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Accuracy of Models Fabricated by a Chair-side Fused Deposition Modeling (FDM) Printer in Stomatology

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Clinical Relevance

The manufacturing process of 3D printing is much easier than the traditional methods. It substantially reduces costs and waiting times for things to be manufactured, however, the printed crowns cannot be properly positioned in the preparation. We put forward the hypothesis that if the 3D printer is properly calibrated, the model printed by it can be used in clinical temporary crowns.

SUMMARY

Purpose: To establish a method to improve the accuracy of a dental chair-side fused deposition modelling (FDM) printer and assess the internal adaptation of full crown casting patterns produced by the FDM printer.

Method: A Lingtong dental three-dimensional (3D) printer (Beijing SHINO Company, China), was used to fabricate six cubes. Deviation analysis was performed between the 3D scanned data and the designed cube data. Fifteen crowns (Group LT) of the right maxillary first molar were printed. A DDP 3D printer (Group EV) and a milling machine (Group ZT) were used to produce the same crowns as controls.

Results: Compared with the designed cube, the 3D deviation of 73.75% points was within 0.1 mm. The calibration parameters (CP) of the X, Y, and Z directions were 1.005, 0.998, and 1.000, respectively. Based on the CP, the X and Y directions of the printer were adjusted in the software to compensate for the mechanical errors. The crowns were fabricated using different types of equipment to evaluate the accuracy of printing by the 3D dental printer. The internal gap of each crown was measured using a silicone replica and the 3D analysing method. In Group LT, the internal gap of the marginal, axial, and occlusal areas were 0.030 ± 0.019, 0.092 ± 0.019, and 0.023 ± 0.009 mm, respectively. In the marginal and occlusal areas, Group EV exhibited the smallest internal discrepancy, whereas in the

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axial area, Group ZT achieved the smallest. Only LT and ZT achieved internal spaces in the marginal area without statistical significance to the prescribed parameters (*p*>0.05).

Conclusion: The crown cannot be placed on the preparation if the printer is not calibrated. This study revealed the inability to produce full crown casting patterns with similar internal adaptations using different machines for fabrication. None of the three groups could reproduce the prescribed internal space. Combined with CAD/CAM technology, 3D printing technology has been gradually applied in stomatology.

INTRODUCTION

There are many medical applications for three-dimensional (3D) printing. In particular, 3D printing is gaining popularity in dentistry. Today, millions of orthodontic braces, dental crowns, and bridges are being fabricated using 3D printing. Industrial 3D printers are being used to create these high-end, high-precision dental components.

The printed models could be created with computer-aided design (CAD) software or by a 3D scanner. The data of an STL file is loaded into the printing software; then, the software converts the data into layers.[1] The data is loaded into the printer and formed integrally. The 3D printing is primarily applied in selective laser melting (SLM), direct metal laser sintering (DMLS), fused deposition modelling (FDM), stereolithography technology (SLA), and digital light processing (DLP).[2-5] Each method has its advantages and disadvantages, and various materials are used to fabricate different objects.

FDM technology is one of the techniques used for 3D printing. It is also widely used in medical applications, such as for surgical guide plates, custom implants, and *in vitro* organ models.[6-8] This technology could also be applied in dentistry, such as for temporary restoration and custom edentulous mandible trays in prosthodontics, as a surgical guide for implant treatment, and surgical guides for oral and maxillofacial surgery.[9-12] This technology could compensate for the deficiencies of traditional manufacturing methods and could play a key role in digital stomatology.[13,14]

The Lingtong dental 3D printer was developed by the Beijing SHINO Company and supports the following materials: polylactic acid (PLA) and thermoplastic polyurethanes (TPU). PLA is a biodegradable thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, tapioca roots and chips, starch, or sugarcane. PLA decays on exposure to the ultraviolet rays of sunlight and oxygen. It decomposes, forming carbon dioxide and water, which are not harmful to the environment.[15,16] To date, PLA is the most commonly used material in desktop 3D printers. PLA has been used in custom trays; the digitally made custom trays could achieve better accuracy than those made by hand.[11] Digital models could overcome the disadvantages of traditional plaster models, and the clinician can view the digital model after leaving the clinic. It could provide clinical information and promote the development of telemedicine. In oral and maxillofacial surgery, PLA has been used as a clinical application model in surgery.[14,17]

