Precision and trueness of dental models manufactured by different 3D printers

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Precision and trueness

of dental models manufactured

by different 3D printers

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D.D.S., M.S.D., Ph.D.)

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감사의 글

부족한 저를 아낌 없는 지도와 따뜻한 격려로 끝까지 이끌어주신 차정열 교수님께 진심으로 감사드립니다. 그리고 바쁘신 와중에도 귀한 시간을 내주시고 조언을 주신 백형선 교수님, 부족한 논문에 대한 가르침을 주신 황충주 교수님, 논문 실험에 대한 소중한 조언을 주신 정휘동 교수님, 논문을 꼼꼼히 살펴주시고 조언을 주신 신유석 교수님께 감사를 드립니다. 또한 연세대학교에서 교정학을 공부할 기회를 주신 김경호 교수님, 유형석 교수님, 이기준 교수님, 정주령 교수님, 최윤정 교수님, 최성환 교수님께 깊이 감사드립니다.

논문 실험에 많은 조언과 도움을 주신 신성환 팀장님과 연세대학교 교정과 의국 선생님들, 그리고 동고동락해 온 동기 신설희에게 감사의 마음을 전합니다.

한결같은 사랑으로 응원해주신 부모님께 감사드리고 늘 옆에서 힘이 되어주는 남편과 부족한 엄마에게 더 큰 사랑을 베풀어주는 딸 혜준이와 이 기쁨을 함께 하고 싶습니다.

2017 년 6 월 저자 씀

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ABSTRACT

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The aim of this study was to assess the precision and trueness of dental models printed with three-dimensional (3D) printers via different printing techniques, with a view to the potential clinical use of 3D printing models. Digital reference models were printed five times using the stereolithography apparatus (SLA), digital light processing (DLP), fused filament fabrication (FFF), and PolyJet technique. The 3D-printed models were scanned and evaluated for tooth, arch, and occlusion measurements. Precision and trueness were analyzed with root mean squares (RMS) for the differences in each measurement. The differences among models that had been repeatedly printed from the same 3D printer were compared to determine precision, and the differences between the reference dental model and the dental models printed from 3D printers were obtained to determine trueness. Statistical analysis was performed using one-way analysis of variance ($\alpha = 0.05$). The following results were obtained:

1. Except in trueness of occlusion measurements, there were significant differences in all measurements among the four techniques ($p < 0.001$).

2. For overall tooth measurements, the DLP (76 ± 14 µm) and PolyJet (68 ± 9 µm) techniques exhibited significantly different mean RMS values of precision from the SLA (88 ± 14 µm) and FFF (99 ± 14 µm) techniques ($p < 0.05$). For overall arch measurements, the SLA (176 ± 73 µm) technique exhibited significantly different RMS values of precision from the DLP (74 ± 34 µm), FFF (89 ± 34 µm), and PolyJet (69 ± 18 µm) techniques ($p < 0.05$). For occlusion measurements, the FFF (170 ± 55 µm) technique exhibited significantly different RMS values of precision from the SLA (94 ± 33 µm), DLP (120 ± 28 µm), and PolyJet (96 ± 33 µm) techniques ($p < 0.05$).

3. There were significant differences in mean RMS values of trueness of overall tooth measurements among all four techniques: SLA (107 ± 11 µm), DLP (143 ± 8 µm), FFF (188 ± 14 µm), and PolyJet (78 ± 9 µm; $p < 0.05$). For overall arch measurements, the SLA (141 ± 35 µm) and PolyJet (86 ± 17 µm) techniques exhibited significantly different mean RMS values of trueness from DLP (469 ± 49 µm) and FFF (409 ± 36 µm) techniques ($p < 0.05$).

The 3D printing techniques exhibited significant differences in precision of all measurements and in trueness of tooth and arch measurements. The PolyJet and DLP techniques were more precise than the FFF and SLA techniques, with the PolyJet technique exhibiting the highest accuracy.

Key words: 3D digital model, 3D printer, computer-aided design, model measurement, precision, trueness

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I. INTRODUCTION

Advances in digital technology and manufacturing have brought about rapid changes in dentistry. In particular, three-dimensional (3D) printing technology, which is considered by the most advanced technology of the 21st century, is expected to transform the manufacturing industry overall, as it shortens manufacturing lead time, reduces required costs, and allows printing of items with complex structures. Thus, it has already been implemented in dentistry to manufacture clear orthodontic aligners, implant surgical templates, orthognathic surgical wafers, and temporary crowns.[1,2]

3D printers produce three-dimensional structures based on 3D-design data. 3D printing is an additive manufacturing process, where materials are added layer upon layer to produce an object, as opposed to reductive manufacturing, where material is subtracted to produce the object. Rapid prototyping (RP) is another term for this process. In 2009, the American Society for Testing and Materials (ASTM) International F42 Committee divided 3D printing technologies depending on the type of material used (i.e., liquid-based, powder-based, solid-based). Liquid-based printing produces a component by instantly curing the material with laser or strong ultraviolet rays, and photocurable resins are most widely used for this type of printing. Powder-based printing heats and combines fine plastic or metal powder or sand. Solid-based printing heats and melts thermoplastic materials, such as wires or filaments, and layers the extruded materials.[3]

Recently, scanning technology has been proposed to convert plaster models or impressions into 3D digital models.[4] Previous studies that examined the trueness of intraoral scanning have reported that, despite the lower accuracy of digital models as compared to plaster models, digital models are clinically acceptable and are good alternatives to plaster models.[5-12] However, physical models are still required; there are some limitations to the fabrication of devices in the absence of physical models. If the digital models that are produced via intraoral scanning could be printed with a 3D printer to fabricate a physical model, several steps of the traditional model-manufacturing process could be omitted, shortening the lead time and facilitating the production of multiple copies without distortion of shapes.[13]

3D-printed models could also be utilized for fabricating orthodontic appliances. Martorelli et al. fabricated customized, clear, and removable orthodontic appliances by printing a dental model using a PolyJet 3D printer.[14] In addition, several studies have also printed orthodontic devices directly from a 3D printer. As early as 2006, Ciuffolo et al. fabricated a tray for indirect bracket bonding via RP for clinical usage[15], and recently, a retainer has been manufactured using a selective laser sintering (SLS) 3D printer [16] and a virtual wafer has been produced using a stereolithography apparatus (SLA) 3D printer.[2]

In order to utilize 3D-printed dental models for clinical purposes, the trueness of the printed outcome must be ensured. Thus far, the precision of 3D-printed outcomes falls short of those produced via computer numerical control (CNC) processing as a reductive manufacturing process, and in some cases, 3D-printed products require post-processing to ensure smooth surfaces.[17] Therefore, the types and features of 3D printers should be considered for appropriate application in orthodontics.

Although many studies have analyzed the trueness of digital models produced by intraoral scanners, only a few studies have validated the trueness of 3D-printed models. Hazeveld et al. have fabricated dental models using three types of RP and measured the size of the teeth by means of digital calipers, to assess the trueness of the models.[18] They measured only the mesiodistal width and heights, and not the buccolingual width; however, the width of teeth is also influenced by the method of polymerization and printing, which may affect the fit of individualized trays or orthodontic appliances. Murugesan et al. manufactured dental models using three types of RP and measured the teeth using digital calipers to compare the accuracies of the models.[19] Both studies used digital calipers for measuring teeth, which may have resulted in measurement errors, because it is difficult to find a reference point on the tooth surface. Furthermore, they printed each model from each printer once only, and compared the accuracies among models printed by different printers. To address the above shortcoming of these studies, the present study established a reference point on the teeth and used 3D software for measurements to validate precision and trueness of dental model fabricated by 3D printers.

Precision is the closeness of the results of repeatedly printed dental models, and trueness is the closeness of a dental model to a true value (ISO 5725-1). The greater the precision, the more predictable is the measurement. A high trueness value is close to or equal to the actual dimensions of the measured object.[20]

The purpose of this study was to analyze the precision and trueness of dental models manufactured using four types of 3D printers. The null hypothesis was that there would be no significant differences between 3D-printed models fabricated by different 3D printing techniques in precision and trueness.

II. MATERIAL AND METHODS

Manufacturing of the Reference Dental Model

1. Selection of Dental Model and 3D Scanning

We chose one set of typodont (D13pp-TR.1, Nissin, Kyoto, Japan) that includes 14 maxillary and 14 mandibular permanent teeth. The dental models were scanned using Trios® (3Shape Dental Systems, Copenhagen, Denmark), a 3D intraoral scanner with a precision of ± 20 μm. Each model was scanned from the buccolingual side to the base. Additionally, the left and right molar bite models were scanned, and all of the scanned files were converted to digital files and saved in stereolithography (STL) format (Fig 1). An .stl file is a format used by stereolithography software to generate information needed to produce 3D models on stereolithography machines by rapid prototyping processes.[16]

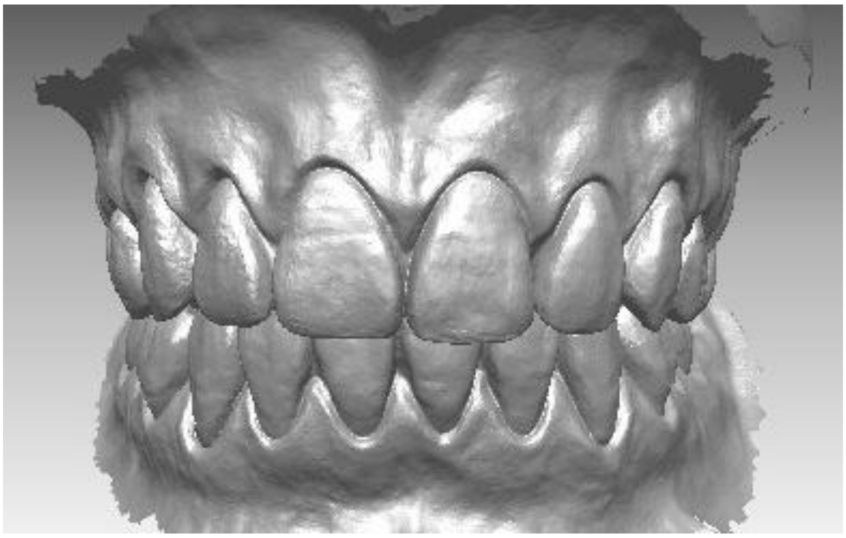


Fig 1. 3D digital model scanned with a 3D intraoral scanner.

