Evaluation of the Accuracy and Fit of 3D-Printed Indirect Bonding Trays Fabricated with Six Different Photopolymer Resins

Eugine Yim

The Graduate School
Yonsei University
Department of Dentistry

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Eugine Yim

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Eugine Yim is approved

Thesis Supervisor: Jung-Yul Cha

Kee Joon Lee

Chooryung J. Chung

Sung-Hwan Choi

Sang-Bae Lee

The Graduate School

Yonsei University

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감사의 글

이제 펜을 내려놓고 지난 시간을 되돌아보니, 새로운 배움에 대한 기대로 가슴 설렜던 대학원 첫 수업의 풍경이 문득 떠오릅니다. 많은 분들의 아낌없는 지지 덕분에 비로소 박사 학위 논문의 결실을 맺을 수 있게 되었습니다. 이 지면을 빌려 이 자리까지 도와주신 모든 분들께 깊은 감사를 전합니다.

무엇보다 숱한 난관에 부딪힐 때마다 든든한 버팀목이 되어주시고, 이 논문이 완성되기까지 끊임없는 격려와 날카로운 지도를 아끼지 않으신 차정열 교수님께 진심으로 존경과 감사를 표합니다. 학위 과정의 첫걸음을 함께 해주신 황충주 교수님께도 감사의 마음을 전합니다. 바쁘신 일정에도 귀한 시간을 내어 논문을 세심하게 검토해주시고, 통찰력 있는 조언을 아끼지 않으신 이기준 교수님, 정주령 교수님, 최성환 교수님, 이상배 박사님께 깊은 감사를 드립니다. 연세대학교 치과교정학교실에서 학문의 기회를 주시고 지원해주신 김경호 교수님, 유형석 교수님, 최윤정 교수님께도 감사드립니다. 또한, 멀리 미국에서 연구를 지원해주신 김기범 교수님, 연구 과정에 많은 도움을 준 Liu Jing 박사님과 유재훈 박사님께도 감사의 마음을 전합니다. 박사 과정 동안 함께 성장하며 큰 위로가 된 동기 및 선후배들에게도 고마움을 전합니다.

치과의사로서 첫 발걸음을 내딛을 때, 스승님이자 멘토가 되어 주신 연치과 김재훈 원장님, 대학원 과정에 대한 지지와 아낌없는 가르침을 주신 고범연 X.O 치과 고범연 원장님께도 진심으로 감사와 존경의 마음을 보내드립니다.

변함없는 믿음과 사랑으로 저의 선택을 지지하고 응원해주신 사랑하는 부모님, 늘 힘이 되어준 언니 희정과 동생 성빈이에게 깊은 사랑과 고마움을 전합니다. 마지막으로 제 삶을 주관하시고 발걸음을 인도하시는 하나님께 이 모든 감사와 영광을 돌립니다.

"거인의 어깨에 올라서서 더 넓은 세상을 바라보라"는 선현의 말씀처럼, 연세에서 받은 값진 가르침을 바탕으로 더욱 넓은 세상과 배움을 향해 끊임없이 정진하겠습니다.

2025 새해 첫날

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ABSTRACT

Evaluation of the Accuracy and Fit of 3D-Printed Indirect Bonding Trays Fabricated with Six Photopolymer Resins

Eugine Yim

The Graduate School of Yonsei University

Department of Dentistry

(Directed by Professor Jung-Yul Cha)

In digital indirect bonding (IDB) systems, IDB trays, utilizing three-dimensional (3D) printing, can introduce output errors due to printer and resin material characteristics. The accuracy of bracket placement in digital indirect bonding systems depends on the fit error associated with the IDB tray and the error that arises when the bracket is inserted into the tray. The purpose of this study is to assess the accuracy and fit of 3D-printed IDB trays fabricated using various photopolymer resin materials.

A reference maxillary plaster model was fabricated, and 60 plaster replicas model using agar impression material were prepared and digitized into standard tessellation language (STL) files with model scanner. An IDB tray with artificial brackets was designed and then 3D printed in 10 identical pieces using six different photopolymer resin: Amber (AB), TC85DAC (TC), Orthoflex (OF), IBT (IT), MED625FLX (MD), and IDB2 (ID). To evaluate the 3D printed IDB tray, a reference plaster model with a computer-aided design (CAD) designed IDB tray (M1), was superimposed with plaster replicas fitted with 3D-printed trays (M2). Changes in the position of artificial bracket were then measured in both linear and angular dimensions using 3D reverse engineering software program. The precision of M2 in three linear dimensions was also evaluated. To assess the accuracy of the printed trays, the CAD-designed IDB tray was superimposed with the printed tray. The dimensions of the printed trays were measured, and the thickness at both the arbitrary bracket configurations (ABCs) and the tray body was compared. IDB Tray fit was evaluated by gap volume between the tooth and the tray using the fit-checker.

IDB trays exhibited significant differences in linear errors, with vertical errors being particularly prominent. Conversely, no significant discrepancies were observed in angular errors across the groups. Precision (linear) was the highest in AB and IT, followed by TC and MD, then ID and OF ($P < 0.05$). Of all tray groups, 90.1% and 68.8% met clinically acceptable linear and angular errors, i.e., < 0.25 mm and 1°. Printing accuracy with different resins depends on tray dimension, thickness error, and gap volume. However, the gap volume was not directly related to the mean tray thickness error or dimensional accuracy.

Linear errors, particularly vertical errors, are more material-dependent than angular errors. Gap volume alone was not a reliable predictor of IDB tray accuracy. Therefore, material-specific designs are needed to control optimal fit and facilitate precise bracket placement.

Key words: Indirect bonding system, 3D Printed IDB tray, Accuracy, Trueness, Thickness, Gap volume

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I. Introduction

In fixed orthodontic treatment, bracket placement is the beginning of orthodontic treatment and is a fundamental element that directly affects tooth movement and orthodontic treatment results. Therefore, many efforts have been made to increase the accuracy of the attachment position of orthodontic bracket placement to maximize the effect of orthodontic treatment and increase its efficiency. For this purpose, the indirect bonding (IDB) system was introduced by Silverman and Cohen in 1972 and has been continuously developed (Silverman et al., 1972). The indirect bonding system is a method of placing a bracket at a desired position on a tooth model and transferring it to the patient's actual dentition using a transfer tray as a template. By allowing brackets to be attached in pre-planned positions, the indirect bonding system helps with precise bracket positioning, resulting in better leveled marginal ridge treatment results and easier overcorrection (Aguirre et al., 1982; Brown et al., 2015). It is also possible to reduce chair time for doctors and staff, which can lead to improved treatment efficiency. In this regard, the accuracy of the transfer tray is critical to increase the efficiency and accuracy of bracket placement for which the indirect bonding system is intended (Castilla et al., 2014; Thomas, 1979). Although the chair time decreases, the total DBS time of the operator is increased due to additional lab work in addition to the clinic time, and the technical proficiency and cost of the related lab work increase, which can be perceived as barriers to the introduction of the indirect bonding system (Czolgosz et al., 2021; Deahl et al., 2007).

Recently, with the emergence of digital dentistry technology, the application of digital workflow is extending to the IDB system. Introduction of digital equipment such as oral scanners, CAD/CAM software, and 3D printers enables digital setup and virtual planning of bracket positions, and IDB trays are manufactured easily and quickly using 3D printing technology to be applied to patients. However, IDB trays 3D printed in digital indirect bonding systems face unique challenges compared to conventional manually fabricated trays such as silicone or double vacuum formed trays. Since 3D printed IDB trays are manufactured using the 3D printer, the fabrication of 3D-printed IDB trays involves potential output errors arising from the printing process and the properties of the resin used.

The accuracy of bracket positioning in digital indirect bonding systems is influenced by the fit error of the IDB tray itself, IDB tray-to-tooth fit , as well as the error that occurs when the bracket is inserted into the tray, bracket-to-IDB tray fit. Therefore, systematic classification and analysis of errors in the digital IDB system are essential for maximizing the accuracy of 3D-printed IDB trays. Previously, research has been primarily focused on the accuracy of bracket positioning in digital IDB systems (Bachour et al., 2022; Hoffmann et al., 2022;

Jungbauer et al., 2021; Xue et al., 2020); however, the independent influence of the fit between the 3D-printed tray and the dentition on bracket positioning has remained unexamined.

