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3D 프린팅 각도와 층 두께가 DLP와 SLA 프린터로 출력한 모델의 정확도에 미치는 영향

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Effect of 3D print orientation and layer thickness on the accuracy of printed models by DLP and SLA printers

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본 연구의 목적은 2가지 서로 다른 종류의 3D 프린터를 이용하여 프린팅 레이어의 두께와 프린팅 방향(모델과 프린터 베드의 각도)의 변화가 모델의 정확도에 미치는 영향을 알아보고자 하는 것이다. 2급 와동을 가진 사각 큐브 형태와 치아 형태의 모델을 레이어의 두께와 방향을 달리하여 DLP 프린터(IMC, Carima)와 SLA 프린터(Form 3, Formlabs)로 각각 제작하였다(n=12). 제작된 모델을 모델 스캐너를 사용하여 STL파일로 변환하고 이를 원래의 삼차원 데이터와 중첩하여 제작된 모델의 진도(trueness)를 살펴보았다. 제작된 모델 표면을 주사전자 현미경으로 관찰하여 비교하였다. One-way ANOVA와 Turkey post hoc으로 레이어의 두께와 프린팅 방향이 정확도에 미치는 영향을 분석하였다. 사각 큐브 모델의 경우 DLP 프린터를 이용하여 0도 각도, 50 ㎛ 두께로 프린팅 되는 경우에 가장 적은 오차(20.49 ㎛)를 보였으며 SLA 프린터로 45도 각도, 100 ㎛ 두께로 프린팅 되는 경우에 가장 큰 오차(61.03 ㎛)를 보였다. 치아 형태의 모델은 SLA 프린터를 이용하여 0도 각도, 50 ㎛ 두께로 프린팅 되는 경우에 가장 적은 오차(25.63 ㎛)를 보였으며 DLP 프린터로 45도 각도, 100 ㎛ 두께로 프린팅 되는 경우에 가장 큰 오차(47.56 ㎛)를 보였다. SEM 이미지에서 SLA 프린터가 DLP 프린터에 비해 전반적으로 완만한 표면을 출력하는 특성을 보였다. 결론적으로 3D프린팅의 정확도는 프린터의 종류, 모델의 형태, 레이어의 두께, 프린팅 방향에 모두 영향을 받는 것으로 보였다.

색인단어 : 3D 프린팅, 진도, 표면 분석, 적층 두께, 출력 각도

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Introduction

CAD/CAM technology in dentistry is mainly divided into subtractive manufacturing (SM) and additive manufacturing (AM) (1, 2). SM involves the process of milling disk or block-type materials into a desired form using a computer numeric controlled (CNC) machine. This process has been widely used due to dimensional stability, but the drawbacks include that only one form can be produced at a time and it is difficult to reproduce complex geometries (2, 3). In contrast, 3D printing is an AM process that creates a 3D physical object by depositing or curing materials in successive layers (2-4). 3D printing generates less waste and is capable of reproducing small details (2, 3).

The types of 3D printers can be divided according to the materials and technologies (2, 5). Among the various technologies, stereolithography apparatus (SLA) and digital light projection (DLP) are the most commonly used 3D printing technologies in dentistry (6). Although both technologies use light source to photopolymerize resin materials, SLA selectively cures the material at each spot in a sequential manner, while DLP cures the entire layer of material on a layer-by-layer basis. In the field of dentistry, 3D printers are used to fabricate physical models for diagnosis and treatment planning, implant surgery guides, and production of various restorations (4, 7-9). The prerequisite for the use of 3D printers in daily clinical practice is that it should be accurate enough to reproduce adequate physical models from digital forms. The accuracy of 3D printed parts could be influenced by printing technology and a range of printing parameters such as layer thickness and orientation. According to the definition provided by ISO 5625-1, trueness refers to the level of agreement between the arithmetical mean of a large number of tests and the true or accepted value (10). Previous studies reported that a 45-degree tilted printing orientation was found to generate the most accurate bar specimens (11) and denture bases (12), 0 and 45-degree printing orientations produced the most accurate surgical templates (13), and disc and plate-shaped samples (14) and denture bases (15) were most accurately printed at a 90-degree orientation (14). Despite the fact that the trueness of 3D printed models could be affected by printing orientation, previous studies compared the trueness using only one type of 3D printer using SLA technology (11-14), except for one study that used two printers with SLA and DLP technologies (15). In addition to printing orientation, printing layer thickness could also be a contributing factor that influences the trueness of the additive technique – theoretically the thinner the layers, the more accurate the printed parts (1, 16, 17). However, a layer thickness of 100 μm appears to produce similar trueness when compared to 25 and 50 μm layers in a DLP printer (18) and 50 μm layers in an SLA printer (19). Considering the controversial results of previous studies, the purpose of this study was to evaluate the influence of printing layer thickness and orientation on printing trueness of DLP and SLA printers, and also to investigate the effect of geometry of printing parts on trueness. The null hypotheses of this study were that the trueness of printed models would not be affected by the geometry of printing models and that there would be no significant difference in trueness between DLP and SLA printers regardless of the printing orientation and layer thickness.

