Three-Dimensional Analysis of Internal Adaptations of Crowns Cast from Resin Patterns Fabricated Using Computer-Aided Design/ Computer-Assisted Manufacturing Technologies

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Purpose: To evaluate the internal adaptations of cast crowns made from resin patterns produced using three different computer-aided design/computer-assisted manufacturing technologies. **Materials and Methods:** A full-crown abutment made of zirconia was digitized using an intraoral scanner, and the design of the crown was finished on the digital model. Resin patterns were fabricated using a fused deposition modeling (FDM) 3D printer (LT group), a digital light projection (DLP) 3D printer (EV group), or a five-axis milling machine (ZT group). All patterns were cast in cobalt-chromium alloy crowns. Crowns made from traditional handmade wax patterns (HM group) were used as controls. Each group contained 10 samples. The internal gaps of the patterns were analyzed using a 3D replica method and optical digitization. The results were compared using Kruskal-Wallis analysis of variance (ANOVA), a one-sample *t* test, and signed rank test ($\alpha = .05$). **Results:** For the LT group, the marginal and axial gaps were significantly larger than in the other three groups ($P < .05$), but the occlusal adaptation did not reveal a significant difference ($P > .05$). In the ZT group, the axial gap was slightly smaller than in the HM group ($P < .0083$). All the means of gaps in all areas in the four groups were less than 150 µm. **Conclusion:** Casting crowns using casting patterns made from all three CAD/CAM systems could not produce the prescribed parameters, but the crowns showed clinically acceptable internal adaptations. *Int J Prosthodont 2018;31:386–393. doi: 10.11607/ijp.5678*

Lost-wax casting has been widely used in dentistry for decades to produce dental prostheses. In this process, the quality of the wax patterns is a determinative factor for the accuracy of the final restorations.[1] A related study found that removing wax patterns from their dies resulted in a maximum gap of 35 µm.[2] With the development of computer-aided design and computer-assisted manufacturing (CAD/CAM), digital technologies have provided a novel method with low technique sensitivity and high-accuracy stability. With digital models, dental technicians are able to design restorations with higher accuracy and fabricate casting patterns with higher mechanical strength using additive and subtractive manufacturing technologies such as digital light processing (DLP) 3D printing and computer numerical controlled (CNC) milling, which can be used with traditional lost-pattern casting techniques to produce final restorations. However, such a workflow still needs many evaluations, as the accuracy of fabrication of casting patterns may vary among different systems when compared to handmade wax patterns.

There are different ways to improve the occlusal adaptation of the final restoration. One is to use physical or virtual articulators; however, the jaw movements on articulators are still simulations rather than repeats of the actual functional movements, resulting in misfits of occlusion that need adjustments in the patient's mouth. With the development of CAM and dental

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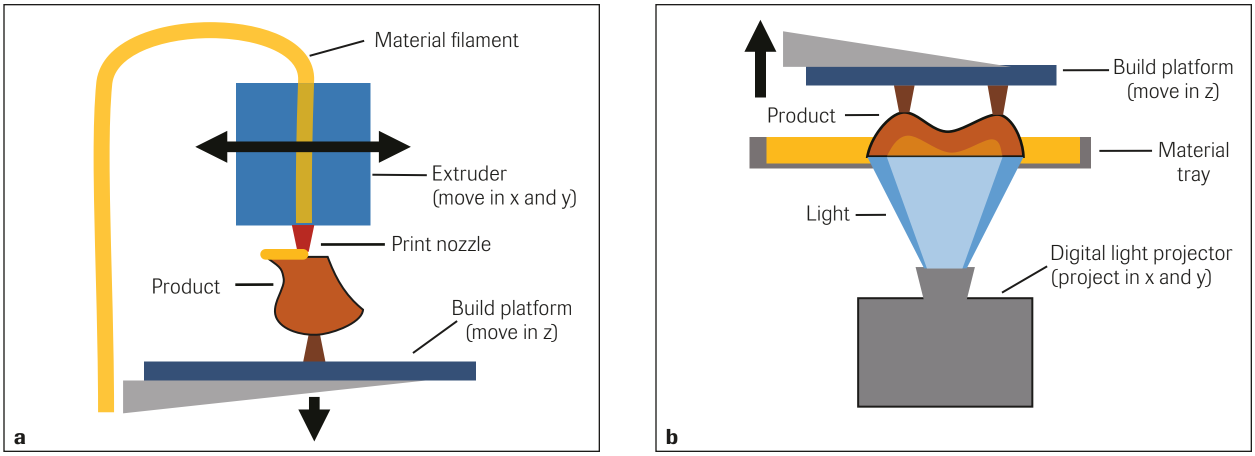