In this study, we aim to bridge this knowledge gap by investigating the transfer error and fit of single-transfer trays 3D-printed from various photopolymer resins. To this end, we designed a novel experimental model explicitly tailored to assess tray accuracy and fit. This model isolates tray fit from the bracket-to-tray interactions, offering a comprehensive understanding of the individual contributions to the final bracket placement accuracy.

II. Materials and Methods

2.1. Study model design and selection of resin material for 3D printers

Figure 1 shows the fabrication process and evaluation of the digital and physical samples for accessing the 3D-printed IDB trays.

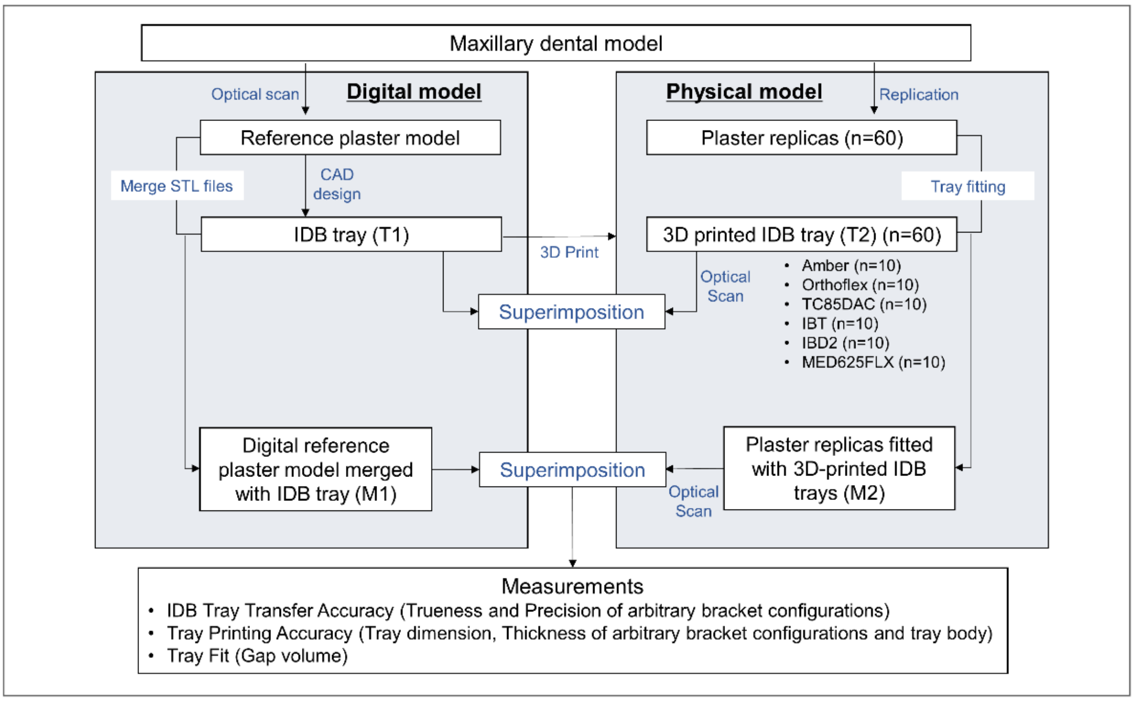

Figure1. Flowchart of experimental design and process

Six commercially available resins with ISO 10993 biocompatibility certification were chosen for this study. These resins, approved for various dental applications including surgical guides, retainers, and clear aligners, were included to assess their potential as materials for IDB trays. The evaluated resins were BioMed Amber (AB) (Formlabs, Milbury, OH, USA), TC85DAC (TC) (Graphy, Seoul, Korea), Orthoflex (OF) (NextDent, Soesterberg, Netherlands), IBT (IT) (Formlabs, Milbury, OH, USA), SprintRay IDB2 (ID) (SprintRay Inc, Los Angeles, CA, USA), and MED625FLX (MD) (Stratasys Ltd, Eden Prairie, MN, USA). A selection of compatible 3D printers was made to fabricate the IDB trays. Form 3B+ (Formlabs, Somerville, MA, USA) was used for AB and IT, NextDent 5100 (NextDent, Soesterberg, Netherlands) for OF, SprintRay pro55 S (SprintRay Inc, Los Angeles, CA, USA) for ID, and Stratasys J5 DentaJet (Stratasys Ltd, Eden Prairie, MN, USA) for MD, and Asiga MAX (Asiga, Alexandria, Australia) was used for TC (Table 1).

2.2. Fabrication of digital and physical models

2.2.1. Fabrication of reference plaster model and plaster replicas

A maxillary dental typodont (Nissin, Kyoto, Japan) was prepared with five reference spheres (diameter, 3.5 mm) placed at specific locations to facilitate superimposition: three on the buccal and palatal sides of the left second molar, one on the right second molar, and one on the labial side of the anterior tooth (Figure 2, A). The reference model was built upon the maxilla standard model proposed by Park et al (Park and Shim, 2019). Afterward, an agar impression material was used to create a silicon impression mold, and a reference plaster model was fabricated by pouring dental stone (SAN ESU Gypsum, Osaka, Japan) into it. This physical model was then scanned using a Medit T710 3D scanner (Medit Co., Seoul, Korea) to generate a reference file. Subsequently, 60 plaster replicas were fabricated using a silicone mold of this reference model and scanned utilizing the same scanner.

2.2.2. Design and fabrication of IDB tray

Computer-aided design (CAD) IBD tray was created using a reference plaster model in the Appliance Designer Program (3Shape Dental Systems, Copenhagen, Denmark). The tray, 1.5 mm thick with a 100 µm internal offset, was extended to the first molar. A transpalatal bar (35 mm × 3.7 mm × 1.8 mm) was incorporated across both molars to minimize potential printing distortions. Non-functional rectangular boxes (3.8mm x 3.9mm x 3.0mm), referred to as arbitrary bracket configurations (ABCs), were positioned on the buccal surfaces of the teeth at the planned bracket locations (Figure 2, C). These ABCs served as reference points for accuracy assessment (Figure 4, A). The tray's buccal surface extended to the top of the tray buccally covered the upper part of the ABC and extended palatally to the teeth's contact points, thus encompassing maximum convexity (Figure 2, B). This CAD-designed tray (T1) was then printed with a 0° orientation for parallel alignment to the horizontal plane (Dai et al., 2023), by using a layer height of 50–100 µm as recommended by the manufacturer (Figure 3, A-E). To assess the influence of resin type on the accuracy of the 3D-printed tray, 60 trays were printed (T2) and post-cured (Groth et al., 2014; Groth et al., 2018) with 10 trays fabricated from each resin (Table 1).

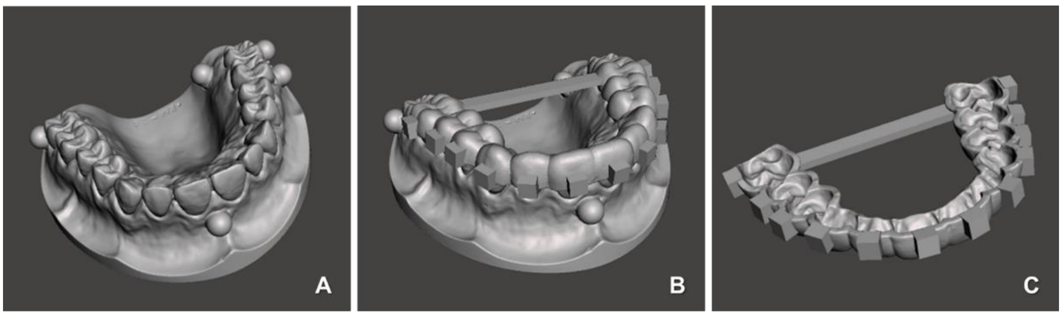

Figure 2. Reference model and tray A, Dental model; B, CAD IDB tray; C, Merged CAD IDB tray on reference dental model.

