Effects of build conditions and angle acuteness on edge reproducibility of casting patterns fabricated using digital light projection

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The aim of the present study was to evaluate the effects of build conditions and angle acuteness on edge reproducibility of the casting patterns fabricated using a digital light process. The prism-shaped patterns with various vertex angles were fabricated in three build orientations. The height from the base to the vertex angle point of the fabricated pattern was measured and the incomplete height was calculated as the discrepancy between the original and measured heights. Two-way ANOVA revealed that the vertex angle and build orientation and their interaction were significant (p<0.05). The incomplete height significantly decreased with an increase of the vertex angle. When the vertex angle was 20° and the build-up direction was parallel to the edge of vertex angle and perpendicular to the triangular base, the incomplete height was the smallest. Therefore, build orientation and angle acuteness influenced the edge reproducibility of the casting patterns fabricated using a digital light process.

Keywords: Build orientation, Angle acuteness, Edge reproducibility, Digital light projection

INTRODUCTION

Traditionally, the fabrication of dental prostheses has been reliant on the skills of dentists and dental technicians. In comparison with this conventional method, fabrication using computer-aided design and computer-aided manufacturing (CAD/CAM) systems can reduce the hands-on involvement of professionals1). In recent years, additive manufacturing has been used as a digital tool and has become more popular in dental and medical fields1-2). This technology is used for fabricating models layer-by-layer directly from a three-dimensional CAD using, for example, standard tessellation language (STL) files3-6). The printing technologies, which involve polymer-based materials, can be categorized by the fabrication process into thermal, chemical/mechanical, and optical: the thermal process includes material extrusion (fused deposition modeling or fused filament fabrication) and sheet lamination; the chemical/mechanical processes involves powder bed fusion and binder jetting; and the optical process includes powder bed fusion, material jetting and vat photopolymerization. Vat photopolymerization, stereolithography (SLA), and digital light projection (DLP) are common printing techniques where an optical light source is used to polymerize a monomer in a vat along the x-y-axis to form solid layers piled up in the z-axis. SLA employs a laser beam to polymerize the monomer; thus, the intensity of each point is stable but fabrication requires a long process time. DLP involves 2D image projection with a digital micromirror device wherein the process is fast but includes deviation of the light intensity. Because of the relatively high resolution and low cost, DLP devices are currently being widely used in the dental field4,5,7). In prosthodontics, many dental prostheses can be developed using DLP printing, such as dental models, resin casting patterns, temporary fixed restorations, and surgical guides8). There are several factors that influence the reproducibility of SLA printing, such as light intensity, exposure time, slice thickness, supporting base design, and build orientation (direction of printing can also be defined as build direction or build angle)7,8,9,10). Similarly, these factors are also considered to influence the reproducibility of DLP printing; however, only a few studies concerning the reproducibility of DLP printed dental products have been reported. The effects of build angle on the reproducibility of DLP printing for temporary dental crown restorations have been examined, wherein a build angle of 135° was recommended for the most accurate reproduction10). Moreover, the acute angle of prism-shaped specimens has been reported to influence the reproducibility of material extrusion and material jetting10-11); therefore, the acute angle is considered to be an influential factor on the reproducibility of specimens fabricated with DLP. There are several methods to evaluate the reproducibility of printed specimens fabricated with additive manufacturing, such as the fitness of a crown-shaped specimen, dimensional size of a bar-shaped specimen, and a prism-shaped specimen7,10,11). The prism-shaped specimen has a simple geometry and is advantageous to investigate the angle acuteness and build orientation arrangement.
Recently, although sharp edge reproducibility utilizing various printing technology have been reported, little is known about sharp edge reproducibility fabricated using DLP technology.

The purpose of the present study was to evaluate the effect of build orientation and angle acuteness on the edge reproducibility of prism-shaped casting patterns fabricated by DLP printing. The null hypothesis was that the build orientation and angle acuteness would not affect edge reproducibility of prism-shaped casting patterns produced by DLP printing.

**MATERIALS AND METHODS**

The three photopolymerized monomers and their exposure times used in the present study are summarized in Table 1. The specifications of the DLP printer and its software are described in Table 2. The exposure time of each monomer was determined to obtain a 0.2-mm-thick polymer sheet using the DLP machine.

