# Comparing the accuracy (trueness and precision) of models of fixed dental prostheses fabricated by digital and conventional workflows

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Original article

# Comparing the accuracy (trueness and precision) of models of fixed dental prostheses fabricated by digital and conventional workflows

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ABSTRACT

*Purpose:* This study aimed to evaluate and compare the accuracy.
*Methods:* A reference model was prepared with three prepared teeth for three types of restorations: single crown, 3-unit bridge, and inlay. Stone models were fabricated from conventional impressions. Digital impressions of the reference model were created using an intraoral scanner (digital models). Physical models were fabricated using a three-dimensional (3D) printer. Reference, stone, and 3D printed models were subsequently scanned using an industrial optical scanner; files were exported in a stereolithography file format. All datasets were superimposed using 3D analysis software to evaluate the accuracy of the complete arch and trueness of the preparations. One-way and two-way analyses of variance (ANOVA) were performed to compare the accuracy among the three model groups and evaluate the trueness among the three types of preparation.
*Results:* For the complete arch, significant intergroup differences in precision were observed for the three groups ($p < .001$). However, no significant difference in trueness was found between the stone and digital models ($p > .05$). 3D printed models had the poorest accuracy.
A two-way ANOVA revealed significant differences in trueness among the model groups ($p < .001$) and types of preparation ($p < .001$).
*Conclusions:* Digital models had smaller root mean square values of trueness of the complete arch and preparations than stone models. However, the accuracy of the complete arch and trueness of the preparations of 3D printed models were inferior to those of the other groups.


## 1. Introduction

An accurate impression technique is a crucial element for the successful fabrication of dental prostheses. The most common conventional method involves making an intraoral impression using an elastomeric impression material, then fabricating a stone model. This technique has been successfully used in dentistry for decades [1]. However, deformation of the impression material [2], a volume change of the model material, and contamination with intraoral saliva and blood [3,4] are reported disadvantages.

With the development of computer-aided design and computer-aided manufacturing (CAD/CAM) technology and the use of intraoral scanners, the fabrication of dental prostheses and models has been changing rapidly to a fully digital production process. Three-dimensional (3D) digital models obtained using an intraoral scanner can eliminate the need for a conventional impression and model fabrication. They have several advantages, such as the permanent storage of data, and reduction of patient discomfort associated with the use of impression materials [5–7]. Furthermore, physical models can be created based on datasets obtained by an intraoral scanner using either milling or a 3D printer.

Some restorations can be directly fabricated using a CAD/CAM system after obtaining a digital impression with an intraoral scanner; thus, fabrication of a physical model is not required. However, a manual veneering restoration still requires a physical model, as the model is needed to determine the relationship between the restoration and adjacent and opposing teeth. The model is also needed when fabricating prostheses that require a manually applied wax-up on the physical model, such as heat-pressing lithium disilicate or casting gold alloy.

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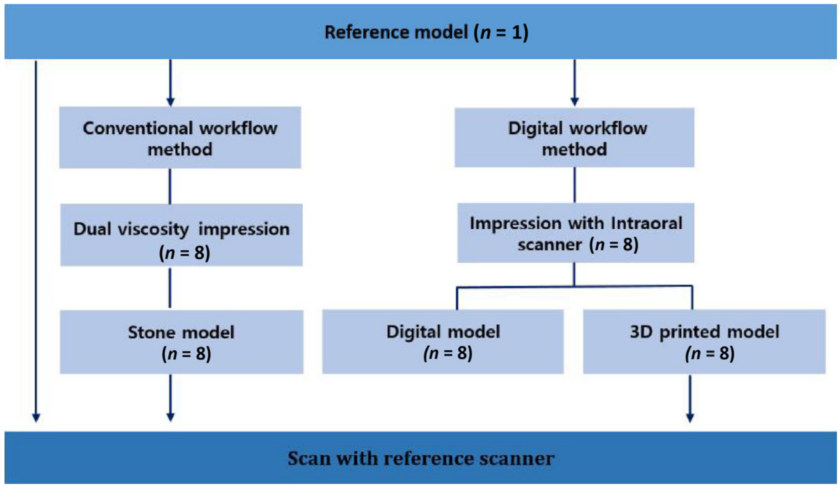


