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RESEARCH AND EDUCATION

Trueness analysis of zirconia crowns fabricated with 3-dimensional printing

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ABSTRACT

Statement of problem. The primary manufacturing method of zirconia ceramic crowns is computer-aided design and computer-aided manufacture (CAD-CAM), but a disadvantage of this technique is material waste. Three-dimensional (3D) printing, which has been recently introduced into dentistry, has improved the processing of polymers and metals, but not yet of ceramic crowns.

Purpose. The purpose of this in vitro study was to evaluate the 3D trueness of zirconia crowns fabricated by 3D printing to investigate the potential application of this technology in dental ceramic restorations.

Material and methods. A typodont tooth was prepared for a ceramic crown, and a digital crown was designed using the CAD software. The digital crown was processed either with a 3D-printing system or with a dental milling system. The crowns were scanned using a dental laboratory scanner, and the data collected for each crown were divided into 4 parts (the external surface, intaglio surface, marginal area, and intaglio occlusal surface). Finally, the trueness of each part was determined using the 3D inspection software. The 3D trueness of the crowns fabricated by either 3D printing or milling was compared by a 1-sided test (α=.05).

Results. The trueness of the external surface, intaglio surface, marginal area, and intaglio occlusal surface of the 3D-printed crowns was no worse than the corresponding trueness of the CAD-CAM crowns (P<.05).

Conclusions. Zirconia crowns produced by 3D printing meet the trueness requirements, and 3D printing may be suitable for fabricating zirconia crowns. (J Prosthet Dent 2019;121:285-91)

Zirconia (ZrO_2) ceramics are popular as esthetic restorative materials for crowns and fixed partial dentures owing to their excellent mechanical properties.[1] Subtractive manufacturing technology is the chief technology used for fabricating ZrO_2 restorations with computer-aided design and computer-aided manufacture (CAD-CAM), in which restorations are milled from large blocks using different cutters. However, approximately 90% of the prefabricated block is wasted during this process.[2] Additive manufacturing (AM) is an alternative process with minimum waste. AM has been defined by the American Society for Testing and Materials as "the process of joining materials to make objects from 3-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[3] Three-dimensional printing, adapted for the AM process, has been successfully used in prosthodontics for the fabrication of resin or metal crowns,[4-7] metal denture frameworks or bases,[8-11] and metal implants.[12] However, 3D printing of ceramic restorations has not yet been routinely used,[13] and only limited research has been done on 3D printing for fabricating ZrO_2 crowns. ZrO_2 frameworks have been printed from

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Clinical Implications

Three-dimensional printed zirconia restorations that satisfy trueness demands can be produced and could be used in clinical applications to prevent material waste.

a suspension of ZrO_2 particles using an inkjet printer.[14,15] However, these studies did not analyze the surface trueness of the crown. In addition, the use of an inkjet printer faces the challenges of nozzle blockage and lack of accuracy when complex shapes are involved. A recent study[16] has reported the dimensional accuracy of 3D printing (Digital Light Processing technique) for ZrO_2 implants but did not evaluate the accuracy of ZrO_2 crowns by trueness analysis.

Restoration fit plays an important role in long-term clinical success. The accuracy of a restoration is the most important indication of fit and depends on the fabrication process.[17-19] Poor marginal fit can result in plaque accumulation, risk of microleakage, and gingival inflammation.[20,21] In addition, an increase in the internal gap reduces the fracture resistance and the thickness of the crown.[22] As restorations with high accuracy reduce the need for adjustments and save clinical time,[17] reducing the finishing steps on the intaglio or occlusal surfaces can prevent damage and improve the quality of restorations.[23]

Trueness is an evaluation of accuracy, which describes how far a measurement value deviates from the true value.[24,25] With 3D printing, the surface-stepping phenomenon during this process affects the trueness of the 3D object.[26,27] With the development of scanners with high accuracy and the popularity of the 3D inspection software, the 3D trueness of ZrO_2 crowns can be analyzed. This type of analysis is more comprehensive than that previously used for 2-dimensional analysis, which ignores dimensional changes on the 3D surface.[28] Moreover, 3D analysis can intuitively reflect the error of multiple surfaces between the true dimension of the restoration and its corresponding computer-aided design (CAD) without using destructive methods.[17,25,29]

Therefore, the purpose of this in vitro study was to evaluate the 3D trueness of ZrO_2 crowns fabricated by 3D printing and to compare it with the trueness of crowns fabricated by CAD-CAM milling as a control. The research hypothesis was that 3D printing would be no worse than CAD-CAM milling.