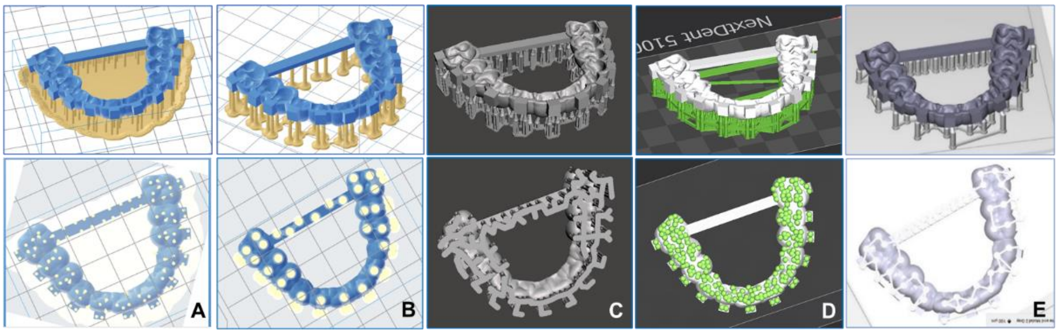

Figure 3. IDB tray printing support design by resin and printing angle A, Amber, Formlabs; B, IBT, Formlabs; C,TC85DAC, Graphy; E, Orthoflex, NextDent; E, IDB2, SprintRay

Table 1. 3D printing resins, material properties and 3D printers used in this study

	Product	Manufacturer	Use of device	Hardness	Material Properties	3D Printer (printing technologies)	Printing layer height	3D print post processing
Hard tray	BioMed Amber (AB)	Formlabs	Surgical guides, medical devices	D84	103 MPa*	Form 3B+ (SLA)	100 um	- Cleaning: ultrasonic bath with 99% IPA (10 min.) - Post-curing (60 °C, 30 min.) in Form Cure (Formlabs, Somerville, MA, USA)
	Orthoflex (OF)	NextDent	Dental Splints, Retainers	D72	67 MPa*	NextDent 5100 (DLP)	50 um	- Cleaning: ultrasonic bath with ethanol (>90%) (2 times within total 5 min with fresh ethanol) - Post-curing (60 °C, 30 min.) in LC-3DPrint Box ((NextDent, Soesterberg, Netherlands)
	TC85DAC (TC)	Graphy	Clear Aligner	D78	≥65 MPa*	Asiga Max (DLP)	100 um	- Cleaning: centrifugal forces with Tera Harz Spinner (Graphy, Seoul, Korea) (5 min.) - Post-curing (2 x 25 min.) using 'level 2' option using Tera Harz Cure (Graphy, Seoul, Korea)
Soft tray	IBT (IT)	Formlabs	Indirect bonding trays	D36	>25%**	Form 3B+ (SLA)	100 um	- Cleaning: ultrasonic bath with 99% IPA (10 min.) - Post-curing (60 °C, 60 min.) in Form Cure (Formlabs, Somerville, MA, USA)
	IDB2 (ID)	SprintRay	Indirect bonding trays	D42	40%**	SprintRay Pro55S (DLP)	100 um	- Orbital shaker (Vevor, Taicang, China) with 99% IPA (3 x 2 min. with fresh IPA each time) - Post-curing (50 °C, 30 min.) using 'IDB2' option in ProCure (SprintRay, Los Angeles, CA, USA)
	MED625FLX (MD)	Stratasys	Indirect bonding trays	D27	45-55%**	Stratasys J5 DentaJet (Polyjet)	100um	- Cleaning: Hand removal, dissolution using 2% NaOH, and water rinse of support materials (SUP711) (Stratasys Inc., Eden Prairie, MN, USA),

* Flexural Strength, ** Elongation at break

2.3. Assessment of the measurements

2.3.1. Assessment of transfer accuracy of arbitrary bracket configurations

After fitting the printed IDB tray on a plaster replica model, transfer accuracy of 3D-printed trays was evaluated by measuring the ABC displacement was evaluated by measuring the ABC displacement into trueness and precision. Trueness indicates how closely the printed IDB trays fitted with the plaster replicas align with the reference model. Precision indicates the consistency between the results of repeatedly printed IDB tray. A high trueness value implies that the measured subject closely matches or is identical to the actual dimensions. Meanwhile, a higher precision indicates greater predictability in the measured values. (Ender and Mehl, 2013); (Kim et al., 2018b) (Pottier et al., 2020)

2.3.1.1. Trueness of arbitrary bracket configuration transfer

The reference plaster model and CAD-designed trays were merged (M1) using he Meshmixer software (Autodesk, San Rafael, CA, USA). The plaster replica models with all printed trays were then scanned (M2). Subsequently, M1 and M2 were super-imposed and aligned in GOM Inspect (GOM Metrology, Braunschweig, Germany) using ‘prealignment’ and ‘local best-fit’ functions using local best-fit functions with reference to spheres on both the palatal and buccal gingival areas. A reference point (P1) was established at the intersection of two tangents drawn 2 mm apart from the upper and distal margins of each buccal bracket surface in M1 (Figure 4, A). After super-imposition of M1 and the scans of M2, the corresponding point (P2) in M2 was mirrored to the location of P1 in M1. To evaluate the accuracy of ABC placement, differences between the reference point P1 in M1 and its corresponding point P2 in M2 were measured on the ABC (Figure 4, B). These differences were quantified as linear errors (mesiodistal, vertical, and buccolingual) and angular errors (torque, rotation, and tip). A local coordinate system was defined for each bracket, with the X, Y, and Z axis aligned with the ABC's long axis, mesiodistal direction, and buccolingual direction, respectively. Negative linear values indicated distal, gingival, and lingual displacement, while negative angular values indicated crown-buccal torque, distal crown tip, and mesial-in rotation (Figure 4, D). Due to a change in the mesial direction of the left ABCs, negative bucco-lingual values appeared for the left side in the coordinate system. To ensure consistency, the bucco-lingual values for the left ABCs were adjusted, resulting in consistent positive values for the buccal direction throughout the system (Figure 4, C).

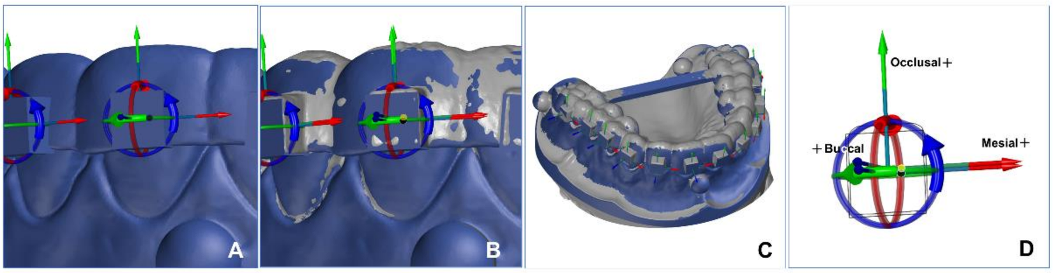

Figure 4. Assessment of arbitrary bracket configurations transfer accuracy in six directions using a semiautomated software. A, Local coordination systems at point (P1) (black point) on the buccal surface of arbitrary bracket configurations of the reference plaster model with reference IDB tray (M1); B, Superimposition of reference plaster model with reference tray (M1) and plaster replica with a 3D-printed tray (M2) and local coordination systems between the point on arbitrary bracket configurations of the reference tray (P1) and registered (P2) (yellow point); C, Overall schematic of the coordinate system after the superimposition of the maxillary arch. The opposing buccal direction signs on the left side of the coordinate system resulted in negative values for the

left buccal ABCs. D, Linear and angular deviations obtained by comparing the positions of the original (blue) and registered (green) local coordinate systems. The arrow heads are directed at the positive directions of the deviations.

2.3.1.2. Precision of the arbitrary bracket configuration transfer

To assess the precision of 3D-printed IDB trays, we measured the Euclidean distance between 120 sets of corresponding points (P1 and P2) in each of 10 samples per group.

Euclidean distance:

$$= \sqrt{(\triangle x)^2 + (\triangle y)^2 + (\triangle z)^2} = \sqrt{(\Sigma\ (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)}$$

$$P_i = \sqrt{(\Sigma\ (xi - x'i)^2 + (yi - y'i)^2 + (zi - z'i)^2)}$$

X (mesiodistal) distance = $\sqrt{\Sigma\ (xi - x'i)^2}$

Y (vertical) distance = $\sqrt{\Sigma\ (yi - y'i)^2}$

Z(buccolingual) distance = $\sqrt{\Sigma\ (zi - z'i)^2}$

2.3.1.3. Frequencies over the clinically acceptable error

The clinical acceptability limits were set at 0.25 mm for linear errors according to the grading system of the American Board of Orthodontics (ABO)(Casko et al., 1998) and at 1° for angular errors based on previous studies (Hoffmann et al., 2022) (Sabbagh et al., 2022). To account for the possibility of two adjacent brackets deviating in opposite directions, the limit of clinical acceptability in the present study was set at 0.25 mm and 1° For the calculation of the frequency of exceeding clinically acceptable limit values, all values were set to the magnitude, excluding directional deviations (+/-).

