150 (100)</td>
<td>150 (100)</td>
<td>145 (96.7)</td>
<td>68 (45.3)</td>
<td>92 (61.3)</td>
<td>77 (51.3)</td>
</tr>
<tr>
<td>U incisor</td>
<td>72</td>
<td>72 (100)</td>
<td>72 (100)</td>
<td>70 (97.2)</td>
<td>35 (48.6)</td>
<td>50 (69.4)</td>
<td>45 (62.5)</td>
</tr>
<tr>
<td>L incisor</td>
<td>78</td>
<td>78 (100)</td>
<td>78 (100)</td>
<td>75 (96.2)</td>
<td>33 (42.3)</td>
<td>42 (53.8)</td>
<td>32 (41.0)</td>
</tr>
<tr>
<td>Canine</td>
<td>74</td>
<td>74 (100)</td>
<td>74 (100)</td>
<td>71 (95.9)</td>
<td>39 (52.7)</td>
<td>46 (62.2)</td>
<td>38 (51.4)</td>
</tr>
<tr>
<td>U canine</td>
<td>38</td>
<td>38 (100)</td>
<td>38 (100)</td>
<td>36 (94.7)</td>
<td>22 (57.9)</td>
<td>26 (68.4)</td>
<td>18 (47.4)</td>
</tr>
<tr>
<td>L canine</td>
<td>36</td>
<td>36 (100)</td>
<td>36 (100)</td>
<td>35 (97.2)</td>
<td>17 (47.2)</td>
<td>20 (55.6)</td>
<td>20 (55.6)</td>
</tr>
<tr>
<td>Premolar</td>
<td>139</td>
<td>139 (100)</td>
<td>139 (100)</td>
<td>134 (96.4)</td>
<td>60 (43.2)</td>
<td>69 (49.6)</td>
<td>74 (53.2)</td>
</tr>
<tr>
<td>U premolar</td>
<td>69</td>
<td>69 (100)</td>
<td>69 (100)</td>
<td>68 (98.6)</td>
<td>32 (46.4)</td>
<td>39 (56.5)</td>
<td>31 (44.9)</td>
</tr>
<tr>
<td>L premolar</td>
<td>70</td>
<td>70 (100)</td>
<td>70 (100)</td>
<td>66 (94.2)</td>
<td>28 (40.0)</td>
<td>30 (42.9)</td>
<td>43 (61.4)</td>
</tr>
<tr>
<td>Total</td>
<td>363</td>
<td>363 (100)</td>
<td>363 (100)</td>
<td>350 (96.4)</td>
<td>167 (46.0)</td>
<td>207 (57.0)</td>
<td>189 (52.1)</td>
</tr>
</tbody>
</table>

n indicates number of brackets used for analysis. Results are expressed as count (percentage).
Figure 8: Percentage of post-bonding bracket position within the selected limits of acceptability.
### Table 5: Frequency of Directional Bias Resulting from the Indirect Bonding Method

<table>
<thead>
<tr>
<th>Tooth Type</th>
<th>n</th>
<th>Mesio-distal</th>
<th>Bucco-lingual</th>
<th>Occluso-gingival</th>
<th>Torque</th>
<th>Tip</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mesial</td>
<td>Distal</td>
<td>Buccal</td>
<td>Lingual</td>
<td>Occlusal</td>
<td>Gingival</td>
</tr>
<tr>
<td>Incisor</td>
<td>150</td>
<td>38.7</td>
<td>61.3</td>
<td>52.0</td>
<td>48.0</td>
<td>49.3</td>
<td>50.7</td>
</tr>
<tr>
<td>Canine</td>
<td>74</td>
<td>68.9</td>
<td>31.1</td>
<td>74.3</td>
<td>25.7</td>
<td>44.6</td>
<td>55.4</td>
</tr>
<tr>
<td>Premolar</td>
<td>139</td>
<td>71.2</td>
<td>28.8</td>
<td>80.6</td>
<td>19.4</td>
<td>66.2</td>
<td>33.8</td>
</tr>
<tr>
<td>Total</td>
<td>363</td>
<td>57.3</td>
<td>42.7</td>
<td>67.5</td>
<td>32.5</td>
<td>54.3</td>
<td>45.2</td>
</tr>
</tbody>
</table>

n indicates the number of brackets used for analysis. BCT indicates buccal crown torque; LCT, lingual crown torque; M-in, mesial-in; M-out, mesial-out. Results are expressed as percentages.
Discussion