2. Reference Dental Model Design

The 3D digital model produced by scanning the typodont was converted to a computer-aided design (CAD) model using Rapidform 2006 (INUS Technology, Inc., Seoul, Korea), a 3D modeling software (Fig 2).

A. Reference dental model base design

As the 3D digital model produced by scanning the typodont is in an open form, a base was established and the inner area was filled to allow printing of the typodont scan using a 3D printer.

B. Half-ball marker design and placement

To standardize the measurement, half-ball markers were placed on the 3D digital model as the reference points. The half-ball markers have a diameter of 1.0 mm and were placed in the following positions:

(1) The dentogingival junction of the line vertical to the occlusal plane at the central point of the incisal edge of the incisors, buccal cusp tip of the canine, or mesiobuccal cusp tip of the first molar (n = 24).

(2) 3 mm to the gingiva from the dentogingival junction (n = 24).

(3) Half-ball markers were placed in the same locations of (1) and (2) for the lingual side as well (n = 48).

(4) One-half point of the clinical crowns of the maxillary and mandibular first molars and left incisors (n = 6).

A total of 102 half-ball markers were placed on the buccolingual side of one maxillary and mandibular model set as reference markers.

C. Reference dental model notch design

To clarify the relative positions of the models for occlusions, semicircular cylinder-shaped notches of 2.0 mm diameter were placed at the base of each of the upper and lower central incisors and the left and right second molars.

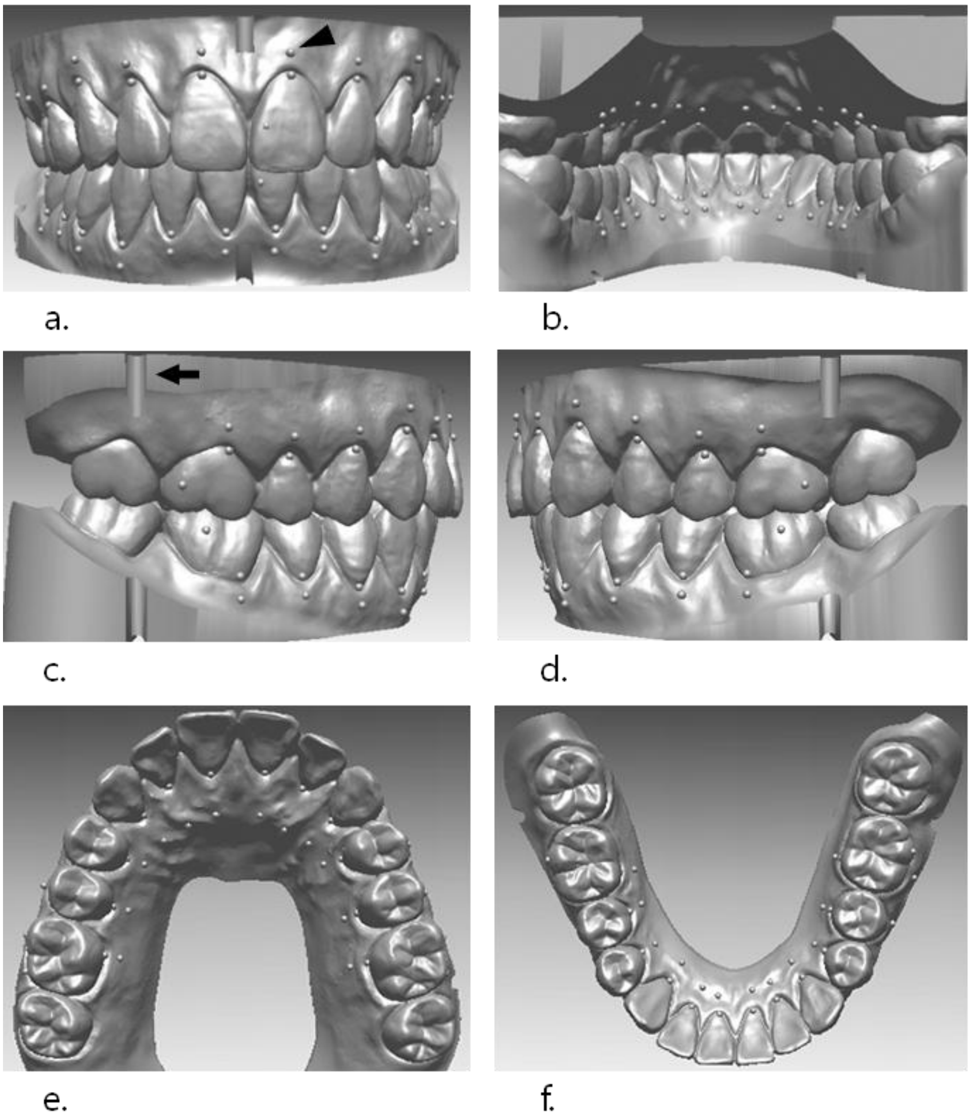


Fig 2. Computer-aided design images of half-ball markers and notches in dental models.

a, Frontal view (arrowhead: half-ball markers); b, Palatal view;

c, Right view (arrow: notches); d, Left view;

e, Upper occlusal view; f, Lower occlusal view.

3. 3D Printing

In 2009, the ASTM International F42 Committee classified 3D printing technologies into seven categories: vat photopolymerization, material extrusion, binder jetting, material jetting, direct energy deposition, power bed fusion, and sheet lamination. Among the seven types of printing techniques, we selected a printer using a stereolithography apparatus (SLA) technique (ZENITH®, DENTIS, Daegu, Korea), a printer using the digital light processing (DLP) technique (M one, MAKEX TECHNOLOGY, Zhejiang, China), a printer using the fused filament fabrication (FFF) technique (Cubicon 3DP-110F, HyVISION SYSTEM, Gyeonggi-do, Korea), and a printer using the PolyJet technique (Objet Eden 260VS, Stratasys, Ltd., Eden Prairie, MN, USA). The STL files of the reference model were printed with these four printers, five times per printer (Table 1).

Table 1. Descriptions of the 3D printers used in this study

Categories	Additive manufacturing process		3D printers	XY resolution	Layer thickness	Print time
Vat photopolymerization	An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.	stereolithography apparatus (SLA)	ZENITH	50 µm	50 µm	4 h and 5 min
		digital light processing (DLP)	M one	70 µm	75 µm	1 h and 35 min
Material Extrusion	An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.	fused filament fabrication (FFF)	Cubicon 3DP-110F	100 µm	100 µm	2 h and 30 min
Material Jetting	An additive manufacturing process in which droplets of build material are selectively deposited.	PolyJet	Objet Eden 260V	1600 dpi	16 µm	1 h and 47 min

Summarized from standard terminology for additive manufacturing technologies (http://www.astm.org/FULL_TEXT/F2792/HTML/F2792.htm)

A. Stereolithography apparatus technique

A UV laser is projected onto liquid, photopolymer resin in a vat to induce a photopolymerization reaction, selectively curing the material for layering (Fig 3). The temperature was set to 10–15 ℃ and humidity to 40 %, and photocurable resin was used. The model was printed with an XY resolution of 50 μm and a layer thickness of 50 μm, and the print time for one maxillary and mandibular pair model was 4 h and 5 min.

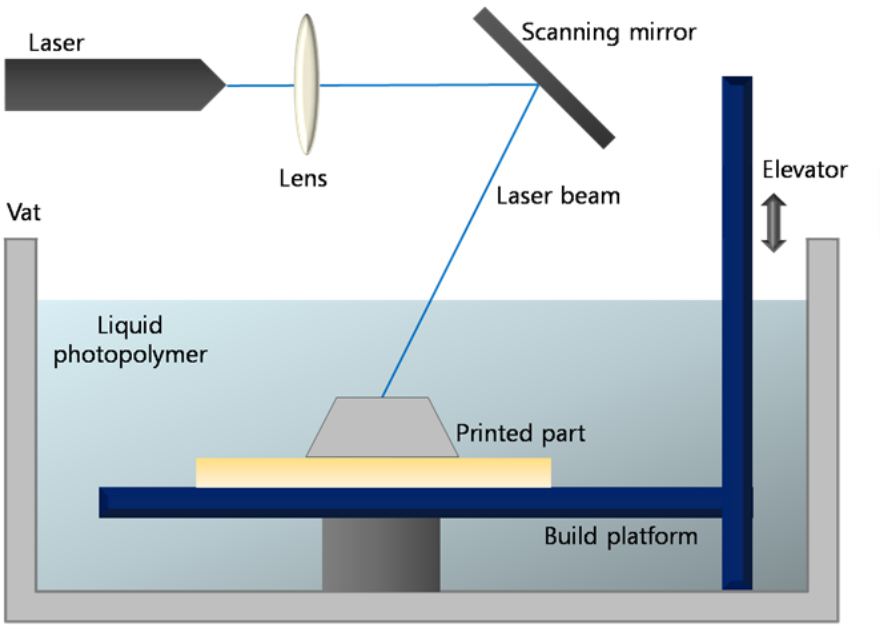


Fig 3. Stereolithography apparatus technique.

B. Digital light processing technique

Visible light was projected onto the vat filled with liquid, photopolymer resin in the form of the desired outcome, to cure and layer the resin (Fig 4). The temperature was set to 22 ℃ and humidity to 20 %, and the photocurable resin was used. The model was printed with a resolution of 70 µm and layer thickness of 75 µm, and the print time for one maxillary and mandibular pair model was 1 h and 35 min.

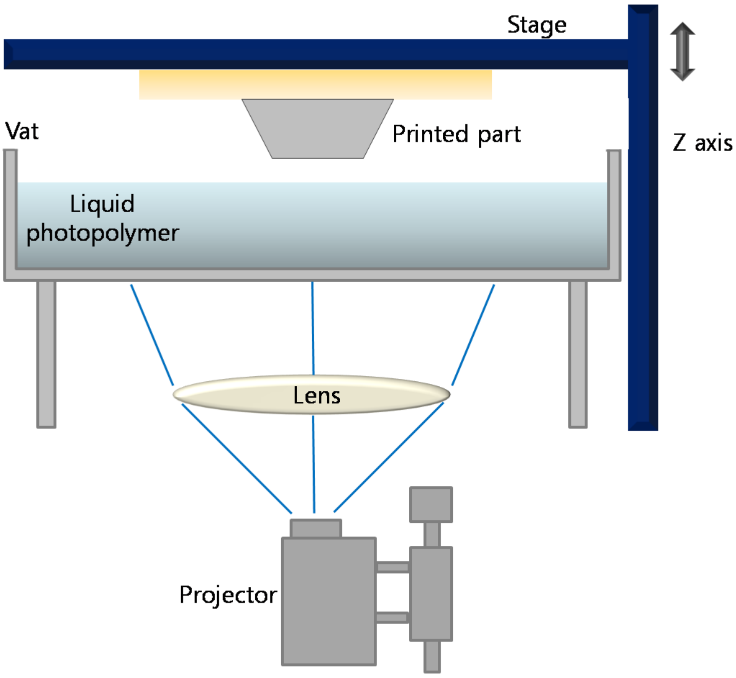


Fig 4. Digital light processing technique.