Fig 1 Schematic diagrams of **(a)** fused deposition modeling and **(b)** digital light processing.

materials, the try-in of casting patterns may become a novel method for reducing adjustments of the final restorations, especially when chairside fabrication of casting patterns is involved. Thus, one remaining concern involves the fabrication of low-cost casting patterns with both high efficiency and accuracy.

Fused deposition modeling (FDM) is a low-cost, high-efficiency additive manufacturing technology (Fig 1a). Its dimensional accuracy in producing dental copings was first evaluated by Ishida[3] using a simplified full crown without cusps or grooves. However, the complexity of the contours of a real crown may affect the accuracy and adaptation of patterns fabricated using FDM—a large nozzle diameter may restrict the printing of a thin margin; the change-of-tilt angle of printing will cause different printing accuracy in different directions (anisotropy); and the overhangs of cusps and margin will cause distortion of the crown. Polylactic acid is a frequently used material in FDM. Its advantages include good biocompatibility, low cost, and appropriate physical properties.[4] Several studies have investigated its performance with the investment casting process[5,6] while others have investigated the accuracy of printing customized trays and complete dentures,[7,8] showing acceptable results. However, there is limited knowledge on the use of this 3D printing technology and materials for the production of casting fixed dental prostheses (FDPs).

Digital light projection (DLP) is a common technology of 3D printing. During this process, a mask of visible light, or UV light, projects onto a liquid photopolymer in a tank and cures the photopolymer layer by layer[9] (Fig 1b). This is a fast and accurate process, since the printing time is mainly determined by the height of models and the mask is composed of tiny pixels. According to some manufacturers' technical data, the accuracy and precision can reach within 60 µm. Ishida also evaluated its dimensional accuracy by printing simplified full crowns,[3] but further investigations on producing real crowns or copings are still limited.

Therefore, the purpose of this study was to investigate the internal adaptations of crowns cast using CAD/CAM casting patterns. Three fabricating machines with different principles were involved: an FDM 3D printer, a DLP 3D printer, and a five-axis milling machine. The null hypotheses were: *(1)* No difference would be observed between the internal adaptations of the crowns cast using the three different CAD/CAM patterns and handmade wax patterns; and *(2)* No difference would be observed between the internal adaptations of the cast crowns and the prescribed die spacer thicknesses.

Materials and Methods

Tooth Preparation, Digitization, and Full-Crown Design

A zirconia abutment of the right maxillary first molar was used for the experiment with an occlusal reduction of 1.0 to 1.5 mm, a circular chamfer of 0.5 mm, and a convergence angle of 6 to 10 degrees. The abutment was fixed on a dental teaching model (Nissin Dental Products) with the artificial gingivae removed to fully expose the margin line. The abutment and its adjacent teeth were digitized using an intraoral scanner (3Shape TRIOS Standard, 3Shape A/S). The digital impression was sent to 3Shape Dental System 2015 (3Shape A/S). Using this software, a full crown was designed with the parameters shown in Fig 2a. The design was exported and saved as a stereolithography (STL) file.