MATERIAL AND METHODS

The 3D-printed ZrO_2 crowns were fabricated using a ceramic 3D-printing system (CERAMAKER 900; 3DCeram Co) that uses hydroxyapatite for custom manufacturing of ceramic implants to reconstruct large and complex bone defects.[30] However, the authors are unaware of previous reports of its effectiveness for printing dental restorations. To assess the accuracy of the 3D-printed crowns, their trueness was evaluated and compared with the trueness of crowns fabricated using a CAD-CAM system (DWX-50; Roland DG Corp). A maxillary right second molar, a typodont tooth, (No. 523; Nissin Corp) was prepared for a ceramic crown by a prosthodontist (B.G.) with 5 years of clinical experience. The prepared tooth was scanned using a dental laboratory scanner (D810; 3shape A/S), and a ceramic crown was designed based on the digital scan of the unprepared tooth and saved as a standard tessellation language (STL) file.[17,31] The STL file was imported into the 3D printing and the CAD-CAM systems.

In the 3D-printing group (n=10), crowns were fabricated using the 3D printer based on the principles of stereolithography (SLA). This printer uses a computer-guided laser and SLA has been successfully used to manufacture surgical implant templates and maxillofacial prostheses.[32-34] The slice dimensions and laser parameters were set based on the imported STL file and then the working tank was filled with a ZrO_2 paste (3DMIXZrO_2L; 3DCeram Co) mixed with liquid photosensitive resin. The paste was selectively solidified under radiation from an ultraviolet laser. The working surface along the z-axis of the device was lowered by one-layer distance, and the working tank was filled with fresh paste. During this cycle, the green crown was printed layer by layer. After printing, the binder was removed thermally, and the ZrO_2 was sintered. No additional processing, such as finishing or polishing, was performed. Figure 1A shows a representative image of the fabricated crown by 3D printing.

Current dental CAD-CAM systems use 3-, 4-, or 5-axis milling machines according to the number of the coordinate axes of the cutters. In this study, for the CAD-CAM group (n=10), the STL files were imported into a 5-axis, 2-bur milling machine (DWX-50; Roland DG Corp) for processing of the ZrO_2 block (Zenostar; Wieland Dental). A 5-axis milling machine has greater accuracy, and the 2 ball-end mill burs have been reported to be more effective than the 3 ball-end mill burs for shaping the intaglio of the prosthesis.[13,29,35] The restorations were sintered without further adjustments. Three-dimensional sintering shrinkage can affect the accuracy of the restoration, which is closely dependent on the raw material and the technology used.[36,37] Figure 1B shows a representative crown fabricated by milling.

After cleaning and drying the restorations, the external and intaglio surfaces of the 20 crowns were lightly powdered (Scan Spray Lab; Dentaco GmbH) and scanned using a dental blue light scanner (DS100; Shining 3D Corp)

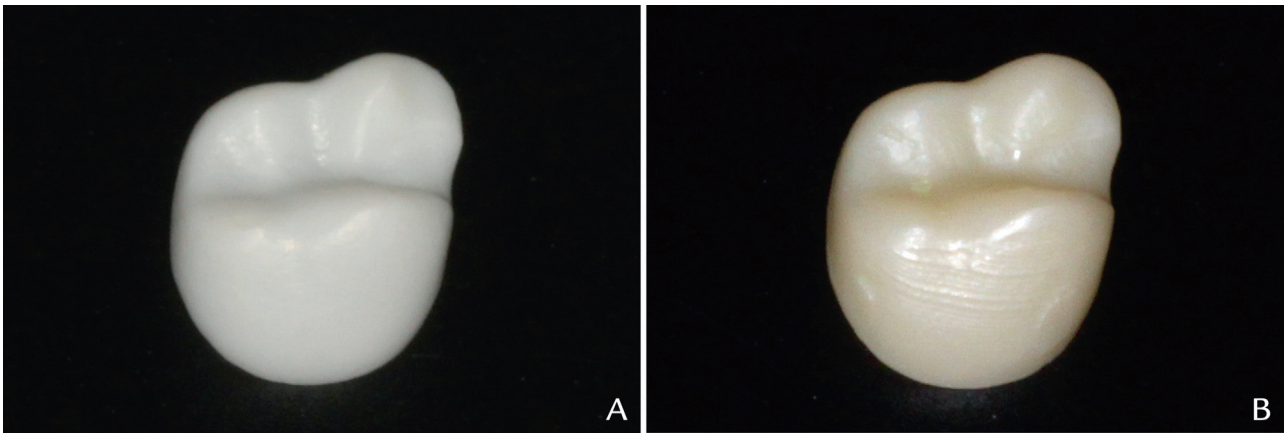

Figure 1. Representative images of crown restorations manufactured by different technologies. A, Three-dimensional printing. B, CAD-CAM. CAD-CAM, computer-aided design and computer-aided manufacture.