Materials and Methods

1. 3D Model Printing

Two types of models were used for comparison of the 3D printing trueness: 1) a natural tooth-replica model and 2) a cube model (10 mm width × 10 mm height × 10 mm depth), both with a proximal box with an occlusal extension (mesio-occlusal) cavity. A commercially available typodont model of the mandibular first molar (A50, Model 364, Nissin Dental Products, Kyoto, Japan) was digitized using a digital scanner (T500, Medit, Seoul, Korea) to obtain a standard tessellation language (STL) file. For the cube, a 3D CAD software (Rhino 3D, Rober McNeel & Associates, Seattle, WA, USA) was used to design and save in an STL file. For each model, a disc (2 mm thick with a diameter of 14 mm) was added on the bottom of the models to provide adequate area for support placement. The digitally converted 3D models were sliced into layers and printed using a DLP printer (IMC, Carima, Seoul, Korea) and an SLA printer (Form 3; Formlabs, Somerville, MA, USA) in two different thickness layers (z-height) (50 vs 100 μm) and two different printing orientations (0-degree; horizontal parallel to the build platform vs. 45-degree; tilted relative to the build platform) (n=12/group) (Table 1). The printing settings were controlled by 3D printer software programs (Carima Slicer V2, Carima) for IMC and (Preform, Formlabs) for Form 3. Each group was printed three sets with four models positioned at the print bed center per each set (Figure 1). Photopolymerizable dental model resins [(Dental Model, Carima) and (Model, Formlabs)] were used for the IMC and Form 3, respectively. The printed models were washed in isopropyl alcohol for 10 min (Form Wash, Formlabs) and post-cured for 30 min (Form Cure, Formlabs).

2. 3D Deviation and Surface Examination

Trueness of the printed models relative to the reference dataset was obtained using the superimposition technique. The postprocessed models were digitized using the 3D scanner (T500, Medit) and saved as STL files. The STL data of the discs, supports, and bases of the 3D printed models were removed, leaving the area of interest, and then superimposed onto the reference STL files by ‘initial alignment’, followed by ‘automatic alignment’ function using metrology software (PointShape Inspector v2.16, DREAMTNS, Seongnam, Korea). For trueness evaluation, the root mean square (RMS) values were calculated using the following equation;

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

where $\chi_{1,i}$ is the measurement point of i of the reference, $\chi_{2,i}$ is the measurement point of i of the dataset of the printed model, and n is the total number of points measured for analysis. Whole deviation was obtained to evaluate the deviation of the entire external surface except for the bottom surface of the models and to generate color-coded maps to visualize the magnitude and direction

Table 1. Study groups

Group	Printer	Technology	Layer Thickness (μm)	Printing Orientation (degree)
C50_0	IMC	DLP	50	0
F50_0	Form 3	SLA	50	0
C50_45	IMC	DLP	50	45
F50_45	Form 3	SLA	50	45
C100_0	IMC	DLP	100	0
F100_0	Form 3	SLA	100	0
C100_45	IMC	DLP	100	45
F100_45	Form 3	SLA	100	45