C. Fused filament fabrication technique

Fused filament fabrication (FFF) technique consists of a movable head which deposits a thread of molten medical grade acrylonitrile butadiene styrene (ABS) material on the substrate.[19] Filament-type ABS resin was selectively heated to 240 ℃ and extruded through a nozzle with a diameter of 0.4 mm, after which it was printed in the correct position, layer upon layer (Fig 5). The layer thickness was set to 100 μm, and the print time for one maxillary and mandibular pair model was 2 h and 30 min.

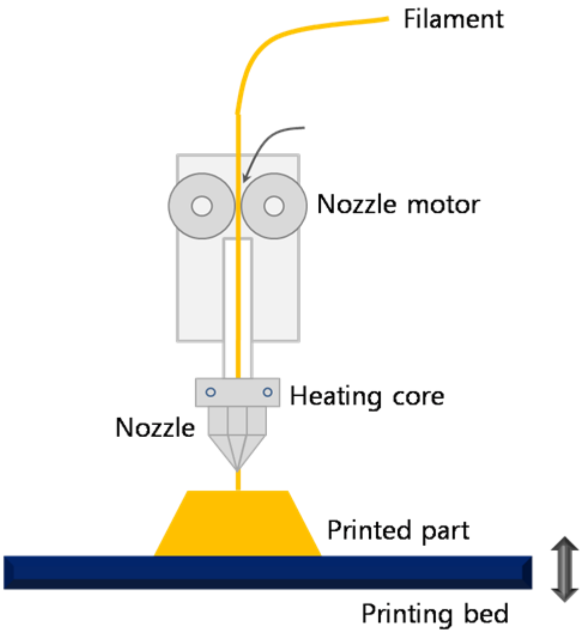


Fig 5. Fused filament fabrication technique.

D. PolyJet technique

A CAD-3D .stl file is virtually sectioned in 16-µm thick layers using the system software. A print head, composed of hundreds of micro jetting heads, injects a 20-µm thick layer of resin on the build tray only in the areas that correspond to the cross-sectional profile previously prepared, and leave the rest of the area free of resin. Simultaneously, the resin is cured with UV light, and each layer is adjusted to 16 µm by a roller that is moved across the build tray immediately after deposition. The repeated addition and solidification of resin layers produces a solid 3D model in acrylic (Fig 6).[21] The temperature was set to 21 ℃ and humidity to 30 %, and the material used was photocurable resin. The models were printed with a resolution of 1600 dpi and a layer thickness of 16 µm, and the print time for one maxillary and mandibular pair model was 1h and 47min.

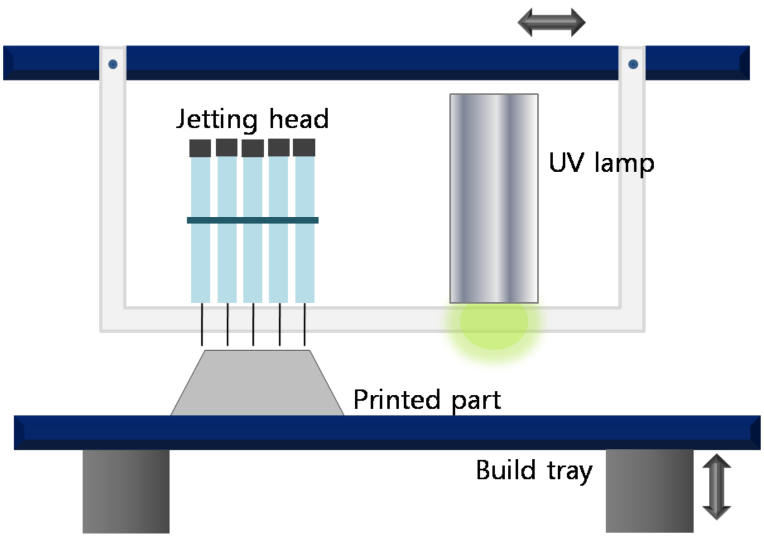


Fig 6. PolyJet technique.

4. 3D-Printed Model Scanning

The 3D-printed models were scanned using an Identica Hybrid (MEDIT, Seoul, Korea), which is a scanner with a precision of ± 7 µm that uses blue light-emitting diode (LED) light; the scanned models were saved as STL files (Fig 7). The maxillary and mandibular models were first scanned separately. To scan the occlusion model, the two models were put together and the designed notch was tied with a elastics, after which the left and right molar, canine, and central incisor areas were scanned. The dental model that was printed via the DLP technique was scanned after applying a scan spray to prevent light from being reflected on the material.

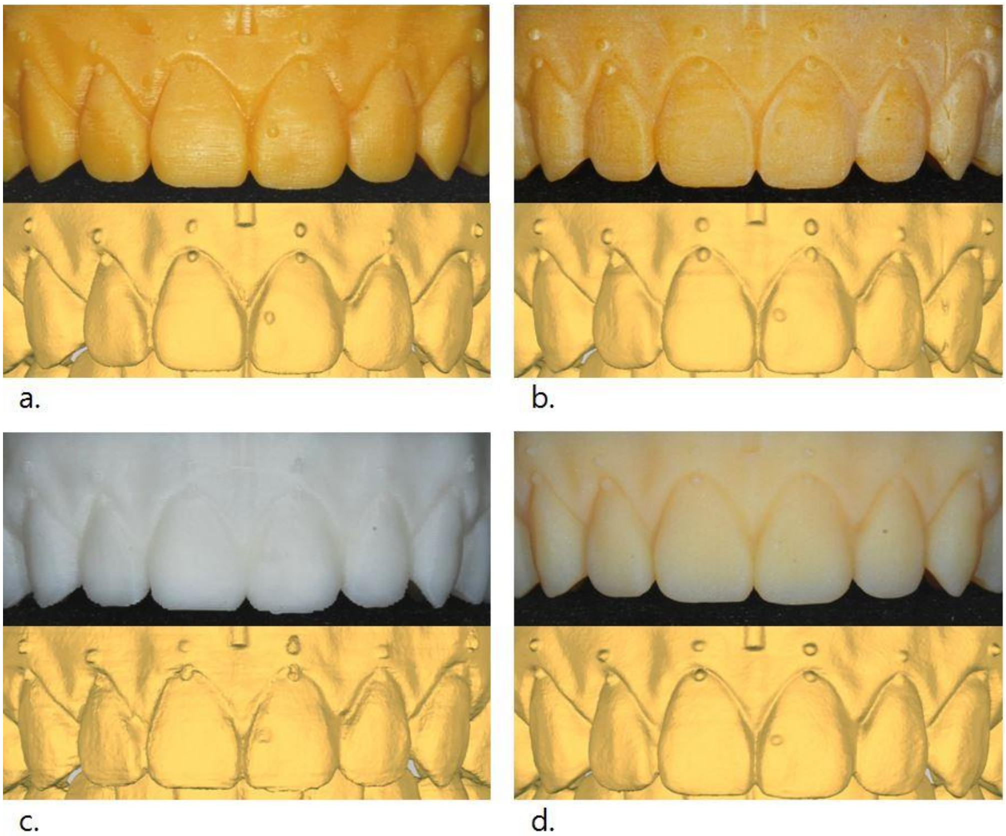


Fig 7. 3D-Printed dental upper models (top) and scanned stereolithographic files (bottom).

a, Stereolithography apparatus technique;

b, Digital light processing technique;

c, Fused filament fabrication technique;

d, PolyJet technique.

Measurement

1. Linear measurements

Using the STL files for the scanned models, we measured the mesiodistal width, buccolingual width of the reference points, buccolingual width, and vertical crown height for each tooth, from the right first molar to the left first molar, as well as the intercanine width and intermolar width (Table 2). To increase the precision of measurement, 3D-inspection software (Geomagic Control; 3D Systems, Rock Hill, SC, USA) was used. If a half-ball marker represented the measurement point, measurement was made with reference to the center of the half-ball.

A total of 2,782 pieces of raw data were collected: types of 3D printers, including the reference model (n = 5), number of repeated prints (n = 5), number of teeth measured for one model pair (n = 24), dimensions of teeth (n = 4), dimensions of arch (n = 4), and dimensions of occlusion measurements (n = 7). All models were measured twice, in 1-week intervals.

Table 2. Linear measurements used in this study

Label		Description
Tooth measurements	Mesiodistal width (Fig 8)	Distance between mesial and distal center of contact area
	Buccolingual width of reference points (Fig 9)	Distance from buccal to lingual cervical half-ball markers
	Buccolingual width (Fig 10)	Parallel buccolingual distance of the arch in the cross section
	Vertical crown height (Fig 11)	Distance from the reference cervical plane to the incisal edge or cusp tip
Arch measurements	Intercanine width (Fig 12)	Distance between canine cervical half-ball markers
	Intermolar width (Fig 12)	Distance between the first molar cervical half-ball markers

Unit: mm.

A. Tooth measurements

To measure the mesiodistal width, we first formed a reference plane by connecting the three half-ball markers that were placed at the half-way point of the clinical crown heights of the first molars and right central incisors (Fig 8a). Then, the mesiodistal width was measured by measuring the distance between the points perpendicular from the mesiodistal contact points to the reference plane (Fig 8b).