Fabrication of Crowns

Crowns were cast in three groups using CAD/CAM casting patterns with different manufacturing

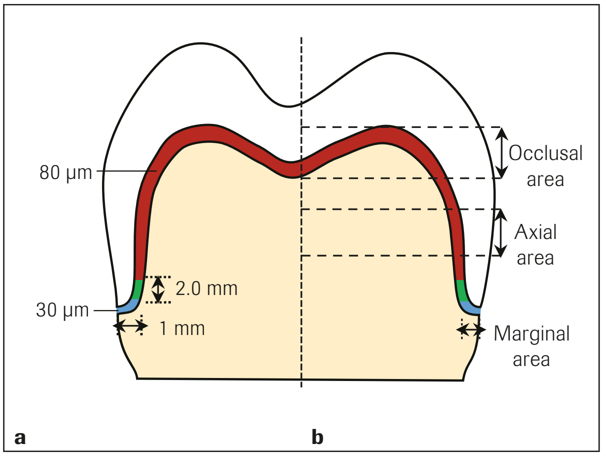

Fig 2 Schematic diagram showing the **(a)** designed parameters of the internal surface of the crown and **(b)** subdivision used for analysis of the internal gap.

Table 1 Specifications of the Three Different Manufacturing Machines

Lingtong-III	Perfactory DDP III	Zenotec T1
Nozzle diameter: 0.2 mm xy positioning accuracy: ± 0.01 mm z positioning accuracy: ± 0.005 mm	Light source: visible light and UV light xy resolution: 60 μm Dynamic z thickness: 15 μm to 150 μm	Minimum drill diameter: 0.6 mm Positioning accuracy: 10 μm

machines. The LT group used an FDM 3D printer (Lingtong-III, Shino) with polylactic acid as the material. The EV Group used a DLP 3D printer (Perfactory DDP III, EnvisionTEC). The ZT group used a five-axis milling machine (Zenotec T1, Wieland Dental). Some specifications of the machines are shown in Table 1. Crowns cast using traditional handmade wax patterns were used as controls (HM group). Each group contained 10 specimens. Specifications of the fabrication of casting patterns were as follows:

- LT group: The casting patterns were printed with a ~50-degree tilt angle of the insertion path (z axis of the original crown model) with the build platform rather than laid flat (the insertion path perpendicular to the platform). The inner surfaces faced obliquely upward (based on preliminary experiments, this would produce a more favorable geometry of the products). Supports were added under cusps and removed before the casting process. The layer thickness was set to 0.05 mm. Only one pattern was printed in each printing process. Due to the optimization of printing parameters, little burr was produced; if any, it could be removed easily with a scalpel. No visible defects were noticed on any sample.
- EV group: The casting patterns were positioned with the insertion path perpendicular to the platform. The outer surface and cusps faced the building platform. Supports were added on the cusps and removed before the casting process. The layer thickness was set to 25 μm based on the instructions of the WIC 300A material. Five patterns were printed in each printing job, located in the center of the platform. Before each printing job, the light source was adjusted using 48-field compensation mask according to the instructions. Postprocessing was also carried out according to the manufacturer's manual. No visible defects were noticed on any sample.
- ZT group: Two or three support bars were added to the axial wall of the pattern, which was removed before the casting process. The smallest drill used during milling was φ1 mm. Five patterns were milled in each milling process. The milling machine was calibrated routinely. No visible defects were noticed on any sample.
- HM group: The abutment and its adjacent teeth were duplicated into the impression using customized tray and vinyl polysiloxane (Variotime Light Flow and Dynamix Monophase, Heraeus Kulzer). The impression was poured into type V dental stone working model (Pemaco). Die spacer (DIE SPACER gold, Yeti Dental) was applied 1 mm from the margin line. According to the instructions, a layer of 13 μm would be formed. To simplify the buildup of the wax pattern, a silicone mold (Rapid putty soft, Coltène/Whaledent AG) was made to form a uniform anatomical contour.

