Dimensional accuracy of dental casting patterns created by 3D printers

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Contrary to widespread incise CAD/CAM, little is known about the dental application of 3D printing, especially the possibility of using 3D printing with organic material. The resin patterns of a full crown model were created by four types of 3D printers, a thermo-fusion device (CX), a digital light processing stereo-lithograph device (B9), a laser stereo-lithograph device (DW) and a multi-jet modeling device (PJ). The dimensional accuracy of the outer and inner diameters and depths of the created model crowns, and the surface roughness of sidewall were investigated. The outer diameters were smaller than the designed value in most conditions. The inner diameters were smaller than the designed value in any enlargement ratio except B9. The depth of CX or B9 tended to become shallower, though that of PJ or DW tended to increase. The surface roughness along the tooth axis direction was greater than that perpendicular to the tooth axis.

Keywords: 3D printer, Dimensional accuracy, Surface roughness, Additive manufacturing

INTRODUCTION

In recent years, the development of 3D printing has been significant, and the technical advancement in their performance and the current trend toward lower prices has progressed at an incredible speed. As a result, more delicate and highly precise modeling has become possible, and attempts to use this technology in medical applications have been made1-3). Dental prosthesis manufacturing methods using an incise CAD/CAM system have been clinically applied to composite resin block4-6), pure titan block7-9), zirconia block8-9), requiring firing after milling and the use of a wax or resin block10) to utilize the casting patterns made by milling. However, due to the limitation of the size and applied angle of the cutting tool in the cutting process, there is a limit to the processing of complex shapes11-12). If it is possible to replace the cutting process of CAM with 3D printing, it will be possible to prepare more complex prostheses, which is considered to be unfeasible in the cutting process. Furthermore, from the viewpoint of the effective utilization of the material, the 3D printer as an additive manufacturing device is believed to be superior to the cutting process. Recently, although the dental application of 3D printing utilizing metal powder and the laser sintering technique have been reported13), little is known about the dental application of 3D printing using resin materials14).

Thus, the purpose of this study was to investigate the possibility of using 3D printing with organic material in dental applications. Four different types of 3D printers, i.e., a thermo-fusion type, which is widely used because of its low price, two stereo-lithographic types and a multi-jet modeling type, were employed to prepare full crowns of a resin pattern, and then, the respective dimensional accuracy of the crowns was compared. The data processing required to increase the dimensional reproducibility during the production was also studied, and then, the possibility of use in dental applications was evaluated.

MATERIALS AND METHODS

In this study, four types of 3D printers, i.e., a thermo-fusion device, which discharges the thermoplastic resin filaments from the nozzle at a high temperature (Cube-X Trio, 3D Systems, SC, USA, hereafter abbreviated as CX), a digital light processing stereo-lithograph device (B9Creator, B9Creations, SD, USA, hereafter abbreviated as B9), a stereo-lithograph device utilizing the laser galvano scanning system (DW028D, DWS s.r.l., Vicenza, Veneto, Italy, hereafter abbreviated as DW), and a multi-jet modeling device, which jets the thin monomer layer from multi-heads, which is then cured by UV laser (Projet DP 3000, 3D Systems, SC, USA, hereafter abbreviated as PJ), were used. The specifications of the 3D printer used in this study are shown in Table 1.

The simplified full crown, applied as a resin pattern for casting to be created by a 3D printer, was designed. The dimensions of the model crown were as follows: an outer diameter of 13 mm, an outer height of 11 mm, an inner diameter of 10 mm, a depth of 10 mm of the inner surface, and the inner wall was shaped to conform to a 1/10 tapered abutment, as shown in Fig. 1. The 3D data of the full crown was created by 3D software (Creo Elements/Direct Modeling Express 4.0, PTC, Needham, MA, USA). The software output the 3D model as STL (Standard Triangulated Language) data. STL is a file format for the CAD/CAM software. An STL file describes a triangulated surface by three vertices of the triangle and by a normal unit vector using three dimensional coordinates, so a total of 12 coordinate values is required for each facet15-17). Utilizing the STL data, the crown was molded by the 3D printers. Because poor fits
Table 1  Specifications of the 3D printers used in this study