from multiple directions. To acquire the complete surface parameters, the nonrelevant parts of the tooth were removed using the bundled software. All these processes were performed by the same experienced operator (W.W.).

The scanned data were saved in STL format and imported into a 3D inspection software package (Geomagic Qualify 2013; Geomagic Inc) to divide the crown into 4 parts (the external surface, intaglio surface, marginal area, and intaglio occlusal surface) as described by Kim et al.[29] The intaglio surface from the margin to 1 mm above the margin was specified as the boundary of the marginal and intaglio surface. These 4 parts were defined as the set test, and the CAD crown was defined as the set reference.

Each part of the 4 divided parts was directly superimposed on the corresponding data of the reference CAD crown with best-fit alignment. During this process, only 1 superimposition was simultaneously performed for the 4 parts instead of separating the intaglio into 2 parts (the marginal and intaglio occlusal surface) to perform the final superimposition after the entire external and intaglio surfaces had been superimposed. Finally, color maps were generated to represent the 3D deviation, with the maximum and minimum critical (nominal) values set at 50 μm (10 μm), and −50 μm (−10 μm), respectively. The root mean square (RMS) was calculated by applying the formula[29,31]

$$\mathrm{RMS}=\frac{\sqrt{\sum_{i=1}^{n}\left(X_{1,i}-X_{2,i}\right)^2}}{\sqrt{n}},$$

where n is the total number of measuring points, $X_{1,i}$ is the measuring point i on the reference data, and $X_{2,i}$ is the measuring point i on the crown scan data. RMS can serve as a measure of how far deviations between the 2 different datasets vary from zero.[31] RMS has been previously used to evaluate the trueness of prostheses.[16,29] In addition, the RMS has also been used as the index of "trueness" for comparing different problems.[31,36,38,39] A low RMS value indicates high 3D trueness.

All experimental data were generated as RMS ±standard deviation. The noninferior test was used to determine statistically significant differences between the 2 groups (α=.05, 1-sided test). Based on clinical experience, the margin of difference was set as 15 μm, which means that if the RMS of the 3D-printed crown group is not greater than that of the CAD-CAM milled crown group by 15 μm, the trueness of the 3D-printing group can be considered no worse than the CAD-CAM milling group. All statistical analyses were performed using a statistical software package (Statistical Analysis System (SAS) v9.2; SAS Institute Inc).

RESULTS

Table 1 shows the RMS ±standard deviation values of the 2 groups and P values of the noninferior test. For the external surface of the crown, the RMS value of the 3D-printing group was greater than that of the milling group, and for the other locations, the RMS values of the 3D-printing group were lower than those of the milling group. The noninferior test shows that each of the P values of the 4 parts was <.05. Therefore, the null hypothesis that the RMS of the 3D-printing group was greater than that of the milling group by 15 μm was rejected. These statistical results determined that the trueness of the 4 parts of the crowns in the 3D-printing group was no worse than that of the corresponding crowns in the CAD-CAM group (P<.05).

Color maps were generated to represent the deviations between the printed crown scan data and the reference CAD data. The deviation range is color coded from −50 μm (blue) to +50 μm (red). Blue areas represent

Table 1. Trueness of different locations of surface of crowns fabricated by 3D printing and CAD-CAM

Area	3D-Printing Group (μm) RMS ±SD	CAD-CAM Group (μm) RMS ±SD	90% CI of Difference Value (3D Printing–Milling)	*P*
External	53 ±9	52 ±18	-9.2 to 12.7	.025
Intaglio	38 ±12	43 ±12	-14.8 to 3.9	<.001
Marginal	34 ±5	35 ±7	-6.3 to 3.1	<.001
Intaglio occlusal	27 ±17	41 ±15	-27.0 to -2.1	<.001

3D, three dimensional; CAD-CAM, computer-aided design and computer-aided manufacture; CI, confidence interval; RMS, root mean square; SD, standard deviation.

