Accuracy of in-office indirect bonding system using 3D printed orthodontic bracket transfer trays

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Accuracy of in-office indirect bonding system using 3D printed orthodontic bracket transfer trays

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감사의 글

본 교실에서의 수련 과정부터 이 논문이 완성되어 나오기까지 항상 따뜻한 가르침으로 이끌어 주신 차정열 교수님께 진심으로 감사드립니다.

바쁘신 와중에도 논문의 완성을 위해 소중한 시간 내주시고 꼼꼼한 조언을 주신 이기준 교수님, 최성환 교수님, 김광만 교수님, 김영준 박사님께 깊이 감사드립니다.

부족한 제게 연세대학교 치과교정학교실에서 공부할 수 있는 기회를 주시고 교정과 전문의로서 올바른 길을 갈 수 있도록 이끌어 주신 황충주 교수님, 김경호 교수님, 유형석 교수님, 정주령 교수님, 최윤정 교수님께도 진심으로 감사드립니다.

또한 논문을 진행하는 동안 많은 도움을 주신 교정과 의국 선후배님들, 신설희 선생님, 최영일 선생님, 유재훈 선생님께도 감사의 마음을 전합니다.

마지막으로 저를 지금까지 키워주시고, 끝없는 응원을 해주시는 부모님들과 가족들, 학생 때부터 늘 함께하고 기다려준 현우에게 사랑의 마음을 전합니다. 그리고 항상 축복하고 사랑하는 리호, 리안 그리고 늘 행복을 느끼게 해주는 가족들과 기쁨을 함께 나누고 싶습니다.

2021 년 6 월

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ABSTRACT

Accuracy of in-office indirect bonding system using 3D printed orthodontic bracket transfer trays

Seong Hun Yoo

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Department of Dentistry

(Directed by Professor Jung-Yul Cha)

In this study, we aimed to evaluate and compare the bracket-positioning accuracy of the indirect bracket bonding (IDB) transfer tray fabricated in-clinic using the tray-printing (TP) and marker-model printing (MP) methods. The TP group was further divided into two groups [single-tray printing (STP) and multiple-tray printing (MTP)] depending on the presence of a tray split created using the 3D software. Five duplicated plaster maxillary models were used for each of the three experimental groups, and a total of 180 artificial teeth, except the second molar, were evaluated in the experiment. Dental model was scanned using a model scanner (E3; 3Shape Dental Systems, Copenhagen, Denmark). Virtual brackets were placed on FA points, and the IDB trays were designed and fabricated using a 3D printer (VIDA; EnvisionTEC, MI, USA). The accuracy of bracket positioning was evaluated by comparing the planned bracket positions and the actual bracket positions using 3D analysis on an inspection software. The main effects and first-order interaction effects were analyzed together by ANOVA.

The mean distance error was 0.06 mm in STP group and 0.09 mm in the MP and MTP groups. The mean height error was 0.10 mm in STP group and 0.15 mm and 0.18 mm in MP and MTP groups, respectively. The mean distance and height errors were significantly lower in the STP group than those in the MP and MTP groups ($p < 0.05$). However, no significant differences were observed in the angular errors among the three groups ($p > 0.05$).

The in-office-fabricated IDB system with computer-aided design and 3D printer is clinically applicable considering the linear and angular errors. We recommend IDB trays fabricated using the STP method owing to the lower distance and height error of bracket-positioning errors and ease of fabrication.

Key words: 3D-printed tray, indirect bracket bonding, bracket position error

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I. Introduction

The purpose of indirect bracket bonding (IDB) is to determine the accurate location of the bracket on the patient's dental model to fabricate transfer trays that would accurately place the brackets chair-side on the intended location on the actual teeth. The IDB method is more convenient than the direct bonding method in terms of better salivary flow control, reduction in patients' stress caused by longer chair time, and improved visibility due to the absence of interferences from the patient's lips, tongue, and cheeks during the bonding procedure (Gange, 2015; Vianna and Mucha, 2006; Yıldırım and Saglam Aydinatay, 2018). Accordingly, the IDB method helps in more accurate bracket positioning at their intended location and renders overcorrection easier than the direct bonding method (Aguirre et al., 1982; Kalange, 2004). With advances in the methods and materials used for fabrication of IDB trays, stability and accuracy have been improved (Aguirre et al., 1982; Yıldırım and Saglam Aydinatay, 2018), chair time has been reduced, and cost efficacy has been ensured (Hodge et al., 2001; Kalange, 2004). In addition, the IDB method has shortened the total treatment time by 5 months, compared to the direct bonding method (Brown et al., 2015).

Dental software and equipment based on computer-aided design (CAD) and computer-aided manufacturing (CAM) have evolved at a rapid pace. Three-dimensional (3D) virtual tooth alignment software ensures that the bracket is positioned to obtain the desired final occlusion. Moreover, precise bracket positioning is possible by considering the proximity and angulation of the tooth root and merging the patient’s craniofacial 3D computed tomography (CT) and intraoral scan data (De Oliveira et al., 2019). Clinicians can now design an IDB tray using 3D software and fabricate the tray directly in-office using a commercially available 3D printer. Technological advances have resulted in wide applications of customized orthodontic systems for both labial and lingual orthodontics (Sha et al., 2020). The number of service providers purveying customized orthodontic devices and bonding trays with 3D printing technology has also increased (Boyd and Waskalic, 2001; Groth et al., 2018; Martorelli et al., 2013; Weber et al., 2013).

Accurate 3D-printed IDB trays are essential to achieve the treatment objective, since the planned bracket position is transferred to the patient’s dentition using the fabricated tray. Selecting a 3D printer that serves the intended purpose is critical, as the fit of the tray can be affected by the quality of printer. In previous studies, digital light processing (DLP) and PolyJet techniques showed greater accuracy for 3D printing along with better results in printing time (Kim et al., 2018b) than fused filament fabrication or stereolithography apparatus techniques (Brown et al., 2018; Hazeveld et al., 2014; Kim et al., 2018b). Therefore, 3D-printed IDB trays have mainly been fabricated using DLP or PolyJet (Brown et al., 2018; Duarte et al., 2020; Hazeveld et al., 2014; Kim et al., 2018a; Shin et al., 2019).