**Design of CAD specimens for DLP printing**

Four prism-shaped specimens, with various vertex angles, were created using the 3D CAD software (FreeForm ModelingPlus V12.0, Geomagic, Morrisville, NC, USA). The dimensions of the specimens were designed to have a height of 15 mm, a length of 20 mm, and various vertex angles of 5°, 10°, 20°, and 30° (Fig. 1).

The designed 3D images were saved as STL files.

**Build orientation of CAD specimens**

Supporting design software (B9creator, B9Creations, Rapid City, SD, USA) was used to create the STL files for printing. A honeycomb supporting base (45×25×1 mm) was placed on the stage. Prism-shaped specimens were assigned according to three build orientations (Fig. 2); A: the triangular base of the prism-shaped specimen is directly placed on the supporting base; B: one lateral side

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### Table 1  Material information and exposure times used for DLP printing

| Brand             | Manufacturer                      | Lot no. | Color | Exposure time (s) | Abbreviated code |
|-------------------|-----------------------------------|---------|-------|-------------------|-----------------|
| NextDent Cast     | NextDent, Soesterberg, Netherlands | XK202N04| Purple| 8                 | ND              |
| FotoDent Cast     | Dreve Dentamid, Unna, Germany     | 707061X0| Red   | 10                | FT              |
| Katana 3D casting | DWS, Vecenza, Italy               | 000003  | Clear | 25                | KT              |

### Table 2  Specifications of the DLP printer

| DLP machine       | ML-48*, Mutoh Industries, Tokyo, Japan |
|-------------------|---------------------------------------|
| Stage size        | 48×27×80 mm                            |
| Light source      | LED light                              |
| Wavelength        | 405 nm                                 |
| Light intensity   | 3.8 Watts                              |
| Resolution        | X=80 µm, Y=40 µm                       |
| Software          | Control software                       |
|                   | Slicer software                        |
|                   | Supporting design software             |
| Enter date format | STL                                    |

*The light intensities of the printed area are adjusted to be constant by the manufacturer.*
of the prism-shaped specimen was directly placed on the supporting base; C: the edge of vertex angle of the prism-shaped specimen was parallel to the supporting base, the triangular base was perpendicular to the supporting base, and the space between the prism bottom base line and the supporting base was 1 mm. For only pattern C, 30 cylindrical supporting bars with 25% cone shape on the top (a diameter of 0.5 mm, a height of greater than 1.0 mm) were designed, 5 groups of 6 bars were assigned parallel to the edge of vertex angle with the nearest located 2 mm from the edge of vertex angle. The vertex angles of 5°, 10°, 20°, and 30° of patterns A or B were printed simultaneously, while two vertex angles (5° and 10°; 20° and 30°) for pattern C were printed at the same time (Fig. 2). Then, these images were exported as STL files.

**Preparation of printing images and DLP printing**
The 50-µm-thick sliced images were prepared using the CAD software (ML_slicer, Mutoh Industries, Tokyo, Japan). The files were saved as bitmap image files.

The DLP machine was operated using control software (Pronterface, Mutoh Industries) to fabricate the specimens. Six prism-shaped specimens with the same vertex angle were prepared for each build orientation. Total number of the specimens were 72 for each material. The printed specimens were removed from the stage and cleaned with isopropanol (Japanese Pharmacopoeia grade, Wako Chemical, Osaka, Japan; >99.9%) for 2 min twice using an ultrasonic cleaner (Bransonic, Branson Ultrasonic, Danbury, CT, USA) without a post-curing process. Specimens were stored in a metal box at room temperature for 1 day.

**Measurement of height of the specimens**
The heights (H) of patterns A, B, and C, where the distance between the prism base plane and edge of vertex angle was perpendicular to their base plane, were measured at 5 locations (a, b, c, d, and e). The distance between neighboring locations was 2.5 mm, as shown in Fig. 3. The three-dimensional positions (x, y, and z coordinates) of the 3 vertex points of patterns A and B in the cross-sectioned plane, which included one of the measured locations perpendicular to the base plane and vertex angle line (Fig. 3A2), were measured using a microscope (MM-60, Nikon, Tokyo, Japan; minimum reading 1 µm). For pattern C, 2 vertex points of the vertex angle point and the higher base plane point were measured (Fig. 3C). The height at location a (H_a) was determined by calculation from the coordinate points. After measuring the 3D printed specimens, the discrepancy between the heights of the specimen and the CAD image was defined as the incomplete height of the vertex angles point (Fig. 4).