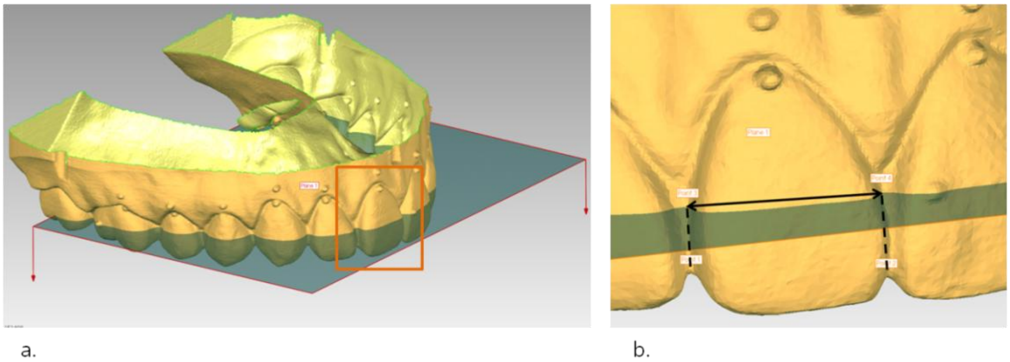


Fig 8. Tooth measurements: mesiodistal width (mm). a, The reference plane (red box) was formed by connecting the three half-ball markers placed in the half-way position of the clinical crown height of the first molars and left incisors; b, Mesiodistal width of the right central incisor (orange box) was measured as the distance between the mesial and distal center of the contact areas, parallel to the reference plane.

The buccolingual width of the reference points was determined by measuring the distance between the half-ball markers at the buccal cervix and lingual cervix (Fig 9).

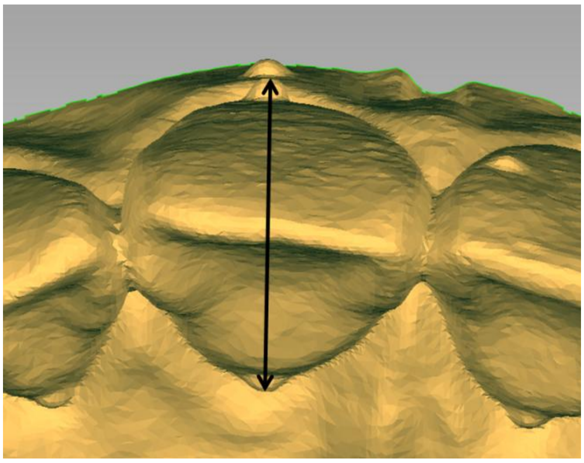


Fig 9. Tooth measurements: buccolingual width of reference points (mm). Buccolingual width of reference points was measured as the distance from the buccal to lingual cervical half-ball markers.

Buccolingual widths were measured by using the section through object function of the Geomagic control to obtain a cross-section of the dental model, using the reference plane. The reference plane was formed by connecting the three half-ball markers that were placed at the half-way point of the clinical crown heights of the first molars and right central incisors (Fig 10).

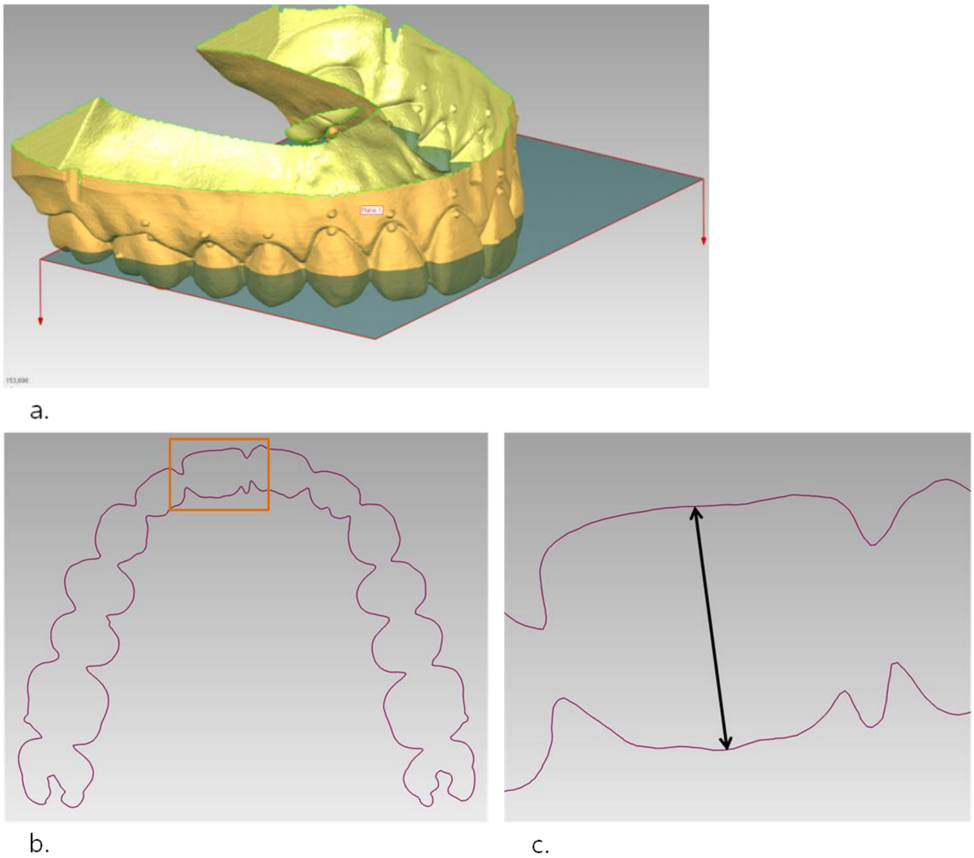
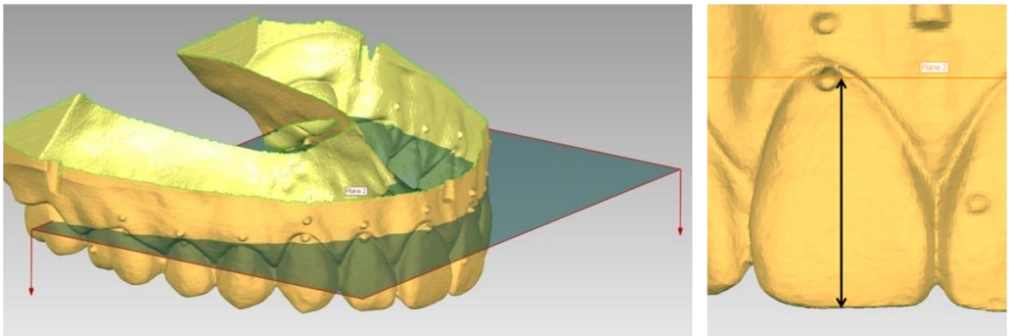


Fig 10. Tooth measurements: buccolingual width (mm). a, The reference plane (red box) was formed by connecting the three half-ball markers placed in the half-way position of clinical crown height of the first molars and left incisors; b, Two-dimensional section obtained by using the section through object function of Geomagic control; c, The buccolingualwidth of the right central incisor (orange box) was measured as the parallel buccolingual distance of the arch in the cross section.

To measure vertical crown height, we measured the incisal edge or cusp tip of teeth on the same reference plane, to quantify vertical change. The reference plane was created by connecting the three ball markers placed in the cervical area of the first molars and the central incisors in each model (Fig 11).



a. b.

Fig 11. Tooth measurements: vertical crown height (mm). a, The reference plane(red box) is created by connecting the three half-ball markers in the cervical area of the first molar and the left central incisor. Then, we measured the incisal edges or cusp tips of teeth on the same reference plane in order to validate vertical height of crown. b, Vertical crown height was measured as the distance from the reference cervical plane to the incisal edge or cusp tip.

B. Arch measurements

Intercanine width was defined as the distance between the canine cervical half-ball markers, and intermolar width was defined as the distance between the cervical half-ball markers of the first molars (Fig 12).

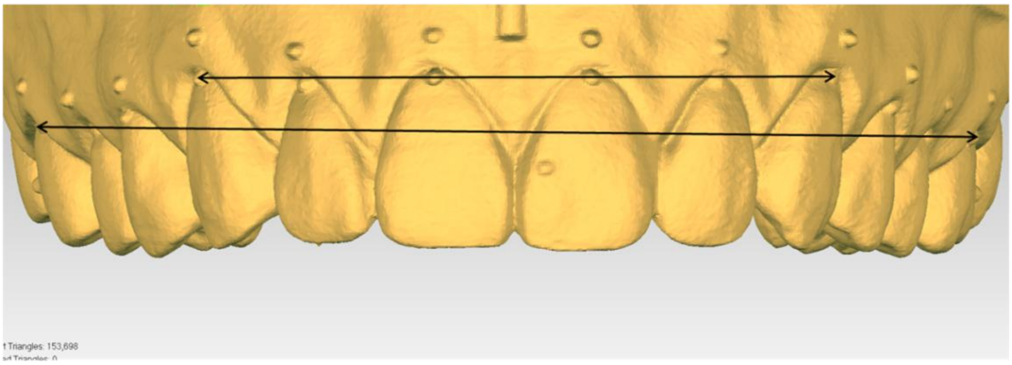


Fig 12. Arch measurements: intercanine width (mm) and intermolar width (mm). Intercanine width was measured as the distance between the canine cervical half-ball markers. Intermolar width was measured as the distance between the first molar cervical half-ball markers.

2. Occlusion Measurements

The interarch distance and occlusion contact volume of the 3D-printed models were measured using Geomagic control and were compared to those of the reference model.

The maxillary and mandibular models were occluded by the union function of the Geomagic Control software, and the interarch distances between the half-ball markers of the left and right central incisors, canines, and first molar cervixes on the maxillary and mandibular models were measured (Fig 13).

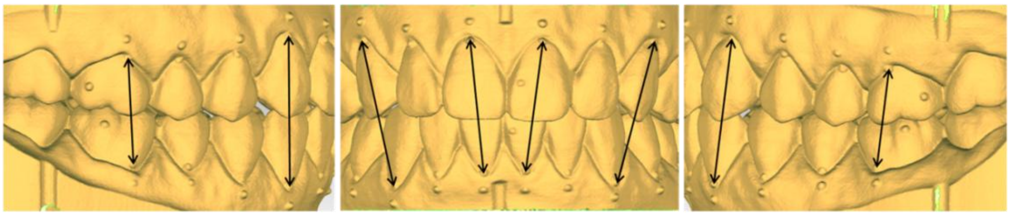


Fig 13. Interarch measurements (mm). Interarch measurements were measured as the distances between half-ball markers in the cervical area of the central incisors, canines and the first molars.

In addition, the boolean operation was used to extract and measure the volume of the occlusion contact area (Fig 14).

Fig 14. Occlusion contact volume (mm^3). Occlusion contact areas were subtracted and extracted by Boolean operation.

a, 3D upper dental model showing the intersection areas (red line);

b, 3D lower dental model showing the intersection areas (red line);

c, Occlusal contact areas extracted with the Boolean operation imbedded in Geomagic control.