| 3D printer | Code | Type          | Material (lot No.)                     | Manufacturer                  | Minimum stacking pitch (μm) |
|------------|------|---------------|----------------------------------------|-------------------------------|----------------------------|
| CubeX Trio | CX0  | Thermo-fusion | PLA Blue M (X12052013-1PLA MLU) PLA    | 3D Systems (Rock Hill, USA)   | 100                        |
|            | CX1  |               | PLA                                    |                               |                            |
|            | CX2  |               |                                        |                               |                            |
| B9Creator  | B9   | DLP-SLA       | B9-R-1-RED (021813) UV curing Acrylic resin | B9Creations (Rapid City, USA) | 25                         |
| Projet DP3000 | PJ | Multi-jet     | VisiJet DP200 (DP132502A) UV curing Acrylic resin | 3D Systems (Rock Hill) | 29–32                      |
| DW028D     | DW   | Laser galvano | RF080 (4120225) Wax resin               | DWS s.r.l. (Vicenza, Italy)   | 10                         |
|            | SLA  |               |                                        |                               |                            |

Fig. 1  Dimensions of the prototype of the model crown.

were frequently observed during the molding process; models enlarged to 101, 103 and 105% of the originally designed entire 3D model size were also created by the 3D printers. Furthermore, in order to perform a precise molding of the marginal portion, the data were arranged to mold the occlusal surface onto the modeling stage.

It is well known that the deformation of the part where the molded object came into contact with modeling stage is significantly large using the CX. Therefore, in order to prevent this effect, three conditions for a support setting were adopted. In the first condition, molding was performed without a support (hereafter abbreviated as CX0); one cylindrical support 3 mm in diameter and 3 mm in height was applied in the second condition (hereafter abbreviated as CX1); and three cylindrical supports of the same size as those in the second condition were applied in the third condition (hereafter abbreviated as CX2). The supports were designed to be placed between the occlusal surface and the modeling stage. In these cases, the bundled software of the CX automatically generated 17 thinner supports 1 mm in diameter and 3 mm in length under the second and third conditions. Moreover, in order to prevent distortion when removing the created crown from the modeling stage, the raft was placed between the model and the stage. The instrumental setting of each of the 3D printers was set to the highest resolution. Removal and post-processing of the created crown from the stage were carried out according to the accompanying manual of each printer.

The dimensions of the created crown, i.e., the outer diameter, inner diameter and depth, were observed by digital microscopy (VHX-2000, Keyence, Osaka, Japan) at a magnification of 200×. In addition, the surface roughness of outer sidewall of the crown along or vertical to the tooth axis was observed (Surfcom 2B, Tokyoseimitsu, Tokyo, Japan).

Specimens were made three times under each molding condition, and then the average of the observed values for each specimen was adopted as the specimen’s value under the specific molding condition. For the outer and inner diameters and depth of crowns molded by 3D printers, the value obtained by subtracting and dividing by the size of the designed prototype shown in Fig. 1 was calculated as the expansion rate (%), with 3 iterations (n=3). For the statistical treatment of the results, a two-way ANOVA (Factor A as the printer types, factor B as the enlargement ratio) for the inner and outer diameters and depth in regard to expansion rate and a two-way ANOVA (Factor A as the printer types, factor B as the scanning direction) for surface roughness were performed. Tukey’s test of multiple comparisons was performed when a significant difference was observed for the main factors or their interaction in the two-way ANOVA.

RESULTS

For the crowns created by 3D printers, the exterior views, in which the occlusal surface and cervical region were directed downward and upward, respectively, are shown in Fig. 2. Concerning the crowns created by CX (CX0, CX1 and CX2), the raft on the occlusal surface could be seen, and the horizontally striped pattern formed during the lamination on the sidewall could be
confirmed. It was clear from the specimen created by DW that support was provided to the occlusal plane so that the modeling stage and occlusal surfaces would not contact directly. Such support was not provided in the specimen created by B9 and PJ. The color of the specimens was different because the materials used in this study were different.

Overall images of the inner ceiling observed from the cervical direction, enlarged pictures of the basal plane of the cervical portion, the occlusal (top) surface and the outer sidewall of the marginal portion are shown in Fig. 3. The gap between the outer and inner sidewall in the basal plane of cervical portion was observed in the CX-molded specimen, and the lamination of the melting resin filament could be visually confirmed. Because a semi-transparent material was used in printing with DW, the support given to the occlusal surface could be seen as whitish. With respect to the expansion rates of the specimens created by following the two-way layout experimental design, whose two factors were type of 3D printer and the enlargement ratios of the prototype, the mean values and standard deviations of the ratio of the prototypes inner and outer diameters and depths are shown in Table 2.