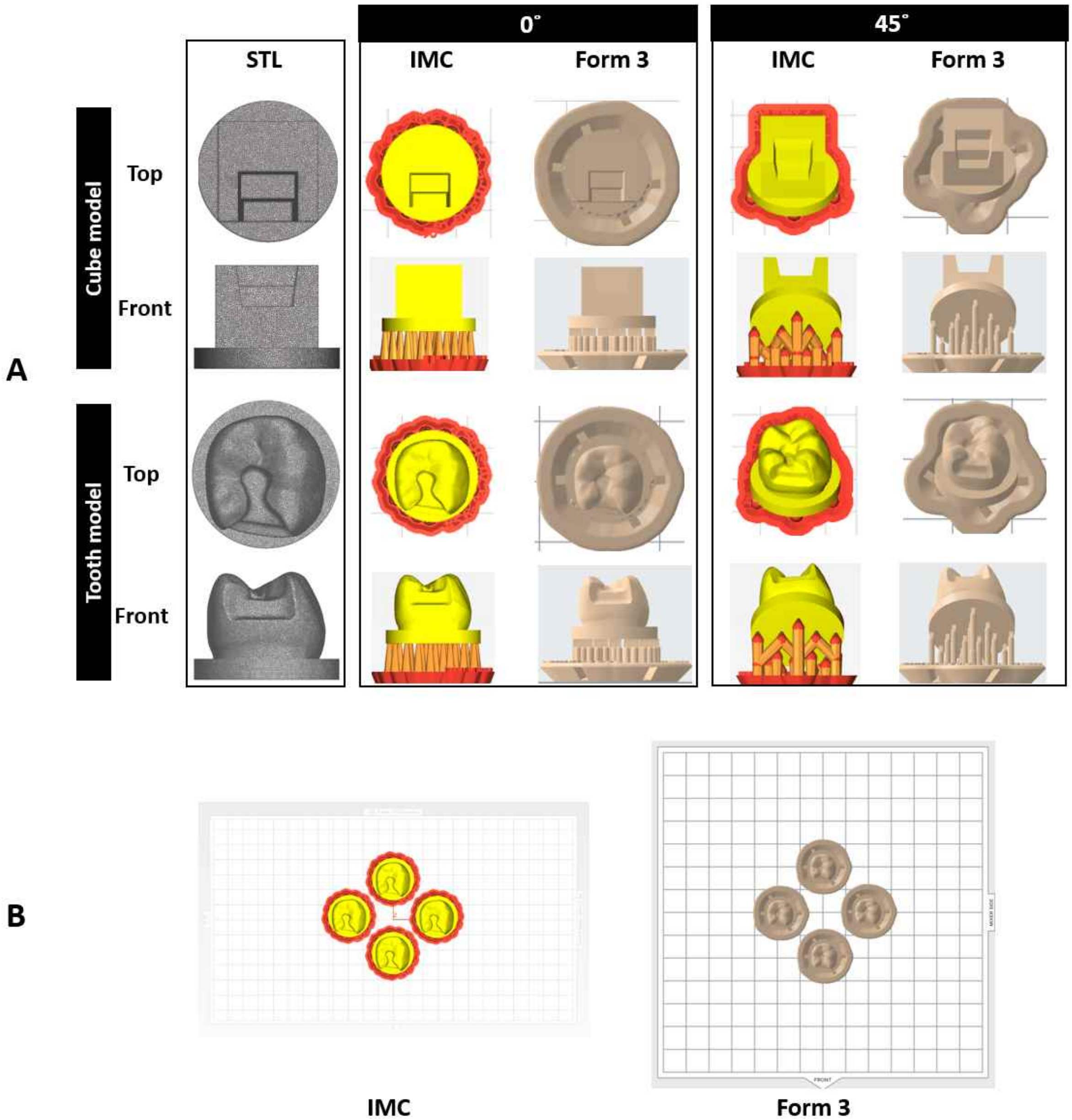

Figure 1. (A) Reference STL images and captured images from slicers for cube and tooth models at 0 and 45-degree orientation. (B) Position of printing models.

of deviation, where the blue and red colors indicate undersized and oversized printed models relative to the reference, respectively, in the range of -100 to +100 μm. For statistical analysis, the Shapiro-Wilk test was used for assessing the normality of the data distribution, and the homogeneity of variances was tested using Levene's test. One-way ANOVA and Tukey post hoc were performed using statistical software (SPSS Version 25.0, IBM, Armonk, NY, USA) under a significance level of 0.05 to analyze the effects of printing thickness and orientation for each printer.

In addition, the printed models were coated with platinum for surface examination under scanning electron microscopy (Apreo 2, ThermoFisher Scientific, Waltham, MA, USA) at 10 kV, 0.1 nA to evaluate the micro-features of the models for each printing group.

Results

The trueness of the printed models varied between the two printers depending on the geometry of the printed part, printing layer thickness, and printing orientation. For the cube model, the IMC exhibited less deviation when compared to the Form 3 within the same printing thickness and orientation. The smallest deviation was observed when the models were printed with a printing thickness of 50 μm at 0-degree printing orientation for the IMC, and at 100 μm thickness and 0-degree orientation for the Form 3 (Table 2, Figure 2). For the tooth model, the smallest deviation was observed when the models were printed by the Form 3 at 50 μm thickness at 0°

Table 2. Mean deviation of the 3D printed models (μm)

Group	Cube Model	Tooth Model
C50_0	20.49 (3.19)^{A}	29.54 (1.18)^{AB}
F50_0	34.04 (3.13)^{C}	25.63 (1.69)^{A}
C50_45	23.02 (2.33)^{AB}	30.15 (2.68)^{AB}
F50_45	42.41 (1.97)^{D}	34.11 (1.80)^{C}
C100_0	25.09 (3.43)^{B}	26.99 (2.41)^{AB}
F100_0	28.35 (2.14)^{B}	31.12 (2.95)^{BC}
C100_45	37.70 (3.57)^{C}	47.56 (2.88)^{E}
F100_45	61.03 (2.35)^{E}	42.84 (2.59)^{D}
F	220.04	109.05
P	< 0.001	< 0.001

Standard deviation in parentheses

Within the same column, values with different capital letters were statistically significantly different between the groups (Tukey HSD, $p<0.05$).

