1. Introduction

The Sustainable Development Goals (SDGs) adopted at the United Nations Summit in 2015 have been attracting attention owing to the current environmental challenges. These SDGs were established by the 193 member countries of the United Nations to be achieved between 2016 and 2030. They consist of 17 goals, including waste reduction, environmental protection, and technological innovation, and 169 targets. Goal 12 of the SDGs, “Ensure sustainable consumption and production patterns,” lists waste management and reduction as targets. Each country and company consider and proactively tackle environmental issues based on their sociocultural background [1-3]. Globally, plastic bag charges are being introduced as a measure to combat plastic waste, and the reduction in disposable plastic products is a major goal [4]. Furthermore, alginate, silicone impression material, and gypsum used in dental care are classified as industrial waste in Japan.

In recent years, digital technology has been widely adopted in dentistry, enabling dentists to provide better treatment to their patients. Prosthodontic treatment is increasingly performed using intraoral scanners (IOS), computer-aided design/computer-aided manufacturing (CAD/CAM) systems, and 3D printers [5-7]. The use of a digital workflow could help reduce the use of alginate and silicone materials conventionally used for making impressions. Two types of 3D printers can replace plaster models: stereolithography apparatus (SLA) and fused deposition modeling (FDM) 3D printers. Most 3D printers used in dentistry are based on SLA [8,9] because they are considered to confer better accuracy to the finished product [10-12]. However, similar to the plaster models, the resin models prepared using this printer were discarded after use. As polylactic...
acid (PLA) is present in the filament that is used as a material for FDM, we believe that the reuse of PLA could reduce industrial waste. Traditionally, FDM uses acrylonitrile butadiene styrene (ABS), which is petroleum-derived. PLA has a lower cost and superior dimensional stability compared to those of ABS. The most important feature of PLA is that it decomposes into water and carbon dioxide in a composting environment with high temperature, high humidity, and microorganisms. As it is plant-derived, less CO₂ emissions are produced than those by petroleum-derived products [13,14]. There are a few reports on the application of FDM and PLA in dental treatment. This study aims to compare the marginal fit of the same provisional crown of PLA models made with IOS and FDM, plaster models obtained by taking impressions with silicone and injecting plaster, and resin models made with IOS and SLA using Micro Focus X-ray CT (micro-CT).

2. Materials and methods

A model of the maxillary left first molar as an abutment tooth (A55A-262, NISSIN, Tokyo, Japan) was attached to a jaw model (Prosthetic Restoration Jaw Model D16FE-500A(GSE)-QF; NISSIN, Tokyo, Japan) as the base model. Digital impressions were obtained using an IOS (Trios 3®; 3 shape, Copenhagen, Denmark), and resin blocks (Asahi PMMA Disk Temp; Asahi Roentgen Ind. Co., Ltd., Kyoto, Japan) were cut using CAD (Exocad®; Exocad, Berlin, Germany)/CAM (Ceramill motion2®; Amann Girrbach, Wien, Austria) from the stereolithography (STL) data obtained to fabricate the provisional crown (Fig. 1). Based on the recommended parameters of the manufacturer, the margin thickness was 0.06 mm and the cement space was 0.11 mm. This in vitro study did not require approval from the Institutional Ethics Committee.

2.1. Fabrication of PLA models

The digital impressions of the base model were obtained using IOS, after which FDM (METHOD X; MakerBot Industries, LLC., New York, USA) and MakerBot Precision PLA 1.75 mm (MakerBot Industries, LLC., New York, USA) PLA models were fabricated. The fabrication conditions were as follows: extruder temperature for the model material, 200 °C; extruder temperature for the support material, 210 °C; fabrication temperature, 40 °C; and laminating pitch, 150 μm.

2.2. Fabrication of plaster models

The impressions of the base model were performed using silicone (Aquasil Ultra® Heavy and XLV, Dentsply Sirona, York, USA). Cementsed carbide gypsum (New Fujirock®; GC, Tokyo, Japan) was prepared using a water-to-powder ratio of 0.20 (water, 20 mL; powder, 100 g) and poured into the impression tray. The curing time of the silicone was 3 min, as specified by the manufacturer. Immediately after curing, a vacuum kneading device was used to mix the plaster with water and inject it into the silicone impression material. The poured plaster model was left to set and harden in a closed box for 11 min. No surfactants or other treatments were used to allow an accurate evaluation of the models.

2.3. Fabrication of resin models

The digital impressions of the base model were acquired using an IOS, and SLA (Form3; Formlabs®, Washington, DC, USA) and light-curing resin (Model Resin Cartridge V2; Form3, Formlabs®, Washington, DC, USA) were used to fabricate the resin model. A laser power of 250 mW and a laminating pitch of 50 μm were used.

Five models were created with each technique, as shown in Figure 2. The specifications of the 3D printers are listed in Table 1.