From the two-way ANOVA of the outer diameter of the expansion rate (%), which was calculated from the value of the prototype shown in Fig. 1, significant differences were found for the type of printer (factor A), the enlargement ratio (factor B) and the interaction of the type of printer and the enlargement ratio (A×B) (p<0.01). The outer diameter became smaller than the designed value in most conditions, except in some cases of CX. B9 showed the smallest value of all of the enlargement ratios. No significant difference (p>0.05) in the number of supports of CX was observed.

From the two-way ANOVA of the expansion rate of the inner diameter (%) calculated from the value of the prototype, significant differences were found for the type of printer (factor A), the enlargement ratio (factor B) and the interaction of the type of printer and the enlargement ratio (A×B) (p<0.01). Generally, each printer in any enlargement ratio showed a smaller value than the designed one, with the exception of B9. In particular, the crowns molded by CX were of a much
Table 2  Mean values and standard deviations of the ratio of inner and outer diameters and depths of the prototypes

| Code | 100%   | 101%   | 103%   | 105%   |
|------|--------|--------|--------|--------|
|      |        |        |        |        |
| Outer diameter |        |        |        |        |
| CX0  | -0.49 (0.04) | 0.92 (0.53) | 2.47 (0.15) | 5.03 (0.50) |
| CX1  | -0.39 (0.21) | 0.98 (0.52) | 2.58 (0.14) | 5.23 (0.41) |
| CX2  | -0.24 (0.16) | 1.05 (0.46) | 3.55 (0.47) | 5.18 (0.20) |
| B9   | -2.82 (0.24) | -0.57 (0.55) | 1.11 (0.49) | 2.74 (0.13) |
| PJ   | -0.16 (0.45) | 0.49 (0.16) | 2.56 (0.08) | 4.42 (0.09) |
| DW   | -0.65 (0.17) | 0.01 (0.07) | 1.18 (0.10) | 3.33 (0.30) |

| Inner diameter |        |        |        |        |
|               |        |        |        |        |
| CX0  | -2.45 (0.71) | -1.73 (0.52) | 0.03 (0.16) | 3.17 (0.29) |
| CX1  | -3.02 (0.15) | -1.07 (0.48) | 0.36 (0.20) | 3.69 (0.35) |
| CX2  | -3.35 (0.08) | -2.59 (0.06) | -0.08 (0.35) | 1.31 (0.34) |
| B9   | 1.87 (0.55)  | 2.39 (0.70)  | 4.44 (0.84)  | 6.80 (0.48)  |
| PJ   | -0.30 (0.21) | 0.66 (0.18) | 2.71 (0.41) | 4.91 (0.42) |
| DW   | -0.07 (0.03) | 0.75 (0.31) | 1.89 (0.44) | 4.01 (0.17) |

| Depth   |        |        |        |        |
|---------|--------|--------|--------|--------|
| CX0    | -5.99 (1.13) | -5.64 (0.83) | -2.99 (1.03) | -2.24 (0.37) |
| CX1    | -5.21 (0.45) | -3.72 (0.25) | -2.43 (0.41) | 0.24 (0.45) |
| CX2    | -5.21 (1.51) | -3.61 (0.64) | -2.36 (0.39) | -0.54 (1.23) |
| B9     | -4.12 (0.38) | -0.45 (0.23) | 2.24 (0.35) | 2.81 (0.49) |
| PJ     | 0.49 (0.32) | 1.59 (0.24) | 3.58 (0.31) | 5.18 (0.55) |
| DW     | 0.43 (0.08) | 1.36 (0.04) | 3.37 (0.16) | 5.28 (0.33) |

The same superscript letters indicate values with no statistically significant difference (p>0.05).

Table 3  Mean values and standard deviations of the deviation from the designed value of the inner and the outer diameters and the depth in millimeters

| Printers | Outer diameter | Inner diameter | Depth |
|----------|---------------|----------------|-------|
| CX0      | -0.035 (0.053) | -0.249 (0.060) | -0.646 (0.093) |
| CX1      | -0.019 (0.054) | -0.226 (0.073) | -0.503 (0.046) |
| CX2      | 0.018 (0.055) | -0.343 (0.032) | -0.518 (0.096) |
| B9       | -0.277 (0.077) | 0.162 (0.060) | -0.213 (0.135) |
| PJ       | -0.055 (0.035) | -0.025 (0.030) | 0.046 (0.036) |
| DW       | -0.166 (0.068) | -0.060 (0.053) | 0.036 (0.017) |

The same superscript letters indicate values with no statistically significant difference (p>0.05).

smaller value than the designed crowns.