Calculation

1. Root mean square

For each variable of tooth and arch measurements, root mean square (RMS) values were calculated with respect to precision and trueness. The overall RMS values of tooth, arch, and occlusion variables were also calculated using the following formula:

$$\mathrm{RMS} = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^{n} (x_{ref} - x_i)^2},$$

where x_{ref} is the measurement of the reference model, x_i is the measurement of the test model being compared, and n is the total number of measurements.

2. Precision and trueness

Dimensional differences in tooth, arch, and occlusion measurements among the 3D-printed and digital reference models were computed for precision and trueness.

A. Precision

The 3D-printed models, which were repeatedly printed (five times from the same printer, for all four types of printers), were combined to make10 pairs to determine the differences in RMS of the lengths and volumes (n = 10).

B. Trueness

The differences in the RMS of the lengths and volumes between the five pairs of models printed from the same 3D printer and the reference model were analyzed (n = 5).

Statistical Analysis

We calculated the means and standard deviations of the 20 RMS that were calculated based on the type of 3D printer (n = 4) and number of prints (n = 5). One-way ANOVA was conducted to compare the precision and trueness of the four types of 3D printers. Then, Tukey's honest significant difference (HSD) post-hoc test was performed.

Additional analysis was performed for teeth measurements. The intraclass correlation coefficient (ICC) was calculated to examine the agreement of the dental models printed via four types of printing techniques with the reference model. Furthermore, the teeth were divided into three groups—incisors, premolars, and molars—to calculate the RMS of the discrepancies between the tooth groups and reference model. One-way ANOVA was conducted to compare the inter-tooth group differences in each of the four types of printing techniques. Thereafter, Tukey's HSD post-hoc test was performed. The repeatability of the measurements was examined by calculating the ICC between two measurements taken at 1-week intervals.

All statistical analyses were performed using SPSS Statistics 21.0 software (IBM SPSS Inc., Chicago, IL,USA). The level of significance, α, was set to 0.05.

III. RESULTS

All measurements were taken twice in 1-week intervals to examine the repeatability of the measurement. The ICC between the two sets of measurements was very high, at 0.998 (95 % confidence interval [CI], 0.998186–0.998478). The specific results for each variable are stated below.

1. Tooth Measurements

A. Precision of tooth measurements

The means and standard deviations of the RMS for the twenty dental models printed from four different types of 3D printers were calculated (Table 3, Fig. 15). There were significant differences in the mesiodistal width, buccolingual width of the reference points, buccolingual width, and vertical crown height among the four different printing techniques ($p < 0.05$). For overall tooth measurements, the precision of the DLP and PolyJet techniques were significantly different from the SLA and FFF techniques ($p < 0.05$). The model printed via the PolyJet technique had the highest precision, followed by those produced using the DLP, SLA, and FFF techniques, with mean RMS of 68 μm, 76 μm, 88 μm, and 99 μm, respectively.

Table 3. Mean (± SD) root mean square (RMS) values and comparison of RMS values of precision for tooth measurements and overall discrepancies of 3D-printed dental models

	RMS (μm)				
	SLA	DLP	FFF	PolyJet	*p* value
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
MD	$102 \pm 14_{B}$	$82 \pm 15_{A}$	$100 \pm 25_{B}$	$83 \pm 18_{A}$	.031*
rBL	$93 \pm 25_{B}$	$61 \pm 14_{A}$	$92 \pm 14_{B}$	$44 \pm 8_{A}$	.000*
BL	$96 \pm 17_{B}$	$79 \pm 36_{A,B}$	$85 \pm 25_{A,B}$	$64 \pm 10_{A}$	.039*
VCH	$54 \pm 13_{A}$	$74 \pm 22_{A}$	$109 \pm 27_{B}$	$72 \pm 20_{A}$	.000*
Overall	$88 \pm 14_{B,C}$	$76 \pm 14_{A,B}$	$99 \pm 14_{C}$	$68 \pm 9_{A}$	.000*

MD, mesiodistal width; rBL, Buccolingual width of reference points; BL, buccolingual width; VCH, vertical crown height, RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A,B,C The same subscripts indicate no significance difference between the indicated group in row;

* $p < 0.05$.

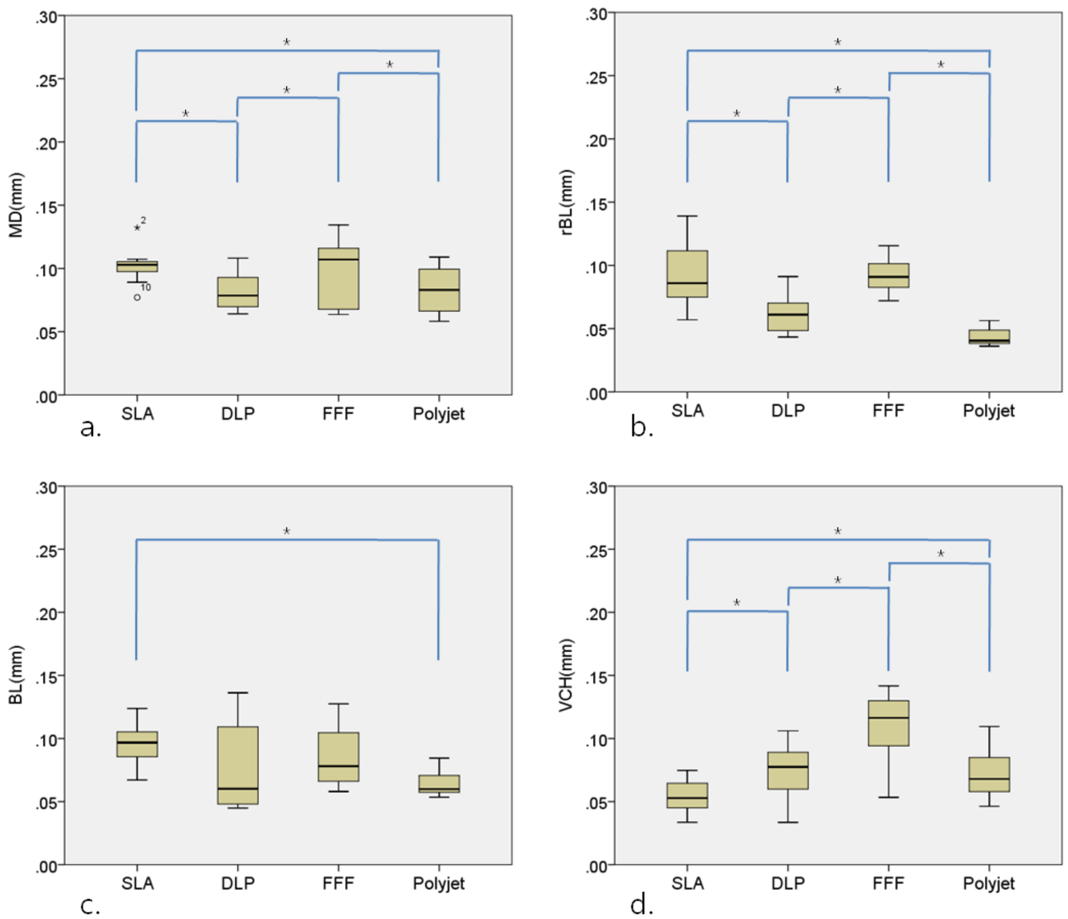


Fig 15. Boxplot of precision for tooth measurements of 3D-printed dental models. X axis: 3D priner, Y axis: root mean square discrepancies of tooth measurements.

a, Mesiodistal width (MD) of 3D-printed dental models;

b, Buccolingual width of reference points (rBL) of 3D-printed dental models;

c, Buccolingual width (BL) of 3D-printed dental models;

d, Vertical crown height (VCH) of 3D-printed dental models.

SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

* $p < 0.05$.

B. Trueness of tooth measurements

The means and standard deviations of the RMS for the dental models printed from four different types of 3D printers were calculated (Table 4, Fig. 16). Although there was no significant difference in the mesiodistal width in terms of the printing technique used (p > 0.05), there were significant differences in the buccolingual width of the reference points, buccolingual width, and vertical crown height (p < 0.05). For overall tooth measurements, there were significant differences in the trueness among all four techniques (p < 0.05). The trueness of all tooth measurements was the highest in the models printed using the PolyJet technique, followed by the SLA, DLP, and FFF techniques, with mean RMS of 78 μm, 107 μm, 143 μm, and 188 μm, respectively.

Table 4. Mean (± SD) RMS values and comparison of RMS values of trueness for tooth measurements and overall discrepancies of 3D-printed dental models

	RMS (μm)				
	SLA	DLP	FFF	PolyJet	p value
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
MD	$93 \pm 16_{A}$	$102 \pm 11_{A}$	$108 \pm 21_{A}$	$83 \pm 11_{A}$	.097
rBL	$131 \pm 18_{B}$	$210 \pm 17_{C}$	$231 \pm 16_{C}$	$44 \pm 6_{A}$	.000*
BL	$99 \pm 20_{A,B}$	$123 \pm 19_{B,C}$	$150 \pm 14_{C}$	$90 \pm 17_{A}$	.000*
VCH	$100 \pm 15_{A}$	$108 \pm 8_{A}$	$230 \pm 36_{B}$	$83 \pm 27_{A}$	.000*
Overall	$107 \pm 11_{B}$	$143 \pm 8_{C}$	$188 \pm 14_{D}$	$78 \pm 9_{A}$	.000*

MD, mesiodistal width; rBL, Buccolingual width of reference points; BL, buccolingual width; VCH, vertical crown height, RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A,B,C,D The same subscripts indicate no significance difference between the indicated group in row;

* p < 0.05.