2.3.2. Assessment of the printed IDB tray accuracy

2.3.2.1. Dimension of the printed IDB tray

Dimensional changes in the reference CAD-designed tray (T1) and printed IDB tray (T2) were determined using GOM Inspect. After aligning T1 and T2 using the pre-alignment function, they were realigned using the local best fit algorithm based on the inner surface of the T1. The measured width was the distance between the buccal planes of ABC (#16 and #26), and the measured length was the perpendicular distance from the midpoint of ABC (#11 and #21) to the width of ABC (#16 and #26) on each tray.

2.3.2.2. Thickness errors of the printed IDB tray

A reference point (P3) was established on the reference tray (T1) at the intersection of: A horizontal plane connecting the three lower mesial point of the ABC #16, #26, and #11, and a line 1.8 mm away from the mesial margin of ABC. Identical points (P4) were set on T2. The vertical distance differences between the vertical lines drawn from points P1 and P2 on the ABCs to the inner surface of the T1 and T2 trays, respectively, were defined as bracket thickness errors (Figure 5, B). Similarly, those at points P3 and P4 on the trays were defined as tray body thickness errors (Figure 5, C). The mean thickness errors were calculated as the average of bracket and tray body thickness errors.

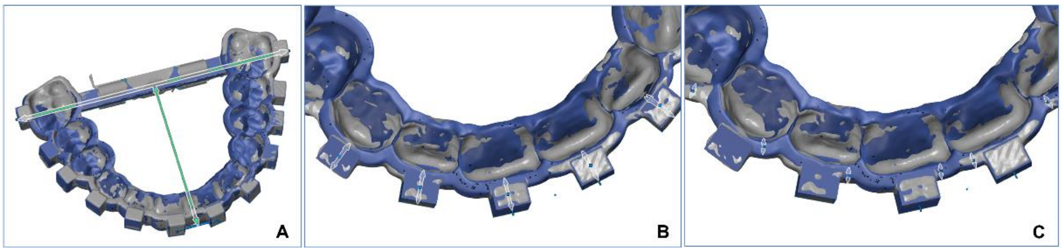

Figure 5. Key dimension and thickness error measurement of printed IDB trays after inner surface superimposition: A, key dimension measurement points of IDB trays at arbitrary bracket surfaces (width and length); B, measurement points for bracket thickness errors in IDB Trays; C, measurement points for tray body thickness in IDB trays

2.3.3. Evaluation of tray fit

2.3.3.1. Gap volume

The gap volume between the 3D-printed IDB tray and the plaster replica was measured using the Fit-Checker Advanced (GC Corporation, Tokyo, Japan). The measurement procedure followed these steps. The Fit-Checker was evenly spread within the tray, ensuring an even layer was distributed throughout the tray, applied onto the model and a weight of 1.5 kg (Inoue et al., 2017) was added for 5 min. To simulate the force applied when the IDB tray is seated on a patient's dentition, a 1.5 kg weight was placed on the tray during the curing process. After waiting 5 minutes to allow the Fit-Checker to harden, Excess Fit-Checker outside the tray was removed and the tray was carefully separated from the plaster replica. Scans of the plaster replica with the fit-checker (V2) were aligned with the pre-application scans (V1). The plaster replica was horizontally cut along the plane of the IDB tray to isolate the region where the Fit-Checker was applied. Subsequently, the volume of the Fit-Checker was measured by calculating the difference between the plaster replica's volume before and after the Fit-Checker was applied.

Figure 6. Measurement of the tray fit. A, T2 with Fit-Checker applied on the plaster replica; B, the plaster replica with Fit-Checker was digitized after the tray removal; C, the volume of fit-checker was measured after superimposition of sectioned fit-checker applied part with before(V1) and after fit-checker(V2).

2.4. Statistical analysis

Sample size calculation was conducted using G*Power (version 3.1.9.2; Universität Dusseldorf, Dusseldorf, Germany) for analysis of variance (ANOVA). The power was set at 80% for a medium effect size (f = 0.5), significance level of 0.05, and observed sample size of n = 60. Accordingly, the analysis considered 10 models per group. As 12 ABCs were analyzed per tray, 720 samples were evaluated in total. Numerical variables were presented as mean (95% confidence intervals). A single examiner performed all the measurements twice. A Shapiro-Wilk test was used to confirm the normality of the data distribution, and subgroup variables were compared using the Kruskal-Wallis test, with post-hoc analysis by Dunn's test. All statistical analyses were performed using the SPSS statistical software (version 24.0, SPSS, Chicago, Ill, USA), and the significance was set at $P < 0.05$.

III. Result

3.1. Reliability of error measurements

The reproducibility of the error measurements was evaluated using Lin's concordance correlation coefficients. All the data were obtained twice by a single examiner. The results showed intra-rater reliability values (α = 5%) of 0.982, 0.990, 0.977, 0.962, 0.935, 0.976, and 0.9, respectively, for the mesiodistal, vertical, buccolingual, torque, tip, and rotation errors, respectively.

3.2. Evaluation of arbitrary bracket configuration transfer accuracy and fit

3.2.1 Trueness of arbitrary bracket configuration transfer

The ID group exhibited the highest mesiodistal error (0.12 mm [95% CI, 0.10-0.13]), whereas the OF group showed the lowest (-0.04 mm [95% CI, -0.06 to -0.03]) among the tray group (P < 0.001). The AB group closely matched the reference model at 0.00 mm (95% CI, -0.02 to 0.01). The vertical error was notably higher in the OF group (0.27 mm [95% CI, 0.19-0.35]) than those in the other trays (P < 0.001). Significant differences in the buccolingual error were observed among all the groups, except for the TC-MD group (P <0.001). The OF group showed the greatest decrease (−0.10 mm [95% CI, -0.11 to 0.15]), P <0.001), while the IT group showed the greatest increase (0.11 mm [95% CI, 0.11-0.14], P <0.001). The AB group closely mirrored the reference at

−0.01 mm (95% CI, -0.02 to 0.00). The angular error was not significantly different among the tray groups (Table 2).

3.2.2 Precision of arbitrary bracket configuration transfer

Analysis of the distances between P2 and P1 for each tray, categorized as mesiodistal, vertical, or buccolingual, revealed that the precision error was the highest in the vertical direction. OF exhibited the largest vertical values at 0.42 mm (95% CI, 0.40-0.44); conversely, the AB and IT groups exhibited the lowest value at 0.17 mm (95% CI, 0.15-0.18) and 0.18 mm (95% CI, 0.16-0.20), respectively (P <0.001). OF and MD groups had the largest values of 0.12 mm (95% CI, 0.12-0.13) and 0.12 mm (95% CI, 0.11-0.13), respectively for mesiodistal distance, and TC group exhibited the lowest value of 0.06 mm (95% CI, 0.05-0.06, P <0.001). In terms of buccolingual distance, the MD and OF groups showed larger values of 0.11 mm (95% CI, 0.11-0.12) and 0.11 mm (95% CI, 0.10-0.12) respectively (P <0.001), whereas the AB group had the smallest value at 0.06 mm (95% CI, 0.05-0.06, P <0.001). In summarizing coordinates across three dimensions, the OF group showed the highest value of 0.48 mm (95% CI, 0.46-0.51), whereas the AB and IT groups showed significantly smaller values of 0.22 mm (95% CI, 0.21-0.23) and 0.23 mm (95% CI, 0.22-0.25), respectively (P <0.001). Significant differences were observed in all group comparisons, except for the AB-IT and TC-MD groups (Table 3).

3.2.3 Frequencies over clinically acceptable errors

Among the 3D-printed trays, 90.1% achieved clinically acceptable linear placement precision (≤ 0.25 mm). However, only 72.5% met the vertical accuracy limit, with the OF group showing the lowest vertical precision (57.5%). Angular accuracy varied by tray group and variable, with 68.8% of ABCs having errors ≤1°, increasing to 93.2% with a 2° limit. Although overall angular errors showed no significant differences among groups, torque errors below 1° were the lowest at 52.2% (Table 4).