**Fig. 1.** Steps of the stone, digital, and 3D printed dental model fabrication methods.

The most common CAD/CAM method used in digital dentistry is the subtractive machining technique. This technique has disadvantages, such as waste of materials and poor reproducibility of complex internal shapes, undercuts, and voids in the teeth. To overcome the disadvantages of the subtractive technique, the additive manufacturing process has been introduced as an alternative, and substantial research into its dental applications is ongoing. The additive manufacturing is a technology in which the desired products are produced through layer-by-layer accumulation of materials [8]. It facilitates the fabrication of complex structures that are difficult to fabricate by milling and allows immediate large-scale fabrication. Due to these advantages, the use of 3D printers for the fabrication of surgical guides, final prostheses, and dental models is increasing in dentistry. In addition, the additive manufacturing method may save time and minimize labor [9].

Although several studies investigating the accuracy of dental models fabricated by digital workflow have been reported, most are limited to the diagnostic models used in orthodontics [10,11]. Since the models used in the fabrication of precisely fitting dental prostheses such as fixed partial dentures and inlays require higher accuracy than those used in orthodontics, further studies of the accuracy of digitally-produced prosthodontic models are required.

As defined by ISO-5725, accuracy consists of trueness and precision. Trueness refers to the closeness of the experimental result to the true value. High trueness indicates that the experimental result is very close or equivalent to the true value. In contrast, precision describes the closeness of agreement between intragroup data obtained by repetitive measurements [12].

The purpose of this study was to evaluate a digital model obtained using an intraoral scanner and a 3D printed model by measuring the accuracy (trueness and precision) of the complete arch and the trueness of preparation, and to compare them with a conventional stone model. The hypothesis of this study was that no significant differences would be found in the accuracy (trueness and precision) of the complete arch or the trueness of preparation among the digital, 3D printed, and stone models.

## 2. Materials and methods

### 2.1. Reference model fabrication

A complete arch model containing three prepared artificial teeth for three different types of restorations (#16 for single crown, #14 and #16 for 3-unit bridge, and #26 for inlay) was fabricated using a maxillary Frasaco model (standard working model AG-3; Frasaco, Tettnang, Germany). Teeth #14 and #16 had standardized preparations from Frasaco, and #26 was prepared for the fabrication of a ceramic inlay. The occlusal depth of the preparation was 2.5 mm, the proximal depth was 5.0 mm, the occlusal width was a minimum of 2.5 mm, the cavity wall was 6° of inclination, and the point angles were rounded. All preparation margins were designed without bevels [13]. To fabricate a reference model with epoxy, an impression of the working model containing three prepared teeth (Frasaco model) was made with silicone (Duguform, DeguDent, Hanau, Germany). The impression was removed from the working model after 1 h. A duplication mold was thus created and the epoxy (Modralit 3K, Dentamid Dreve, Unna, Germany) was poured into the duplication mold. The model obtained was then used as the reference model.

The reference model was scanned using a high-resolution industrial optical reference scanner (Comet L3D; Carl Zeiss, Neubeuern, Germany). According to the manufacturer's data, the camera resolution is 2448 × 2050 (5 mega pixels), and the scanner has a point distance of 18 μm and a trueness of 6 μm. The scanner uses blue LED light scanning technology.