Digital indirect bonding is a promising method that offers all the advantages of traditional indirect bonding, in addition to the added advantages of a completely digital workflow, computer-aided model analysis and bracket placement, standardization and ease of tray fabrication, and fewer manufacturing steps.\textsuperscript{19–21} The results of this study provide insight into the positional accuracy of a method for indirect bonding in a clinical setting using 3D-printed transfer trays.

The present study found the indirect bonding trays to have high transfer accuracy in the linear dimensions—statistically within the acceptable range of 0.5 mm—for all tooth types in all dimensions. In the MD and BL dimensions, 100\% of the bracket positions were within an acceptable range of error, and in the OG dimension, 96.4\% were within acceptable range. The mean positioning errors between the digital setup and bonded bracket positions ranged from 0.071±0.053 mm (maxillary incisors, BL) to 0.193±0.134 mm (mandibular incisors, OG). These high rates of acceptable error and small mean errors—approximately a tenth of a millimeter in most cases—suggest that the 3D-printed indirect bonding method has a high transfer accuracy in the linear dimensions, with greatest accuracy in the MD and BL dimensions.

When comparing the discrepancy between upper and lower teeth within a given linear dimension, there was consistently a greater magnitude of error in the BL dimension for the lower arch compared to the upper arch in all tooth types, suggesting a greater transfer
accuracy of the upper trays in the BL dimension. This could possibly have been due to variable pressure applied to seat the lower trays, or, less likely, a systematic error in amount of bond material applied to lower brackets. Due to the thickness of the trays, access, and moisture control concerns, placing the trays on the lower arch more often presented challenges for the operator compared to the upper arch.

The results of this study found the mean transfer accuracy in the angular dimensions—torque, tip, and rotation—to be statistically outside of acceptable range of 2°. This was true for all tooth types and all three angular dimensions, with the exception of maxillary canines, which had acceptable errors in the dimension of tip. Mean errors in the angular dimensions ranged from 1.75±1.82° (maxillary incisor, tip) to 3.17±2.65° (mandibular premolar, rotation). Only about half of the brackets were positioned within acceptable range for any given dimension. Taken together, these results suggest poor transfer accuracy in the angular dimension, outside of clinically acceptable limits.

The results for the angular dimensions must be interpreted with caution for several reasons. The Bland-Altman analysis showed a greater difference between the upper and lower limits of agreement and a larger bias for the angular dimensions compared to the linear dimensions when repeat measurements were performed. (Table 2). This raises questions regarding the ability to reproduce angular measurements on the scans. Furthermore, while identifying bracket landmarks for coordinate generation on the post-bonding scans, it was noted that some of the surfaces upon which the datum points fell
appeared to be multiplanar (Fig 9). This contrasted with the smooth virtual brackets on the pre-bonding models.

**Figure 9:** Digital model quality. Example of the same bracket a: Post-bonding scan. b: Pre-bonding virtual model with bracket selected from bracket library.
While a multiplanar surface would have minimal effect on differences in the linear dimensions, it could very well impact angular dimensions. One could imagine, for example, a theoretical bracket that was perfectly transferred to its intended position, and perfectly superimposed between models. Identifying a datum in the corner of the bracket base on the pre- and post-bonding models in a slightly different position (for instance, 0.02 mm) would result in minimal linear positional differences for the resulting coordinate systems, equal to the human error (in this example, 0.02 mm). However, if those same datums fell on an angled plane of the post-bonding scan surface, an inaccurate orientation of the coordinate system in the post-bonding model could result, creating the illusion of large angular discrepancies.