2.4. Measurement of accuracy

To measure the marginal fit of the models and provisional crowns, identical provisional crowns were placed on all models without any intervention, and the occlusal surfaces of the provisional crowns and adjacent teeth were fixed with utility wax (GC, Tokyo, Japan). After fixation, the model with the provisional crown was placed perpendicular to the X-ray beam in the micro-CT tube; thereafter, micro-CT (ScanXmate-L080T; Comscantecno Co., Ltd., Kanagawa, Japan) was performed using the following imaging conditions: 70 kV; 100 μA; voxel size, 34.5 μm; and magnification, 2,891×. After each model was photographed, the marginal fit between the abutment tooth and provisional crown was measured using the distance measurement function in the 3D viewer of the 3D image analysis system, Volume Analyzer (Synapse Vincent®, Fujifilm, Tokyo, Japan). Measurements were performed at four points around the tooth: the buccal center (B), palatal center (P), mesial center (M), and distal center (D) points (Fig. 3). Each measurement was performed once at each point by the same examiner.

2.5. Statistical processing

The accuracy of the models at each measurement site was verified using the Tukey-Kramer method. Statistical analyses were performed using Bell Curve for Excel (Social Survey Research Information Co., Ltd., Tokyo, Japan). Differences were considered statistically significant at P < 0.05.

3. Results

In position B, the marginal gaps of the provisional crown relative to the PLA, resin, and plaster models were 118 ± 21.7, 62 ± 16.4, and 50 ± 26.5 μm, respectively. There was a significant difference between the accuracy of the PLA model and those of the SLA and plaster models (P < 0.05). However, the marginal gap at all other measurement points was not significantly different between the models (P > 0.05; Fig. 4; Table 2).
4. Discussion

Conventionally, crowns are fabricated on plaster models, and the accuracy of the prosthesis is therefore dependent on these models. However, since the introduction of digital workflows in prosthetic dentistry, crowns have been fabricated using IOS and CAD/CAM based on STL data. Therefore, the role of plaster models has become less significant.

There are two types of 3D printers: SLA that forms layers of liquid resin by irradiating it with ultraviolet light and hardening it, and FDM that first softens the filament material by heating it and then ejects it through a nozzle. SLA is commonly used as a 3D printer in dentistry owing to its fine stacking pitch [15]. However, a disadvantage of SLA is that the used resin model must be discarded. In recent years, FDM has demonstrated the same performance as that of SLA. Various types of materials are used for FDM with PLA being the most common. As PLA is a plant-derived plastic material, such as starch found in corn and potatoes, it is currently attracting attention for its ability to reduce carbon dioxide emissions as an alternative to petrochemical plastics, which are associated with global warming and petroleum resource depletion [16-18]. We considered that fabricating models using IOS and PLA and reusing these models could help reduce waste and realize a dental practice that incorporates the SDGs. However, if the accuracy of PLA models is inferior to that of the resin or plaster models, the reuse of PLA models is not worthwhile.

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

<table>
<thead>
<tr>
<th>3D printing technique</th>
<th>3D printer used</th>
<th>Specifications</th>
</tr>
</thead>
</table>
| SLA                   | Form3 (Form3; Formlabs*, Washington, DC, USA) | XY resolution: 25 μm  
Laser power: 250 mw  
Laminating pitch: 25 – 300 μm  
Modeling size: 145 mm × 145 mm × 185 mm |
| FDM                   | METHOD X (METHOD X; MakerBot Industries, LLC., New York, USA) | Laminating pitch: 0.02 – 0.4 mm  
Dimensional accuracy: ±0.2 mm  
Modeling size  
(X) 190 mm × (Y) 190 mm × (Z) 196 mm (single)  
(X) 152 mm × (Y) 190 mm × (Z) 196 mm (dual) |

3D, three-dimensional; SLA, stereolithography apparatus; FDM, fusion deposition modeling

Fig. 2. (a) Polylactic acid (PLA) model created fused deposition modeling (FDM) after obtaining the stereolithography (STL) data of the base model following intraoral scanning. (b) Resin model created with stereolithography apparatus (SLA) after obtaining the STL data of the base model following intraoral scanning. (c) Plaster model of a base model obtained by taking impressions with the silicone and pouring plaster.