The casting patterns were invested with phosphate-bonded investment material (Bellavest SH, BEGO). After burnout, cobalt-chromium (Co-Cr) alloy (Wirobond 280, BEGO) was applied for casting. The

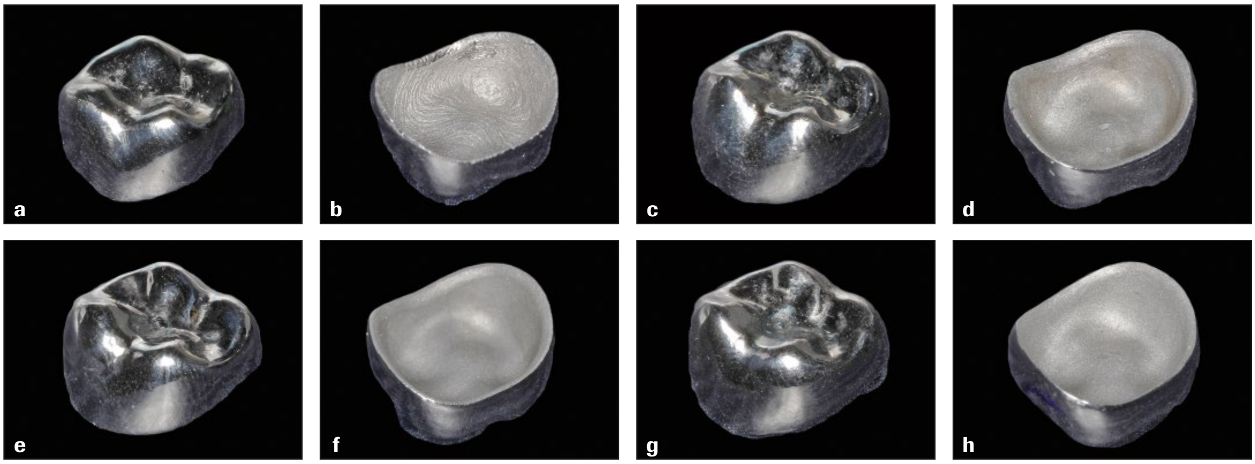

Fig 3 Casting crowns after finishing and polishing. **(a)** Outer surface and **(b)** inner surface of LT group. **(c)** Outer surface and **(d)** inner surface of EV group. **(e)** Outer surface and **(f)** inner surface of ZT group. **(g)** Outer surface and **(h)** inner surface of HM group.

cast crowns were devested and polished (Fig 3). The same dental technician finished this process.

3D Analysis of Internal Adaptation of Full Crown Resin Patterns

Based on the methods of Luthardt,[10] Kim,[11] and Ohlmann,[12,13] a 3D method was adopted to analyze the internal adaptations of the casting crowns. The abutment was removed from the dental model and fixed in a custom-made holder with its adjacent teeth fixed approximately 5 mm mesially and distally. Because the high reflection and translucency of the typodont surface prevented digitization using a dental model scanner (for higher-accuracy scanning of the dies), the assessment was performed indirectly. An impression was made using the single-stage/double-mix technique with a custom tray and vinyl polysiloxane. After complete polymerization, the impression was poured into type V dental stone at room temperature. Forty stone dies were duplicated in a single day by the same operator using the same batch of materials and randomly assigned to each crown.

For each measurement, the stone die was digitized with an optical dental scanner (Activity 880, smart optics Sensortechnik). The measurement uncertainty given by the manufacturer was ≤ 10 µm. The scan data were exported as an STL file and named “Ref model.” The internal surface of the crown was coated with a thin layer of silicone oil, which was dried with a cotton swab and high-pressure air. The crown was filled with light-body addition silicone (Variotime Light Flow) and seated on its corresponding stone die. A 2-kg load was uniformly applied on the crown for at least 5 minutes. After complete polymerization, the excess silicone was carefully removed with a scalpel; therefore, the space between the crown and stone die was filled