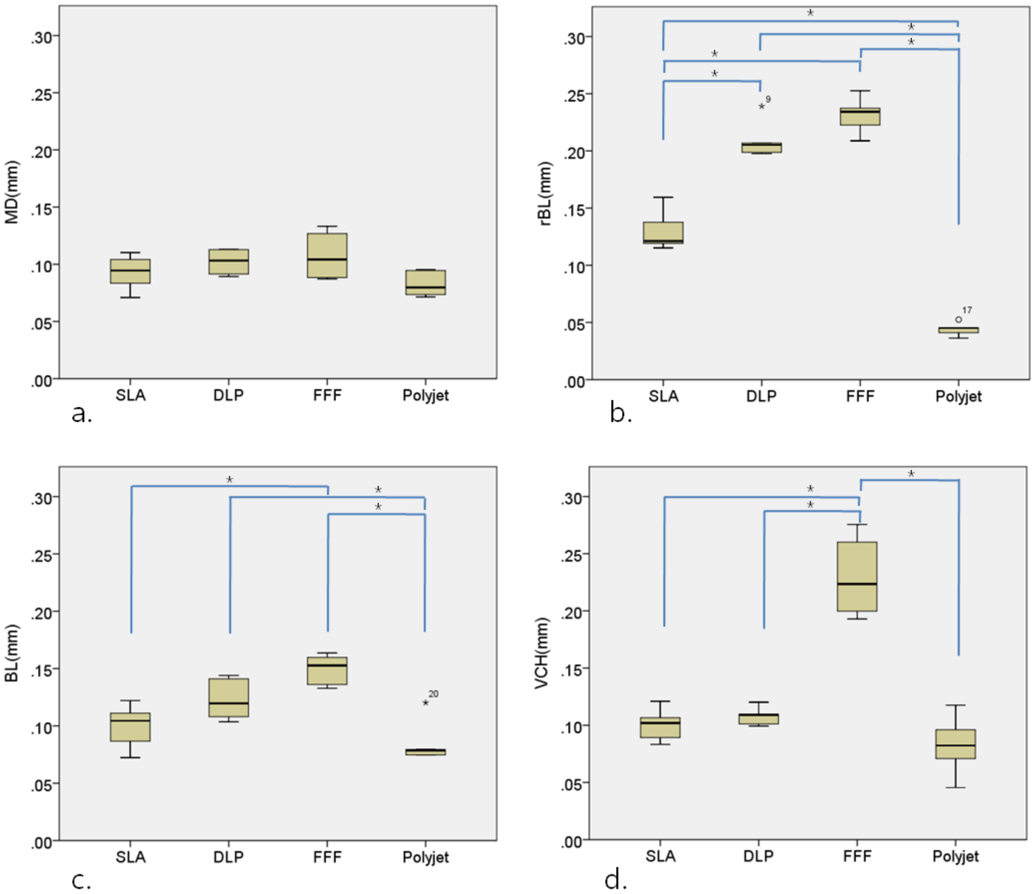


Fig 16. Boxplot of trueness for tooth measurements of 3D-printed dental models. X axis: 3D priner, Y axis: root mean square discrepancies of tooth measurements.

a, Mesiodistal width (MD) of 3D-printed dental models;

b, Buccolingual width of reference points (rBL) of 3D-printed dental models;

c, Buccolingual width (BL) of 3D-printed dental models;

d, Vertical crown height (VCH) of 3D-printed dental models.

SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

* $p < 0.05$.

C. Agreement of tooth measurements

We analyzed the agreement of each individual tooth measurement between the reference dental model and the 3D-printed models and found a minimum ICC of 0.987 (95 % CI: 0.951–0.991), indicating a high level of agreement (Table 5). Although there was little difference in terms of printing techniques or measurement dimensions, the vertical crown heights measured—compared to other measurements—in the dental models printed via the FFF technique had relatively low agreement with the reference model.

Table 5. Reliability Analysis for tooth measurements of 3D-printed dental models

		ICC (95% CI)			
Measurements	Model	SLA	DLP	FFF	PolyJet
MD	1	0.997 (0.993-0.999)	0.997 (0.992-0.999)	0.995 (0.988-0.998)	0.998 (0.996-0.999)
	2	0.998 (0.996-0.999)	0.997 (0.993-0.999)	0.995 (0.989-0.998)	0.996 (0.991-0.998)
	3	0.998 (0.996-0.999)	0.998 (0.994-0.999)	0.997 (0.993-0.999)	0.998 (0.995-0.999)
	4	0.997 (0.992-0.999)	0.997 (0.993-0.999)	0.997 (0.993-0.999)	0.998 (0.995-0.999)
	5	0.996 (0.992-0.998)	0.997 (0.994-0.999)	0.997 (0.993-0.999)	0.998 (0.995-0.999)
rBL	1	0.998 (0.996-0.999)	0.999 (0.999-1.000)	0.998 (0.996-0.999)	1.000 (0.999-1.000)
	2	0.999 (0.997-0.999)	0.999 (0.997-0.999)	0.998 (0.996-0.999)	0.999 (0.998-1.000)
	3	1.000 (0.999-1.000)	0.999 (0.998-1.000)	0.999 (0.997-0.999)	1.000 (0.999-1.000)
	4	0.998 (0.994-0.999)	0.999 (0.998-1.000)	0.999 (0.997-0.999)	1.000 (0.999-1.000)
	5	0.998 (0.997-0.999)	0.999 (0.997-0.999)	0.998 (0.996-0.999)	1.000 (0.999-1.000)
BL	1	0.999 (0.997-0.999)	0.999 (0.998-1.000)	0.999 (0.998-1.000)	1.000 (0.999-1.000)
	2	0.999 (0.998-1.000)	0.999 (0.999-1.000)	1.000 (0.999-1.000)	1.000 (0.999-1.000)
	3	1.000 (0.999-1.000)	0.999 (0.999-1.000)	1.000 (0.999-1.000)	1.000 (0.999-1.000)
	4	0.999 (0.998-1.000)	0.999 (0.998-1.000)	0.999 (0.997-1.000)	1.000 (0.999-1.000)
	5	0.999 (0.997-0.999)	0.998 (0.995-0.999)	1.000 (0.999-1.000)	1.000 (0.999-1.000)
VCH	1	0.999 (0.998-1.000)	0.995 (0.989-0.998)	0.978 (0.951-0.991)	0.999 (0.998-1.000)
	2	0.998 (0.995-0.999)	0.998 (0.995-0.999)	0.988 (0.972-0.995)	0.999 (0.997-0.999)
	3	0.999 (0.998-1.000)	0.997 (0.993-0.999)	0.990 (0.978-0.996)	0.999 (0.999-1.000)
	4	0.999 (0.998-1.000)	0.995 (0.988-0.998)	0.985 (0.967-0.994)	0.998 (0.996-0.999)
	5	0.998 (0.997-0.999)	0.995 (0.989-0.998)	0.992 (0.981-0.996)	0.997 (0.994-0.999)

MD, mesiodistal width; rBL, Buccolingual width of reference points; BL, buccolingual width; VCH, vertical crown height, CI, confidence interval, SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication.

D. Tooth group-specific trueness

In a given dental model, teeth of similar size were classified into incisors, premolars, and molars, and calculated the RMS against the measurements in the reference model for each tooth group (Table 6). There was a significant difference among the tooth groups in the mesiodistal width and vertical crown height measurements in the DLP technique ($p < 0.05$), and a significant difference among the tooth groups in the mesiodistal width, buccolingual width of the reference points, and vertical crown height measurements in the FFF technique ($p < 0.05$). There were no significant inter-tooth group differences in all variables in the models printed using the SLA and PolyJet techniques ($p > 0.05$).

Table 6. Mean (± SD) RMS values and comparison of RMS values for tooth measurements of dental models divided by three groups

		RMS (μm)			
		SLA	DLP	FFF	PolyJet
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
MD	Anterior teeth	86 ± 18	96 ± 13[b]	98 ± 16[a]	82 ± 23
	Premolars	64 ± 23	60 ± 12[a]	80 ± 26[a]	70 ± 24
	Molars	126 ± 71	164 ± 17[c]	160 ± 38[b]	90 ± 32
	p value	.124	.000*	.002*	.508
rBL	Anterior teeth	127 ± 17	215 ± 29	246 ± 20[b]	38 ± 8
	Premolars	130 ± 19	193 ± 13	225 ± 16[a,b]	45 ± 8
	Molars	139 ± 33	224 ± 6	196 ± 20[a]	54 ± 20
	p value	.741	.061	.004*	.211
BL	Anterior teeth	123 ± 46	129 ± 27	149 ± 25	93 ± 35
	Premolars	76 ± 18	113 ± 15	145 ± 15	73 ± 7
	Molars	103 ± 13	121 ± 26	156 ± 10	76 ± 17
	p value	.080	.545	.596	.364
VCH	Anterior teeth	99 ± 19	104 ± 22[a]	298 ± 51[b]	88 ± 41
	Premolars	109 ± 22	92 ± 12[a]	136 ± 22[a]	73 ± 19
	Molars	81 ± 15	138 ± 18[b]	112 ± 35[a]	71 ± 30
	p value	.114	.005*	.000*	.655

MD, mesiodistal width; rBL, Buccolingual width of reference points; BL, buccolingual width; VCH, vertical crown height, RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

a,b,c The same subscripts indicate no significance difference between the indicated group in column; * $p < 0.05$.

2. Arch Measurements

A. Precision of arch measurements

The precision of maxillary and mandibular intercanine width and intermolar width were examined, based on the RMS values (Table 7). The precisions of all arch measurements were significantly different depending on the type of printing technique used ($p < 0.05$). In particular, the overall precision of arch measurements was considerably higher in models printed using the DLP, FFF, and PolyJet techniques (mean RMS: 74 μm, 89 μm, and 69 μm, respectively) as compared to those printed via the SLA technique (mean RMS: 176 μm).

Table 7. Mean (± SD) RMS values and comparison of RMS values of precision for arch measurements and overall discrepancies of 3D-printed dental models

		RMS (μm)				
		SLA	DLP	FFF	PolyJet	*p* value
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Mx	ICW	$114 \pm 83_{B}$	$34 \pm 27_{A}$	$92 \pm 76_{A}$	$84 \pm 48_{A}$	.046*
	IMW	$148 \pm 89_{B}$	$53 \pm 39_{A}$	$74 \pm 47_{A}$	$47 \pm 32_{A}$	.001*
Mn	ICW	$106 \pm 63_{B}$	$58 \pm 35_{A}$	$32 \pm 20_{A}$	$21 \pm 23_{A}$	.001*
	IMW	$245 \pm 146_{B}$	$95 \pm 87_{A}$	$102 \pm 56_{A}$	$73 \pm 40_{A}$	.001*
Overall		$176 \pm 73_{B}$	$74 \pm 34_{A}$	$89 \pm 34_{A}$	$69 \pm 18_{A}$	.000*

Mx, maxillary; Mn, mandibular; ICW, intercanine width; IMW, intermolar width; RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A,B The same subscripts indicate no significance difference between the indicated group in row;

* $p < 0.05$.

B. Trueness of arch measurements

The trueness of the maxillary and mandibular intercanine width and intermolar width were examined, based on RMS values (Table 8). The trueness of all arch measurements were significantly different depending on the type of printing technique used ($p < 0.05$). In particular, the overall trueness of arch measurements was considerably higher in the models printed via the SLA and PolyJet techniques (mean RMS: 141 µm and 86 µm, respectively) than in those printed using the DLP and FFF techniques (mean RMS: 469 µm and 409 µm, respectively).