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Table 2. Comparison of mean transfer errors among six tray groups with different resin materials

Variables	n	**AB**	**TC**	**OF**	**IT**	**ID**	**MD**	**Total**	***P***	**Dun 's post-hoc test**
Mesiodistal mm	120	0.00 (-0.02 to 0.01)[b]	-0.03 (-0.04 to -0.02)[a]	-0.04 (-0.06 to -0.03)[a]	-0.02 (-0.03 to -0.01)[a,b]	0.12 (0.10-0.13)[c]	0.00 (-0.02 to 0.02)[b]	0.00 (-0.01 to 0.000)	< 0.001	a<b< c
Vertical mm	120	0.14 (0.11- 0.16)[a,b]	0.12 (0.08-0.15)[a,b]	0.27 (0.19-0.35)[b]	0.12 (0.09-0.15)[a]	0.10 (0.06-0.14)[a]	0.16 (0.13-0.19)[b]	0.15 (0.10-0.15)	0.004	a<b
Buccolingual mm	120	-0.01 (-0.02 to 0.00)[c]	0.03 (0.00-0.04)[d]	-0.10 (0.15 to -0.11))[a]	0.11 (0.11-0.14)[e]	-0.07 (0.07 to -0.05)[b]	0.03 (0.03-0.07)[d]	0.00 (-0.01 to -0.01)	< 0.001	a<b<c<d<e
Torque, °	120	-0.15 (-0.39 to 0.05)	-0.17 (-0.41 to 0.04)	-0.24 (-0.55 to 0.00)	0.02 (-0.32 to 0.27)	0.12 (-0.08 to 0.29)	0.03 (-0.27 to 0.23)	-0.06 (0.02 to -0.24))	0.194	
Tip, °	120	-0.02 (-0.18 to 0.11)	-0.07 (-0.22 to 0.06)	0.1 (-0.09 to 0.42)	-0.01 (-0.15 to 0.14)	-0.12 (-0.28 to 0.04)	0.11 (-0.04 to 0.36)	0.00 (-0.06 to 0.1)	0.237	
Rotation, °	120	0.05 (-0.04 to 0.13)	0.10 (-0.01 to 0.23)	0.05 (-0.23 to 0.24)	0.00 (-0.13 to 0.14)	-0.08 (-0.17 to 0.01)	-0.11 (-0.29 to 0.11)	0.00 (-0.01 to 0.1))	0.270	

* Note. Values are mean (95% confidence of interval)
*$P < 0.05$; *P* values were derived from Kruskal Wallis test with Dun's post-hoc test; a Shapiro-Wilk test was employed to test the normality assumption,
* AB, Amber; TC,TC85DAC; OF, Orthoflex; IT, IBT; ID, IDB2; and MD, MED625FLX
* Negative linear values: indicated distal, gingival, and lingual displacement.
* Negative angular values: indicated crown-buccal torque, distal crown tip, and mesial-in rotation.

Table 3. Comparison of precision based on the distance between corresponding points in arbitrary bracket configurations across each tray group

Variables	n	AB	TC	OF	IT	ID	MD	Total	*P*	Dun's post-hoc test
Mesio-distal	720	0.08 (0.07-0.08)[c]	0.06 (0.05-0.06)[a]	0.12 (0.12-0.13)[d]	0.07 (0.06-0.07)[b]	0.08 (0.08-0.09)[c]	0.12 (0.11-0.13)[d]	0.09 (0.09-0.09)	<0.001	a<b<c<d
Vertical	720	0.17 (0.15-0.18)[a]	0.23 (0.21-0.24)[b]	0.42 (0.40-0.44)[d]	0.18 (0.16-0.20)[a]	0.28 (0.26-0.30)[c]	0.17 (0.16-0.19)[a]	0.24 (0.23-0.25)	<0.001	a<b<c<d
Bucco-lingual	720	0.06 (0.05-0.06)[a]	0.08 (0.07-0.09)[c]	0.11 (0.10-0.12)[d]	0.09 (0.08-0.10)[c]	0.06 (0.06-0.07)[b]	0.11 (0.11-0.12)[d]	0.09 (0.08-0.09)	<0.001	a<b<c<d
Precision Total	720	0.22 (0.21-0.23)[a]	0.27 (0.26-0.29)[b]	0.48 (0.46-0.51)[d]	0.23 (0.22-0.25)[a]	0.32 (0.30-0.34)[c]	0.27 (0.26-0.28)[b]	0.30 (0.29-0.31)	<0.001	a<b<c<d

* Note. Values are mean (95% confidence of interval)
* $P < 0.05$; *P* values were derived from Kruskal Wallis test with Dun's post-hoc test; a Shapiro-Wilk test was employed to test the normality assumption.
* AB, Amber; TC, TC85DAC; OF, Orthoflex; IT, IBT; ID, IDB2; and MD, MED625FLX

Table 4. Frequencies of linear errors (>0.25 mm) and angular errors (>1°) among six tray groups

Tray groups	MD error			Vertical error			BL error			Total		
	≤0.25 mm (%)	0.25 mm< (%)	χ^2 (*P*)	≤0.25 mm (%)	0.25 mm< (%)	χ^2 (*P*)	≤0.25 mm (%)	0.25 mm< (%)	χ^2 (*P*)	≤0.25 mm (%)	0.25 mm< (%)	χ^2 (*P*)
AB	120(100.0)	0(0.0)		93(77.5)	27(22.5)	19.812	120(100.0)	0(0.0)		333(92.5)	27(7.5)	
TC	120(100.0)	0(0.0)	12.101 (0.033)	90(75.0)	30(25.0)	(0.001)	118(98.3)	2(1.7)	18.565 (0.002)	328(91.1)	32(8.9)	13.672 (0.018)
OF	119(99.2)	1(0.8)		69(57.5)	51(42.5)		120(100.0)	0(0.0)		308(85.6)	52(14.4)	
IT	120(100.0)	0(0.0)		95(79.2)	25(20.8)		114(95.0)	6(5.0)		329(91.4)	31(8.6)	
ID	116(96.7)	4(3.3)		83(69.2)	37(30.8)		120(100.0)	0(0.0)		319(88.6)	41(11.4)	
MD	119(99.2)	1(0.8)		92(76.7)	28(23.3)		119(99.2)	1(0.8)		330(91.7)	30(8.3)	
Total	714(99.2)	6(0.8)		522(72.5)	198(27.5)		711(98.8)	9(1.3)		1947(90.1)	213(9.9)	

Tray groups	Torque errors				Tip errors				Rotation errors				Total			
	≤1°(%)	1°<x≤2°(%)	2°< (%)	χ^2 (*P*)	≤1°(%)	1°<x≤2°(%)	2°< (%)	χ2 (P)	≤1°(%)	1°<x≤2°(%)	2°< (%)	χ2 (*P*)	≤1°(%)	1°<x≤2°(%)	2°< (%)	χ2 (*P*)
AB	76(63.3)	32(26.7)	12(10.0)		92(76.7)	25(20.8)	3(2.5)		113(94.2)	7(5.8)	0(0.0)		281(78.1)	64(7.5)	15(4.2)	
TC	62(51.7)	46(38.3)	12(10.0)	1.557 (0.669)	99(82.5)	21(17.5)	0(0.0)	3.193 (0.363)	105(87.5)	14(11.7)	1(0.8)	0.356 (0.949)	266(73.9)	81(8.9)	13(3.6)	85.636 (<0.001)
OF	57(47.5)	43(35.8)	20(16.7)		69(57.5)	36(30.0)	15(12.5)		76(63.3)	30(25.0)	14(11.7)		202(56.1)	109(14.4)	49(13.6)	
IT	53(44.2)	44(36.7)	23(19.2)		98(81.7)	22(18.3)	0(0.0)		96(80.0)	19(4.2)	5(2.5)		247(68.6)	85(8.6)	28(7.8)	
ID	72(60.0)	40(33.3)	8(6.7)		89(74.2)	28(23.3)	3(2.5)		113(94.2)	7(5.8)	0(0.0)		274(76.1)	75(11.4)	11(3.1)	
MD	56(46.7)	49(40.8)	15(12.5)		80(66.7)	34(28.3)	6(5.0)		80(66.7)	30(25.0)	10(8.3)		216(60.0)	113(8.3)	31(8.6)	
Total	376(52.2)	254(35.3)	90(12.5)		527(73.2)	166(23.1)	27(3.8)		583(81.0)	107(14.9)	30(4.2)	0.356	1486(68.8)	527(24.4)	147(6.8)	

* Data is given as the frequency and percentage. *P* values were derived from chi-square test. *P* <0.05.
* AB, Amber; TC, TC85DAC; OF, Orthoflex; IT, IBT; ID, IDB2; and MD, MED625FLX

3.2.4 Interaction

A 2-way analysis of variance (*P* <0.05) confirmed significant interactions among variables. The tray group, linear error, and their interaction had a significant effect, as did the interaction between the tray group and angular error. (Table 5).