**Cross-section image of specimens**
To observe the surface outline of the prism-shaped specimen, the specimen was cross-sectioned at point b in Fig. 3 using a low-speed saw with a diamond blade (IsoMet Low Speed Precision Cutter, Buehler, Lake Bluff, IL, USA). A digital microscope (VHX-S50, Keyence, Osaka, Japan), at a magnification of 20×, was used to record the surface outline of the specimens.
**Statistical analyses**
The incomplete heights of each material were analyzed with two-way ANOVA, by selecting build orientation and angle acuteness as the main factors. The incomplete heights for the vertex angles with the same pattern and those for the patterns with the same vertex angles were compared using Tukey's post-hoc test. Statistical software (SPSS Statistics for Windows, version 24, IBM, Armonk, NY, USA) was used at a significance level of 5%.

**RESULTS**
The prism-shaped specimen was generally printed with smooth surfaces except for the vertex angle portion. The apex of the vertex angle of 5° was obviously bent, and those of the vertex angles of 10°, 20°, and 30° for pattern C were slightly distorted. The measured incomplete heights are summarized in Table 3. The maximum incomplete height was observed for pattern B with a vertex angle of 5° for KT, (1.92±0.12) mm, while the minimum was observed for pattern C with a vertex angle of 20° for ND, (0.03±0.00) mm.

Two-way ANOVA of all materials suggested that two main factors and their interaction were significant. The incomplete heights significantly decreased with an increase of the vertex angle except for pattern C with a vertex angle of 20° and 30°; the incomplete height of the pattern C was significantly smaller than those of the other patterns except for a vertex angle of 30° for pattern A. The incomplete height of KT was generally greater than those of the other materials at the same condition, while that of ND was generally smaller than those of the other materials at the same condition.

A bending was observed at the apex for a vertex angle of 5° for all patterns of the cross-section images, but such bending was not obvious at 10° except for pattern C. For pattern C, a bending was observed at the apex of the vertex angle of 5°.

| Material code | Pattern | Angle | 5°   | 10°   | 20°   | 30°   |
|---------------|---------|-------|------|-------|-------|-------|
| ND            | A       | 1.09 (0.07) | 0.47 (0.04) | 0.30 (0.05) | 0.16 (0.03) |
|               | B       | 1.37 (0.1)  | 0.66 (0.15) | 0.45 (0.03) | 0.44 (0.16) |
|               | C       | 0.38 (0.02) | 0.08 (0.01) | 0.03 (0.00) | 0.12 (0.01) |
| FT            | A       | 1.24 (0.04) | 0.54 (0.03) | 0.33 (0.02) | 0.19 (0.06) |
|               | B       | 1.73 (0.14) | 0.95 (0.2)  | 0.51 (0.04) | 0.44 (0.04) |
|               | C       | 0.49 (0.02) | 0.19 (0.01) | 0.14 (0.01) | 0.24 (0.01) |
| KT            | A       | 1.43 (0.09) | 0.60 (0.04) | 0.37 (0.02) | 0.19 (0.02) |
|               | B       | 1.92 (0.12) | 0.96 (0.06) | 0.56 (0.03) | 0.44 (0.04) |
|               | C       | 0.53 (0.01) | 0.22 (0.01) | 0.11 (0.02) | 0.18 (0.01) |

Standard deviations are in parentheses and the same superscript capital letter indicates no significant differences among vertex angles within the same pattern (p>0.05). The same superscript small letter indicates no significant differences among patterns within the same vertex angle (p>0.05). The same superscript number indicates no significant differences among the interaction between vertex angle and build orientation within the same material (p>0.05).

**Table 3**  Incomplete height of the specimens

**Fig. 5**  Cross-section images for vertex angles of 5° and 10° for patterns A, B, and C and vertex angles of 20° and 30° for pattern C, printed using ND, FT, and KT.
apex for all vertex angles. Comparing the bending at the apex of pattern C for the 3 materials, the bending of KT was obviously greater than ND and FT. In addition, observation of the supporting area, which was between the specimen and the supporting base, indicated that the supporting area of KT was more occupied by resin than that of ND, while that of FT was not blocked (Fig. 5).

**DISCUSSION**

The null hypothesis that the build orientation and angle acuteness would not affect edge reproducibility of prism-shaped patterns produced by DLP printing was rejected because the build orientation and angle acuteness significantly influenced the incomplete heights.