The tremendous benefit of 3D printing is the ability to customize individualised objects. The manufacturing process of 3D printing is much easier than those of traditional methods. It substantially reduces costs and waiting times for objects to be fabricated. However, the printed crowns cannot be properly positioned in the preparation. Therefore, we hypothesised that if the 3D printer is properly calibrated, the 3D printed model can be used for temporary crowns. The 3D printer calibration method is very useful, and is efficient, accurate, and easy to implement. This study aimed to quantitatively assess the accuracy of the FDM printer and evaluate the internal adaptation of full crown casting patterns produced by the FDM printer.

METHODS AND MATERIALS

All the hardware and software used in the study are summarized in Table 1.

Table 1: *Hardware and Software Used in the Study*
Hardware
Lingtong 3D FDM printer (Beijing SHINO Company, China)
Perfactory P3 DDP (ENVISIONTEC, Germany)
Zenotec T1 (Wieland Dental, Germany)
D700 3D Scanner (3Shape, Denmark)
Activity 880 Dental Scanner (Smart Optics, Germany)
Software
Geomagic Qualify 2012 (3D Systems Company, USA)
Solidworks 2012 (Solidworks Company, USA)
Dent100 (Beijing SHINO Company, China),
SPSS 17.0 (IBM Company, USA)
Other
Vernier calliper (Mitutoyo, Japan)

Computer-Aided Design

Solidworks 2012 (Dassault Systèmes Solidworks, Waltham, MA, USA) was used to design a 5-cm cube and then saved as "cube.stl." A 3D printer, which was developed by SHINO Company, was used to print the 5-cm cube model, which was used as a calibration cube.

3D Printing

The CAD cube data was imported to the Dent100 computer software (Beijing SHINO Company) connected to the FDM printer (Lingtong I, Beijing SHINO Company) , and the cube was printed layer upon layer at 0.1 mm/layer using a PLA filament (diameter: 1.75 mm). The mechanical accuracy of the FDM printer was as follows: X, Y: ± 0.01 mm, Z: ± 0.005 mm.

FDM technology uses high temperatures to heat and melt the PLA material for deposition modeling. Simultaneously, the sprinklers of the printer move along the horizontal direction, whereas the working platform moves along the vertical direction. The process is repeated until the object is completely fabricated. The printing process was repeated three times; three 20% infill cubes were printed and named Cubes 1, 2, and 3. Three hollow cubes were printed and named Cubes 4, 5, and 6.

Measurement of the Cube and the Deviation Analysis

A vernier calliper (Mitutoyo) was used to measure the length, width, and height at the corresponding positions. The front surface was divided into five areas when measuring the magnitudes of the X directions. Length 1 was the average thickness of the x-axis direction at the line 1 position 10 times. Line 1 position is shown in Figure 1. Length 2 was the average thickness of the x-axis direction at the line 2 position. Length 3, Length 4, and Length 5 were the averages of the line 3, line 4, and line 5 positions, respectively. The width and height measurements were obtained similarly. Height was measured at four positions on each side and repeated 10 times for each position.