In addition to the quality of the printer, the design and materials of IDB trays are critical factors that affect the into the following. According to the first method, the IDB tray designed by the CAD software is directly printed using a 3D printer in the shell-type. In the second method, a dental model containing a marker that guides the actual brackets to the intended position is printed using a 3D printer, and IDB trays are manually fabricated using silicone or thermoplastic materials.

However, few studies have analyzed the accuracy of bracket positioning according to the design and material of the CAD/CAM IDB tray (Kim et al., 2018a; Shin et al., 2019). Previous studies were conducted with individual transfer jigs, which are not commonly used in clinical trials, rather than with single or split type trays. In this study, we aimed to evaluate and compare the bracket-positioning accuracy of IDB trays fabricated using the tray-printing (TP) and marker model printing methods (MP). Additionally, trays fabricated using the TP method were divided into two groups depending on the presence of a tray split formed using a 3D software. The null hypothesis of this study is that there will be no difference in the bracket positioning error according to the design and manufacturing method of in- office 3D-printed IDB trays.

II. Materials and methods

1. Fabrication of the working model

In this study, we made 15 plaster replicas of a maxillary dental model (Dentiform, Nissin Dental Products, Kyoto, Japan) using agar impression material. The 15 duplicated models were allocated to three groups. The IDB trays in the single-tray printing (STP) and multiple-tray printing (MTP) groups were directly fabricated using 3D printing, while those fabricated using the marker-model printing (MP) method were fabricated manually. Accordingly, two groups were formed: the TP group, which was further divided into STP and MTP groups, and the MP group. Conventional silicone was used to fabricate IDB trays in the MP group. We used self-ligating brackets (0.022´´ Slot, Damon Q®, Ormco, USA) in this study (Fig 1).

2. Bracket positioning using the CAD software

The maxillary dentiform was scanned using a model scanner (E3; 3Shape Dental Systems, Copenhagen, Denmark) and was converted into standard triangle language (STL) files. Virtual brackets were placed on Andrews' facial axis (FA) point using the Trios software program (3Shape Dental Systems, Copenhagen, Denmark) (Fig 2, A) (Andrews, 1989).

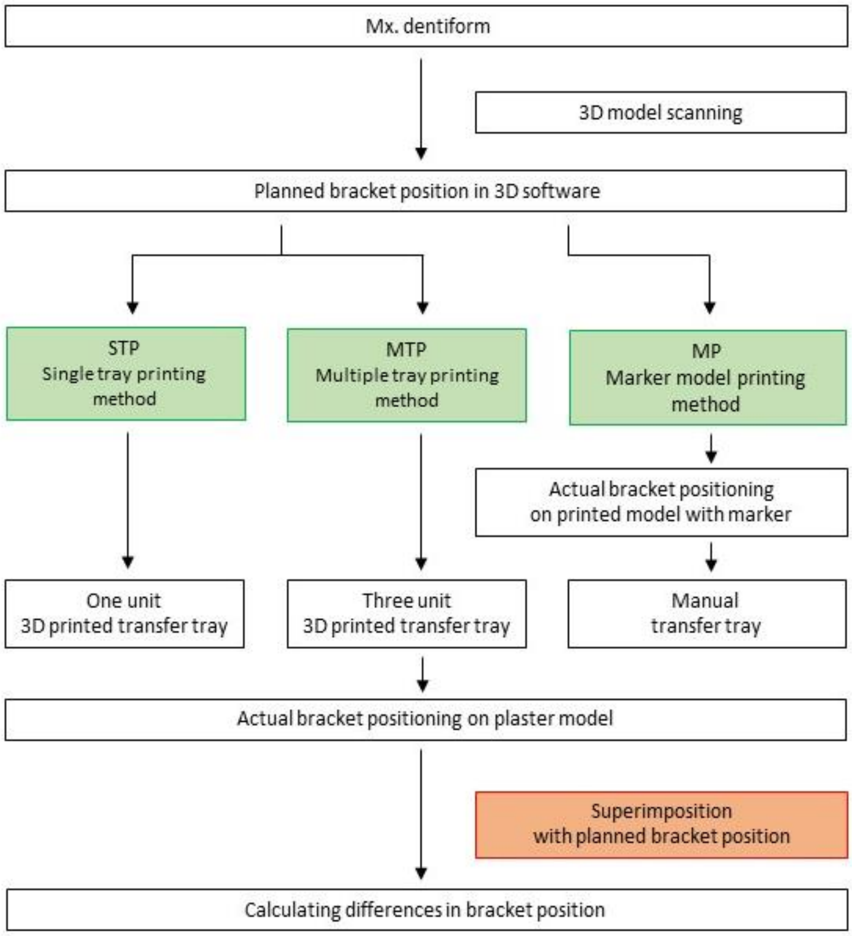

Figure 1. Schematic diagram indicating the study flow.

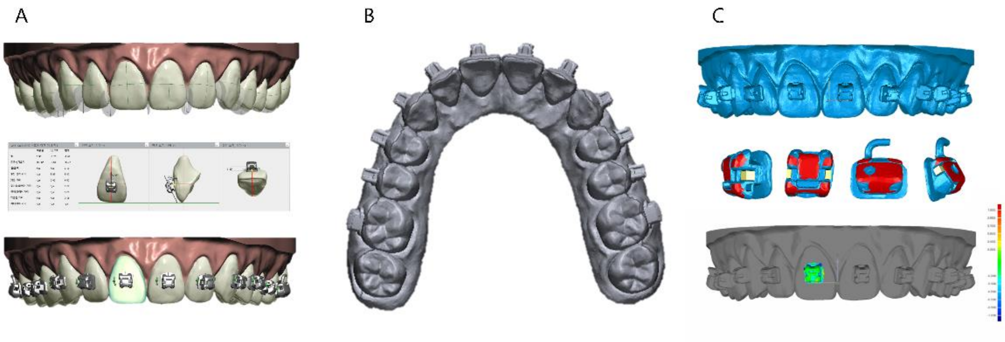

Figure 2. Designing reference digital model with ideal bracket position using CAD/CAM software: A, process of bracket placement on digital model (using FA point) using CAD/CAM program; B, exporting digital model with block-out virtual bracket to STL file using CAD/CAM program; C, superimposition of original bracket - CAD model to exported digital model.