F, F-value, *P*, P-value.

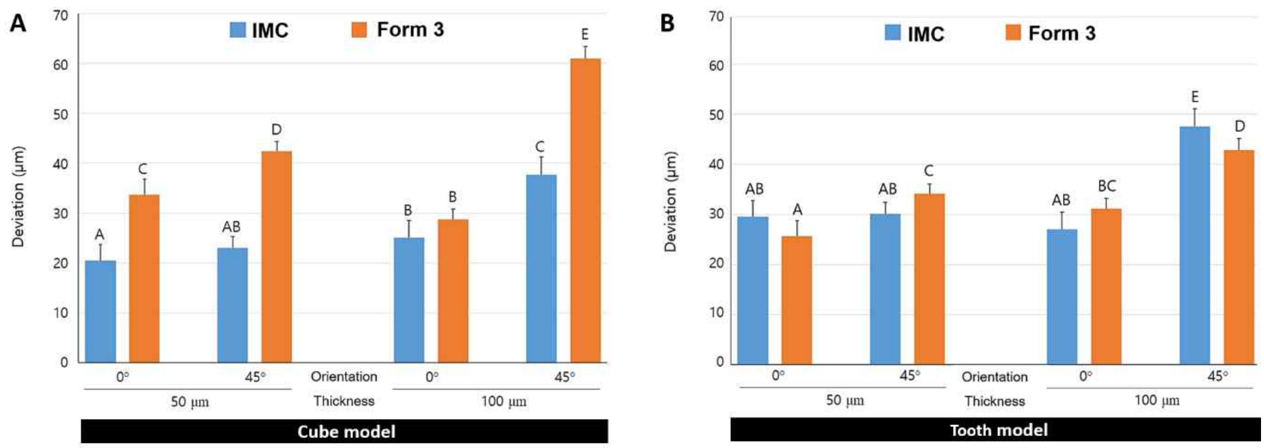

Figure 2. Deviation of (A) cube models and (B) tooth models printed at different settings. Different letters indicate statistical significance between the groups ($p<0.05$).

orientation. Regardless of the shape of the printing model, the deviation was greater when the models were printed at 45-degree in an increment of 100 μm by both printers.

Color maps show the magnitude and direction of the deviation of the printed models (Figure 3). In general, the Form 3 exhibited an overall tendency to have a positive deviation compared to the IMC within the same given printing orientation and layer thickness. Negative deviation was observed in the frontal side of the models printed at 45-degree orientation. The deviation was more pronounced in the Form 3 for the cube model, and in the IMC for the tooth shape model, particularly at the 45-degree printing orientation. Positive deviation was often found at the internal line angle of the cavity especially when the models were printed by the Form 3. The accumulation of resin at the internal line angle of the cavity was more marked in the cube model when printed at a 45-degree orientation in 100 μm thickness.

At a microscopic level, both 3D printers exhibited staircase effects that varied depending on the geometry of the model (Figure 4 and 5). The IMC exhibited an inherent square pattern made of pixels on the surface, while the Form 3 demonstrated a relatively smoother transition between the layers. In the cube model, the sharp line angles in the cube model were more readily reproduced by the IMC.