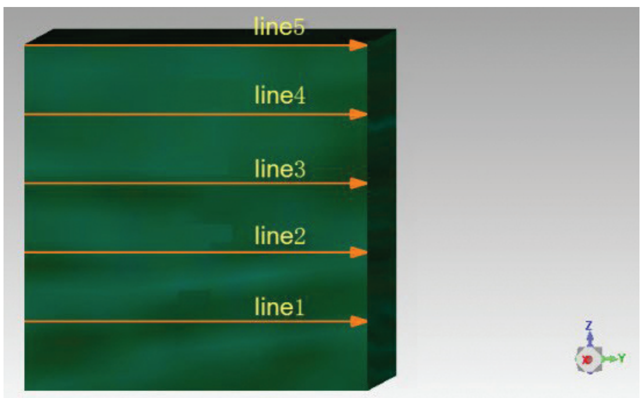

Figure 1. *Schematic diagram of measurements in the X- and Y- directions.*

Before scanning, a layer of powder was sprayed on Cube 2, which was randomly selected. The powder material was Developer UD-SD (Marktec Corp, Tokyo, Japan). Because the model was slightly reflective, the surface data could not be directly obtained from the scanner and needed to be dusted. In the field of stomatology, if the object is unable to be scanned because it is reflective, the developer could be used to make the surface non-reflective, and the object can then be scanned. The 3D data of the model is acquired using a 3D scanner (D700, 3Shape, Copenhagen, Denmark), with an accuracy of 20 μm. The data was named "Data_Scan.stl." Geomagic Qualify 2012 software was used to analyse differences between the designed 3D data and the scanned data. The designed data were set as the "Reference model," and the scanned data were set as the "Test model." Deviation analysis was implemented in Geomagic Qualify 2012 software (3D Systems Company, Cary, NC, USA).

3D Printer Accuracy Verification

The first molar model (Nissin Dental Products Inc, Kyoto, Japan) was prepared, and the intraoral scanner was used to obtain 3D data for the preparation and its adjacent teeth (Figure 2). A full crown was designed with the 3Shape Dental System 2015 (3Shape A/S, Denmark) software. The design data was exported as an STL file.

The full crowns were fabricated by three different machines (3 groups × 15). The machines and materials

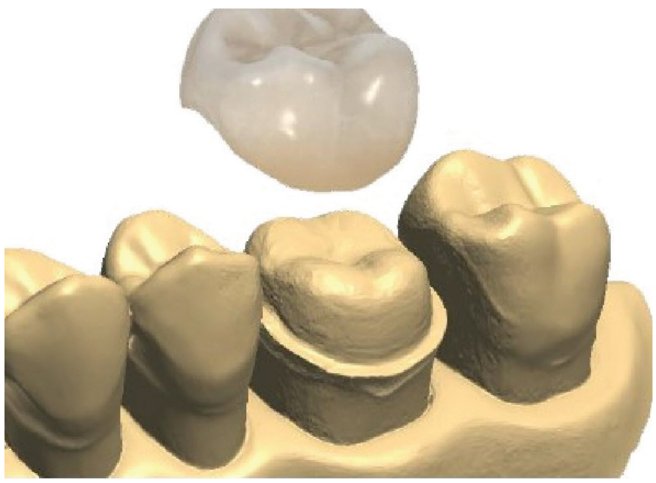

Figure 2. *Designed full crown, preparation and adjacent teeth.*

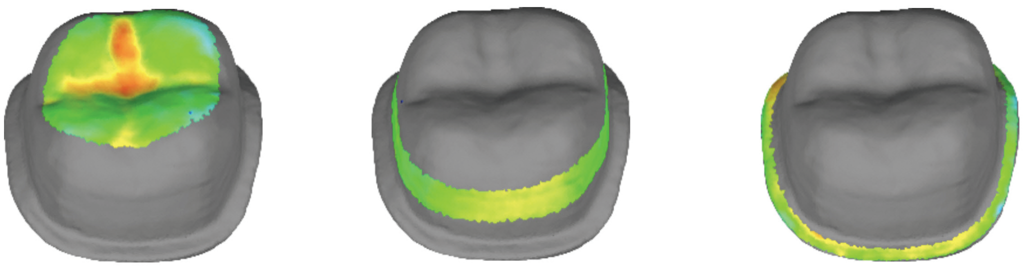

Figure 3. *Design parameters of the internal surface of the crown; values of the occlusal, axial, and marginal areas were set at 0.08, 2.00, and 0.03 mm, respectively.*

used were as follows: Group LT, Lingtong 3D FDM printer (Beijing SHINO Company) + PLA filament (raw material: Ingeo biopolymer, NatureWorks LLC, Plymouth, MN, USA); Group EV, Envisiontec Perfactory 3 Digital Dental Printer (DDP) (ENVISIONTEC, Gladbeck, Nordrhein-Westfalen, Germany) + light-curing castable resin; Group ZT, Zenotec T1 (Wieland, Pforzheim, Germany) + castable resin block.