3. Reference model with the 3D constructed brackets

After virtual bracket placement, the reference model was converted to a digital model with the brackets being blocked-out and was exported as an STL file using a CAD/CAM program (Appliance designer; 3Shape Dental Systems, Copenhagen, Denmark) (Fig 2, B). The bracket CAD models embedded with full-sized rectangular objects constructed using the reverse engineering technique with microCT, were merged with each blocked-out bracket using the Best-Fit algorithm (Fig 2, C).

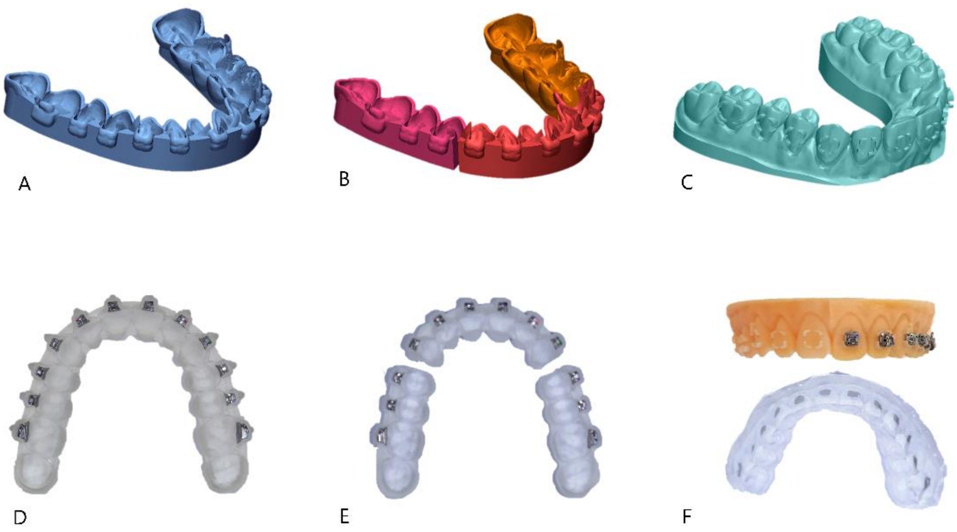

Figure 3. CAD images of transfer tray and marker type model for bracket positioning using CAD/CAM program. And three type of bracket transfer trays: A, STP (single-tray printing method); B, MTP (multiple-tray printing method); C, marker type model for the fabrication of MP (marker model printing method); D, STP tray; E, MTP tray; F, MP tray. Brackets were positioned on marker type model (top) and transfer trays were fabricated using silicone and polyvinyl siloxane (bottom).

4. Fabrication of transfer trays

The IDB trays were designed using Appliance Designer (Fig 3). The trays were fabricated using the TP or MP methods. The TP method was divided into the STP and MTP methods. The STP and MTP trays were designed using the CAD/CAM software (Fig 3, A, B) and were printed using the

DLP technique (VIDA, EnvisionTEC, MI, USA) (Fig 3, D,E) with a build layer thickness of 0.05 mm. Flexible 3D resin (OrthoIBT, NextDent, Seosterberg,Netherland) was used to fabricate the trays. MP trays were designed with a bracket-positioning guide on the surfaces of the teeth (Fig 3, C). The MP model was printed using the PolyJet technique (Objet30 OrthoDesk, Stratasys, MN, USA) with a build layer thickness of 0.028 mm. 3D resin (VeroDentPlus MED690, Stratasys, MN, USA) was used. All models were printed with a horizontal orientation.

After the brackets were positioned according to the guides, the MP tray was fabricated with soft silicone (Emiluma,Opal Orthodontics, Utah, USA) as the inner layer, and clear polyvinyl siloxane (Memosil, Heraeus Kulzer, Hanau,Germany) as the outer layer (Castilla et al., 2014).

For the IDB procedure, each tray was seated completely and was held in place with firm pressure applied parallel to the occlusal plane by the investigator’s right hand (Castilla et al., 2014). A trained orthodontist bonded the brackets with adhesive resin (Transbond TM XT Light Cure Adhesive, 3M Unitek) under photopolymerization. After bonding, the model was scanned using a model scanner (E3; 3Shape Dental Systems, Copenhagen, Denmark).