The apparent multiplanar surfaces on the digital post-bonding scans could possibly be attributed to image distortion caused by the scattered reflection of light rays by the metal brackets in the mouth during scanning with the iTero scanner, which operates according to the principle of light emission. The iTero scanner used in this study demonstrated excellent precision and trueness and has been found to be one of the most accurate of the commercially available intraoral scanners. It also was found to produce the most clear boundaries and sharpest images compared to other tested scanners; an in-vitro study on typodont brackets found the iTero scanner capable of reproducing the shape of the entire bracket slot. However, the in-vivo clinical situation is much different, where moisture and accessibility are factors. In an in-vivo study on scanner accuracy on bonded dentition, Kang et al. demonstrated image distortions were present within 0.5 mm of brackets, but found good accuracy of the scans on the tooth surfaces greater than 0.5 mm away from
the brackets.52 This supports the idea that, although the post-bonding scans with brackets in this study were accurate enough for close superimposition on tooth structure, it is likely that distortions were present on the reflective bracket surfaces, negatively affecting the coordinate orientations in space and, consequentially, the angular measurements.

No other in-vivo study of indirect bonding transfer accuracy has used an iTero scanner for post-bonding scan acquisition. Grünheid et al. used CBCT images to capture post-bonding scans, as a part of SureSmile treatment.8 Chaudhary et al. and Xue et al. used a TRIOS intraoral scanner and sprayed the teeth to decrease reflectivity of the brackets prior to scanning, possibly resulting in more clear scan.34,47 It is unknown whether the differences in scan methodology could have contributed to a difference in measured angular transfer accuracy in these studies. Repetition of the present study using a different scanner and anti-reflective spray would shed light on the effects of this variable.

It is possible, however, that the poor angular transfer accuracy was not entirely due to scan error, but rather to an inherent property of the tray or bonding procedure that resulted in poor angular control. Interestingly, several in-vitro studies with 3D-printed trays,33 3D-printed jigs,44 and traditional transfer trays28 also demonstrated better linear transfer accuracy compared to angular transfer accuracy. For instance, Niu et al. found the mean MD, BL, and OG transfer errors of 3D-printed trays to be 0.07 mm, 0.13 mm, and 0.19 mm, respectively, with errors falling within the acceptable range in 100% (MD), 95.4% (BL), and 96.3% (OG) of cases—consistent with the present findings.33 Also similar to the current study, they found a low transfer accuracy in the angular dimensions,
with acceptable errors present only 57.4%, 50.9%, and 85.2% of the time for tip, torque, and rotation, respectively. Similarly, Kim et al. found high transfer accuracy in the linear dimensions (93–100% within acceptable range), and low transfer accuracy in the angular dimensions (43–73% within acceptable range) using 3D-printed jigs in vitro. 44 Schmid et al. had a similar pattern of findings using traditional methods. 28

Niu et al. attributed the high transfer accuracy in the linear dimensions to the relatively rigid printed tray material. 33 They attributed the low angular transfer error to inconsistencies in the amount of bonding resin adhesive used, as well as to tray design which provided relief for hooks and undercuts, potentially weakening angular control of bracket positioning. By this rationale, thicker or more rigid closed trays could lead to enhanced angular control. However, this would likely come with the tradeoff of difficulty removing the trays following bonding, resulting in patient discomfort and a potential for higher bond failures. Although the bond failure rate of 4.63% in the present study was consistent with that reported in the literature for 3D-printed indirect bonding trays in vivo, 40 bond failures were almost invariably a result of bracket engulfment in the tray material. In nearly all instances of bond failure in the present investigation, the hook or gingival tie wings were covered by tray material, requiring considerable force for tray removal. Shorter trimming and reduced thickness of the trays could conceivably reduce the bond failure rate, but perhaps come at the expense of poorer transfer accuracy due to less rigidity. A future study comparing transfer accuracy of printed trays with different trim margins, thicknesses, and rigidity would be valuable in this regard.
While the similarities between the current results and those of select *in-vitro* studies are interesting, it is perhaps more valuable to compare the current study to another *in-vivo* study evaluating 3D-printed transfer trays. Similarly to the present study, Chaudhary *et al.* found low magnitudes and rates of *in-vivo* transfer errors in the linear dimensions when using 3D-printed transfer trays (means ranging from 0.002–0.032 mm for MD, 0.046–0.078 mm for OG, and 0.000–0.016 mm for BL dimensions). They report 100% of positional discrepancies were within the acceptable range for the linear dimensions, with the exception of 9 brackets that fell out of the acceptable range of 0.25 mm in the OG dimension. These findings are consistent with those of the present study, which found the vertical dimension to have slightly lower accuracy than the other linear dimensions. However, in sharp contrast to present findings, Chaudhary *et al.* measured the greatest transfer accuracy in the angular dimensions, with 100% of brackets falling within the relatively stringent acceptability range of 1° for torque, tip, and rotation. This difference could perhaps be due to differences in scan quality, or to a difference in the trays themselves. In addition, it could be attributed, at least in part, to differences in the subjects and dentitions evaluated. Chaudhary *et al.* included patients who were older (no subjects were below 17 years of age) and who had milder malocclusions than those in the present study. The influence of gingival margin position (often more occlusally positioned in younger patients) and degree of crowding on tray adaptation and transfer accuracy cannot be overlooked.