To reproduce a designed shape is an important criterion for casting patterns. Edge reproducibility, which refers to the printed sharp part of a pattern, such as the margin of a dental crown, is a requirement to achieve a sound pattern. Therefore, the present study focused on edge reproducibility using DLP printing. Build orientation and angle acuteness were selected to be the evaluated factors based on the knowledge from previous studies that used vat photopolymerization and sharp edge patterning.

The DLP printer used in the present study allowed customization of many parameters such as exposure time, z-axis speed, and thickness of printed layer. The light intensity deviation of this printer had been adjusted by the manufacturer. Three different printing monomers were used in the present study; therefore, their polymerization properties were not identical owing to the different types of monomer, photoinitiator systems, viscosities, and translucencies. Regarding our preliminary study, suitable exposure times for ND, FT, and KT were determined to achieve a 0.2-mm polymerized layer. If the polymerized layer was thinner than this value, the shape of the specimen could not be obtained.

The prism-shaped pattern was suitable to evaluate the effect of angle acuteness and was applicable to assign a different build orientation. The accuracy of edge reproducibility of the prism-shaped pattern was determined by the incomplete heights of the vertex angle. The deformation at the edge of the vertex angle was also observed.

There are several processes that reduce the edge reproducibility. One potential process is the sliced-image making process in which a 3D CAD design is sliced into 2D images. The created sliced images used in the present study were observed. The total number of images should be equal to the height of the specimen divided by 50 μm. The height of printing images of vertex angles of 5°, 10°, 20°, and 30° for pattern A were until 14.60, 14.70, 14.90, and 14.90 mm, respectively (Fig. 6); as a result, images regarding 5°, 10°, 20°, and 30° within 0.40, 0.30, 0.10, and 0.10 mm from the apex were not fabricated, respectively.

The complete height for pattern C along the x-axis was smaller than that of pattern A along the z-axis and B along the x-axis. These results arose from the exposure shape of the specimen layer and the resolution of the printing machine. The exposure shape of the specimen layer for patterns A and C was rectangular, while that of pattern B was triangular. Moreover, the height of pattern A was measured along the z-axis, but those of patterns B and C were measured along the x-axis. The edge reproducibility was limited by the resolution of the printer, where the resolution along the x-axis and y-axis were 80 and 40 μm respectively. The height of pattern A was measured along the z-axis and was limited by the resolution along the y-axis. For example, the incomplete height of pattern A at a vertex angle of 5° in modeling could be calculated to be 0.45 mm, because 20 μm (half of the y-axis resolution) is divided by the tangent 2.5° (half of the vertex angle). The incomplete height of pattern B was measured along the x-axis and was limited by the resolution along the y-axis, therefore the incomplete height of pattern B in modeling calculated to be 0.45 mm; but that of pattern C was the resolution along the x-axis, which was 0.08 mm. These calculated results, where the incomplete height of C was better than those of A and B, agree with the previous study that used material jetting and the material extrusion technique. However, these calculated values are smaller than the observed incomplete heights. Another factor, such as a bending edge, might be the reason for this discrepancy.

The bending at the edge of the apex was found for a vertex angle of 5° for all patterns, and at vertex angles of 10°, 20°, and 30° for pattern C, while such bending was not obvious at these vertex angles for patterns A and B. The bending at the apex for a vertex angle of 5° for patterns A and B occurred owing to their thin layers. The apex for all vertex angles of pattern C bent towards the opposite side of the supporting base because of the lack of supporting base connecting the edge of the vertex angle and the supporting base. This shrinkage-induced bending has been reported to arise from internal compressive stress of the polymerized layer. When a polymer layer is constantly photopolymerized from one side, the material which was cured first becomes smaller to release internal stress, whereas the newly cured material shrinks under the confinement of the previous layer.

Regarding the occupied space by the resin at the supporting area of the pattern C, KT was more occupied than ND and FT, where FT was not occupied at all.
These differences in the occupied space among the 3 printing materials probably arise from their viscosity, color, and level of transparency. The viscosities of KT and ND are higher than that of FT. In the supporting area, the monomer with a high viscosity could not escape from the supporting side of the specimen. Thus, there is the possibility that the monomer remained and was polymerized. It has been reported that light can penetrate through the transparent solidification layer and induce polymerization of the monomer\textsuperscript{12,13}. Concerning the transparency, KT has a higher transparency than ND and FT, and FT is the most opaque monomer among the 3 materials. The darker colored monomer, which contains more opaque pigmentation, requires higher light intensity or longer exposure time for photopolymerization\textsuperscript{11,14}. Therefore, the occupied space of FT with pattern C was small.