### 2.2. Stone model fabrication using a conventional workflow

Following the conventional workflow method (Fig. 1), to achieve uniform thickness of the impression material, one layer of baseplate wax (Daeodogn, Seoul, Korea) was applied to the reference model, followed by the fabrication of eight individual impression trays (SR Ivolen; Ivoclar-Vivadent, Schaan, Liechtenstein). To maximize the adhesion between the trays and the impression material and minimize the potential of impression distortion and resulting poorly-fitting restorations, an adhesive (Identium Adhesive; Kettenbach, Eschenburg, Germany) was applied to the trays. Dual viscosity impressions ($n = 8$) of the reference model were made using a polyvinyl siloxane impression material (Honigum Light Body, Heavy Body DMG, Hamburg, Hamburg, Germany); the impressions were removed from the reference model after 10 min (three times longer than the manufacturer's recommendation) [14] and stored at 23 °C for 8 h. The impressions were poured with type IV dental stone (FujiRock; GC, Leuven, Belgium) and mixed according to the manufacturer's instructions. The stone models were separated from the impressions after 40 min, stored at room temperature for 48 h, and then scanned with the reference scanner (Comet L3D;

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Carl Zeiss) ($n = 8$) to obtain the dataset of the conventional stone model group.

The number of specimens was determined by a power analysis (actual power = 93.4 %; power = .90; $\alpha = .05$).

### 2.3. Digital and 3D printed models fabrication using a digital workflow

Following the digital workflow method (Fig. 1), the digital impressions ($n = 8$) of the reference model were obtained by an experienced clinician (DL) using an intraoral scanner (CS3500; Carestream Dental, NY, USA). Scanning was performed in restoration mode following the manufacturer's recommended scanning sequence of: occlusal surface, buccal surface, lingual surface. The datasets from each scan were automatically saved as STL files, which were later used as the digital model. 3D printed models ($n = 8$) were fabricated using a 3D dental model printer (3Dent; EnvisionTEC, Gladbeck, Germany). After printing, all models were detached from the build platform with a separating tool and cleaned with ethanol. The models were then post cured for 30 min using an ultraviolet light-curing unit (JW400; EnvisionTEC). The models were subsequently scanned with the reference scanner (Comet L3D; Carl Zeiss) to obtain the dataset for the 3D printed model fabricated based on the digital workflow.

The datasets of the stone, 3D printed, and reference models scanned by the reference scanner were converted into STL files using manufacturer-certified software (Colin 3D; Carl Zeiss).

All STL files (reference, digital, 3D printed, and stone models) were exported to 3D analysis software (Geomagic Verify; 3D Systems, Rock Hill, SC, USA). The unnecessary portion located under the margin of the complete arch models in the stereolithofraphy (STL) file was removed. To measure the trueness among the prepared teeth for the three different types of restoration, for single crown preparation evaluation, only #16 was retained. Teeth #14 and #16 were retained for 3-unit preparation, and #26 was retained for inlay preparation; all other unnecessary sections were removed.

### 2.4. Three-dimensional analysis

To measure the accuracy (trueness and precision) of the complete arch and the trueness among the preparations of the model groups, the datasets were superimposed via a best-fit alignment method utilizing a 3D analysis program (Geomagic Verify; 3D Systems). The trueness of the complete arch was evaluated by superimposing the STL file data of the reference model with STL file data obtained from the conventional stone ($n = 8$), digital ($n = 8$), and 3D printed models ($n = 8$). The precision of the complete arch was evaluated by superimposing the scan data within each group ($n = 28$). In addition, the trueness of preparation was measured for each type of preparation (inlay, single crown, and 3-unit bridge) by superimposing the STL file of each preparation with the reference model in the STL files of the three corresponding preparations in the different model groups (each, $n = 8$). The quantitative values were automatically calculated by the 3D analysis program based on the root mean square (RMS). The RMS values were used to determine the average of the positive and negative values using the following formula:

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

where $n$ is the sum of the measured points, $x_{1,i}$ is the measurement point of $i$ of the reference model, and $x_{2,i}$ is the measurement point of $i$ of the dataset of the test model.

