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# Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs

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ABSTRACT

Subtractive manufacturing has become the dominant method in fabricating zirconia dental restorations while additive manufacturing is emerging as a potential alternative. The aim of this in vitro study was to investigate the performance of stereolithography (SLA) and milling in fabricating monolithic zirconia crowns with different finish line designs. Full-contour crowns with three finish lines (chamfer, rounded shoulder, knife-edge) were designed and fabricated by SLA and milling. Fabrication accuracy was accessed by 3D deviation analysis and margin quality was characterized under microscopes. The obtained root mean square value was significantly influenced by finish line design ($P < 0.05$) but not by fabrication method ($P > 0.05$). However, the color-difference map showed crowns fabricated by SLA and milling had different error distribution in external surfaces. SLA-printed crowns exhibited margins of rounded line angle and without small flaws, although large chippings were found in knife-edged crowns. In milling group, crowns showed margins of sharp line angle and with separate chippings. More and larger margin chippings were found in knife-edged crowns by milling. The results indicate that SLA and milling can fabricate monolithic zirconia crowns of comparable accuracy and knife-edged crowns are prone to large margin chippings by either of the two manufacturing methods.

## 1. Introduction

In fixed prosthodontics, esthetic restorations of reliable mechanical performance and with minimal tooth preparation design are favorable (Findakly and Jasim, 2019; Yu et al., 2019b). Tooth-colored zirconia is widely used due to its high toughness and strength (Denry and Kelly, 2008; Stawarczyk et al., 2017). Moreover, with the improved translucency and developments of coloring techniques, monolithic zirconia restorations are increasingly advocated in clinical practice to eliminate the risk of veneer chipping and minimize tooth preparation (Malkondu et al., 2016; Pereira et al., 2018).

Since it was introduced into dentistry in the 1970s (van Noort, 2012), subtractive computer-aided manufacturing (CAM) technology has become the dominant method in fabricating zirconia restorations with good efficiency and efficacy. In the past decade, additive manufacturing (AM) is emerging as a potential alternative fabrication method although it remains to be developed (Galante et al., 2019; Methani et al., 2020; Revilla-León et al., 2020b). The American Society for Testing and Materials (ASTM) classifies the various AM technologies into 7 categories: stereolithography (SLA), material jetting, material extrusion, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition. With its capability to shape specimens with good surface quality and high feature resolution, SLA is one of the most promising AM technologies in fabricating zirconia restorations (Chen et al., 2019). In brief, it shapes a green body by curing the resin-based ceramic suspension layer-by-layer with an ultraviolet laser and densify it by the subsequent thermal treatment (Mitteramskogler et al., 2014). Wang (Wang et al., 2019) reported that the trueness of the SLA-printed crowns is no worse than that of the milled crowns. However, Revilla-León (Revilla-León et al., 2020a) reported that the SLA-printed full-contour crowns show higher marginal and internal discrepancies (146.0 ± 103.2 and 79.0 ± 46 μm) than the milled ones (37.5 ± 50 and 73 ± 44.7 μm).

Finish line design is an extensive concern in clinical decision-making. It is desirable to achieve a balance between tooth preservation and the fracture resistance of restorations (Monaco et al., 2019; Skjold et al., 2019). Finish line design of chamfer or rounded shoulder is generally recommended for the preparation of zirconia restorations (Miura et al., 2018; Reich et al., 2008). As for knife-edge finish line, it is mainly

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applied in metal restorations and is indicated for teeth of young individuals or periodontally involved teeth with severe gingival recession (Poggio et al., 2012; Reich et al., 2008). Given the high mechanical properties of zirconia, clinicians and researchers are exploring the feasibility of using zirconia restorations with knife-edge margin to preserve more sound tooth substances in cervical and axial areas (Borelli et al., 2015; Monaco et al., 2013; Serra-Pastor et al., 2019). Previous studies have demonstrated that finish line design affects the marginal and internal adaptations of restorations but there is no consensus on which design can achieve the best adaptations (Cetik et al., 2017; Comlekoglu et al., 2009; Yu et al., 2019a). Moreover, studies revealed that zirconia restorations of different finish lines show different stress distributions and load-bearing capacities (Beuer et al., 2008; Miura et al., 2018; Pan et al., 2020).

It is noteworthy that the margin quality plays a more essential role in both marginal sealing and load-bearing capacity of restorations (Schriwer et al., 2017; Tsitrou et al., 2007). Margin defect could become a stress concentration zone when functionally loaded and is likely to develop to be a fracture origin (Schriwer et al., 2017). Besides, margin defect would increase the local margin gap, resulting in risks of microleakage and endangering the periodontal health. The milling process involved in subtractive manufacturing could potentially introduce margin defects in the fabricated restorations (Giannetopoulos et al., 2010). Zirconia crowns fabricated by SLA were also reported to show margin defects (Revilla-León et al., 2020a).