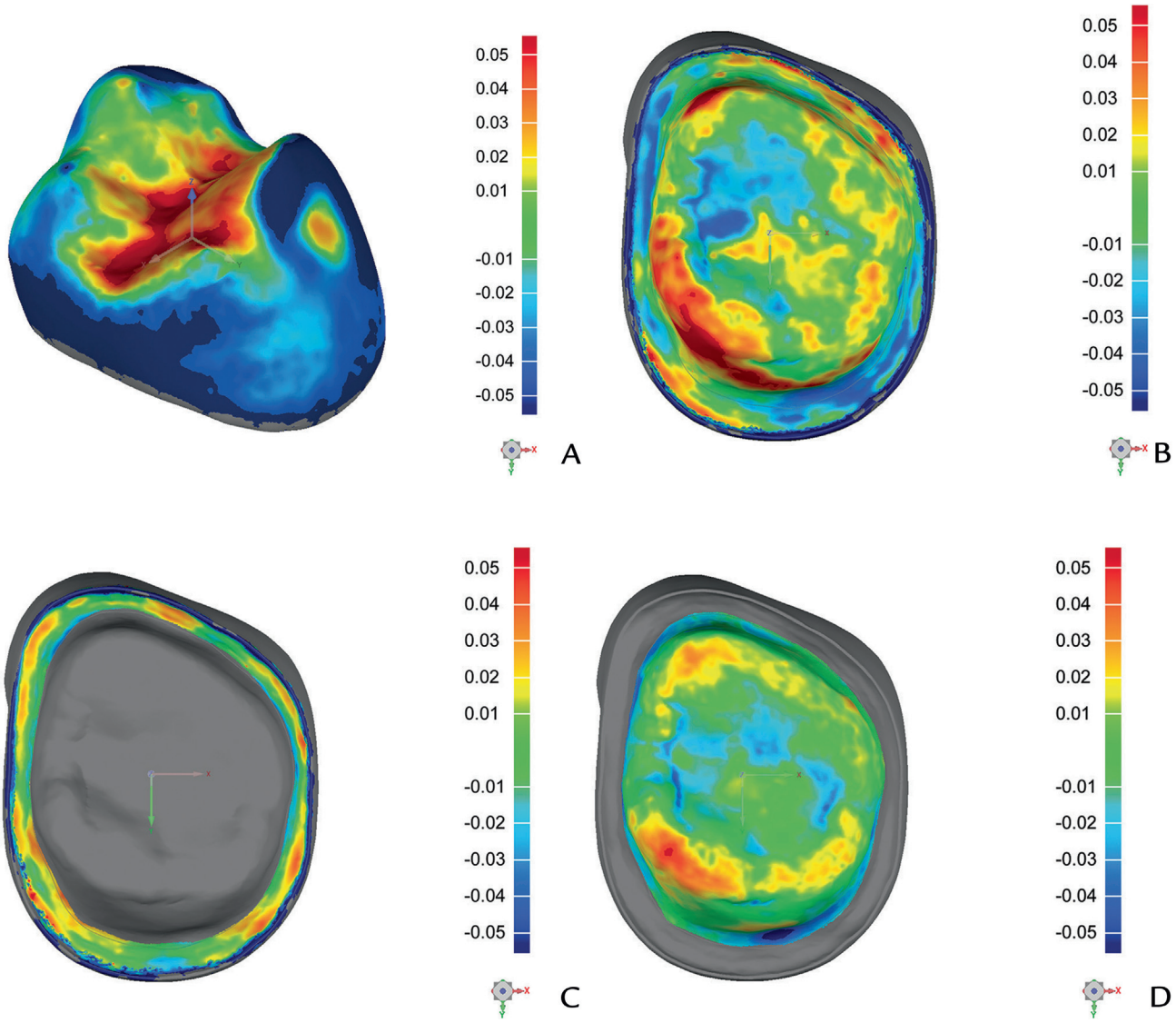

Figure 2. Color maps representing deviation values (mm) in 4 crown locations fabricated by 3D printing. A, External surface. B, Intaglio surface. C, Marginal area. D, Intaglio occlusal surface. 3D, three dimensional.