A color map representing visual deviation was set with 20 color segments. For the complete arch, the range of the maximum and minimum nominal values was set at $\pm$ 50 μm, and the range of the maximum and minimum critical values was set at $\pm$ 500 μm. For the color map demonstrating the trueness among the preparations, the range of the maximum and minimum nominal values was set at $\pm$ 10 μm, and that of the maximum and minimum critical values was set at $\pm$ 100 μm.

### 2.5. Statistical analysis

A Shapiro–Wilk test was conducted to test intergroup normality, and homogeneity of variance was tested using the Levene test ($\alpha = .05$). A one-way analysis of variance (ANOVA) and the post-hoc Tukey honest significant difference (HSD) test were conducted to assess differences in the accuracy of the complete arch among the three model groups. In addition, a two-way ANOVA was performed to evaluate the trueness of the preparation, and the post-hoc Tukey HSD test was used to compare the differences among the three model groups and preparation types. The level of statistical significance was set at 0.05 for both statistical methods. All statistical values were analyzed using SPSS software (IBM SPSS Statistics for Windows, Version 21.0; IBM, Armonk, NY, USA).

## 3. Results

### 3.1. RMS mean values of the accuracy (trueness and precision) of the complete arch and the trueness of preparation

The accuracy of the complete arch of each of the three model groups is reported in Table 1.

For the complete arch, the trueness and precision of the stone models were 28.49 $\pm$ 1.74 μm and 22.79 $\pm$ 5.76 μm, respectively. The trueness and precision of the digital models generated by the intraoral scanner were 28.09 $\pm$ 2.11 μm and 34.07 $\pm$ 5.83 μm, and 55.16 $\pm$ 2.70 μm and 54.93 $\pm$ 8.44 μm for the 3D printed models, respectively. Hence, the trueness of the stone and digital models were significantly different from the 3D printed model ($p < .001$). Additionally, significant differences in precision were found among the three model groups ($p < .001$).

The values of the trueness of the single crown, 3-unit bridge, and inlay preparations of each model group are reported in Table 2. The two-way ANOVA revealed a significant difference in the trueness of preparation based on the model group ($p < .001$) and preparation type ($p < .001$). Furthermore, an interaction effect based on the model group and preparation type was determined to be significant ($p < .001$). Tukey's multiple comparison test demonstrated a significant intergroup difference for single and

**Table 1**
The accuracy (trueness and precision) of the stone, digital, and 3D printed model groups for the complete arch (trueness [$n = 8$], precision [$n = 28$]).

| | Stone RMS (μm) (mean $\pm$ SD) | Digital | 3D printing | $p$-value |
|---|---|---|---|---|
| Trueness | $28.49 \pm 1.74^{Aa}$ | $28.09 \pm 2.11^{Aa}$ | $55.16 \pm 2.70^{Ab}$ | 0.001 |
| Precision | $22.79 \pm 5.76^{Ba}$ | $34.07 \pm 5.83^{Bb}$ | $54.93 \pm 8.44^{Bc}$ | 0.001 |

Values with different letters indicate statistically significant difference based on Tukey's test at $p < .05$.

**Table 2**
The trueness of three types of preparations for single crown, 3-unit bridge, and inlay ($n = 8$).

| | Stone<br>RMS (μm) (mean ± SD) | Digital | 3D printing |
|---|---|---|---|
| Single | 17.70 ± 1.3[a] | 13.98 ± 1.87[c] | 46.93 ± 2.28[d] |
| 3 unit | 18.03 ± 0.57[a] | 14.65 ± 1.66[ac] | 51.39 ± 3.74[e] |
| Inlay | 22.86 ± 0.98[b] | 17.75 ± 1.94[ac] | 46.0 ± 1.58[d] |

Values with different letters indicate statistically significant difference based on Tukey's test at $p < .05$.
Two-way ANOVA: model group ($p < .001$), preparation type ($p < .001$), model group* preparation type ($p < .001$), $R^2 = 0.985$.

inlay preparations among the stone, digital, and 3D printed model groups. However, no significant difference was observed for the 3-unit bridge preparations between the stone and digital models.