Fig. 3. Provisional crown was placed on each model, and the marginal fit was measured using micro-CT at the buccal center (B), palatal center (P), mesial center (M), and distal center (D) of the tooth.
In this study, the accuracy of the PLA model was not significantly different from that of the other models, except at point B, suggesting that PLA could be useful. The significant difference between the PLA, resin, and plaster models at point B was attributed to the difference in the laminating pitch; however, Kamio et al. [19] reported that the accuracy of their model did not decrease when the laminating pitch was increased. Therefore, the surface roughness generated after molding using the FDM method may have caused this difference [20]. A drawback of FDM is the development of surface roughness after molding, as it is common to polish or chemically treat the surface to make it smooth. However, this was not performed in this study because it may have affected the accuracy of the crown. Since a precision of several micrometer units is required to fit the crown, the effect of surface finish on FDM performance is an issue to be addressed in the future [21,22]. Muta et al. [23] compared a plaster model with a polyvinyl alcohol (PVA) model fabricated using FDM and measured the internal fit of an acrylic resin and resin composite crown using the silicone fit test. The marginal fit of both crowns was better with the plaster model, while the marginal gap with the PVA model was within 100 µm, indicating the usefulness of FDM and PVA. Wang et al. [24] compared the accuracy of edentulous trays made using SLA and FDM with that of conventional manual edentulous trays. They reported good accuracy of the models in the decreasing order of SLA, FDM, and conventional methods. As shown above, the FDM method approaches the accuracy of SLA, and its application in dental treatment is expected to increase in future. Benili et al. [25] compared the accuracy of provisional crowns made with PLA to that of provisional crowns made with polymethyl methacrylate (PM) and polyetheretherketone (PE). They reported the following marginal fit values with different models: PE, 56.00 ± 4.67 µm; PM, 61.15 ± 4.44 µm; and PLA, 60.40 ± 2.85 µm. Similarly, Molinero-Mourelle et al. [26] measured the fit of provisional crowns made with PLA and PMMA and reported the usefulness of PLA. Thus, the application of PLA in dentistry could be expanded in the future.

Research on filament recycling has already been conducted. Lagazzo et al. [27] used FDM to evaluate the recyclability of biocomposites based on PLA and poly-3-hydroxybutyrate-co-3-hydroxyvalerate. They found that both materials retained their mechanical and thermal properties until the third cycle, indicating their promising recyclability. Vidakis et al. [28] investigated the effect of reusing polyamide 12 polymer using FDM on its mechanical and thermal properties and reported that the mechanical properties decreased after the fifth to sixth recycling. It was also reported that the mechanical properties of polypropylene did not degrade until it was reused six times [29]. According to Beltrán et al. [30], the mechanical properties of PLA deteriorate when recycled. They reported that the addition of organic fillers during recycling improved the thermal stability and mechanical properties of the PLA. Dental models are necessary to confirm the fit of the prosthetic appliance and to make adjustments. Therefore, although superior mechanical properties are not necessary, there is a concern that the accuracy of the materials may degrade with reuse. This is the subject of future research. PLA has various other applications [31,32]. Efforts to produce PLA filaments by waste recycling are ongoing. [33]. The use of FDM and filaments could help establish a dental practice that incorporates the SDGs, reduces waste, and encourages the development of novel environment-friendly materials. However, there are concerns that the filament used for FDM may generate dangerous volatile organic compounds during molding. Therefore, health hazards should be prevented by ensuring that the FDM installation area is well ventilated, that no one enters the area during the molding process, that appropriate filters are attached to the FDM, and that air purifiers are installed. This phenomenon has been extensively studied [34,35].

There are many reports on the marginal fit of prosthetic devices determined using micro-CT [36-38]. Ricciottiello et al. [39] reported that the marginal gap between zirconia crowns and anterior teeth was 63 ± 32 µm on the buccal/mesial aspect and 89 ± 42 µm on the palatal/distal aspect. Daou et al. [40] reported mean marginal gaps of 35.69 ± 9.25 and 46.85 ± 18.25 µm for zirconia three-unit fixed prosthesis and cobalt crown three-unit fixed dental prosthesis, respectively. It has been reported that the marginal gap of the crown should be less than 120 µm [41-43]. According to the results of this study, considering the standard deviation, the gaps at points B and D of the FDM models exceeded 120 µm. This could be resolved by changing the molding conditions or using a FDM with a higher accuracy. The accuracy of FDM differs depending on the modeling along the X-, Y-, and Z-axes. In this study, we fabricated a model along the Z-axis from the cervical area to the occlusal surface, which resulted in a slight error. In future, it will be necessary to verify whether modeling in the X or Y direction improves the accuracy of dental models [44,45].

Table 2. Results of the marginal fit of three different models and provisional crowns.

<table>
<thead>
<tr>
<th></th>
<th>PLA (µm)</th>
<th>Resin (µm)</th>
<th>Plaster (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>118±21.7</td>
<td>62±16.4</td>
<td>50±26.5</td>
</tr>
<tr>
<td>P</td>
<td>64±32.1</td>
<td>48±23.9</td>
<td>76±11.4</td>
</tr>
<tr>
<td>M</td>
<td>62±27.7</td>
<td>50±17.3</td>
<td>78±20</td>
</tr>
<tr>
<td>D</td>
<td>86±43.4</td>
<td>50±12.2</td>
<td>80±38.7</td>
</tr>
</tbody>
</table>

B, buccal center; P, palatal center; M, mesial center; D, distal center; PLA, polyactic acid;
significantly different from that of the other models, except at the buccal center, indicating the usefulness of this combination. In future, FDM and PLA may become essential for dental treatment. In addition, we intend to study the reuse of PLA in clinical settings in the future.

Acknowledgements

We express our sincere gratitude to Nihon Binary Co., Ltd., for providing the PLA models used in this study.

Conflicts of interest

All authors declare no conflicts of interest.

References