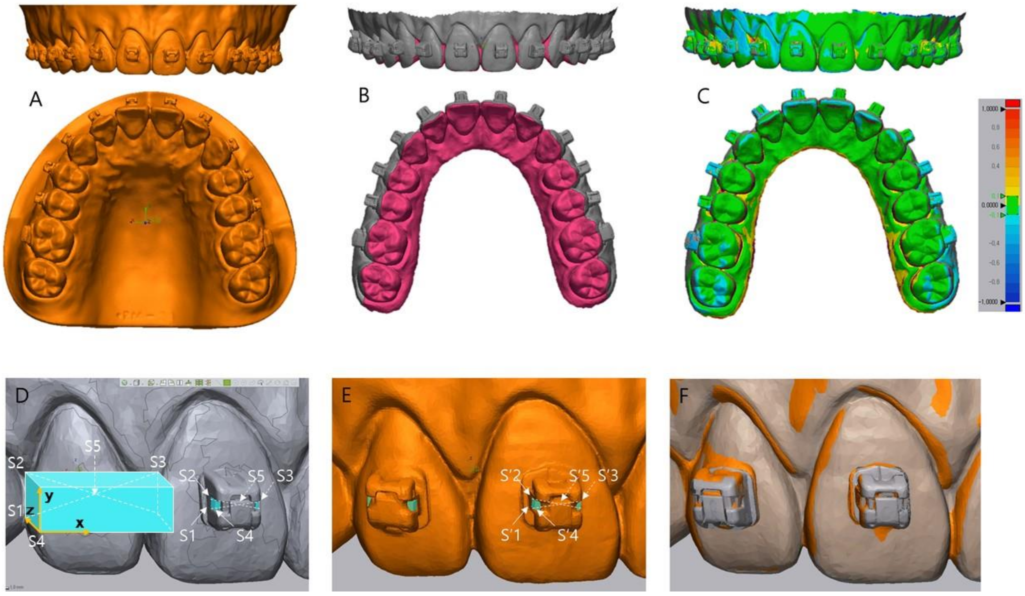

Figure 4. Superimposition of two digital models with planned and actual bracket position on maxillary dentition by best-fit algorithm, for measuring bracket placement error. By measuring the coordinates of the 4 vertex points of the rectangular slot (S1-S4), and the slot center (S5): A, scanned digital model with bonded actual bracket by indirect bracket bonding tray group; B, reference digital model with planned bracket position in the CAD/CAM program and localization of reference region for superimposition, lingual surface and occlusal area (red area); C. superimposed two digital models with planned and actual bracket position, the color scale presenting three dimensional deviation, the deviation of green scale was ±250 μm; D, reference digital model with planned bracket position in the CAD/CAM program and the reference point for calculating bracket placement error (S1: distolinguoocclusal point, S2: distolinguocervical point, S3: mesiolinguocervical point, S4: distobuccoocclusal point, S5: calculated slot center); E, scanned digital model with bonded actual bracket by indirect bracket bonding tray group; F, superimposed image of planned and actual bracket position.

5. Calculating the differences in bracket positioning

First, the scanned bonded brackets were merged with the scanned virtual bracket model (Fig. 2) using the 3D inspection software (Geomagic control X®2017, 3D Systems, Rock Hill, SC, USA) to improve the quality of the scanned images of the brackets. Second, the images of the occlusal and lingual surfaces of the teeth without the brackets were superimposed using a Best-Fit algorithm, and the planned bracket positions were compared with the actual bracket positions using the 3D inspection software (Geomagic control X®2017, 3D Systems, Rock Hill, SC, USA) (Fig 4). Constructed a coordinate system by measuring the coordinates of the 4 points of the rectangular slot and used it to obtain the coordinates of the center of the slot (Fig. 4). We calculated the linear errors (height, depth, and distance) using a position equation by measuring the distance from a plane to a point and the angular errors (torque, rotation, and tip) using vectors passing through each plane and applying them to an equation to calculate the angle between the two vectors (Fig. 5). We measured a total of 6 types of error using the following equations (https://en.wikipedia.org/wiki/Inner _product _space):

Height Error = $\Delta \frac{|S_c \cdot \hat{Y}|}{||\hat{Y}||}$ $\hat{Y}$: normal vector of XZ plane

Depth Error = $\Delta \frac{|S_c \cdot \hat{Z}|}{||\hat{Z}||}$ $\hat{Z}$: normal vector of XY plane

Distance Error = $\Delta \frac{|S_c \cdot \hat{X}|}{||\hat{X}||}$ $\hat{X}$: normal vector of YZ plane

$$\text{Torque Error} = \cos^{-1}\left\{\frac{\left[S_v - \frac{S_v \cdot \hat{X}}{||\hat{X}||}\hat{X}\right] \cdot \left[S_v - \frac{S_v' \cdot \hat{X}}{||\hat{X}||}\hat{X}\right]}{||S_v - \frac{S_v \cdot \hat{X}}{||\hat{X}||}\hat{X}||\ ||\left[S_v' - \frac{S_v' \cdot \hat{X}}{||\hat{X}||}\hat{X}\right]||}\right\}$$

$$\text{Rotation Error} = \cos^{-1}\left\{\frac{\left[S_h - \frac{S_h \cdot \hat{Y}}{||\hat{Y}||}\hat{Y}\right] \cdot \left[S_h' - \frac{S_h' \cdot \hat{Y}}{||\hat{Y}||}\hat{Y}\right]}{||S_h - \frac{S_h \cdot \hat{Y}}{||\hat{Y}||}\hat{Y}||\ ||\left[S_h' - \frac{S_h' \cdot \hat{Y}}{||\hat{Y}||}\hat{Y}\right]||}\right\}$$

$$\text{Tip Error} = \cos^{-1}\left\{\frac{\left[S_v - \frac{S_v \cdot \hat{Z}}{||\hat{Z}||}\hat{Z}\right] \cdot \left[S_v' - \frac{S_v' \cdot \hat{Z}}{||\hat{Z}||}\hat{Z}\right]}{||S_v - \frac{S_v \cdot \hat{Z}}{||\hat{Z}||}\hat{Z}||\ ||\left[S_v' - \frac{S_v' \cdot \hat{Z}}{||\hat{Z}||}\hat{Z}\right]||}\right\}$$