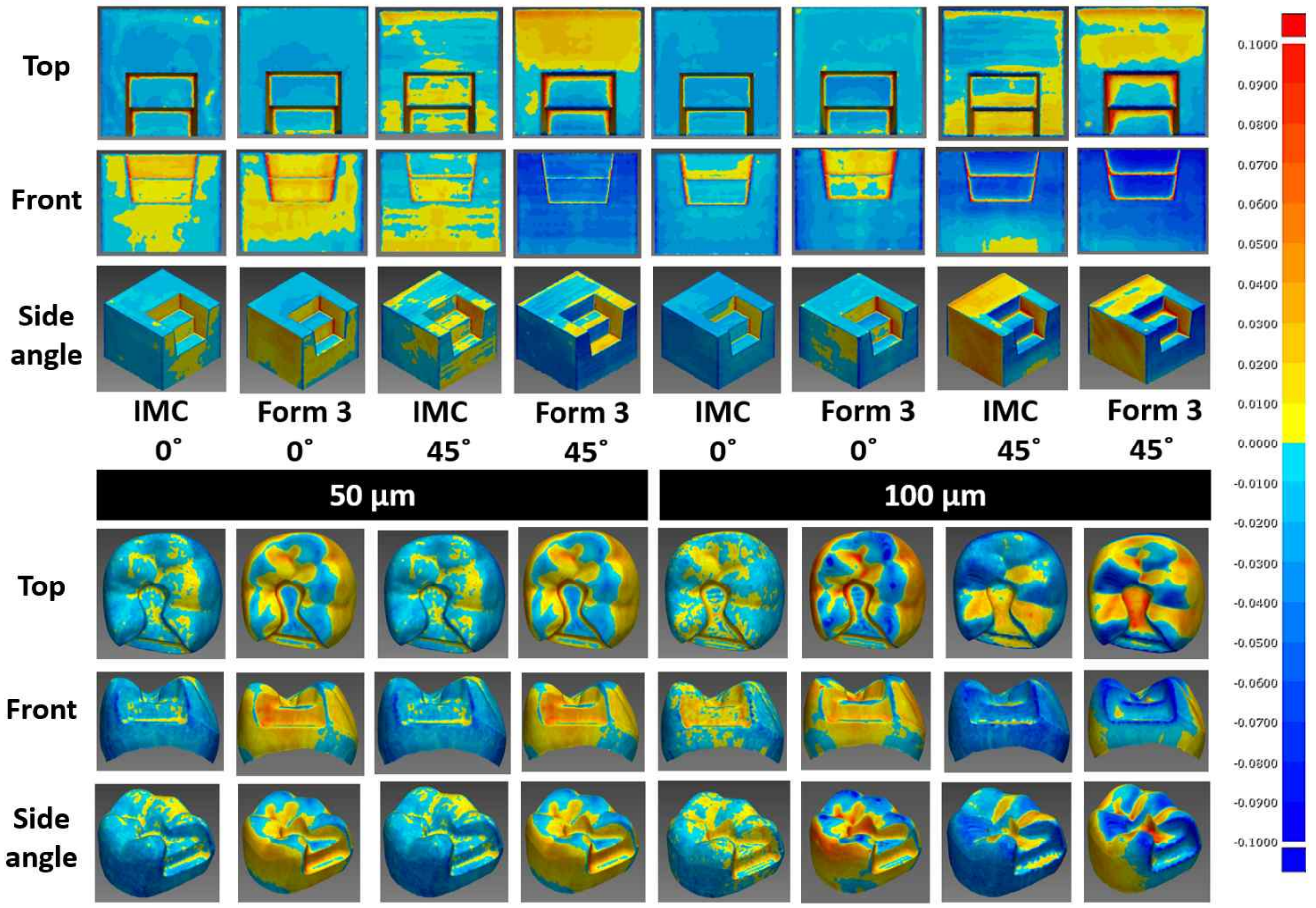

Figure 3. Representative deviation color map of 3D printed cube and tooth models from top, front, and side angle views. Color-coded deviation of 3D printed models relative to the master model. Range from -100 (blue) to +100 μm (red).