The inlay preparation, which had the highest RMS values (22.86 ± 0.98 μm), was significantly different compared to the other preparation types within the stone group ($p < .001$). The 3-unit bridge preparation, which had the highest RMS values (51.39 ± 3.74 μm), was significantly different compared to the other preparation types within the 3D printed model group ($p < .001$). No significant difference was observed among the three different types of preparations in the digital model group ($p > .05$). Furthermore, the digital model group showed the smallest RMS values of all preparations.

### *3.2. Analysis on the color difference map*

For the complete arch, the trueness and precision of the three model groups are presented as color difference maps (Fig. 2). Fig. 2(c) and (f), demonstrates notable differences in the anterior labial and posterior regions. Horizontal deviation is demonstrated in Fig. 2(c), the entire arch is contracted horizontally. The stone (Fig. 2(a) and (d)) and digital model groups (Fig. 2(b) and (e)) are within the tolerance range; most of the arch is presented in green.

The color difference map for each preparation (single crown, 3-unit bridge, and inlay) demonstrating the differences within the three model groups is presented (Fig. 3). Positive deviations are exhibited in Fig. 3(a) and (b), by the yellow color in the proximal and occlusal regions of the preparation, those of the digital model group are shown to be similar to the stone model.

In Fig. 3(g) and (h), negative deviations are exhibited over most of the preparation surfaces, excluding the marginal and occlusal surfaces. As shown in Fig. 3, (c) and (f), most of the preparation is within the range of tolerance. However, negative deviation is demonstrated by most of the preparation surfaces, excluding the internal line angles, as shown in Fig. 3(i).

## 4. Discussion

Based on the results of this study, the null hypothesis was rejected because significant differences were found among the trueness and precision of the three model groups ($p < .05$).

In a comparison of the two physical models (stone and 3D printed models) of the complete arch, the trueness and precision of the stone model were significantly better than those of the 3D printed model ($p < .001$).