S_c: center of the slot $= \int ds = \frac{\sum_{i=1}^{4} S_i}{4}$

S_v: vertical vector of lingual plane

S_h: horizontal vector of lingual plane

Lingual plane: plane made by S1, S2, and S3

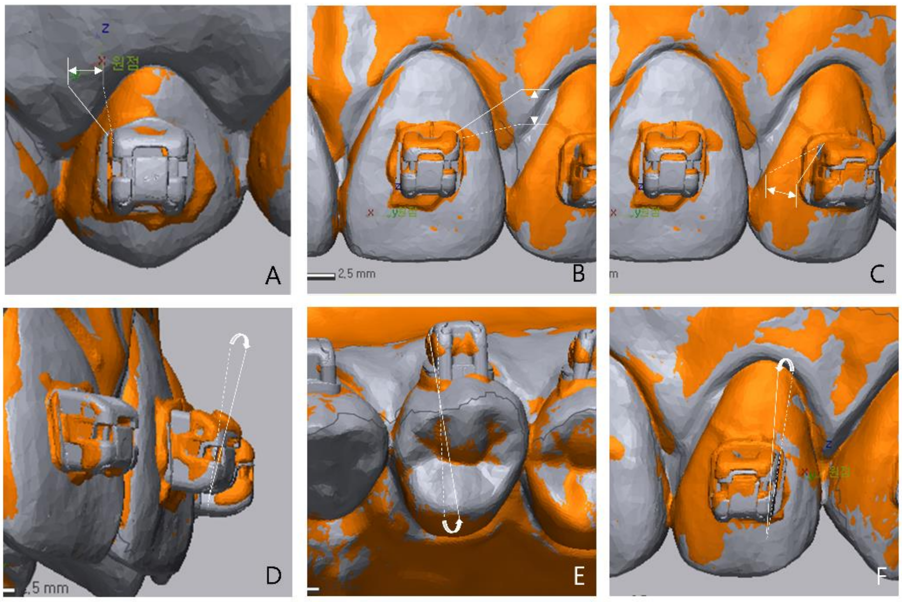

Figure 5. Representative bracket position error images of actual and planned position; A, distance error. Difference in the X value of each slot center projected onto the XZ plane; B, height error. Difference in the Y value of each slot center projected onto the XY plane; C, depth error. Difference in the Z value of each slot center projected onto the YZ plane; D, torque error. Angular difference in the direction vector of each Y axis projected onto the YZ plane; E, rotation error. Angular difference in the direction vector of each X axis projected onto the XZ plane; F, tip error. Angular difference in the direction vector of each Y axis projected onto the XY plane.

6. Statistical analysis

A sample size of 180 (12 brackets per bracket type per study specimen) was examined in this study. Power analysis for the analysis of variance (ANOVA) (two-tailed), which was conducted using G*Power 3.1.9.2, indicated 85% power to detect a medium effect size (Cohen's d = 0.25) at a significance level of 0.05 with an observed sample size of n= 60. The numeric variables were represented as the mean (95% confidence interval). The reliability of the measurement of error in bracket placement was calculated by determining the intraclass correlation (ICC) (2-way random model). The lowest acceptable interclass and intraclass coefficient (ICC) was set at ≥ 0.70. We used the Shapiro–Wilk test to determine the normality of data distribution. The differences in the variables of the subgroups were compared using the ANOVA or Kruskal-Wallis test, as appropriate. Dunn's test was used for post-hoc comparison. The main effects and first-order interaction effects were considered together in the ANOVA. All statistical analyses were conducted using SPSS version 24.0 statistical software. P-values less than 0.05 were considered statistically significant.

III. Results

1. Reliability of error measurements

We analyzed the reliability of measurements and found that the ICCs for intra-rater reliability and inter-rater reliability were 0.978–0.996 and 0.894–0.996, respectively.

Table 1. Comparison of bracket position errors between three groups

Position	Variable	(unit)	Group				Dunn's post hoc test
			STP[a]	MTP[b]	MP[c]	p value	
Maxillary	Distance Error	(mm)	0.06 (0.04,0.07)	0.09 (0.07,0.11)	0.09 (0.07,0.10)	.015*	a<b,c
	Height Error		0.10 (0.07,0.13)	0.18 (0.14,0.22)	0.15 (0.12,0.17)	.001*	a<b,c
	Depth Error		0.26 (0.23,0.29)	0.23 (0.20,0.25)	0.12 (0.10,0.14)	<.001*	a,b>c
	Torque Error	(°)	2.69 (2.05,3.32)	2.13 (1.62,2.63)	2.46 (1.88,3.05)	.373	NA
	Rotation Error		2.52 (2.06,2.97)	1.97 (1.56,2.37)	2.05 (1.61,2.50)	.101	NA
	Tip Error		2.98 (2.46,3.51)	2.84 (2.32,3.36)	2.46 (2.06,2.86)	.470	NA

Value: mean(95% confidence interval)
Data are given as the mean (95% confidence interval)
p values were derived from Kruskal-Wallis test with Dunn's post-hoc test; *p < 0.05.
NA = not applicable

2. Bracket position errors in three group

The mean (95% confidence interval) distance error was 0.06 mm (0.04, 0.07) in the STP group and 0.09 mm (0.07, 0.10) and 0.09 mm (0.07, 0.11) in the MP and MTP groups, respectively (Table 1). The mean distance error was significantly lower in the STP group compared to those the MP and MTP groups (p =.015). The mean height error was 0.10 mm (0.07, 0.13) in the STP group and 0.15 mm (0.12, 0.17) and 0.18 mm (0.14, 0.22) in the MP and MTP groups, respectively. The mean height error was significantly lower in the STP group compared to those in the MP and MTP groups (p =.001). In contrast, the mean depth error was 0.12 mm (0.10, 0.14) in the MP group and 0.23 mm (0.20, 0.25) and 0.26 mm (0.23, 0.29) in the MTP and STP groups, respectively. The mean depth error was significantly lower in the MP group compared to those in the MTP and STP groups ($p < .001$). There were no significant differences in angular errors such as torque, rotation, and tip errors among the three groups ($p > 0.05$).