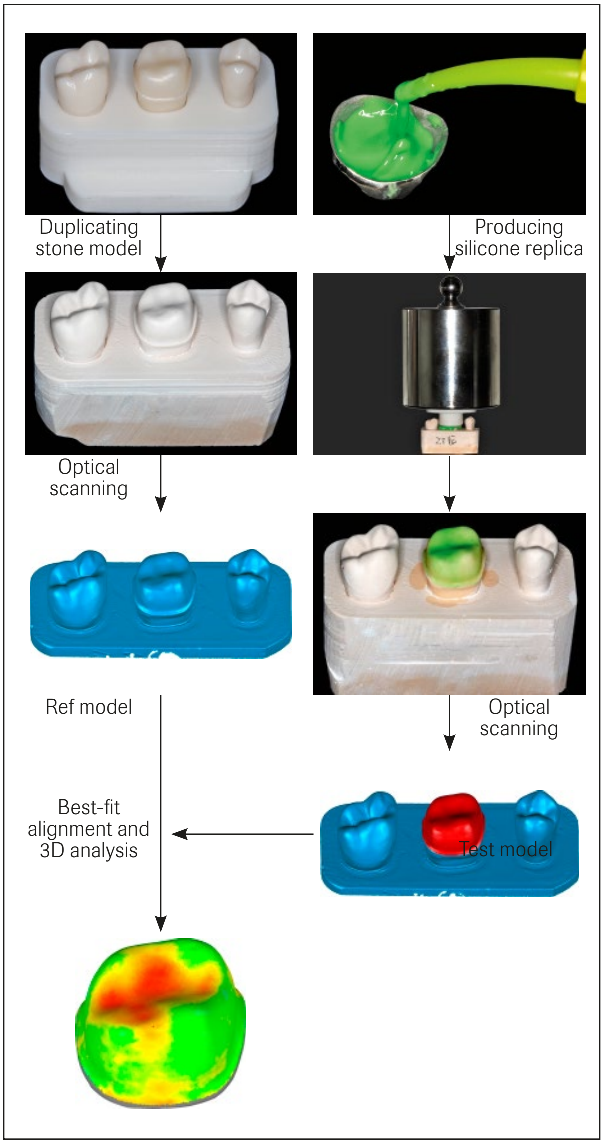

Fig 4 Workflow for 3D analysis of internal adaptation of crowns.

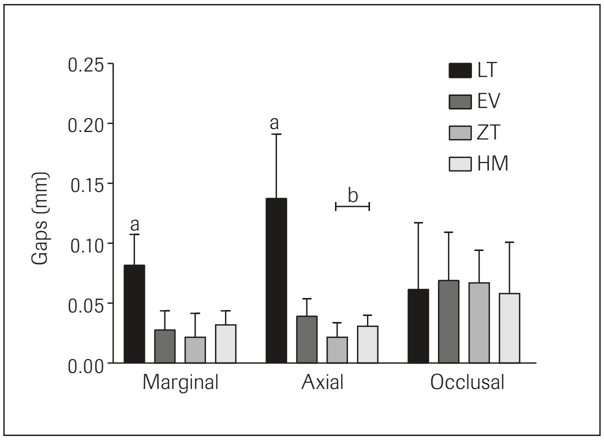

Fig 5 Medians of internal gaps in different areas of all groups. [a]Significant difference with all other groups. [b]Significant difference between groups.

Table 2 Mean and Standard Deviation (SD) and Median and Interquartile Range (IQR) of Internal Gap (mm) of Different Areas in Each Group

Area/group	Mean	SD	Median	IQR
Marginal				
LT	0.0744	0.0172	0.0811	0.0262
EV	0.0274	0.0094	0.0277	0.0160
ZT	0.0253	0.0122	0.0215	0.0199
HM	0.0332	0.0083	0.0320	0.0116
Axial				
LT	0.1299	0.0311	0.1367	0.0541
EV	0.0373	0.0126	0.0391	0.0150
ZT	0.0226	0.0083	0.0216	0.0128
HM	0.0336	0.0062	0.0308	0.0098
Occlusal				
LT	0.0764	0.0366	0.0614	0.0563
EV	0.0808	0.0245	0.0689	0.0409
ZT	0.0688	0.0180	0.0669	0.0277
HM	0.0521	0.0287	0.0580	0.0432

LT = fused deposition modeling 3D printer; EV = digital light projection 3D printer; ZT = five-axis milling machine; HM = handmade wax patterns (control group).