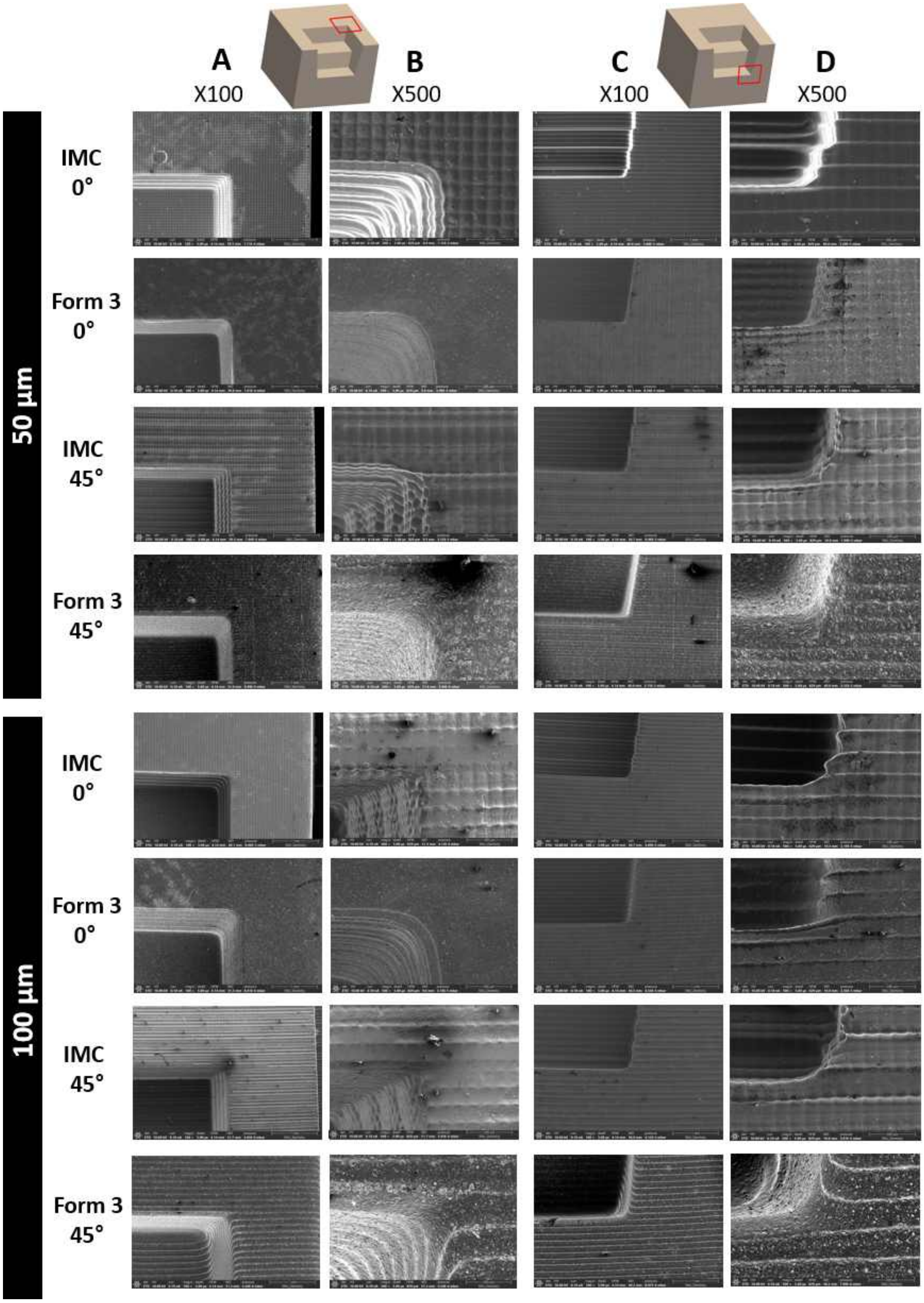

Figure 4. SEM images of the red-shaded box areas of the cube model at the top-right corner of the occlusal cavity from the top view at (A) ×100 and (B) ×500 magnifications; and at the bottom-right corner of the proximal box from the frontal view at (C) ×100 and (D) ×500 magnifications.