Table 2. Comparison of linear and angular errors between three groups by tooth

	STP[a]	MTP[b]	MP[c]	p value	Post-hoc test	STP[a]	MTP[b]	MP[c]	p value	Post-hoc test	STP[a]	MTP[b]	MP[c]	p value	Post-hoc test
Variable	Distance (mm)					Height (mm)					Depth (mm)				
Incisor	0.04 (0.02, 0.05)	0.05 (0.03, 0.06)	0.08 (0.06, 0.10)	.021*	a<c	0.14 (0.09, 0.19)	0.11 (0.08, 0.14)	0.15 (0.11, 0.20)	.436	NA	0.18 (0.13, 0.23)	0.18 (0.15, 0.21)	0.09 (0.07, 0.11)	<.001*	a,b>c
Canine	0.11 (0.05, 0.17)	0.14 (0.04, 0.23)	0.09 (0.05, 0.14)	.777	NA	0.08 (0.00, 0.15)	0.13 (0.08, 0.18)	0.14 (0.07, 0.22)	.141	NA	0.24 (0.22, 0.27)	0.24 (0.21, 0.27)	0.08 (0.05, 0.12)	<.001*	a,b>c
Premolar	0.05 (0.03, 0.07)	0.13 (0.10, 0.16)	0.05 (0.03, 0.07)	<.001*	b>a,c	0.04 (0.03, 0.06)	0.23 (0.13, 0.33)	0.08 (0.06, 0.10)	<.001*	b>a,c	0.38 (0.33, 0.42)	0.30 (0.27, 0.33)	0.21 (0.16, 0.25)	<.001*	a>b,c
Molar	0.05 (0.02, 0.08)	0.04 (0.02, 0.06)	0.16 (0.12, 0.21)	<.001*	a,b<c	0.15 (0.06, 0.23)	0.24 (0.13, 0.35)	0.26 (0.19, 0.33)	.112	NA	0.20 (0.15, 0.26)	0.16 (0.10, 0.23)	0.05 (0.02, 0.08)	<.001*	a,b>c
Variable	Torque (°)					Rotation (°)					Tip (°)				
Incisor	2.18 (1.67, 2.68)	1.72 (1.15, 2.29)	2.50 (1.17, 3.83)	.406	NA	2.04 (1.56, 2.53)	1.37 (0.89, 1.85)	2.29 (1.53, 3.06)	.096	NA	2.55 (1.77, 3.32)	2.77 (1.64, 3.91)	2.11 (1.42, 2.79)	.673	NA
Canine	1.51 (0.56, 2.45)	0.96 (0.46, 1.45)	3.26 (1.60, 4.91)	.045*[1]	NA	2.79 (1.22, 4.37)	1.67 (0.62, 2.71)	2.48 (0.78, 4.17)	.496	NA	3.65 (2.06, 5.24)	2.64 (1.45, 3.82)	2.50 (1.50, 3.50)	.285	NA
Premolar	2.44 (1.76, 3.12)	1.92 (1.32, 2.52)	1.98 (1.42, 2.55)	.496	NA	3.07 (2.10, 4.04)	3.12 (2.32, 3.91)	2.01 (1.28, 2.75)	.071	NA	2.22 (1.47, 2.96)	3.00 (2.04, 3.95)	2.17 (1.53, 2.80)	.426	NA
Molar	5.37 (2.13, 8.61)	4.51 (2.26, 6.75)	2.55 (0.65, 4.45)	.144	NA	2.07 (0.97, 3.18)	1.15 (0.32, 1.99)	1.22 (0.26, 2.18)	.229	NA	4.73 (3.11, 6.35)	2.86 (1.69, 4.02)	3.71 (2.51, 4.92)	.153	NA

Incisors, central and lateral incisors; Premolars, 1st and 2nd premolars; Molars, 1st molars. *$p < 0.05$.
Data are given as the means (95% confidence intervals).
[1]All pairwise post-hoc tests were not significant although Kruskal-Wallis test was significant due to the small sample size.

3. Between-group comparison of variables based on tooth position

The mean distance error in premolars was significantly higher in the MTP (0.13 mm) group compared to those in the STP (0.05 mm) and MP (0.05 mm) groups ($p <.001$) (Table 2). The mean height error in the premolars in the MTP group was significantly larger than those in the other groups ($p <.001$). The mean depth error for each tooth group was smallest for the MP group ($p <.001$). The mean depth error in the premolars was 0.21 mm in the STP and MTP groups. The mean depth error for the molars was significantly lower in the MP group [0.05 mm (0.02, 0.08)] compared to the STP (0.20 mm) and MTP groups (0.16 mm) ($p <.001$). There were no significant differences in the angular errors among the three groups in any tooth group (Table 2).

4. Simultaneous analysis of factors affecting bracket error

We conducted an ANOVA, which considered the main effect and primary interaction, to simultaneously analyze the factors affecting the linear and angular errors. We found significant effects of the teeth, group, linear, teeth*group, teeth*linear, and group*linear according to the ANOVA ($p < 0.05$) on the linear error. And we found that teeth, group, angular, teeth*group, and teeth*angular had a significant effect on the angular error (Table 3).

Table 3. Statistical analysis of main effects and first-order interactions using ANOVA in linear and angular errors.

Catergory	Variable	DF	Sum of Squares	Mean squares	F	p value
Linear errorrs	Teeth (incisors, canine, premolars, molars)	3	.240	.080	10.289	<.001
	Group (STP, MTP, MP)	2	.144	.072	9.276	<.001
	Linear (distance, height, depth)	2	.982	.491	63.126	<.001
	Teeth*Group	6	.241	.040	5.174	<.001
	Teeth*Linear	6	.871	.145	18.656	<.001
	Group*Linear	4	.666	.166	21.390	<.001
Angular errors	Teeth (incisors, canine, premolars, molars)	3	56.143	18.714	5.476	.001
	Group (STP, MTP, MP)	2	30.912	15.456	4.522	.011
	Angular (rotation, torque, tip)	2	51.753	25.876	7.571	.001
	Teeth*Group	6	55.831	9.305	2.723	.013
	Teeth *Angular	6	130.855	21.809	6.381	.000
	Group*Angular	4	8.530	2.132	.624	.646

5. Comparison of bracket position errors in three groups

The clinical limit of the linear error in bracket positioning was set between 0.5 mm and 0.3 mm. Significant differences were observed only in depth errors measured as 0.3 mm among the three groups, and the MP group showed a significantly low error. Significant differences were observed in the ratio of depth error (> 0.3 mm) between the three groups (p <.001) (Table 4). The clinical limit of the angular bracket position error was set at 5°. The frequency of angular errors in bracket positioning exceeding 5° ranged from 3.3 to 16.7% in the three groups (Table 5).

Table 4. Frequencies over 0.3 mm and 0.5 mm in linear errors among three groups

Variable		Group			Group		
		>0.3 mm	≤0.3 mm	p value	>0.5 mm	≤0.5 mm	p value
Distance Error	STP	0 (0.0)	60 (100.0)	1.000	0 (0.0)	60 (100.0)	-
	MTP	1 (1.7)	59 (98.3)		0 (0.0)	60 (100.0)	
	MP	0 (0.0)	60 (100.0)		0 (0.0)	60 (100.0)	
Height Error	STP	3 (5.0)	57 (95.0)	.410	1 (1.7)	59 (98.3)	.326
	MTP	7 (11.7)	53 (88.3)		3 (5.0)	57 (95.0)	
	MP	6 (10.0)	54 (90.0)		0 (0.0)	60 (100.0)	
Depth Error	STP	23 (38.3)	37 (61.7)	.001*	1 (1.7)	59 (98.3)	1.000
	MTP	14 (23.3)	46 (76.7)		0 (0.0)	60 (100.0)	
	MP	5 (8.3)	55 (91.7)		0 (0.0)	60 (100.0)	

Data are given as the frequency and percentage. Value: n(%).
p values were derived from chi-square test, *$p < 0.05$.