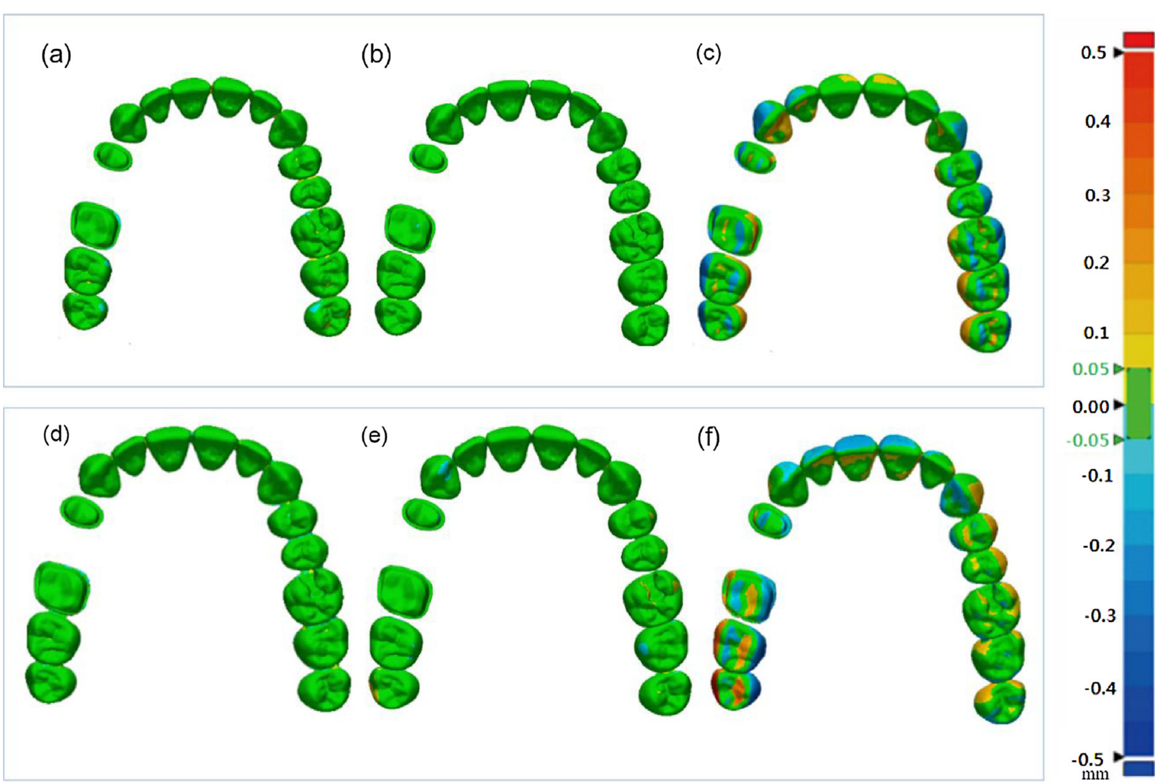


**Fig. 2.** Color difference map showing the trueness and precision of the complete arch. Max/min nominal ± 50 μm (green). Max/min critical ± 500 μm (dark red and dark blue). Trueness of the (a) stone, (b) digital, and (c) 3D printed models. Precision of the (d) stone, (e) digital, and (f) 3D printed models.