Table 5. Statistical analysis of main effects and first-order interactions using 2-way ANOVA in linear and angular errors

Variables	*Df*	*Mean Squares*	*F*	*P*
Linear errors				
Tray Group (AB, TC, OF, IT, ID, MD)	5	0.55	27.31	< 0.001
Linear errors (MD, Vertical, BL)	2	4.16	206.75	< 0.001
Tray Group * Linear errors	10	0.44	21.66	< 0.001
Angular errors				
Tray Group (AB, TC, OF, IT, ID, MD)	5	0.31	0.29	0.92
Angular errors (torque, tip, rotation)	2	0.62	0.58	0.56
Tray Group * Angular errors	10	2.85	2.66	< 0.001

3.2.5 *Evaluation of tray printing accuracy*

3.2.5.1 Tray dimension

The TC group showed the smallest change (-0.03 mm [95% CI, -0.08 to 0.02]) in tray length dimensions, whereas the ID group exhibited the most significant alteration (-0.23 mm [95% CI, -0.31 to -0.15], *P* <0.001). The AB group indicated the smallest change (0.03 mm [95% CI, -0.06 to 0.13]) in tray width dimensions, whereas the IT and ID groups demonstrated substantial changes (0.38 mm [95% CI, 0.28-0.48]) and −0.38 mm [95% CI, -0.52 to -0.25]), respectively (*P* <0.001) (Table 4).

3.2.5.2 Tray Thickness

The MD group had the largest ABC thickness error, showing an average expansion of 0.33 mm (95% CI, 0.31-0.35) more than the reference tray (*P* <0.001), and the largest tray body thickness error, with an average of 0.14 mm (95% CI, 0.12-0.16, *P* <0.001). All groups showed significantly different mean thickness errors from the reference (*P* <0.001). The AB group had the smallest mean thickness error, with an average change 0.00 mm (95% CI, 0.01-0.03) in both ABC and tray body thicknesses. The MD group showed a significant increase of 0.23 mm (95% CI, 0.22-0.27), indicating potential dimensional discrepancies (Table 4).

Table 6. Comparison of mean tray dimension, thickness errors and gap volume among six tray groups

Variables	**n**	**AB**	**TC**	**OF**	**IT**	**ID**	**MD**	**Total**	*P*	Post-hoc test
Tray dimension										
Length, *mm* (#11/21-#16/26)	10	0.06 (0.01-0.11)^{b,c}	-0.03 (-0.08-0.02)^{b}	0.18 (0.1-0.25)^{d}	0.11 (0.04-0.17)^{c,d}	-0.23 (-0.31-(-0.15))^{a}	-0.19 (-0.25-(-0.13))^{a}	-0.02 (-0.06-0.03)	<0.001	a<b,c<c,d<d
Width, *mm* (#16-26)	10	0.03 (-0.06-0.13)^{b}	0.15 (0.05-0.25)^{b,c}	-0.27 (-0.34-(-0.20))^{a}	0.38 (0.28-0.48)^{d}	-0.38 (-0.52-(-0.25))^{a}	0.27 (0.17-0.37)^{c,d}	0.03 (-0.05-0.11)	<0.001	a<b,c<c,d<d
Thickness errors										
Bracket thickness error, *mm*	720	0.04 (0.03-0.05)^{b}	0.13 (0.12-0.15)^{c}	-0.04 (-0.06-(-0.03))^{a}	0.10 (0.08-0.13)^{c}	0.04 (0.03-0.05)^{b}	0.33 (0.31-0.35)^{d}	0.10 (0.09-0.11)	<0.001	a<b<c<d
Tray body thickness error, *mm*	720	-0.04 (-0.05-(-0.03))^{a}	0.04 (0.03-0.06)^{c}	-0.02 (-0.04-(-0.01))^{a}	0.00 (-0.02-0.02)^{b}	-0.01 (-0.02-0.01)^{b}	0.14 (0.12-0.16)^{d}	0.02 (0.01-0.03)	<0.001	a<b<c<d
Mean thickness error, *mm*	720	0.00 (0.01-0.03)^{a}	0.09 (0.10-0.13)^{b}	-0.03 (-0.04-(-0.02))^{c}	0.05 (0.03-0.07)^{d}	0.02 (0.01-0.03)^{e}	0.23 (0.22-0.27)^{f}	0.06 (0.04-0.05)	<0.001	c<a<e<d<b<f
Gap volume										
Gap volume, mm^3	60	257.16 (250.3-282.07)^{d}	155.24 (144.18-162.76)^{b}	239.24 (221.82-260.34)^{c}	183.23 (153.6-204.43)^{b}	157.36 (154-161.89)^{b}	95.08 (87.07-107.98)^{a}	181.22 (156.63-197.92)	<0.001	a<b<c<d

*Note. Values are mean (95% confidence of interval)
*P < 0.05; P values were derived from Kruskal Wallis test with Dun's post-hoc test; a Shapiro-Wilk test was employed to test the normality assumption.
* AB, Amber; TC, TC85DAC; OF, Orthoflex; IT, IBT; ID, IDB2; and MD, MED625FLX

3.2.6 3.2.6. Evaluation of the tray fit

3.2.6.1. Gap volume

The MD and AB groups exhibited the smallest and largest gap volumes, averaging 95.08 mm^3 (95% CI, 86.54-103.63) and 257.16 mm^3 (95% CI, 232.91-281.40), respectively (P <0.001). The 3D image superimposition analysis of ap volume revealed variations in fitting accuracy across different intradental regions. Distinct error color maps were observed, depending on the IDB tray material (Figure 7, A-F). Moreover, the gap volumes of the soft trays (IT, ID, and MD) were comparable to those of the TC (hard trays) and smaller than those of the other hard trays (AB and OF) (Figure 7, Table 6).

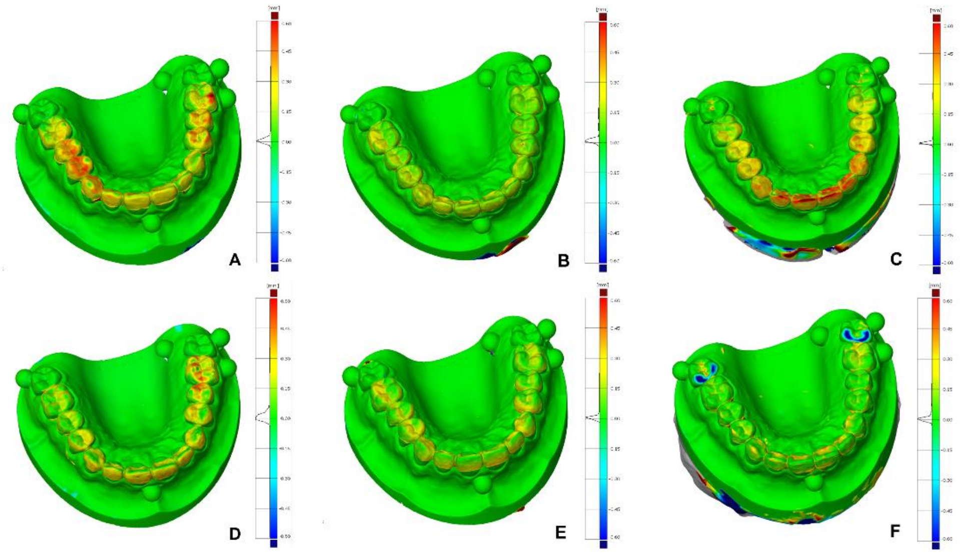

Figure 7 Color maps of Fit-Checker-applied plaster replica for six-different IDB trays. 3D image superimposition analysis revealed differences in fitting error color maps according to IDB tray material: A, Amber (AB); B, TC85DAC (TC); C, Orthoflex (OF); D, IBT (IT); E, IDB2 (ID); F, MED625FLX (MD)

IV. Discussion

The printed trays with ABC exhibited significant differences in linear errors among groups, with the highest mean transfer error observed in the vertical direction. In previous studies, the highest vertical errors were consistently below 0.2 mm, within a range of 0.08-0.193 mm (Bachour et al., 2022; Shin et al., 2021; von Glasenapp et al., 2022). The average vertical error (0.15 mm [95% CI, 0.10-1.15]) obtained in this study falls within this range. Previous studies using conventional IDB trays, such as silicone, PVS, single or double vacuum-formed trays, have also demonstrated notable linear errors in the vertical direction, ranging from 0.07 to 0.49 mm (Castilla et al., 2014; Schmid et al., 2018). This suggests a significant potential vertical error in bracket placement, depending on the material and methods used for manufacturing the tray. Buccolingual error, ranging from ———— 0.10 to 0.11 mm among different tray groups, was similar to the 0.07-0.11 mm range (absolute value) obtained in previous CAD and manufacturing studies. (Kim et al., 2018a; Kim et al., 2018b; Shin et al., 2021). Yoo et al (Yoo et al., 2022) suggested that the difference in linear error could occur depending on the resin material used, with hard trays showing better holding orthodontic brackets. Apart from material properties, factors such as tray design, output resolution, and technician skill can also influence accuracy (Niu et al., 2021).