Table 5. Frequencies over 3˚ and 5˚ in angular errors among three groups

Variable		Group			Group		
		>3°	≤3°	p value	>5°	≤5°	p value
Torque Error	STP	19 (31.7)	41 (68.3)	.257	6 (10.0)	54 (90.0)	.635
	MTP	12 (20.0)	48 (80.0)		4 (6.7)	56 (93.3)	
	MP	19 (31.7)	41 (68.3)		7 (11.7)	53 (88.3)	
Rotation Error	STP	24 (40.0)	36 (60.0)	.176	2 (3.3)	58 (96.7)	.495
	MTP	17 (28.3)	43 (71.7)		5 (8.3)	55 (91.7)	
	MP	15 (25.0)	45 (75.0)		5 (8.3)	55 (91.7)	
Tip Error	STP	23 (38.3)	37 (61.7)	.932	10 (16.7)	50 (83.3)	.364
	MTP	24 (40.0)	36 (60.0)		9 (15.0)	51 (85.0)	
	MP	22 (36.7)	38 (63.3)		5 (8.3)	55 (91.7)	

Data are given as the frequency and percentage. Value: n(%).
p values were derived from chi-square test.

IV. Discussion

This study evaluated the accuracy of 3D-printed IDB trays from various perspectives. As the conventional method of manually fabricating IDB trays showed errors of different patterns in the anterior and posterior teeth (Martorelli et al., 2013). This study evaluated bracket-positioning errors with a split-tray design (STP/MTP) so that the anterior and posterior teeth could be compared separately. Furthermore, these two types of 3D-printed IDB trays were tested to evaluate the errors in bracket positioning.

High levels of intra-rater and inter-rater reliability were observed. We were able to ensure high levels of intra-rater and inter-rater reliability, as this study used the reverse engineering software, which can represent scanned 3D images in voxels and can automatically guide the measuring vertex point on a rectangular column in the bracket slot that was used as the basis of measurement (Fig. 4).

The depth error was slightly higher than the height and distance errors. The depth error in previous CAD/CAM studies ranged from 0.07 to 0.11 mm (Kim et al., 2018a; Shin et al., 2019), which was lower than that observed in this study. This was because previous studies used hard type of trays, which had to be sectioned for each individual tooth to reduce bonding gap between the tooth surface and brackets compared to the one-unit or three-unit soft type of trays used in this study. The depth error in the MP group was 0.12 mm, which was significantly lower than those in the STP and MTP groups, respectively ($p<0.001$), and closer to those reported by previous studies. This was because the MP group used a marker with the 3D-printed model, and the actual brackets were bonded directly to the tooth surface during the fabrication of the trays.

In a previous study on 3D printed IDB trays, the tip error was 0.18 to 4.15° (Duarte et al., 2020). In that study, the placement error of the bracket was measured from the digital model obtained through intraoral scanning process, and the tip and angle errors were measured based on the long axis of the bracket. The intraoral scanner has been improved recently, but it has been reported that the accuracy decreases as the scan range increases (Bohner et al., 2017; Vecsei et al., 2017), and the accuracy may vary depending on the order and starting point of the full arch scan (Müller et al., 2016; Park et al., 2019). Therefore, a model scanner was used to reduce scan errors in this study. In addition, we evaluated the bracket positioning error by merging the reverse engineered bracket library with the 3D scan model (Fig. 2), taking into account the case where the shape of the bracket was distorted or lost during the scanning process. When measuring the displacement of the planned bracket position and the actual bracket position, the four corners of a rectangular object can be the exact reference point of the 3D coordinate system, allowing clear distance and angle measurements. The previous study observed torque errors of 1.99 to 3.36 (Kim et al., 2018a; Shin et al., 2019), while we found a torque error of 3.13 to 2.69° in this study, which was consistent with the previous study results and there was no significant difference between the three groups.

The comparison of the errors among the three groups revealed that values of the height and distance errors were significantly lower in the STP group. The tray manufacturing process was simpler compared to the MP group, and hence, this technique could be applied more effectively in clinical practice. However, indirect bracket bonding of the anterior teeth can be difficult with STP in case of severe crowding.

Adaptation errors that might have occurred while placing the tray onto the teeth may have increased the linear errors. A previous study that used vinyl polysiloxane putty for tray fabrication also found that the linear error, especially the depth error, was higher in the premolars (Grünheid et al., 2016). The depth error was the highest in the premolars in all groups (Table 3). This suggests that the 3D-printed IDB tray may cause some problems in the fit between the tooth surface and brackets on the premolars. A study with conventional IDB trays also showed the highest depth error in premolars.

The angular error showed higher incidence in the molars (Table 3), which was probably influenced by the shape of the molar tube and the anatomical characteristics of the molars. A previous study reported high angular errors in molars (1.67-2.43˚) (Shin et al., 2019),(Grauer and Proffit, 2011), and a study with conventional IDB trays also reported large angular errors in molars (Grünheid et al., 2016).

Certain criteria were applied to the linear and angular errors for frequency analysis. The frequency of depth errors over 0.3 mm in the MP group (8.3%) was significantly lower than those in the STP (38.3%) and MTP groups (23.3%) (p=0.001) (Table 7). The mean depth error was 0.26 mm and 0.23 mm in the STP and MTP groups, respectively. The depth errors in all groups were larger than that reported for the conventional IDB trays (0.08-0.18 mm) (Martorelli et al., 2013). However, the differences in depth errors can be resolved by clinical adjustments.