Limited information is available on fabrication accuracy and margin quality of monolithic zirconia crowns with different finish line designs. The aim of this in vitro study was to investigate the performance of SLA and milling in fabricating monolithic zirconia crowns with different finish line designs by characterizing the fabrication accuracy and margin quality. The null hypothesis of this study was that the fabrication accuracy of monolithic zirconia crowns would not be influenced by fabrication method or finish line design.

## 2. Materials and methods

### *2.1. Crown design and fabrication*

A typodont left maxillary first molar (Nissin Dental Products, Japan) was scanned (DS-EX Pro, Shining3D, China) and digitally prepared in reverse engineering software (Geomagic Studio, 2013; Raindrop, USA). Three digital abutment models were created (Fig. 1), with finish line design of chamfer (0.5 mm depth), rounded shoulder (0.5 mm depth), and knife-edge respectively. The abutments have an occlusal reduction of 1.0–1.5 mm and a taper of 6–10°. The three abutments were 3D printed (DLP1080E, Han's Laser, China) and scanned (DS-EX Pro, Shining3D, China). Accordingly, three crowns with different margins but identical anatomic contours were designed using DentalCAD (ExoCAD, Germany) and exported as standard tessellation language files (CAD data).

Five crowns of each finish line design were fabricated by the two manufacturing methods. An SLA 3D printer (CSL 100, Porimy, China) was used to additively fabricate crowns with a 47 vol% 3 mol zirconia suspension. The 355 nm ultraviolet laser scanned at a speed of 1200 mm/s and the layer thickness was set at 25 μm. After printing, the green specimens were ultrasonically cleaned. Two-stage thermal treatment of de-binding and sintering was performed in a furnace (KSL-1700X, Kejing, China). In subtractive manufacturing, crowns were milled from a partially sintered zirconia blank (SHT, Aidite, China) using a milling machine (AK-D4, Aidite, China). The milled crowns were then sintered at 1450 °C for 2 h.

Totally, thirty zirconia crowns were fabricated and no additional manual adjustments were performed.

### *2.2. Fabrication accuracy analysis*

An intraoral scanner (3Shape Trios 3, 3Shape A/S, Denmark) was used to digitalize the fabricated crowns (Scan data). The collected data was imported to the software (Geomagic Studio, 2013; Raindrop, USA) for fabrication accuracy analysis. The Scan data were aligned to the CAD data according to a registration strategy which was described in detail in a published study (Li et al., 2020). 3D deviation analysis was performed to detect the distance between the two data in external (occlusal and mid-axial) and intaglio areas. Color-difference map and the root mean square (RMS) were obtained to manifest the three-dimensional accuracy of the fabricated crowns. RMS indicates how far deviations between the two datasets (Scan data and CAD data) vary from zero (Schaefer et al., 2012). A low RMS value indicates high accuracy of the fabricated crown.

### *2.3. Margin quality characterization*

Crowns were examined by an optical stereomicroscope (SZX7, Olympus, Japan, 5 × magnification) and graded based on the number and severity of margin defects. The grading scale was developed by Schriwer (Schriwer et al., 2017) and as follows:1, smooth edge with no defects; 2, smooth edge with few, small separate defects; 3, several small defects; 4, rough edge with continuous defects; 5, large defects. 3D laser scanning microscope (VK-X200, Keyence, Japan) was used for detailed observation at 200 × magnification.

### *2.4. Statistical analysis*

Data were analyzed using SPSS (IBM SPSS Statistics 21, IBM, USA). The data were positively tested for normality distribution and equivalence of variances. Two-way analysis of variance (ANOVA) was performed and Tukey post hoc analysis for multiple comparison test was used to analyze the influence of finish line design on fabrication accuracy. The level of significance was set at 0.05.

**Table 1**
Fabrication accuracy characterized by the RMS of the fabricated crowns, x ± s, μm, N = 30.

| Method | Area | Chamfer | Rounded shoulder | Knife-edge |
|---|---|---|---|---|
| **SLA** | External | 19.22 ± 0.91 | 26.20 ± 2.04 | 25.92 ± 3.62 |
| | Intaglio | 22.68 ± 4.03 | 17.04 ± 2.65 | 22.48 ± 6.00 |
| **Milling** | External | 20.82 ± 4.47 | 20.42 ± 4.10 | 23.06 ± 4.65 |
| | Intaglio | 20.76 ± 2.65 | 20.38 ± 1.54 | 22.64 ± 1.81 |