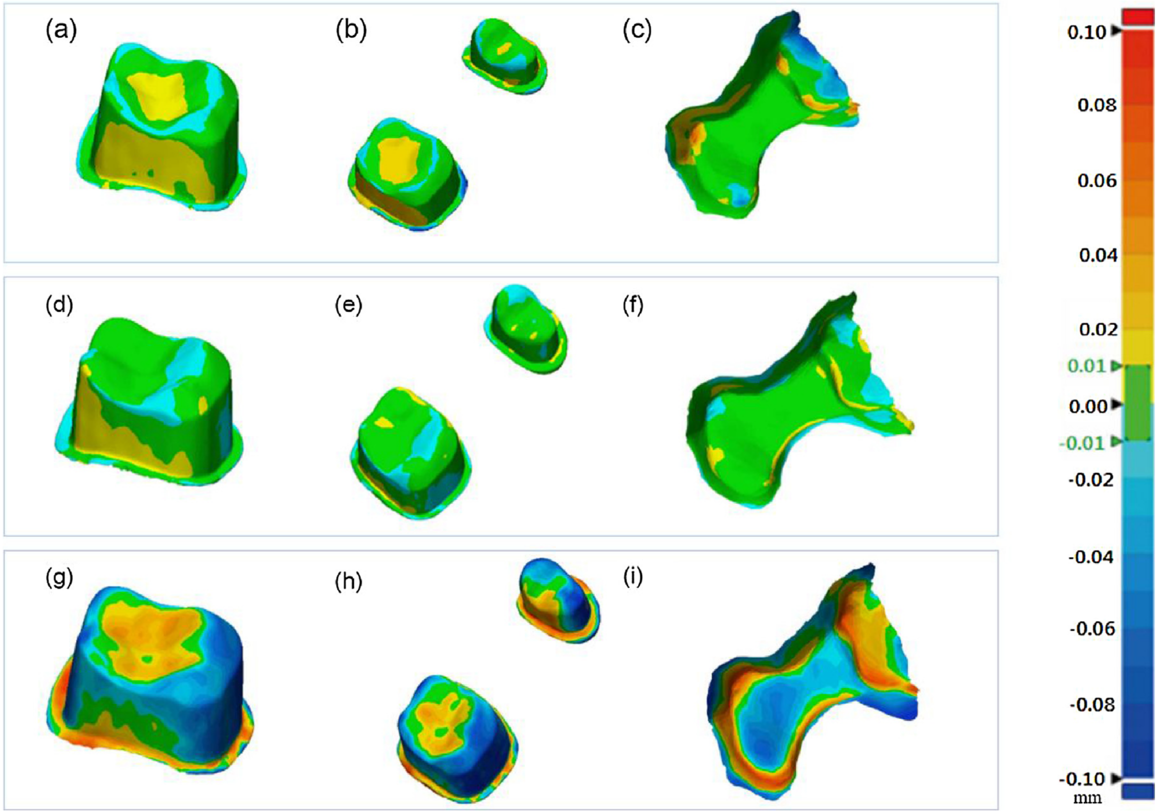


**Fig. 3.** Color difference map showing the trueness of a single crown, 3-unit bridge, and inlay preparation. Max/min nominal ± 10 μm (green). Max/min critical ± 100 μm (dark red and dark blue). Stone model: (a) single, (b) 3-unit, (c) inlay. Digital model: (d) single, (e) 3-unit, (f) inlay. 3D printed model: (g) single, (h) 3-unit, (i) inlay.

Cho et al. reported significantly better accuracy for the complete arch of the conventional stone model compared to that of the model made by digital method, which is consistent with our findings [15]. The accuracy (trueness and precision) of a model fabricated using the conventional workflow is determined by the impression tray and materials, as well as the type of stone used [16]. In contrast, the accuracy of a model fabricated using a digital workflow is determined by the type of intraoral scanner, material used by the 3D printer, and type of 3D printer. In this study, individual custom-made impression trays were used, which ensured reliability of the impression technique by providing the impression material of a consistent thickness. Moreover, the polyvinyl siloxane impression material used in this study has better dimensional stability compared to other elastomeric impression materials [1].

In terms of the complete arch, the digital model showed slightly smaller RMS mean values of trueness compared to the stone model, although the difference was not significant ($p > .05$). However, Ender and Mehl reported that the stone model fabricated using conventional impression showed significantly smaller mean values in trueness (20.4 ± 2.2 μm) than the digital model created using an intraoral scanner (58.6 ± 15.8 μm) [17]. These differences may be attributed to the use of different conventional impression materials and intraoral scanners.

Intraoral scanners are classified into two image recording systems (point-and-click and video-based systems) [18,19] and utilize various scanning techniques, including triangulation [20], parallel confocal [21], and active wave front [22]. The CS3500 intraoral scanner used in this study uses a point-and-click recording system and a triangulation scanning technique. Previous studies have argued that the impression data obtained using an intraoral scanner presented horizontal deviations in the distal region, and reported that such deviations were due to inaccurate software stitching processes and matching errors in the captured data [7,19]. Ender and Mehl reported that an intraoral scanner based on the video system showed a larger deviation in the posterior area than one based on the stitching system [19]. In the present study, the color map differences of the digital model were similar to those of the stone model (Fig. 2(a) and (d)).

The 3D printer used in this study uses digital light processing (DLP) technology. The DLP method involves fabrication of the model by light curing one sequential cross-sectional layer after another of photoreactive liquid resin. As the image is projected across the entire screen, the printer rapidly prints a single additive layer. Dawood et al. reported that DLP technology has good accuracy and results in smooth surfaces [9].

However, contraction of the materials while constructing layers of minimum thickness, as well as further contraction and residual stress accumulation during the post curing process, occur during 3D printing. The consequent distortion and cracks produce differences in the reference models [23]. In addition, major differences in 3D printed models occur in the Z plane [24].

The layer-by-layer technique creates a stair-step effect on the object's surface. Whether the surface of the object is smooth and detailed depends on the thickness of the layers. The stair-step effect may lead to dimensional errors and surface roughness [25,26]. The thickness of the layers of the 3D printer used in this study was 50 μm. The deviations associated with the 3D printed model are thought to be due to the thickness of the layers of material and contraction caused by post curing.