The linear errors in bracket positioning did not exceed 0.25 mm for the anterior teeth, and the mean linear error did not exceed 0.5 mm in any group. These results suggest that the IDB tray fabricated with CAD/CAM can be applicable in clinical practice. Armstrong et al. reported that a bracket-positioning error over 0.25 mm had a clinical effect on anterior teeth, while error over 0.5 mm had a clinical effect on the posterior teeth (Armstrong et al., 2007). In addition, the model grading system developed by the American Board of Orthodontics noted that discrepancies over 0.5

mm in the alignment and leveling of teeth would result in subtraction of the score in the grading system (Casko et al., 1998). However, the fact that the height error exceeded 0.5 mm in 5% of the total brackets of the MTP group placed in this experiment suggests that the 3D-printed IDB tray causes difficulties in the uniform positioning of all brackets in the patient's dentition. Therefore, in order to prevent these bracket position errors, it is necessary to carefully evaluate not only the suitability of the tray for the patient's actual dentition, but also whether the bracket is well seated on the tray.

The angular errors in bracket positioning were analyzed for 3˚ and 5˚ of cut-off angulations. However, a previous study (Grünheid et al., 2016) reported that an angulation error of less than 2˚ was clinically acceptable, and that a crown-tip inadequacy of 2° causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar. Actually, we set 3° as the minimum cut-off angulation, because mean angular errors were close to under 3˚ in all groups. The frequency of the bracket angulation errors over 3˚ ranged from 20-40% and those over 5˚ from 3.3-16.7% among the groups. A tip change of 6.7˚ could cause a difference of 0.5 mm in the marginal ridge, if the mean tooth width was set and calculated as 8 mm by engineering calculation. Therefore, further research for defining the cut-off point is needed to study the relationship between tip errors and marginal discrepancy considering clinical situations such as wire-bracket play and size of the teeth.

The frequency of torque errors over 5˚ was 10% in the STP group and 6.7% and 11.7% in the MTP and MP groups, respectively. However, torque errors would have little impact on the final occlusion if the play between the wire and bracket were to be considered. The wire-bracket play is 7.24˚ assuming that a 0.19 x 0.25-inch wire is placed in the 0.22 slot (Arreghini et al., 2014).

Bracket bonding errors vary depending on the type of the scanner and 3D printer (Kim et al., 2018b). These errors may be influenced by the knowledge and skill of the operator using the CAD/CAM software. The study was limited to a laboratory investigation of dental models without crowding. Recently, Kim et al. reported the differences in the accuracy of bracket position in posterior teeth with different cusp heights by 3D-printed IDB trays (Kim et al., 2018b). Therefore, a diverse range of shapes and sizes of different teeth needs to be considered for evaluating the accuracy and clinical performance of 3D-printed IDB trays. Moreover, the suitability of 3D-printed IDB trays for prosthetic crowns, which can be affected by various printing conditions and materials, needs to be studied in the future.

V. Conclusion

1. Errors in bracket positioning differed significantly among the three groups. The linear errors, height (0.10 mm) and distance errors (0.06 mm), were significantly lower in the STP group, and the depth error (0.12 mm) was significantly lower in the MP group ($p < 0.05$).

2. The angular error did not differ significantly for the three tray groups, with respect to torque, rotation, and tip errors. However, the angular errors in molars were larger than those in other teeth and were within a range that could be overcome during clinical procedures.

The CAD/CAM-based IDB tray is clinically applicable, considering the linear and angular errors. We recommend IDB trays fabricated using the STP method due to the low frequency of bracket-positioning errors and ease of fabrication.

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국문요약

3차원 출력 방식 트레이를 이용하여 클리닉에서 제작 가능한 교정 간접 부착 시스템의 정확성

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유 성 훈

이 연구는 tray-printing method (TP) 및 marker-model printing method (MP)를 사용하여 클리닉에서 제작된 IDB 트레이의 브라켓 위치 정확도를 평가하고 비교하는 것을 목표로 하였다. TP group 은 3D 소프트웨어를 사용하여 제작된 트레이의 분할 여부에 따라 두 그룹 [single-tray printing (STP) 및 multiple-tray printing (MTP)]으로 나누었다. 세 그룹의 실험군 각각에 대해 5 개의 복제된 상악 석고모델을 사용하였고, 제 2 대구치를 제외한 총 180 개의 인공 치아를 평가하였으며, 모델 스캐너(E3; 3Shape Dental Systems, Copenhagen, Denmark)를 이용하여 치아 모델을 스캔하였다. 삼차원 소프트웨어를 이용

하여 치아의 FA point 에 가상 브라켓을 위치시키고 IDB 트레이를 디자인하였으며, 3D 프린터(VIDA; EnvisionTEC, MI, USA)를 사용하여 트레이를 출력하였다. 브라켓의 위치 정확성은 3D 분석을 사용하여 소프트웨어 상에서 계획된 브라켓 위치와 실제 브라켓 위치를 비교하여 평가하였다. ANOVA 를 이용하여 main effects 와 first-order interaction effect 를 분석하였다.

평균 거리 오차는 STP 그룹에서 0.06 mm, MP 및 MTP 그룹에서 0.09 mm 를 보였다. 평균 높이 오차는 STP 그룹에서 0.10 mm, MP 및 MTP 그룹에서 각각 0.15 mm 및 0.18 mm 이였다. 평균 거리 및 높이 오차는 MP 및 MTP 그룹보다 STP 그룹에서 유의성 있게 낮은 결과를 보였다 ($p < 0.05$). 그러나 세 그룹 간의 각도 오차에서는 유의성 있는 차이가 관찰되지 않았다 ($p > 0.05$).

CAD(computer-aided design)과 3D 프린터를 이용한 in-office IDB 시스템은 선형 및 각도 오류를 고려하였을 때, 임상적으로 적용이 가능하다. 본 연구 결과, 브라켓 위치 오류 빈도가 낮고 제작이 용이한 STP 방법을 사용하여 제작된 IDB 트레이를 임상에 적용하는 것을 권장한다.

핵심이 되는 말: 3 차원 출력된 트레이, 간접 브라켓 부착, 브라켓 부착 오류