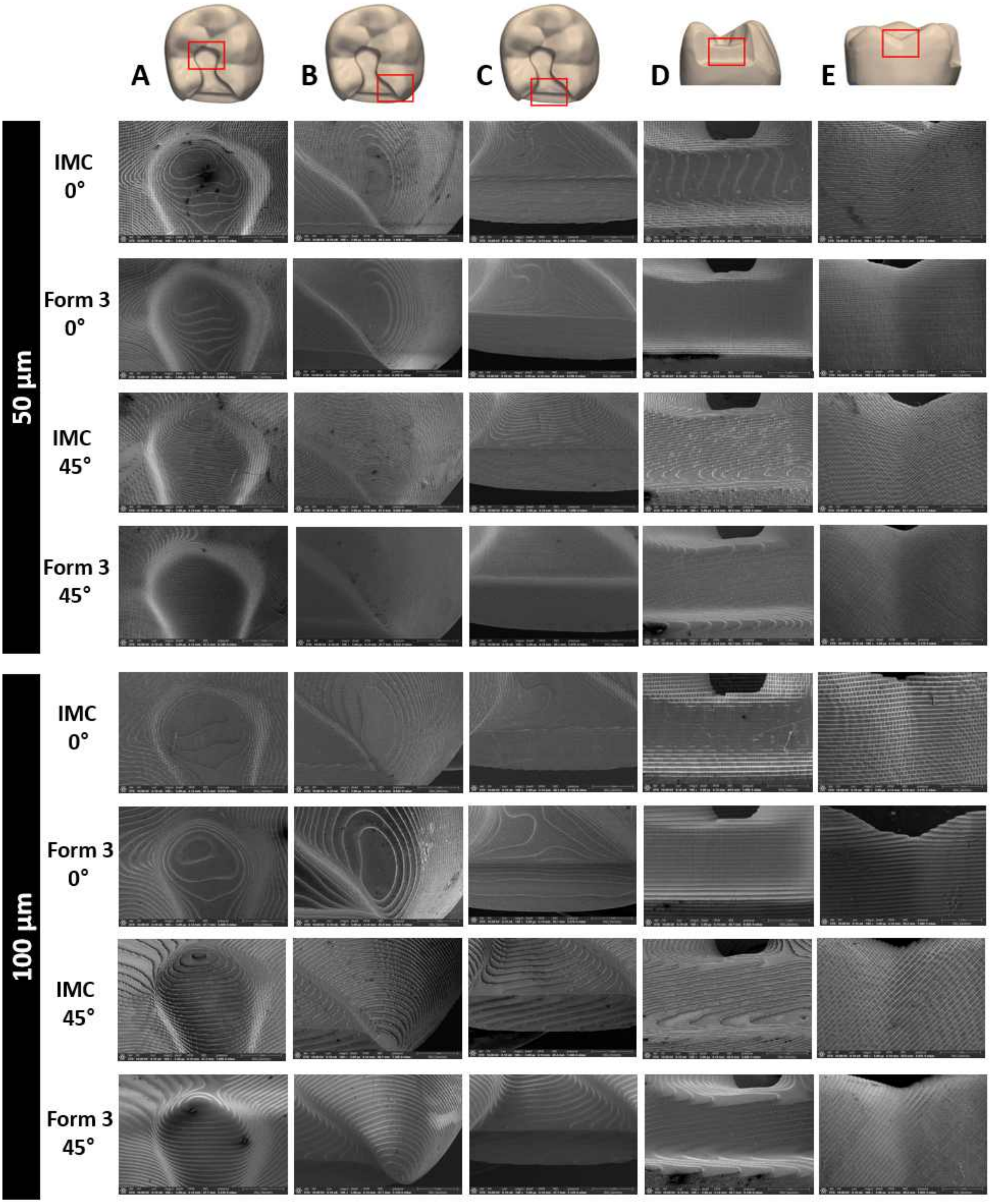

Figure 5. SEM images of the red-shaded box area of the tooth model at the (A) occlusal cavity and (B) mesio-buccal cusp tip, proximal box from the (C) top view, (D) front view, and (E) lingual side at ×100 magnification.

Discussion

This study aimed to evaluate the effects of printing layer thickness and printing orientation on the trueness of 3D printers in printing cube and tooth models through quantitative trueness analysis using the superimposition technique and qualitative examinations using color maps and SEM evaluations. The findings of this present study showed significant differences in trueness between SLA and DLP printers depending on the layer thickness and print orientation, thus rejecting the null hypothesis.

With regard to print orientation, no consensus could be made from previous studies in terms of the trueness of the printed parts (11-15). The trueness was influenced by print orientation depending on the type of print models: bar specimens were most accurately reproduced at a 45-degree orientation (11); denture bases at 45-degrees (12), 90-degrees (15); disc and plate-shaped specimens at 90-degrees (14); and surgical templates at 0- and 45-degree orientations (13). The varying trueness despite the same type of desktop SLA printer used in previous studies suggests that the type and geometry of printing models is one of the determining factors in the trueness of 3D printed parts. In the present study, the cube and tooth models were most accurately printed by IMC (DLP) and Form 3 (SLA) printers, respectively, both when the parts were printed at 0-degree orientation at 50 μm thickness. The color maps indicated that the direction and magnitude of deviations varied depending on the print orientation with both printers exhibiting greater deviations when the models were printed at 45-degree orientations. This finding suggests that the print orientation influences printing trueness in the XYZ axes. The difference in the findings between this study and previously related investigations could also be attributed to the different sizes and shapes of models used for evaluation. A 90-degree orientation was not included in the study because such an orientation requires supports placed on the models that could lead to false or misleading deviation comparisons.

In 3D printing, the light source determines the XY resolution. The Form 3 has a round laser with an 85 μm spot size, whereas the IMC uses a projector made of squared pixels with a 57 μm resolution. Although the size of the light source is larger in the Form 3, the manufacturer claims that constant line scanning processes in smaller increments allows for the printing of parts with 25 μm XY resolution. The different light source between the two 3D printers explains the difference in trueness depending on the type of printed models. The IMC exhibited better trueness in printing the cube model with sharp corners that was made of right angles due to the squared pixels in the IMC. Positive deviation caused by the accumulation of resin was more frequently observed at the sharp internal line angles of the cavity when the models were printed by the Form 3, particularly at 45-degree orientation in 100 μm thickness. In contrast, the round laser spot equipped in the Form 3 reproduced rounded lines more accurately, exhibiting better performance in printing the tooth model that had an organic shape with curved lines unlike the cube model.