Table 8. Mean (± SD) RMS values and comparison of RMS values of trueness for arch measurements and overall discrepancies of 3D-printed dental models

		RMS (µm)				
		SLA	DLP	FFF	PolyJet	*p* value
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Mx	ICW	$123 \pm 52_A$	$389 \pm 30_B$	$345 \pm 82_B$	$62 \pm 37_A$	.000*
	IMW	$138 \pm 79_A$	$446 \pm 46_B$	$307 \pm 61_B$	$74 \pm 39_A$	.000*
Mn	ICW	$74 \pm 44_A$	$373 \pm 48_B$	$533 \pm 26_B$	$65 \pm 21_A$	.000*
	IMW	$176 \pm 66_A$	$622 \pm 89_B$	$404 \pm 81_B$	$106 \pm 58_A$	.000*
Overall		$141 \pm 35_A$	$469 \pm 49_B$	$409 \pm 36_B$	$86 \pm 17_A$	.000*

Mx, maxillary; Mn, mandibular; ICW, intercanine width; IMW, intermolar width; RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A,B The same subscripts indicate no significance difference between the indicated group in row;

* $p < 0.05$.

3. Occlusion measurements

A. Precision of occlusion measurements

The precision of interarch distances between the left and right first molars, canines, and central incisors and occlusion contact volume were examined, based on RMS values (Table 9). The mean RMS of the interarch distances in the SLA, DLP, and PolyJet techniques were 94 μm, 120 μm, and 96 μm, respectively, but that in the FFF technique was significantly higher, at 170 μm ($p < 0.05$). The precision of occlusion contact volume was significantly higher in the models printed via the DLP technique (mean RMS: 0.006 mm^3) than that in the SLA, FFF, and PolyJet techniques (mean RMS: 0.083 mm^3, 0.281 mm^3, and 0.110 mm^3, respectively; $p < 0.05$).

Table 9. Mean (± SD) RMS values and comparison of RMS of precision for interarch distance and occlusal contact volume discrepancies of 3D-printed dental models

	RMS (μm, mm^3)				
	SLA	DLP	FFF	PolyJet	*p* value
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Interarch distance	$94 \pm 33_A$	$120 \pm 28_A$	$170 \pm 55_B$	$96 \pm 33_A$	.000*
Occlusion contact volume	$0.083 \pm 0.064_B$	$0.006 \pm 0.002_A$	$0.281 \pm 0.345_B$	$0.110 \pm 0.079_B$	.014*

RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A,B The same subscripts indicate no significance difference between the indicated group in row;

* $p < 0.05$.

B. Trueness of occlusion measurements

The trueness of interarch distances between the left and right first molars, canines, and central incisors and occlusion contact volume were examined, based on RMS values (Table 10). There were no significant differences in the trueness of any occlusion measurements according to the printing technique used ($p > 0.05$).

Table 10. Mean (± SD) RMS values and comparison of RMS of trueness for interarch distance and occlusal contact volume discrepancies of 3D-printed dental models

	RMS (μm, mm^3)				
	SLA	DLP	FFF	PolyJet	*p* value
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Interarch distance	$237 \pm 15_A$	$260 \pm 46_A$	$241 \pm 53_A$	$208 \pm 21_A$	.215
Occlusion contact volume	$56 \pm 51_A$	$9 \pm 6_A$	$143 \pm 295_A$	$167 \pm 94_A$	.370

RMS, root mean square; SD, standard deviation; , SLA, stereolithography apparatus; DLP, digital light processing; FFF, fused filament fabrication;

A The same subscripts indicate no significance difference between the indicated group in row.

IV. DISCUSSION

The aim of this study was to analyze the precision and trueness of dental models fabricated by four types of 3D printers. Our findings rejected the null hypothesis that there would be no significant differences between the 3D-printed models produced by these printers in precision and trueness.

The repeatability of the measurements in this study was very high, with an ICC value of 0.998, and the agreement of tooth measurements in dental models printed from the four types of 3D printers was also very high, with ICC values ranging from 0.978 to 1.000. In general, it is difficult to find a clear reference point on a tooth surface for taking tooth measurements; therefore, we designed 1.0-mm half-ball markers to place on the cervical area of tooth surface as reference points and used as a standard of measurements. These reference points are presumed to have produced the high agreements in repeated measurements and tooth measurements per se. Salmi et al. also reported a high repeatability of measurements in a model measured using a 10.0-mm reference point.[22] Furthermore, half-ball markers placed on the tooth surface were also used as reference points for establishing a reference plane, with which a cross-section of a dental model was established to measure the buccolingual width. To examine the actual vertical differences in dental models printed from different types of 3D printers, another reference plane was created to measure the vertical crown heights. Moreover, measurement of mesiodistal widths of crowns is susceptible to error due the vertical differences in the measurement points. In order to reduce the measurement errors, this study measured the distance between the points perpendicular from the mesiodistal contact points to the reference plane.

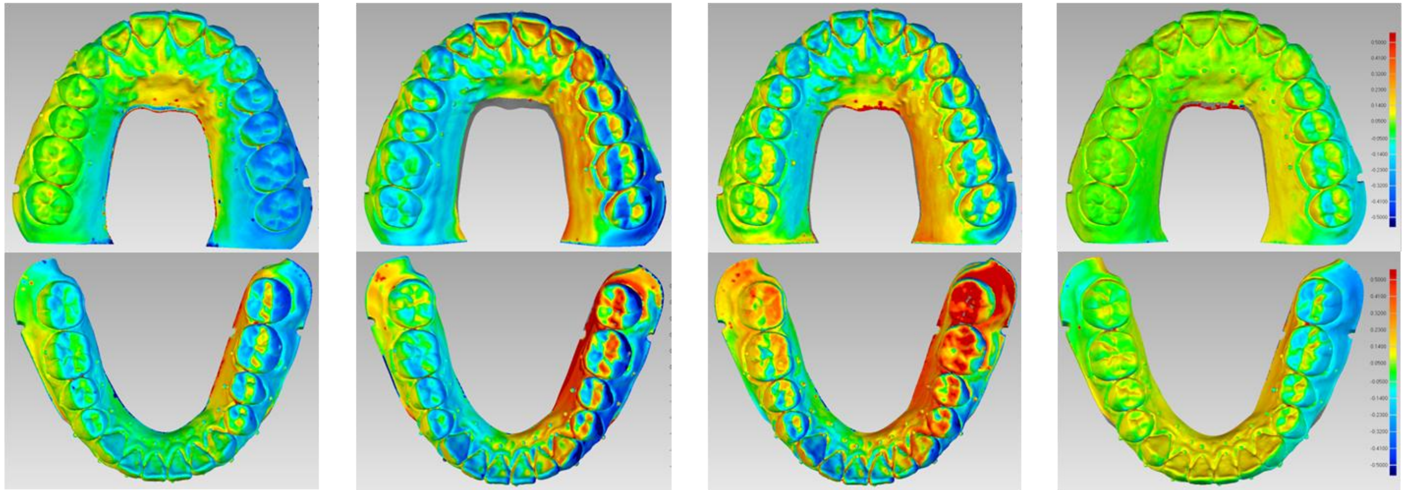
Several previous studies have compared the accuracies of dental models printed from different types of 3D printers. Hazeveld et al. compared dental models printed from 3D printers using the PolyJet, DLP, and three-dimensional printing (3DP) techniques. They found that clinical crown heights in the dental models printed using the PolyJet, DLP, and 3DP printers were −0.02 mm, 0.04 mm, and 0.25 mm, respectively, and the differences in the mesiodistal width were −0.08 mm, −0.05 mm, and −0.05 mm, respectively.[18] Another study that fabricated dental models using three different types of 3D printers reported that trueness was the highest for the PolyJet technique, followed by 3DP and FFF, with dimensional errors of 0.133 %, 1.67 %, and 1.73 %, respectively.[19] In this study, the trueness of tooth measurements was highest for the PolyJet, followed by the SLA, DLP, and FFF techniques, with mean RMS 78 μm, 107 μm, 143 μm, and 188 μm, respectively.

In previous studies, differences (mm) or dimensional errors (%) in measurement were employed for comparison of 3D printing techniques. Differences in measurements alternate between positive and negative values. Addition of these values for determining differences or dimensional errors will result in the error being smaller than the actual value because of the positive and negative values being offset. Therefore, we used RMS values in this study in order to represent the offset error more accurately. Consequently, the present findings are not directly comparable to those of previous studies.

Moreover, a study that compared 3D skull models printed via the SLS, 3DP, and PolyJet techniques suggested that models printed with the PolyJet printer had the smallest dimensional error, followed by those printed with the 3DP and SLS printers.[22] In another study, which printed mandibular models using the SLS, 3DP, and PolyJet techniques, dimensional error was smallest for the SLS, followed by the PolyJet and 3DP techniques.[21] Results pertaining to the trueness of 3D printers may differ due to different sizes of print outcomes, the 3D printing environment, manufacturing conditions of 3D printers, and research methods used.

In particular, the findings of this study indicated that the range of measurement dimensions may influence the trueness of 3D printers. This was evident when we compared the arch widths and interarch distances with the tooth measurements. In this study, the mean RMS for tooth measurements in the PolyJet, SLA, DLP, and FFF techniques were 78 µm, 107 µm, 143 µm, and 188 µm, respectively. The mean RMS for arch widths were 86 µm, 141 µm, 469 µm, and 409 µm, respectively, and those for interarch distance were 208 µm, 237 µm, 260 µm, and 241 µm, respectively. In other words, the mean RMS for arch widths and interarch distances were always greater than those for tooth measurements, regardless of the type of 3D printer used. This is also shown in the comparison of 3D printer models to the reference models, based on the half-ball markers (Fig 17), which implies that size of the measurement dimension influences the trueness of 3D printers. When we compared tooth measurements by classifying the teeth into incisors, premolars, and molars, the mesiodistal width of the molars was significantly larger than that of the incisors and premolars in the DLP and FFF printing techniques, supporting the above notion. However, not all tooth measurements were significantly different, presumably because tooth measurement variables are markedly smaller than arch width or interarch distance.

Given that no prior studies had analyzed the precision of 3D-printed dental models, this study repeatedly printed the reference model to compare the precision in the four types of



a. b. c. d.