The present study found a modest directional bias of the transferred brackets toward the buccal compared to the intended position. This bias was observed in 67.5% of the
brackets. This is consistent with the findings of Grünheid et al., who measured a bias toward the buccal in 79% of brackets bonded with an indirect method using PVS trays.\textsuperscript{8} This is thought to be a consequence of the amount of adhesive applied to the brackets during the bonding procedure. Notably, the current study did not find a consistent bias in the other linear and angular dimensions. Transfer error in either direction for a given dimension could have been influenced by tray seating and adaptation, tray rigidity, adhesive quantity, and operator technique.

On the one hand, the current study was designed to limit confounding variables and thus used a single-operator protocol for the indirect bonding procedures. While this eliminates inter-operator variability, it also reduces the generalizability of the results. Future studies involving multiple operators would be informative. On the other hand, this study examined adults and children with a variety of malocclusions. While such inclusivity aimed to mirror clinical practice, it could have also introduced variability in tray seating, adaptation, and ease of removal, all of which could influence bracket position. In the present study, bond material was manually placed on the bracket bases prior to bonding. The amount of bond material was not standardized but rather left to operator judgement, which could have introduced error in bracket positioning. Using pre-coated brackets could be one way to circumvent this problem. In order to reduce variability stemming from isolation and visibility, this study did not assess indirect bonding of molars. Since molars present challenges in both direct bonding and indirect bonding alike, a future study including the first and/or second molars would be valuable. Finally, it should be noted that errors in bracket positioning can be additive. For example, if two adjacent
brackets are off in opposite directions, the resulting discrepancy is magnified. For this reason, the selected limits of acceptability used in this study must be evaluated by the clinician in order to determine whether they are willing to accept these errors as they consider using this method in practice.

There is little doubt that digital orthodontics is the way of the future. As offices increasingly embrace 3D technologies, analog indirect bonding may soon become an item of the past. Digital indirect bonding offers many advantages, is already being utilized in some clinics today, and will likely continue to increase in popularity as in-house 3D printing becomes more prevalent. The findings of the current study show that 3D-printed indirect bonding trays have modest bond failure rates and high transfer accuracy in the linear dimensions. Questions remain regarding the transfer accuracy of 3D-printed indirect bonding trays in the angular dimensions, which has shown a great degree of variability in the literature. Future studies with more standardized methodology are needed to elucidate this point.
Conclusions

- Indirect bonding using 3D-printed trays transfers the planned bracket position from the digital setup to the patient’s dentition with a high positional accuracy in the mesio-distal, bucco-lingual, and occluso-gingival dimensions. A clear conclusion cannot be made regarding the transfer accuracy for torque, tip, and rotation. While low transfer accuracy was found in the angular dimensions, this could have been complicated by limitations of the scan data.

- The frequency of bracket transfer error is approximately the same for all tooth types.

- The transferred bracket position demonstrated a modest bias toward the buccal.
References


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