Table 3 Differences Between Mean/Median Gaps and Prescribed Die Spacer Thickness Parameters (mm)

Area/group	Mean/Median	Prescribed parameters	Difference (mean/median – setting)	*P* value
Marginal				
LT	0.0744	0.030	0.0444	< .001
EV	0.0274		–0.0026	.404
ZT	0.0253		–0.0047	.255
HM	0.0332	0.0	0.0332	< .001
Axial				
LT	0.1299	0.080	0.0499	.001
EV	0.0373		–0.0427	< .001
ZT	0.0226		–0.0574	< .001
HM	0.0336	0.013	0.0206	< .001
Occlusal				
LT	0.0764	0.080	–0.0036	.765
EV	0.0689[a]		–0.0111	.959[a]
ZT	0.0688		–0.0112	.080
HM	0.0521	0.013	0.0391	.002

[a]Median value was tested with Wilcoxon signed rank test.

with the silicone replica. The crown was removed, and the silicone replica remained on the stone die. The stone die covered with the silicone replica was digitized using the same optical scanner, and the data were exported as an STL file and named "Test model."

The Ref and Test models were imported into a reverse engineering software (Geomagic Studio 2012). The Test model was aligned with the Ref model using the "Best Fit Alignment" command with a selected area of the teeth adjacent to the crown. The project file was then imported into 3D analysis software (Geomagic Qualify 2012). To assess the alignment quality, the root mean square (RMS) of the selected area involved in the alignment process was calculated using the "3D Compare" command. The 3D deviation of the surfaces inside the finishing line of the Test and Ref models was considered the thickness of the silicone replica. The measurements were separated into three distinct areas: marginal (area of 0.4-mm width from the finishing line), axial (middle third of the axial wall), and occlusal (occlusal surface of the abutment) (Fig 2b), and the average deviations (Average Distances) were recorded to represent the internal gap of the corresponding area. This workflow is shown in Fig 4.

Statistical Analyses

Before testing the statistical differences between each group, Shapiro-Wilk test and Levene test were performed to test the normality and equality of variance, respectively. A Kruskal-Wallis nonparametric analysis of variance (ANOVA) was performed followed by Mann-Whitney post hoc comparisons with Bonferroni adjustments to test the differences among the medians of gaps in all three areas between each group. In the EV group, the median occlusal gap was compared with prescribed die spacer thickness parameters using Wilcoxon signed rank test, and the means of marginal and axial gaps in other areas or other groups were tested using one-sample *t* test (IBM SPSS 20 for Windows). Statistical significance was accepted at a level of $P < .05$ except for Mann-Whitney post hoc comparisons, for which the significance level was adjusted to $P < .0083$.

Results

All of the crowns were tried in on the zirconia abutment to confirm that there was no friction between the crown and abutment; thus, damage of the stone models caused by friction of the crowns was avoided.

The RMS of the alignment area of each measurement was in the range of 5.1 to 9.9 µm. According to the quality scale of Peters et al,[14] RMS < 10 µm is considered excellent.

Shapiro-Wilk test indicated that the occlusal gap of the EV group did not satisfy the assumption of normality ($P = .02$). Levene test indicated that the marginal and axial gaps of all groups did not satisfy the assumption of equality of variance ($P < .05$).

The mean/median marginal, axial, and occlusal gap measurements and standard deviations (SDs)/interquartile ranges (IQRs) for each group are listed in Table 2. For both marginal and axial areas, the LT group achieved the largest internal gap, with statistically significant differences ($P < .0083$). In the axial area, the medians of the ZT and HM groups showed statistically significant differences ($P < .0083$); however, the difference was just 9.2 μm, which might not be clinically important. Kruskal-Wallis test indicated no significant differences for the medians of the occlusal gap for all groups ($P = .159 > .05$) (Fig 5).