negative deviations, indicating that the printed crown dimension was smaller than the reference CAD dimensions, whereas red portions represent positive deviations, indicating that the printed crown dimension was larger than the reference CAD dimensions. The deviation results of the 3D-printing group are illustrated in Figure 2. The occlusal grooves in the external surface of the crown show particularly strong positive values, whereas the axial surfaces display negative deviation values (Fig. 2A). The intaglio and intaglio occlusal surfaces (Fig. 2B, 2D) mainly exhibit similar values except at the junction between the axial surface and the occlusal surface, which shows high positive deviation values (Fig. 2B). The marginal surface shows negative values,

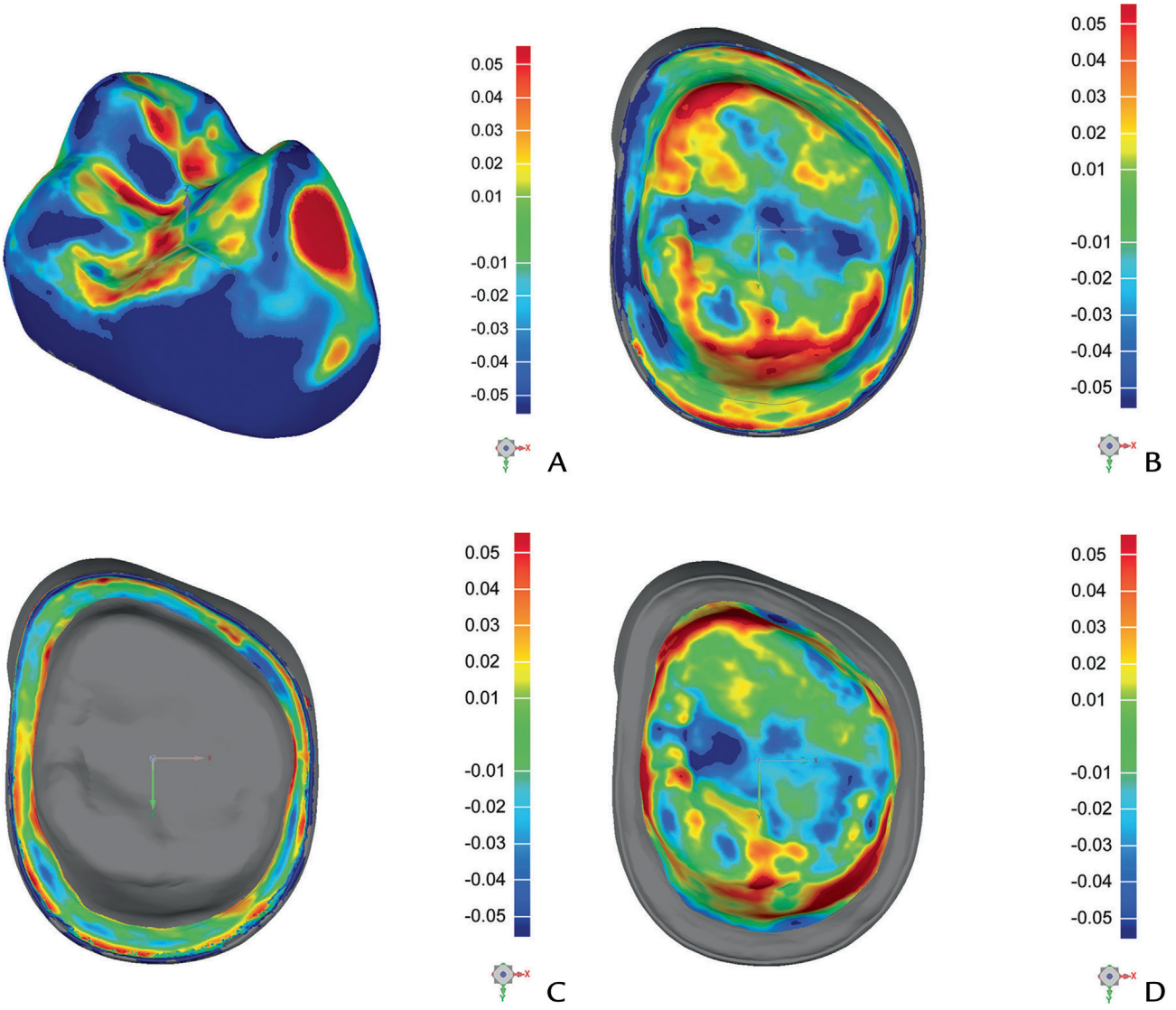

Figure 3. Color maps representing deviation values (mm) in 4 parts of crown fabricated by CAD-CAM milling. A, External surface. B, Intaglio surface. C, Marginal area. D, Intaglio occlusal surface. CAD-CAM, computer-aided design and computer-aided manufacture.

whereas the remaining area mostly shows similar values (Fig. 2C).