Fig 17. Colored presentation of superimposed 3D digital models for each 3D printer.

a, Superimposition between reference dental models and dental models printed using stereolithography apparatus technique;

b, Superimposition between reference dental models and dental models printed using digital light processing technique;

c, Superimposition between reference dental models and dental models printed using fused filament fabrication technique;

d, Superimposition between reference dental models and dental models printed using polyJet technique.

3D printers. In this study, the precision of tooth measurements was the highest in the dental models printed via the PolyJet technique, followed by those printed via the DLP, SLA, and FFF techniques, with mean RMS of 68 µm, 76 µm, 88 µm, and 99 µm, respectively. In addition, the precision of arch measurements was the highest in the PolyJet technique, followed by the DLP, FFF, and SLA techniques, with mean RMS of 69 µm, 74 µm, 89 µm, and 176 µm, respectively. Although the SLA technique had a higher trueness than the DLP technique for both the tooth measurements and arch measurements, it had lower precision in the measurements. Dental models printed via a 3D printer are fabricated by slicing a model in several layers and adding layer by layer. Because the SLA technique completes a layer by projecting a laser beam and curing line by line, it is prone to error caused by the mirror that moves the laser beam and is also slow. On the other hand, the DLP technique uses a projector to cure the material layer by layer, which reduces the error associated with repeated printing, and is also faster. Therefore, the SLA technique, which involves lower XY resolution and smaller layer thickness, was more accurate than the DLP technique, but was less precise than the DLP technique, due to the differences in the manufacturing technique.

Sweeney et al. quantified the trueness of occlusion and defined that an interarch distance, with an error of less than 0.5 mm compared to the gold standard, is a successful occlusion. The range of error (< 0.5 mm) was determind based on the clinical validity and the standard set by the American Board of Orthodontics' increments for grading plaster models.[23] In the present study, the mean RMS values of all interarch distances were between 208 and 260 µm, which were all within an error of 0.5 mm, suggesting that the occlusion of the 3D-printed models are clinically acceptable. There were also no significant differences among different manufacturing techniques. Furthermore, although occlusion contact volumes did not differ significantly, depending on the manufacturing technique, further studies are needed for confirmation, as no such studies have previously been performed.

When scanning the models, we applied scan spray to DLP-printed models due to their high reflection of light. Although we were able to apply a thin coating by using a spray, as opposed to powder, which improved the quality of scan, it must be noted that the DLP results reflect error arising from the thickness of the scan spray. For reference, a prior study that compared three spray systems suggested that all of them were clinically acceptable, with thicknesses of 25.3 μm, 18.9 μm, and 19.2 μm.[24]

There has been no study that examined whether the discrepancies of 3D-printed models to the reference model are clinically acceptable. It has only been suggested that the differences in dimensions between the reference model and 3D-printed models did not affect their clinical applications.[13,25] Furthermore, it has been suggested that a dimension difference of 0.3 mm in dental models is adequately accurate for orthodontic purposes.[26] however, clinical standards for assessing the trueness of dental models should be changed depending on the method of treatment. In this context, the dental models printed via the four types of printing techniques in the present study may be used for orthodontic purposes, but additional studies are required to assess their clinical efficacy.

The increased availability of oral scanners in clinics will also expand the scope of applications of 3D-printed dental models for fabricating orthodontic appliances. Hence, differences in measurements that occur in these 3D-printed dental models will affect the accuracy of the fabricated orthodontic appliance. Martorelli et al. reported that aligners fabricated using dental models manufactured from a CNC milling machine have better fit and stimulate more rapid tooth movement than aligners fabricated from 3D-printed dental models[14], however, this study did not measure the differences between the two dental models, and could not perform a quantitative assessment of the fabricated aligners. Invisalign aligners comprise several aligners, with the maximum tooth movement in each aligner ranging from 0.25 to 0.3 mm.[27] Thus, the difference in the trueness of dental models must be smaller than 0.25–0.3 mm for the fabricated aligner to exert an orthodontic force on the teeth. An aligner fabricated based on a model printed via the FFF technique (mean RMS: 188 μm) would not have the desired orthodontic force as compared to one fabricated based on a model printed using the PolyJet technique (mean RMS: 78 μm), and thus would not be able to induce precise tooth movement, ultimately influencing the treatment outcome. Therefore, the findings of this study indicate that 3D printers should be selected based on the desired trueness and precision required for the specific orthodontic appliance.

Furthermore, while some studies fabricated trays or retainers for indirect bonding by means of 3D printers, none of the existing studies have examined the trueness of the printed devices.[15,16] Thus, follow-up studies are needed to assess the trueness of 3D-printed orthodontic appliances quantitatively.

This study did not compare models printed with equal resolutions. This study selected 3D printers that are clinically applicable for diagnostic and manufacturing purposes, and whose print time ranges from 2-4 hours per maxillary or mandibular model; that is, this study evaluated the models based on print times that are clinically applicable. Hence, resolutions were set according to the print time generally used. We could not use equal layer thickness, XY resolution, and manufacturing environments for all printers, which limits the generalization of the findings of this study as absolute standards for comparison of 3D printers.

Different types of 3D printing techologies incur different costs. It costs 10 EUR per model to print via the PolyJet tehcnique, while it costs 1 EUR to print a plaster model using the FFF technique, which is associated with RepRap (open source).[13] Since the first introduction of 3D printers in 1986, 3D-printing technology and materials have continuously advanced. Further progressin technology will reduce the high costs of 3D printing, which is one of the greatest drawbacks of 3D printers. Costs, in addition to the trueness of outcome, should also be considered when using 3D printers.

V. CONCLUSION

1. Except in trueness of occlusion measurements, there were significant differences in all measurements among the four techniques ($p < 0.001$).

2. For overall tooth measurements, the DLP (76 ± 14 μm) and PolyJet (68 ± 9 μm) techniques exhibited significantly different mean RMS values of precision from the SLA (88 ± 14 μm) and FFF (99 ± 14 μm) techniques ($p < 0.05$). For overall arch measurements, the SLA (176 ± 73 μm) technique exhibited significantly different RMS values of precision from the DLP (74 ± 34 μm), FFF (89 ± 34 μm), and PolyJet (69 ± 18 μm) techniques ($p < 0.05$). For occlusion measurements, the FFF (170 ± 55 μm) technique exhibited significantly different RMS values of precision from the SLA (94 ± 33 μm), DLP (120 ± 28 μm), and PolyJet (96 ± 33 μm) techniques ($p < 0.05$).

3. There were significant differences in mean RMS values of trueness of overall tooth measurements among all four techniques: SLA (107 ± 11 μm), DLP (143 ± 8 μm), FFF (188 ± 14 μm), and PolyJet (78 ± 9 μm; $p < 0.05$). For overall arch measurements, the SLA (141 ± 35 μm) and PolyJet (86 ± 17 μm) techniques exhibited significantly different mean RMS values of trueness from DLP (469 ± 49 μm) and FFF (409 ± 36 μm) techniques ($p < 0.05$).

The 3D printing techniques exhibited significant differences in precision of all measurements and in trueness of tooth and arch measurements. The PolyJet and DLP techniques were more precise than the FFF and SLA techniques, with the PolyJet technique exhibiting the highest accuracy. Therefore, 3D printing techniques should be selected in accordance with the desired precision and trueness of the orthodontic appliances. The findings of this study indicated that all four types of 3D printers studied here may be used for orthodontic purposes, but the clinical efficacies of their outcomes should be examined by additional studies.

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국문 요약

다른 방식의 3D 프린터로 제작한 치과 모형의 정밀도와 정확도

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김수연

이 연구의 목적은 제작 방식이 다른 3D 프린터로 제작한 치과 모형의 정밀도와 정확도를 임상적인 관점에서 평가하는 것이었다. 참고 치과 모형을 제작 방식이 stereolithography apparatus (SLA), digital light processing (DLP), fused filament fabrication (FFF)과 PolyJet 방식인 네 종류의 3D 프린터로 5 회 반복 출력하였다. 출력한 치과 모형을 스캔하여 치아, 악궁 그리고 교합 계측을 시행하고 계측값의 차이를 root mean square (RMS)로 계산하여 정밀도와 정확도를 분석하였다. 정밀도를 분석하기 위해서는 동일한 3D 프린터로 반복 출력한 모형들 사이의 차이를 비교하였고, 정확도를 분석하기 위해서는 동일한 3D 프린터로 출력한 치과 모형과 참고 모형의 차이를 비교하였다. 통계 분석은 95% 신뢰수준의 one-way ANOVA 를 수행하여 다음과 같은 결과를 얻었다.

1. 교합의 정확도를 제외한 모든 계측에서 네 가지 방식의 3D 프린터로 출력한 치과 모형 사이에는 유의한 차이가 존재하였다 ($p < 0.001$).

2. 치아의 정밀도 분석에서 DLP (RMS: 76 ± 14 μm)과 PolyJet (68 ± 9 μm) 방식은 SLA (88 ± 14 μm)과 FFF (99 ± 14 μm) 방식과 유의한 차이를 보였다 ($p < 0.05$). 악궁의 정밀도에서 SLA (176 ± 73 μm) 방식은 나머지 DLP (74 ± 34 μm), FFF (89 ± 34 μm), PolyJet (69 ± 18 μm) 방식과 유의한 차이가 있었다 ($p < 0.05$). 교합의 정밀도에서는 FFF (170 ± 55 μm) 방식이 나머지 SLA (94 ± 33 μm), DLP (120 ± 28 μm), PolyJet (96 ± 33 μm) 방식과 유의한 차이를 보였다 ($p < 0.05$).

3. 치아의 정확도 분석에서 네 가지 출력 방식 사이에는 모두 유의한 차이가 존재하였다: SLA (107 ± 11 μm), DLP (143 ± 8 μm), FFF (188 ± 14 μm)과 PolyJet (78 ± 9 μm; $p < 0.05$). 악궁의 정확도에서는 SLA (141 ± 35 μm)과 PolyJet (86 ± 17 μm) 방식이 DLP (469 ± 49 μm)과 FFF (409 ± 36 μm) 방식과 유의한 차이를 보였다 ($p < 0.05$).

네 가지 방식의 3D 프린터로 출력한 치과 모형은 정밀도와 정확도에서 유의한 차이가 존재하였다. PolyJet 과 DLP 방식이 FFF 과 SLA 방식보다 더 정밀하였다. 네 가지 출력 방식 중에서는 PolyJet 방식이 가장 정확하였다.

핵심이 되는 말: 3D 프린터, 3D 디지털 치과 모형, computer aided design, 모형 계측, 정밀도, 정확도