From the two-way ANOVA for expansion rate of depth (%) calculated from the value of the prototype, significant differences were found for the type of printer (factor A), the enlargement ratio (factor B) and the interaction of the type of printer and the enlargement ratio (A×B) (p<0.05). In any enlargement ratio, printing with CX and B9 showed a tendency to become quite shallow, although printing with PJ and DW showed a tendency to become slightly greater in depth.

The deviation of the inner and outer diameters and depths from the designed values were easily calculated from the above data. The results indicated significant differences in factor A, i.e., the type of printer, and the deviations between the measured values of molded crown and the designed values (n=12) in millimeters are shown in Table 3. The inner diameters and depths of the crowns created by PJ or DW showed a relatively high precision.

The mean values and standard deviations of...
the surface roughness of the crown, formed by the different types of 3D printers and measured in different operating directions, are shown in Table 4. From the two-way ANOVA of surface roughness, significant differences were found for the type of printer (factor A), the scanning direction (factor B) and the interaction of the type of printer and the operating direction (A×B) \((p<0.05)\). As for the type of printer, surface roughness along the tooth axial direction was greater than the roughness in a direction horizontal to the tooth, except for that of CX or DW. The surface roughness observed in the crown molded by CX was the largest; the roughness observed along the tooth axial direction of the crown molded by DW was the smallest, and the roughness observed in the crown created by PJ in the direction horizontal to the tooth axis was the smallest.

### DISCUSSION

The patent of thermo-fusion technology for 3D printers expired in 2009, and low-cost thermo-fusion 3D printers appeared on the market soon after and were widely distributed\(^{21,22}\). However, if low-cost printers are compared to printers for professional use, it is clear that the former is inferior in terms of precision. With respect to the printers used in this study, the CX thermo-fusion type and B9 digital light processing stereo-lithograph type 3D printers are regarded as relatively low-cost printers, while the DW laser stereo-lithograph type of 3D printer and the PJ multi-jet modeling device utilizing a UV laser are regarded as professional devices.

The lamination pitch of CX was 0.1 mm, which is quite large compared to that of other printers used in this study, therefore, the striped pattern contour caused by laminations was clearly observed in the crowns made by CX. The lamination pitch of B9 was 25 \(\mu\)m\(^{23}\) and was regarded as being relatively large, but the appearance of the crown was relatively smooth because of the molding method performed by lifting a product from a monomeric solution. The lamination pitch of DW was the smallest at 10 \(\mu\)m\(^{23}\), so the crown showed a very smooth appearance when created with the molding method utilizing a stereo-lithograph device with laser light in a monomer liquid. Because PJ uses multi-jet modeling technology, it was not possible to directly compare the stacking pitch for the other methods of 3D printers. Although it was considered that the lamination pitch of 29–32 \(\mu\)m\(^{23}\) is relatively large, it exhibited a very smooth appearance.

The inner and outer diameters of the crown tended to be formed slightly smaller as a whole. The outer diameter of several crowns molded by CX showed a larger value than the designed value. Because the thermo-fusion method consisted of stacking the molten filaments by pushing the molten plastic from a nozzle tip with a diameter of 0.5 mm, the extruded thermoplastic resin was compressed, leading to the slight swelling of the crown. The inner diameter of the crown formed by B9 was exceptionally large, and the outer diameter was considerably smaller than those formed by the other printers. This might be due to the adoption of the digital light processing (DLP) projector because the focus of the illuminating light at an edge became blurred as the distance from the center of the designed area increased, so the edge of the crown tended to remain unpolymerized; therefore, when viewed from the entire modeling area, the molded crown grew thinner. In general, as for the printer using the laser stereo-lithograph or inkjet with UV laser method, due to the contraction during polymerization of the monomer by the laser, the dimension of the molded crown tended to become smaller than the designed value. PJ cured the thin layer of the jetted monomer droplet, so polymerization shrinkage was also present, but the influence of the contraction due to the site was considered to be smaller. DW adopted a galvano scanning system for laser irradiation, so the difference due to the site was reduced, contrary to the case of B9. From the viewpoint of extra-coronal restoration, when the crown was molded by a 1% increase of the prototype using PJ or DW, the inner diameter between both sides was shaped approximately 70 \(\mu\)m larger in inside diameter on both sides. Considering the thickness of the cement component, the molded product obtained an excellent fit in terms of compatibility.