Although no significant differences in overall angular error were found among the tray groups, the torque had the highest mean transfer error. This finding may be related to our observation that vertical error was the largest among linear errors, which is known to correlate with torque. (Germane et al., 1989; Miethke and Melsen, 1999). Indirect attached actual brackets consistently exhibited higher torque errors than other angular errors (Hoffmann et al., 2022; Niu et al., 2021), supporting this observation. Furthermore, real clinical settings introduce additional variables such as tooth surface shape, adhesive distribution, and virtual bracket library parameters. These factors can significantly influence the final outcome, potentially leading to even greater discrepancies than those observed in controlled experimental settings (Wang et al., 2023).

Our analysis of 3D-printed resin trays, comprising three hard and three soft materials, revealed diverse error patterns across materials, challenging the simplified hard vs soft categorization. While the AB and TC hard trays showed higher linear accuracy than the IT, ID, and MD soft trays, the OF-hard tray exhibited significantly larger vertical and buccolingual errors. In addition, among the soft-type trays (IT, ID, and MD groups), the ID group exhibited a significantly higher mean transfer error in the mesiodistal error compared to other tray groups. Similarly, the MD group showed a significantly higher value in vertical error, and the IT group demonstrated a significantly higher buccolingual error. These findings highlight the material-specific patterns of error directionality. Such resin-specific errors are inconsistent with those reported by Schwarzer et al (Schwarzler et al., 2023), who found mandibular mesiodistal and angular errors in hard trays and smaller vertical errors in soft trays. However, they compared only one type of each resin, which probably influenced their different findings. The comprehensive analysis in this study further revealed different precision levels among resins, with groups AB (hard) and IT (soft), TC (hard) and MD (soft), and ID (soft) and OF (hard) demonstrating higher precision in that particular order ($P < 0.05$). These diverse transfer error and precision patterns highlight the need for further research beyond simplistic hard vs soft categorization. Such advancements are crucial to optimize both tray design and material selection for orthodontic applications.

Our findings indicate better control over linear errors than that of angular errors in 3D-printed IDB trays (Hoffmann et al., 2022). Clinically acceptable values have been assessed in many studies using standard linear errors of 0.5 mm and errors of 2° as thresholds for linear and angular errors, respectively (Castilla et al., 2014; Grünheid et al., 2016; Niu et al., 2021; Sabbagh et al., 2022; Xue et al., 2020). Considering potential opposing deviations in adjacent brackets, stricter thresholds for clinical acceptability were set at 0.25 mm and 1°, respectively (Hoffmann et al., 2022; Hofmann et al., 2022; Sabbagh et al., 2022; Süpple et al., 2021). On average, 90.1% and 68.8% of the trays met the clinically acceptable linear and angular error limits of 0.25 mm and 1°, respectively. Expanding the angular error range to 2° resulted in a success rate of 93.2%. These results are in agreement with observations from previous studies (Jungbauer et al., 2021; Kim et al., 2018a; Niu et al., 2021; Schmid et al., 2018), suggesting a significant challenge in achieving precise angular positioning rather than linear accuracy.

In this study, we evaluated the printing accuracy and fit of 3D-printed IBT trays fabricated from various resins by assessing dimensional fidelity, thickness errors, and gap volume (Table 6). However, based on the results of this analysis, we could not directly predict the printed trays' from these dimensional metrics. The gap volumes for the soft trays (IT, ID, and MD groups) were smaller than those of other hard trays (AB and OF groups). These findings suggest that material properties are crucial. The inherent elasticity of the soft tray materials could enhance adherence to the dental model during the Fit-Checker curing process with a 1.5 kg weight (Inoue et al., 2017). This simulated placement force likely promotes consistent tray adaptation, facilitating standardized evaluation. Notably, the MD group exhibited the smallest gap volume but the highest mean tray thickness error; however, there was no direct relation between these two parameters for the other tray groups. These findings underscore the importance of material properties in determining the fit of 3D-printed trays and highlight the complexity of predicting tray performance based solely on dimensional metrics.

Our results demonstrate that printing accuracy and fit of 3D-printed orthodontic trays. While printing accuracy varied across different resins, it was not the sole determinant of optimal tray fit. Other factors, such as inherent resin properties and delivery conditions, likely play a significant role. In addition, gap volume, measured by the tray-tooth interface using a fit-checker, does not directly contribute to the printing accuracy or the 6-errors of ABCs' on IDB trays. This is further supported by the AB group; despite showing relatively high trueness, dimension, and thickness errors, this group exhibited the highest gap volume. Visual inspections showed further variations in printing accuracy, with the OF group contracting inward (Figure 8, A and B) and the MD group expanding significantly toward the inner surface compared to the reference tray (Figure 8, C and D). Notably, even the MD group's minimal gap volume was attributed to this internal expansion. To compensate for printing accuracy variability, we adopted a uniform 0.1-mm offset across all tray groups, as suggested by Ye et al (Ye et al., 2019) and Lim et al (Lim et al., 2021), who recommended a 0.1-mm offset for splints and surgical guides. However, a recent study by Wang et al (Wang et al., 2023). reported gingival displacement of brackets with a 0.1-mm offset. Our findings, both visual (Figure 8) and quantitative (Table 6), along with those of Wang et al., suggest that resin properties and tooth-fit interactions can vary significantly. A single universal offset setting may not be ideal, emphasizing the need for further research on individualized strategies to compensate for material variability.

This study evaluated trays printed with 50 and 100 μm layer heights, following manufacturer recommendations. We followed the printing parameters recommended by resin and printer manufacturers. In the absence of specific guidelines for the optimal layer heights for IDB trays, this study used a 100 μm layer height for efficient and accurate tray production. Prior research supports this choice, demonstrating that 100 mm layer height in stereolithography apparatus (SLA) printers balance accuracy and speed for dental models (Favero et al., 2017; Loflin et al., 2019). Studies on liquid-crystal display (LCD) printers demonstrated similar findings (Lo Giudice et al., 2022), and research on digital light processing (DLP) printers suggests that a 100 mm layer height reduces printing time for complete dentures without compromising accuracy (Song et al., 2023). Previous studies on IDB trays have used layer heights 50-140 μm (Hoffmann et al., 2022; Pottier et al., 2020;

Wang et al., 2023; Yoo et al., 2022), but no research has compared specific layer heights. Further investigation is needed to determine the optimal layer height for IDB trays.

While our focus was on efficiency and adherence to manufacturer recommendations, we recognize that different layer thicknesses could potentially optimize clinical resolutions. Therefore, further research is necessary to investigate the clinical implications of these variations in layer thickness.

This study investigated the influence of resin properties on the accuracy of IDB trays fabricated using three distinct 3D printing technologies: SLA, DLP, and PolyJet 3D printing (Groth et al., 2014; Groth et al., 2018; Hofmann et al., 2022; Kim et al., 2018a). Although trueness and tray printing accuracy varied by resin material, precision depended on both resin and printer. Hard-type resins printed with SLA (AB) had lower precision errors, whereas soft-type resins showed lower errors with SLA (IT), PolyJet (MD), and DLP (ID) in that order. Gap volume was generally smaller or comparable for soft-type resins compared with hard-type resins, suggesting a stronger influence of material properties than printer type. Previous research on clear aligners found SLA had the lowest trueness error, and DLP had the lowest precision error compared with LCD and SLA (Venezia et al., 2022). Another study on dental models showed PolyJet had the smallest trueness and precision errors compared with SLA and DLP (Kim et al., 2018b). These discrepancies likely stem from variations in manufacturer specifications, printer quality, and ongoing technological advancements. To mitigate this confounding factor, each resin in our study was printed using its corresponding manufacturer's recommended 3D printer and validated printing conditions. This approach ensured optimal printing parameters specific to each resin's properties. Consequently, our focus was on the intrinsic properties of the resins as dictated by manufacturer guidelines, rather than controlling for variations in printer or printing method. However, variations in recommended printers, printing layer height, and resin hardness in this study complicate generalizing accuracy based on printing technology. Further research is needed to optimize printing parameters for specific resin-printer combinations.