To detect the accuracy of the full crowns, we measured the gap of the corresponding position between the inner crown and the preparation body. The measurement positions are shown in Figure 3. The preparation and its adjacent teeth were duplicated by the same operator on the same day using the same material, and an optical dental scanner (Activity 880, smart optics, Bochum, Germany) was used to obtain 3D data (data I) (3 groups × 15). The crown was seated on the preparation with its internal space filled with light-body addition silicone (Variotime Light Flow, Kulzer, GmbH, Hanau, Germany). A load of 2 kg was applied to the crown for five minutes. After complete polymerization, the excess silicone was carefully removed with a scalpel. The crown was removed, and the silicone replica was kept intact on the stone die. After the silicone was completely polymerised, the space between the preparation and crown was filled with silicone. The preparation model covered with silicone film was scanned using the same optical scanner, and the data were exported as an STL file (data II) (3 groups × 15).

Data I and data II were loaded into Geomagic software 2012. To analyse the printing error, data II was registered using the "Best Fit Alignment" to the corresponding data I. After the registration, a 3D deviation analysis command in Geomagic software was used to measure the deviation between the two data sets (data I and data II). The root mean square (RMS) of the selected area was calculated using the "3D Compare" command. The 3D deviation of the surfaces inside the finishing line of data I and data II represented the thickness of the silicone film. The measurement areas were separated into three distinct zones: occlusal, marginal, and axial. Color surface maps were created to generate a visual display of the thinness in the three distinct areas. The workflow chart is shown in Figure 4.

RESULTS

The average X, Y, and Z dimensions of the 20% infill cube were 49.732 ± 0.042, 50.088 ± 0.049, and 49.992

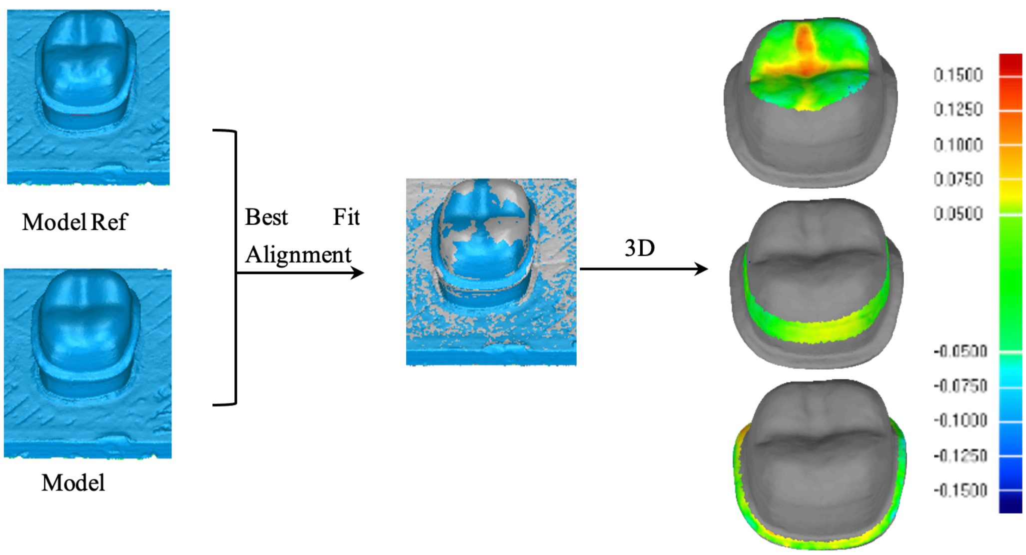

Figure 4. *Workflow of 3D analysis of the internal adaptation of full crown casing patterns.*

Table 2: *Means and Standard Deviations of 20% Infill and Hollow Cubes' Size in Different Directions (mm)*[a]

Cube	Size at Different Directions	Average	Standard Deviation	Error	*p*-value
20% infill cube	L	49.732	0.042	0.268	<0.001
	W	50.088	0.049	0.088	<0.001
	H	49.992	0.090	0.008	0.617
Hollow cube	L	49.550	0.021	0.450	<0.001
	W	49.843	0.023	0.157	<0.001
	H	49.905	0.052	0.095	<0.001

[a] *α=0.05, one sample t-tests, μ is 50.*

± 0.090 mm, respectively. The average X, Y, and Z dimensions of the hollow cube were 49.550 ± 0.021, 49.843 ± 0.023, and 49.905 ± 0.052 mm, respectively. As shown in Table 2, the *p* values of the X and Y directions of the 20% infill cube and those of the hollow cubes' X, Y, and Z directions were <0.001. At the Y direction, the size of the 20% infill cube exceeded 50 mm. The sizes of the others were <50 mm.