The stacking direction of the printer was coincident with the crown depth; the accuracy in depth was particularly susceptible to the performance of each printer. The depth of the crown molded by thermo-fusion printer CX became much smaller than the designed value because of the large stacking pitch of 0.1 mm; it also became much smaller in B9. The depth of the crown molded by PJ and DW was almost equal to the designed

### Table 4 Surface roughness in \(\mu\)mRa of the crowns molded by the 3D printers

| Code | Vertical direction | Horizontal direction |
|------|--------------------|----------------------|
| CX   | 7.67 (0.44)        | 7.22 (1.06)          |
| B9   | 5.50 (0.76)*       | 2.80 (0.47)*         |
| PJ   | 4.61 (0.49)*       | 2.09 (0.14)*         |
| DW   | 1.39 (0.10)        | 2.73 (0.13)*         |

The same superscript letters indicate values with no statistically significant difference \((p>0.05)\).
value; therefore, the thickness of a sufficient cement layer depth could be obtained without any scaling.

With respect to the type of printers, although CX showed the best accuracy in terms of the outer diameter, i.e., less than 50 μm, CX showed the worst accuracy in terms of the inner diameter and the depth, as shown in Table 3. Because PJ and DW showed the best accuracy, i.e., less than 60 μm, in terms of the inner diameter and depth, by understanding the characteristics of these printers, it is possible to prepare excellent compatible prostheses using these printers.

Regarding the horizontal surface roughness, as a significant difference was not observed among the printers; however, in the comparison with CX, uniform polymerization seemed to be induced, and then a relatively smooth surface was obtained by DW, a stereolithograph printer, and PJ, a multi-jet modeling printer. The surface roughness of the axial (vertical) direction indicated the largest value in CX and was regarded to directly reflect the magnitude of the lamination pitch. As a pattern for the dental crown, the roughness was so significantly large that preprocessing such as polishing prior to investing would be required for practical use. Compared to the vertical surface roughness of the crowns made by B9 and PJ, a considerably small value was observed in modeling with DW, due to the direct reflection of the size of the stacking pitch.

From the results of this study, as for CX, which is a thermo-fusion 3D printer, although the surface roughness and dimensional accuracy seemed to be problematic in terms of oral prosthesis applications, the relative dimensional accuracy could be improved with an increase in the size of the products, as in the jaw model. Dental applications of this type of 3D printer could be made possible by data processing, considering the compatibility of the abutment. However, current 3D printers utilizing stereo-lithography, regardless of whether they are of the DLP projector or galvano laser type or the multi-jet method, were believed to provide sufficient accuracy for dental applications by modifying some of the modeling data. Pattern casting has already been clinically applied in laser cutting using CAD/CAM technology. Additive manufacturing technologies, such as 3D printers, have a definite advantage in terms of the effective use of raw materials. The development of high-accuracy and low-cost instruments in the near future could be further applied to the dental industry.

CONCLUSIONS

Four 3D printers differing in their molding processes were employed to create resin patterns of the model crown, and the following conclusions were drawn.

1. The outer diameter of the created crown was smaller than the designed value in most conditions, especially that created by B9, which showed the smallest value. Some crowns created by CX showed greater values in the outer diameter than the designed ones.

2. The inner diameter of the created crown by the printers except B9 became smaller than the designed value at any magnification. In particular, the crown created by CX showed a much smaller inner diameter than the designed one.

3. In any of the enlargement ratios, although the depth of the crown created by CX and B9 tended to decrease considerably, that created by PJ and DW inversely showed a slightly increasing tendency.

4. With respect to the deviation from the designed value, CX showed the best accuracy in terms of the outer diameter and the worst accuracy in terms of the inner diameter and depth. PJ and DW showed the best accuracy for the inner diameter and depth.

5. The surface roughness of the crown created by CX was the largest, and the roughness along the tooth axial direction was greater than that along the horizontal direction for B9 and PJ. The roughness along the tooth axis of the crown created by DW was the smallest and that along the horizontal direction of the crown created by PJ was the smallest.

ACKNOWLEDGMENTS

We would like to thank Mr. Noriyuki OTAKE of 3D Solution Group, Department of Dental Solution, Toyotsu Machinery for assistance with the 3D printing. We also express our sincere appreciation to the staff of Department of Dental Materials Science, School of Life Dentistry at Tokyo, The Nippon Dental University for their invaluable support of this study.

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