Referring to the prism-shaped pattern, the edge of the apex was similar to the margin of a dental crown. The results of the present study state that vertex angle of at least 20° is recommended to create a complete pattern. The casting patterns margin for a full coverage dental crown should be at least 20°\textsuperscript{15}, therefore, the thickness of the crown margin should be increased to avoid incomplete printing and deformation. Moreover, the influence of the build orientation is reduced when a larger vertex angle is used.

The results from the present study were limited owing to different monomers and the printing machine. The resolution and light intensity of the DLP printer used in the present study were in the range of other DLP printers available in the market. Therefore, similar phenomenon might occur when another DLP machine is used. The present study focused on edge reproducibility, which refers to a printed sharp part of a model, such as a margin of a dental crown. Thus, the present study added to the knowledge to apply the printed polymer pattern to use for the “lost wax” method. Moreover, further studies are also needed to evaluate the dimensional accuracy of a crown-shaped casting pattern fabricated using DLP as a preferred alternative to the “lost wax” method.

CONCLUSION

Within the limitations of the present study, it concludes that the build orientation and angle acuteness influence the edge reproducibility of casting patterns fabricated by DLP. The recommended vertex angle and build orientation were at least 20° and fabricated in pattern A or C, respectively.

ACKNOWLEDGMENTS

Part of this study was supported by JSPS KAKENHI Grant No. JP18K09677 and Project for Leading-edge Research in Oral Sciences at Tokyo Medical and Dental University (TMDU).

REFERENCES

1) Sun J, Zhang FQ. The application of rapid prototyping in prosthodontics. J Prosthodont 2012; 21: 641-644.
2) Nayar S, Bhuminathan S, Bhat WM. Rapid prototyping and stereolithography in dentistry. J Pharm Bioallied Sci 2015; 7: 216-219.
3) van Noort R. The future of dental devices is digital. Dent Mater 2012; 28: 3-12.
4) Stansbury JW, Idacavage MJ. 3D printing with polymers: challenges among expanding options and opportunities. Dent Mater 2016; 32: 54-64.
5) Ide Y, Nayar S, Logan H, Gallagher B, Wolfardt J. The effect of the angle of acuteness of additive manufactured models and the direction of printing on the dimensional fidelity: clinical implications. Odontology 2017; 105: 108-115.
6) Mitteramskogler G, Gmeiner R, Felzmann R, Gruber S, Hofstetter C, Stampfl J, et al. Light curing strategies for lithography-based additive manufacturing of customized ceramics. Addit Manuf 2014; 1-4: 110-118.
7) Osman R, Alharbi N, Wismeijer D. Build angle, does it have an influence on the accuracy of 3D-printed dental restorations using digital light-processing technology. Int J Prosthodont 2017; 30: 182-188.
8) Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in prosthodontics: where do we currently stand? A critical review. Int J Prosthodont 2017; 30: 474-484.
9) Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J Prostheth Dent 2016; 11: 760-767.
10) Alharbi N, Osman RB, Wismeijer D. Factors influencing the dimensional accuracy of 3D-printed full-ceramic dental restorations using stereolithography technology. Int J Prosthodont 2016; 29: 503-510.
11) Tahayeri A, Morgan MC, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, et al. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater 2018; 34: 192-200.
12) Zhao Z, Wu J, Mu X, Chen H, Qi H J, Fang D. Origami by frontal photopolymerization. Sci Adv 2017; 3: e1602326.
13) Vitale A, Hennessey MG, Matar OK, Cabral JT. A unified approach for patterning via frontal photopolymerization. Adv Mater 2015; 27: 6118-6124.
14) Dikova T, Dzhendov D, Katrena I, Pavlova D. Accuracy of polymeric dental bridges manufactured by stereolithography. Arch Mater Sci Eng 2016; 78: 29-36.
15) Bernard S, Leslie H. Planning and making crowns and bridges. 4th ed. Abingdon: Informa Healthcare; 2007. p. 53-54.