Compared with the prescribed die spacer parameters, the EV and ZT groups in the marginal area and all three CAD/CAM groups in the occlusal area achieved values without statistically significant differences. The HM group did not reproduce the internal gap reserved by the die spacer (Table 3). Therefore, both the previously described null hypotheses were rejected.

Discussion

CAD/CAM technologies have been widely accepted in fixed prosthodontics and have been mainly adopted in all-ceramic restorations with acceptable clinical performance.[15–18] However, metal, metal-ceramic, and castable glass-ceramic restorations fabricated indirectly from casting patterns are still important options for dentists and patients. Because of the limitations of the manufacturing method and material properties, CAD/CAM has several shortcomings for the fabrication of these types of restorations: *(1)* CAD/CAM systems mostly employ subtractive manufacturing (milling and grinding) to fabricate the final products, resulting in up to 90% of the material block being removed,[19] which increases the cost; *(2)* Dental alloys typically exhibit high mechanical strength, which requires higher performance of the milling machine; and *(3)* Areas with radii of curvature smaller than the radius of the milling tools cannot be correctly fabricated.

The popularity of additive manufacturing in dentistry has increased in recent years. Metal additive manufacturing techniques, represented by selective laser melting and selective laser sintering, have been highlighted in research.[11,20–24] However, the limited types of material (mainly Co-Cr and titanium alloys), expensive facilities and materials, and lack of laboratory and clinical data have restricted their application. Only one study[24] investigated the adaptations of precious alloy copings produced by CAD/CAM laser melting and, based on its results, could not demonstrate the advantage of additive manufacturing for precious alloys. Therefore, resin patterns fabricated using CAD/CAM will instead serve as an integration point between CAD/CAM technology and casting restorations.

A few studies have focused on CAD/CAM fabrication of wax/resin patterns for casting. Hoang et al produced resin crowns with different die spacer parameters using a 3D printer and revealed, along with their instability,[25] the inability to produce resin crowns with prescribed die spacer parameters, but the means of the internal gap were all less than 100 μm. Bhaskaran et al observed that smaller marginal and internal gaps could be achieved by casting crowns fabricated from 3D printing patterns than from handmade wax patterns.[21] Fathi et al compared the marginal and internal adaptations of crowns fabricated from handmade, milled, and 3D-printed patterns and observed that the crown wax patterns made using CAD/CAM were as reliable as the handmade wax patterns; in addition, 3D printing was the most accurate in terms of internal and marginal fit, with a 30-μm cement gap parameter.[26] Various technologies were evaluated in these studies, including high-performance milling, DLP, and ink-jet printing, which produced favorable results. However, for 3D printing using FDM technology, only Ishida et al[3] have evaluated the dimensional accuracy by producing casting patterns of a simplified crown. Therefore, an evaluation of the internal adaptations of crowns cast with complex geometries is necessary.

To evaluate the internal adaptation of a restoration, traditional methods have included cross-sectional measurement after cementation, cross-sectional measurement of a silicone replica, or the use of micro–computed tomography data.[21,27–30] These methods had the shortcoming of limited sample size and so could not demonstrate the distribution of the internal space. Groten et al determined that a minimum of 50 randomly or systematically selected points were needed to estimate the marginal adaptation of a crown,[31] and few studies have met this requirement. Although the minimum amount of points needed to determine the internal adaptation remains unclear, traditional 2D cross-sectional measurement methods are unlikely to meet the minimum. Three-dimensional evaluation was first introduced by Luthardt to evaluate the fit of copings.[10] It can determine the entire surface morphology of the abutment and can therefore fully demonstrate the internal space distribution. In the present study, the authors further referred to Ohlmann's[12,13] and Hartkamp's[32] method of measuring clinical wear of crowns: the unchanged areas were used to align digital models digitized from stone models in the same coordinates; thus, the changes of the region of interest (ROI) could be observed. However, the duplication of stone dies could produce errors. To minimize the bias among each measurement, the stone dies were duplicated by the same operator in a single day. The sample sizes of the marginal, axial, and occlusal areas were approximately 3,100, 4,000, and 3,900; thus, the 3D distribution of internal space could be demonstrated. The shortcoming of this method was that it only partially demonstrated the marginal gap by the internal gap in the marginal area, which was smaller than the clinically acceptable cut value of 120 μm[33] used in this study. Marginal defects such as overhangs, overextended margins, and underextended margins could not be detected by this method.