Despite this, Patzelt et al. reported that the models (Lava C.O.S. with SLA, CEREC AC with SLA, and iTero with milled casts) fabricated using a digital workflow demonstrated a clinically acceptable level of accuracy, as they all presented with a trueness ≤ 100 μm (67.50, 75.80, and 98.23 μm, respectively) [27]. Ender et al. reported that a deviation of ≥ 100 μm across the complete arch produces inaccurate fitting of the final prostheses [28]. In this study, the RMS mean values of trueness and precision of the complete arch of 3D printed models were <100 μm. Therefore, cautious clinical use for complete arch models is suggested.

Cho et al. reported no significant difference between the conventional and 3D printed models in a comparison of prepared teeth (single and 3-unit bridge). Therefore, digital fabrication methods are compatible with conventional methods in terms of the surface accuracy of single and 3-unit bridge preparation [15].

However, this study found some significant differences among all preparation types of the three model groups. In a comparison of trueness among the three preparations, the digital model group showed smaller RMS values for all types of preparations than those of the stone model. Ng et al. reported that digital impressions using an intraoral scanner showed better results than conventional impressions of single restorations [29]. Those results were consistent with our findings. Although the digital model group showed the smallest RMS values of trueness in all preparation types, the 3D printed model based on the dataset obtained by an intraoral scanner showed the largest RMS values for all preparations among the three model groups.

As shown in Fig. 3(a) and (b), expansion of the model is denoted in yellow, indicating positive deviation on the proximal and occlusal surfaces. This can be explained by the setting expansion of type IV dental stone, which compensates for the polymerization shrinkage of the elastomeric impression material and even increases the dimension. This is consistent with the results of Stober et al. [30].

Moreover, Fig. 3(g) and (h), appears to be contracted compared to the reference model, as the blue color observed on most of the axial wall indicates negative deviation. Therefore, it is thought that increased cement space should be maintained in the axial wall area of the teeth preparation model when fabricating prostheses using 3D printed models based on a digital workflow.

An advantage of the 3D printing method is that it enables the successful formation of concave and complex shapes [8,31]. Although the inlay preparation presented the highest RMS values of trueness in the digital model, it presented the smallest RMS values in the 3D printed model. However, the 3-unit bridge preparation demonstrated larger RMS values compared with the single preparation in the 3D printed model. This finding could be explained by the fact that the reproducibility of the 3D printed model may decrease as the span increases. Meanwhile, the inlay preparations demonstrated the highest RMS values in the stone model group. It seems that the reproducibility of concave shapes is worse than that of convex shapes in conventional stone models.

Despite the numerous advantages of the digital workflow impression method in dentistry, including time saving and reduction of patient discomfort, limitations remain that prevent it from completely replacing the conventional stone model. Numerous studies investigating the accuracy of digital impressions made by intraoral scanners are ongoing [6,7,18,19,29,32], and it has been reported that the accuracy of digital impressions is sufficient for clinical use [29,32]. Conversely, few studies have investigated the accuracy of 3D printed models, and most studies focusing on the preparation of teeth for prosthesis fabrication have been limited to single crown and 3-unit bridge preparations. Therefore, further studies on the accuracy of long-span prostheses, such as half-arch or full arch restorations, are required.

This in vitro study has some limitations. The reference model was scanned using an intraoral scanner to obtain a digital impression. The influence of intraoral factors, including saliva and a limited mouth opening space, was not considered. Further studies that consider the true clinical environment are required.

## 5. Conclusion

Within the limitations of this study, the following conclusions may be drawn. Although the digital model obtained by an intraoral scanner showed results comparable to those of a conventional stone model in terms of both complete arch and preparations, the 3D printed models showed the highest RMS mean values in the accuracy (trueness and precision) of the complete arch and the trueness of preparation. Therefore, the 3D printed model cannot completely replace conventional stone models until further improvements are made.

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