The D700 3D scanner (3Shape) was used to obtain 3D data of Cube 2. The scanned data was saved as "Data_S.stl." The designed data was saved as "Cube. stl." The "Geomagic Qualify" alignment features were used, and the two models were aligned with the "Aligning Objects" function. The "3D Deviation" function was used to analyze the distance from the Test to any point on the Reference. The results revealed that 73.75% of the points were within the range of 0.1 mm, and also showed that <10% of the points exhibited a difference exceeding 0.2 mm (Table 3).

The marginal, axial, and occlusal area discrepancy measurements for each group are shown in Table 4. In Group LT, the internal gap of the marginal, axial, and occlusal areas were 0.030 ± 0.019, 0.092 ± 0.019, 0.023 ± 0.009 mm, respectively. In marginal and occlusal areas, Group EV achieved the smallest internal discrepancy. In the axial area, Group ZT achieved the smallest. Only LT and ZT achieved internal spaces in the marginal area without statistical significance to the prescribed parameters (p>0.05).

One-way analysis of variance indicated statistically significant differences in the means of the marginal discrepancies among the three groups (p<0.001), whereas the Kruskal–Wallis test indicated statistically significant differences in the medians of the axial

Table 3: *Deviation Between the Scanned 3D Data and Designed 3D Data*

#	d	# of Points	Percentage (%)
1	d<-0.5	13	0.02
2	-0.5≤d<-0.4	81	0.09
3	-0.4≤d<-0.3	1073	1.25
4	-0.3≤d<-0.2	3928	4.56
5	-0.2≤d<-0.1	13568	15.77
6	-0.1≤d<0.1	63467	73.75
7	0.1≤d<0.2	3022	3.51
8	0.2≤d<0.3	465	0.54
9	0.3≤d<0.4	184	0.21
10	0.4≤d<0.5	107	0.12
11	0.5≤d	151	0.18

Abbreviations: d, the distance between the points.

Table 4: *Mean and SD Range of Internal Discrepancy of Different Areas in Each Group (mm)*[a]

Areas	Groups	Means	SDs
Marginal	LT	0.030 a	0.019
	EV	0.006 ab	0.014
	ZT	0.029 b	0.019
Axial[b]	LT	0.092	0.019
	EV	0.024	0.012
	ZT	0.019	0.021
Occlusal[b]	LT	0.023	0.009
	EV	0.001	0.011
	ZT	0.019	0.016

Abbreviations: EV, Envisiontec Perfactory 3 Digital Dental Printer; LT, Lingtong 3D FDM printer; ZT, Zenotec T1+ castable resin block.

[a] *The same lowercase letters indicate significant differences between groups (p<0.05).*

[b] *Non-parametric analyses were performed on these groups.*

and occlusal discrepancies among the three groups (p<0.001).

DISCUSSION

Before the Lingtong I 3D printer based on FDM technology was used in oral clinical applications, we conducted a calibration test, obtained calibration parameters, and performed a clinical application test. The maximum error of the 20% infill cube was 0.268 mm in the X direction, and the maximum error of the hollow cube was 0.450 mm in the X direction. The infill percentage could be set from 0%-100% of the cube, which is used to change the interior solidity of the 3D print, whereby 0% is completely hollow, and 100% is completely solid. The print accuracy of the Z direction is significantly better than those of the x- and y-axes. In the X and Y directions, when the printed materials are melted and solidified, the process leads to some contraction errors. The results revealed that the Lingtong I 3D printer calibration parameters (CP) differ for the printing of hollow objects compared to those for the printing of solid objects. Using CP=T/M, where T is the target value, and M is the measured value, we set T at 50; the measured value is the average value of the vernier calliper that measures the same axial result. The average values of the X, Y, and Z directions of the 20% infill cube were 49.732, 50.088, and 49.992, respectively. The CP of the X, Y, and Z directions were 1.005, 0.998, and 1.000, respectively. Based on the CP, the X and Y directions of the printer were adjusted in the software to compensate for the mechanical errors.