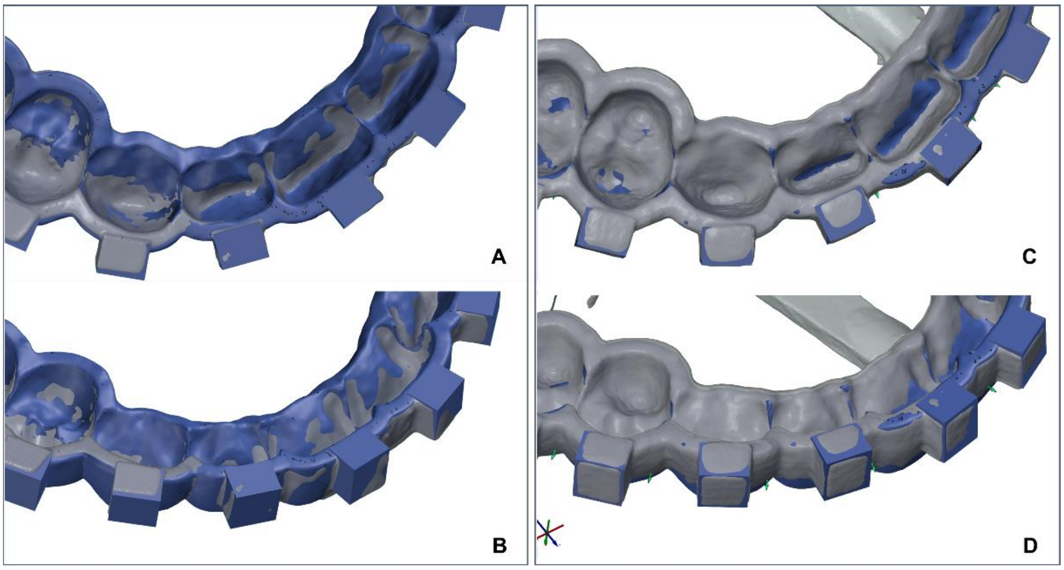

Figure 8. Comparison of internal and buccal surface by super-imposition of reference CAD IDB tray (blue) and printed IDB tray (grey) based on tray's inner surface. A, internal surface of Orthoflex (OF); B, buccal surface of Orthoflex (OF); C, internal surface of MED625FLX (MD); D, buccal surface of MED625FLX (MD)

V. Conclusion

The following conclusions can be drawn based on the obtained results:

1. Significant differences in linear transfer errors were observed among the six tray groups, with vertical errors being particularly prominent. Conversely, no significant discrepancies were observed in angular errors across the groups.

2. Although 90.1% of trays achieved clinically acceptable linear errors of less than 0.25 mm, certain resins (OF and ID) exhibited higher vertical errors. For angular errors, 68.8% of the trays met the 1° threshold, while 93.2% of the trays met the 2° threshold.

3. The measured printing accuracy varies across different resins. The gap volumes of the soft trays (IT, ID, and MD group) were smaller than the hard trays (AB and OF group). However, the gap volume was indirectly related to the mean tray thickness error or dimensional accuracy.

Our findings revealed that linear transfer error, particularly in the vertical dimension, is more resin-dependent than angular transfer error. Additionally, gap volume was not a reliable sole indicator of IDB tray accuracy. Therefore, considering the observed variations in accuracy and fit for different resins, material-specific designs would compensate for material differences and ensure optimal fit and facilitate precise bracket placement.

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국문요약

6 종의 광중합 수지로 제작한 3D 프린팅 간접 부착 트레이의 정확성 및 적합성 평가

연세대학교 대학원 치의학과

임 유 진

(지도교수: 차 정 열)

디지털 간접부착 시스템에서는 3D 프린터나 프린팅 레진의 물성에 따라 각각 다른 출력 오차가 발생할 수 있다. 또한 브라켓의 위치오차는 출력된 간접 부착 트레이의 구강내 시적 시 치열 적합성의 오차와 교정용 브라켓을 트레이에 삽입했을 때의 오차가 더해져 발생하게 된다. 따라서 본 연구의 목적은 현재 시판 중인 다양한 물성의 레진과 3차원 프린터를 이용하여 제작한 교정용 단일 간접 부착 트레이의 출력 정확성과 모델상에서의 적합도를 비교하고, 전달 오차(transfer error)를 계측하기 위해 설정한 임의의 브라켓 형태의 직육면체 구조물(arbitrary bracket configurations)의 위치 오차를 평가하는 것이다.

비교 평가를 위하여 표준 상악 치아모형을 석고로 제작하고 이를 바탕으로 디지털 스캔 파

일과 석고 복제 모형을 제작했다. 간접 부착 트레이는 표준 치아 모형을 기준으로 각 치아에 임의의 브라켓 형태의 구조물을 설정하고, 5종류의 3D 프린터와 6개의 광중합형 프린트 레진,(Amber(AB), TC85DAC(TC) Orthoflex(OF), IBT(IT), IDB2(ID), MED625FLX(MD)으로 레진 소재 별 10개씩 총 60개의 트레이를 출력하였다. 기준 CAD 트레이를 장착한 치아모델 파일과 출력된 간접부착 트레이를 장착한 복제한 석고모형의 스캔 파일을 중첩하여 간접부착 트레이의 인공 브라켓의 3개의 선형 오차와 3개의 각도 오차를 리버스 엔지니어링 검사 프로그램을 이용하여 계측하였다. 또한 각 선형 차원에서 출력된 트레이 별, 2점의 거리를 계측함으로써 정밀도 (precision)을 평가하였다. 트레이의 출력 정확성은 출력된 트레이의 치수 (dimension)와 임의로 설정한 브라켓 형상 구조에서의 두께와 트레이 본체 두께를 측정하였고, 이를 기준 CAD 트레이와 정합한 후 비교하여 치수와 두께 오차를 계측함으로써 평가하였다. 트레이 적합성은 핏-체커를 이용하여 치아 모형과 출력된 간접부착 트레이 사이의 공간 부피 (gap volume)로 평가하였다.

3D 프린트된 IDB 트레이의 전달 오차는 선형 오차에서 트레이 그룹 간 유의적인 차이를 보였으며 (P <0.001), 그 중에서도 수직 오차가 가장 컸다. 트레이의 전달 정확도 (transfer accuracy)의 정확도 (trueness)와 정밀도 (precision)에서 경질 (hard type) 트레이인 AB, TC 그룹이 연질 (soft type) 트레이 IT, ID, MD 그룹에 비하여 일관적이고 안정적인 오차 평균 결과를 보여주었다. 단, 경질 트레이 범주 내에서 OF 그룹은 수직 및 협설 방향의 오차, 정밀도 (precision) 계측에서 모두 높은 유의성을 보였다 (P <0.001). 트레이 두께는 OF 그룹을 제외한 다른 모든 트레이 그룹에서 두께의 확장 경향을 보였고 그 중 MD 그룹은 유의적으로 큰 두께 확장 출력 경향이 나타났다. 공간 부피는 MD그룹이 가장 작았으며, AB 그룹이 가장 컸

다 (P <0.001). 연질 트레이인 IT, ID, MD 그룹이 경질 트레이인 AB, TC, OF 그룹과 비교하여 비교적 낮은 공간 부피를 보였다. 실험에 사용한 6 종류의 트레이 중에서 90.1%와 68.8%가 각각 <0.25 mm 및 1°의 보수적으로 설정한 임상적으로 허용 가능한 선형 및 각도 오류 범위 안에 포함되었다.

선형 오차, 특히 수직 오차가 각도 오차보다 재료에 대한 영향을 더 크게 받았다. 트레이와 치아 모형간 공간 부피만으로는 간접부착 트레이 성능의 정확한 예측이 어려웠다. 따라서 최적의 적합성과 정확한 브라켓 위치 설정의 가능성을 높이기 위해서는 재료에 따른 간접부착 트레이의 설계와 맞춤화가 필요하다.

핵심이 되는 말: 3D 프린팅 간접부착 트레이, 정확성, 적합성, 두께, 갭 부피