Print layer thickness is another determining factor for resolution along the Z-axis. The trueness of 3D printers would be seemingly enhanced with a decrease in layer thickness since surface stepping becomes more prominent with thicker layers when printing models that are not vertically straight, also known as the staircase effect (1, 16, 17). The discrepancy between layers caused by the staircase effect adversely affects the surface texture and dimensional trueness of printed objects (18). Although, both 3D printers exhibited improved surface quality with less visible steps when the models were printed at 50 μm compared to those printed at 100 μm, the Form 3 demonstrated a trend of relatively smoother transition between layers. Nonetheless, surface quality and thinner layers were not decisive factors for the overall deviation.

The deviation of 50 μm layer thickness was not always clearly better than 100 μm layer thickness, which was in agreement with previous studies that also showed similar trueness between 50 and 100 μm layer thickness (19, 20). Another study reported that the 25 μm layer thickness exhibited the greatest deviation, while the 100 μm layer showed the least deviation (17). Optimal outcomes may not be achieved because printing thinner layers requires more successive layers to fabricate the same model, which in turn could cause more potential artifacts and errors during printing unless a perfect additive manufacturing process can be guaranteed (21).

The high trueness of 3D printers is a mandatory requirement for use in dental applications. If models were fabricated by 3D printers for restorative work, the longevity of the restorations is directly influenced by the trueness of 3D printers since any deviation could impair the proper adaption of the restorations (22). For intracoronal restorations, a model with a wider cavity relative to the actual dimensions would result in a larger restoration that may not be properly seated or produce a smaller restoration due to a narrower cavity model that would be more prone to fracture and require a greater amount of cement to occupy the interface between the tooth and restoration. Conversely, for extracoronal restorations such as crowns, an oversized model will lead to a larger restoration with a thicker cement space and vice versa for an undersized model. Despite the fact that the trueness of all the printed models at various printing parameters were within the clinically acceptable marginal discrepancy of 120 μm (23), possible errors during the restoration fabrication process should also be taken into account in the final outcome.

The findings of the present study should not be generalized because individual printers from each type of printing technology were tested. In addition, the printed models were limited to the size of a single tooth. Therefore, the result may not be identical if a larger model, for example a full arch model, was compared, considering the greater shrinkage in vat polymerization and greater peeling forces during printing associated with a larger printed model. Nevertheless, the findings of the present study provide an understanding of the variable effect of print orientation, layer thickness, and printing technology on the trueness and morphological features of printed objects depending on the geometry of the printed models. 3D printer users should consider the geometry of the printing parts and the degree of trueness required for certain applications when deciding on printing orientation and layer thickness.

Conclusion

Within the limitations of this study, the printing trueness was affected by the geometry of the printing model, thickness of the printing layer, and printing orientation. The cube model was more accurately printed by IMC (DLP), while the tooth-shaped model was more accurately printed by Form 3 (SLA) when both models were printed at 0-degree orientation with 50 μm thickness. Regardless of the geometry of the models, both printers exhibited greater deviation when the models were printed tilted at 45-degrees with a printing thickness of 100 μm.

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Original Article

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The aim of this study was to evaluate the influence of print layer thickness and orientation of two 3D printers on the trueness of printed models. Two different models (cube and tooth form models with class II cavity) were printed with a DLP printer (IMC, Carima) and an SLA printer (Form 3, Formlabs) with different layer thickness and printing orientation (n=12). The printed models were scanned to obtain STL datasets. Trueness of the printed models relative to the reference dataset was obtained using the superimposition technique. The surface of the 3D printed models was evaluated by SEM. One-way ANOVA and Tukey post hoc were performed. For the cube model, the overall mean trueness values were lowest by the DLP printer at 0-degree orientation in 50 μm layer thickness (20.49 μm), while the highest deviation was observed with the SLA printer at 45-degree orientation in 100 μm layer thickness (61.03 μm) ($p < 0.001$). For the tooth-shaped model, the lowest deviation was observed with the SLA printer at 0-degree orientation in 50 μm layer thickness (25.63 μm), while the highest deviation was found with the DLP printer at 45-degree in 100 μm layer thickness (47.56 μm) ($p < 0.001$). In SEM image, the SLA printer exhibited a relatively smoother surface compared to the DLP printer. In conclusion, the trueness was affected by the type of 3D printer, the geometry of the printing model, the thickness of the printing layer, and printing orientation for each printer.

Keywords : Three-dimensional printing, Trueness, Surface analysis, Layer thickness, Printing orientation.