The positioning accuracy of the Lingtong I 3D FDM printer was X, Y: ±0.01 mm, and Z: ±0.005 mm. Therefore, additional calibrating and precompensating for shrinkage are required for different printed models. Before clinical application, the printer's accuracy must be confirmed to ensure that it could satisfy the clinical requirements, such as printing the diagnostic, test, and working models, complete dentures, and fixed restoration models, as well as skull models for surgery, individual trays, implant surgical guides, and orthodontic transfer trays, etc.

The "3D Deviation" function was used to analyse the distance from the Test to any point on the Reference. The results showed that 73.75% of the points were within the range of 0.1 mm. This result is consistent with the measurements obtained using the vernier calliper. The results revealed that the total sizes of the X-axes for the 20% infill cube and the hollow cube were less than the designed value. Further, the size of the Y-axis of the 20% infill cube was greater than the designed value. For the hollow cube, the Y and Z axes were less than the designed values.

The accuracy of the 3D printers may be influenced by many factors, such as: a) mechanical precision of the printer itself in the different x-, y-, and z-axial directions; b) The parameter settings of the printer, including the thickness of each layer, and the percentage of infill material; c) Properties of the printed material; d) The setting mode during the printing process, such as the direction of the printed model placed in the software, the supporting number, and placement; e) The infill mode of the printed model, to release stress and reduce deformation; and f) The working environment of the printer such as the placement stability, indoor temperature, and humidity.

Individualized designed products could be created using FDM technology. In the process of printing, the fabricated model was affected by the placement of the model and the supporting design approach. FDM technology has limitations, such as the suitability of the 3D printing material for use in humans. When printed using FDM technology, the material was extruded ahead of the printer. As a result, the material must exhibit good mechanical properties and possess good tensile and flexural strengths. Currently, PLA and acrylonitrile butadiene styrene (ABS) filament are the most popular materials. ABS is a common thermoplastic polymer and is easily machined; commonly used machining techniques include turning, drilling, milling, sawing, die-cutting, and shearing. ABS is amorphous and therefore has no true melting point. Its glass transition temperature is approximately 105°C (221°F). Therefore, it exhibits considerable shrinkage, and the molding precision is difficult to control. Moreover, when ABS is heated, it produces a pungent odor. As such, the ABS filament is not suitable for use in stomatology. PLA is created by the processing of various plant products, including corn, potatoes, or sugar beets. PLA is considered a more earth-friendly plastic compared to petroleum-based ABS. It can be colored to various degrees of translucency and opacity. When properly cooled, PLA has higher maximum printing speeds, lower layer heights, and sharper printed corners. Further, PLA displays low warping, thereby making it a popular plastic for home printers, hospitals, and schools.[18]

The three fabricating machines involved in this study have their respective advantages. The Lingtong 3D printers have advantages in terms of price and size. It is more suitable for small dental laboratories or chairside. The Zenotec T1 is more suitable for batch processing because of its large size. Lingtong uses biodegradable PLA as its material, which is readily available, creates little pollution, and is low cost.[19] Perfactory DDP III and Zenotec T1 employ dedicated castable light-curing resin and milling discs, respectively, resulting from higher production costs. Above all, various fabricating methods impact the accuracy of restorations differently. FDM technology deposits semifluid material layer by layer and can produce objects with overhangs within certain limits. As a result, the operator can use the least amount of supporting structures that can be placed outside the areas of interest, such as occlusal contacting points. DLP technology cures the liquid resin layer by layer, causing dimensional shrinkage. There are more supporting structures when working with DLP, most of which are located on the cusps of the crowns. The supporting structures will make it impossible to restore the contour of restorations to its design, particularly the occlusal contacts. Grinding and milling are considered the most reliable production methods. During this process, the supporting structures can be placed on the axial surfaces of the restorations to avoid their influence on the occlusal surfaces. Moreover, the potential of fabricating casting patterns chair side makes it possible to adjust casting patterns in patients' mouths during a single visit, resulting in individualized restoration contours based on patients' functional movement with better clinical acceptability and less adjustment time of final restorations. Finally, clinical effect and efficiency will be enhanced.

CONCLUSION

This study revealed the inability to produce full crown casting patterns with similar internal adaptations between FDM printers or manufacturing machines. None of the three groups could reproduce the prescribed internal space parameters. In this study, the clinical accuracy of a crown could be met when the FDM technology was calibrated. FDM technology is one of the 3D printing technologies that could be used in dental clinics.

Acknowledgments

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Conflicts of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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