In this study, a clinically oriented workflow of intraoral scanning and then CAD milling/additive manufacturing was explored. Each step could produce different errors, and their effects on the final restorations were difficult to assess. Moldovan considered the die spacer parameter to be a semi-quantitative tool to compensate for the errors of the process chain; therefore, a certain process chain should have its own spacer settings based on the operator's experience to achieve the best fit.[34] Although the results showed clinically acceptable internal fit,[35] some suggestions for improvement might be made for the Lingtong-III FDM 3D printer: *(1)* an axial space of less than 80 μm might be more favorable to reduce the axial gap of the crown; and (*2*) considering the difficulty of producing a thin margin, the existence of "stairs" caused by layer deposition around the margin, and the limitations of FDM technology, additional adjustments to casting patterns, such as adding wax to the margin line on the stone model in the dental lab, might be a feasible solution.

Although the accuracy of casting crowns using resin patterns directly fabricated by an FDM 3D printer still needs improving, the FDM 3D printer may still be a good choice for chairside application. FDM 3D printers occupy little space and have good efficiency. In the present study, the printing process for each crown was about 30 minutes, compared with 25 minutes/unit for the ZT group and 2.5 hours/plate for the EV group, and little preparation of the printer and postprocessing of the product was needed. Moreover, the FDM 3D printer uses biodegradable polylactic acid, which has extensive sources, results in little pollution, exhibits strong impact resistance, and is of low cost.[4,36] Although the properties of this material after printing still need investigation, the intrinsic good biocompatibility of polylactic acid makes it possible to be used intraorally. Thus, practitioners may adjust casting patterns in the patient's mouth in a single visit to improve the occlusal adaptation of the final restoration.

Conclusions

Casting crowns using casting patterns made from all three CAD/CAM systems could not produce the prescribed parameters but showed clinically acceptable internal adaptation.

Acknowledgments

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Literature Abstract

Marginal Bone Loss at Implants with Different Surface Characteristics—A 20-year Follow-up of a Randomized Controlled Clinical Trial

This report is a 20-year follow-up of a randomized controlled clinical trial evaluating the potential long-term effects of a modified implant surface on the preservation of the peri-implant marginal bone level. In each of 51 patients and for each fixed partial denture (FPD), at least one implant installed had a nonmodified turned surface and one a modified and roughened surface (TiOblast). Clinical and radiologic examinations were performed at various follow-up intervals. The primary outcome variables were peri-implant marginal bone level change from time of loading and the proportion of implants with no bone loss at 20 years. Multilevel analysis followed by nonparametric and Pearson chi-square tests were applied for statistical analyses. At the 20-year follow-up, 25 patients carrying 64 implants were available for evaluation. Turned and TiOblast implants presented with a mean bone level change from the time of FPD delivery amounting to –0.41 mm (95% confidence interval [CI] –0.84 to 0.02) and –0.83 mm (95% CI –1.38 to –0.28), respectively (inter-group comparison $P > .05$). Of the turned and TiOblast implants, 47% and 34%, respectively ($P > .05$), showed no bone loss. All but one of these implants were free of bacterial plaque and inflammation and presented with probing pocket depth ≤ 5 mm at both the 5- and 20-year follow-up examinations. It is suggested that a moderate increase of implant surface roughness has no beneficial effect on long-term preservation of the peri-implant marginal bone level.

Donati M, Ekestubbe A, Lindhe J, Wennström JL. *Clin Oral Implants Res* 2018;29:480–487. **References:** 24. **Reprints:** Mauro Donati, mauro.donati@odontologi.gu.se —*Steven Sadowsky, USA*