Figure 3 displays the deviation results of the milled crowns. The occlusal grooves in the external surface and on the line angle between the intaglio and the intaglio occlusal part show positive deviation values (Fig. 3A, 3B, 3D), whereas the axial surfaces (Fig. 3A) exhibit negative deviation values. This indicates that less material was removed from the grooves relative to the axial surfaces during the milling process. However, the remaining portions and the marginal part (Fig. 3C) mainly show similar values.

DISCUSSION

The trueness of ZrO_2 crowns fabricated by 3D printing and CAD-CAM milling was examined in this in vitro study. According to the results, the research hypothesis was supported, indicating that 3D-printing technology can be effectively used to fabricate ZrO_2 crowns with the same trueness value as the milling method.

We assessed the trueness of the crown-manufacturing process, instead of directly measuring the fit of the crowns. This approach avoids the need for the silicone replica technique[40] or for sectioning multiple dies.[6] Instead, the point-to-point differences were evaluated between the scan data and the corresponding CAD model data. The generated color maps directly show which areas of the crown had been accurately or inaccurately reconstructed and demonstrated that there was a similar error distribution between the 3D-printing and the milling techniques.

After milling, the restoration is in the presintered state and is then sintered to its final dimensions. Therefore,

the trueness of the technology and the control of the 3D sintering shrinkage will affect the accuracy of the restorations.[36] In the present study, the milling machine was used as a control because it has excellent accuracy. The results revealed that the grooves in the external surface and the line angles in the intaglio surfaces display low trueness. This is because the intaglio surface is complex and difficult to mill. Sintering shrinkage is approximately 25%.[37] Therefore, the negative deviation values observed from the axial external surfaces may be attributed to insufficient sintering shrinkage compensation.

The industrial grade ceramic 3D printer used in this study is based on the principles of SLA, which has been more thoroughly studied and more widely used than other 3D-printing technologies. The materials commonly processed by this 3D printer are ZrO_2, alumina (Al_2O_3), and hydroxyapatite. Previous studies have reported preliminary research on the 3D printing of ceramic prostheses.[14-16] However, the authors are unaware of reports of ZrO_2 crowns produced by this method or this printer. The trueness of 3D objects produced by SLA depends on 2 production variables, the technology applied and the 3D sintering shrinkage. Owing to the surface-stepping phenomenon in 3D printing, occlusal surfaces or large curved surfaces are more error-prone than vertical surfaces,[26,27,35] which adversely affects the trueness of the crowns in the larger grooves and line angle areas. The thickness of a layer is related to this error, and a measurable error can occur independent of the minimal error of each layer.[8] In addition, compensation for the sintering shrinkage should be adequate; otherwise, the axial surface will show negative deviation values and low trueness.

The scanning of the crowns and the alignment process in the software can also affect the results. Powdering the crowns before scanning is necessary but can introduce error. However, the DS100 scanner used in this study, with a precision of 15 μm for a single tooth, is sufficiently accurate for trueness evaluation of the production technology.[17] The scanning of sharp edges, such as margins, is limited because of a rounding effect.[25] In addition, an error may occur when certain processes, such as alignment, are conducted in the software.

The ZrO_2 slurry used for the 3D printing is produced on demand rather than being mass produced because of storage difficulties. Moreover, the high cost of the machinery affects the cost of crowns fabricated by 3D printing. In addition, fewer color options are currently available. These are the challenges for the successful application and development of this method in dentistry. In the future, reduction in the material and equipment costs, improved accuracy, and the development of an adequate shade range will enable the application of this technology in clinical practice.

This study has limitations. The tooth preparation used may not reflect the actual clinical conditions. Additional research is required for the application of ZrO_2 ceramic crown produced by 3D printing. Nonetheless, this work has shown that there is great potential to use 3D-printing technology for the fabrication of ZrO_2 crowns.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. ZrO_2 crowns produced by 3D printing meet the surface trueness requirements.
2. Three-dimensional printing is a potentially effective method for fabricating ZrO_2 crowns.

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