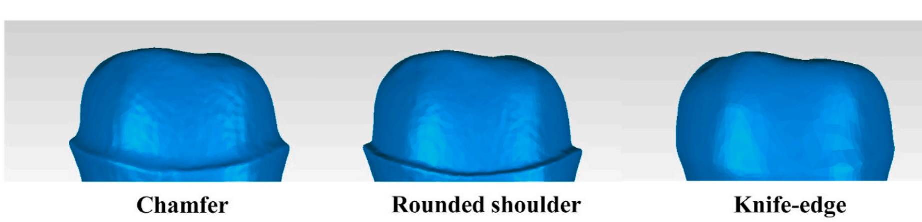


**Fig. 1.** Schematic diagram of each finish line design.

## 3. Results

Table 1 shows the mean and standard deviation of RMS value of the fabricated crowns. Statistical analysis indicated that the RMS value was significantly influenced by finish line design (external: $P = 0.027$, intaglio: $P = 0.049$) but not by fabrication method (external: $P = 0.084$, intaglio: $P = 0.680$), as shown in Table 2. Tukey post hoc showed the RMS value in external area of knife-edge design (SLA: 25.92 ± 3.62 μm, milling: 23.06 ± 4.65 μm) was higher than that of chamfer design (SLA: 19.22 ± 0.91 μm, milling: 20.82 ± 4.47 μm). Representative color-difference maps of 3D deviation analysis are shown in Fig. 2. A major positive error was found at fossae and grooves in milled crowns while at cusp inclines in SLA-printed crowns. For intaglio surface, all crowns showed a similar error distribution.

Table 3 shows the margin quality of the crowns. Observed at 5 × magnification, crowns with chamfer and rounded shoulder finish line designs showed smooth edges with no defects while knife-edged crowns by both fabrication methods showed minor and large defects. When observed at 200 × magnification (Fig. 3), milled crowns showed margins of sharp line angle and with separate chippings. More and larger chippings were found in those with knife-edge margin. For SLA-printed crowns, margins of rounded line angle showed a smooth contour without small flaws. However, large chippings also occurred in knife-edged crowns.

## 4. Discussion

This in vitro study investigated the performance of SLA and milling in fabricating monolithic zirconia crowns with different finish line designs. The null hypothesis that the fabrication accuracy of monolithic zirconia restorations would not be influenced by fabrication method or finish line designs was rejected.

The accuracy of dental restorations is generally evaluated by internal and marginal adaptations (Mahmood et al., 2019; Shimizu et al., 2017). With the development of data acquisition and analysis, 3D deviation analysis, which is comprehensive and evaluates both the external and intaglio surfaces, has been developed to manifest the fabrication accuracy (Bosch et al., 2014; Kang et al., 2018). In the present study, crowns fabricated by SLA showed comparable RMS values with those by milling ($P > 0.05$). This result was consistent with a previous study where RMS values were reported at 53 ± 9 μm (external), 38 ± 12 μm (intaglio) in SLA group and 52 ± 18 μm (external), 43 ± 12 μm (intaglio) in milling group (Wang et al., 2019). A smaller RMS value in the present study could be ascribed to the different devices and processing parameters adopted during fabrication and data acquisition.

However, color-difference maps of crowns by the two fabrication methods showed different error distributions in external surfaces. A major positive error was found at fossae and grooves in milled crowns, which is common in subtractive-manufactured restorations. It is a limitation posed by the size and shape of the milling bur (Abduo et al., 2014). In SLA-printed crowns, a major error occurred mainly at cusp inclines. Such an error would pose more effects on occlusal contact and require more adjustments in clinical application. SLA technology shapes specimens in a layer-by-layer way and thus they present a staircase-like surface. The dimensional accuracy of a curved surface is more affected by the staircases (Abduo et al., 2014; Choi and Chan, 2004). Moreover, building supports were attached to the occlusal surface in the present study. The manual operations to remove the building supports were likely to introduce sporadic dot-like positive or negative error. Similar errors occurred at axial area in milled crowns when removing the supporting bars. Whereas, error at axial area has less influence on physiological contact of the crown.

For knife-edged crowns, large chippings existed and the margin area was difficult to be digitalized. As a result, the margin area was excluded when analyzing the intaglio surface of knife-edged crowns. A statistically significant difference in fabrication accuracy was found among crowns with different finish line designs ($P < 0.05$). Previous studies on adaptations of crowns with different finish lines reported various results. Comlekoglu (Comlekoglu et al., 2009) reported 1.2-mm shoulder (absolute marginal opening, AMO: 114 ± 16 μm, marginal opening, MO: 95 ± 9 μm) and 0.8-mm chamfer (AMO: 114 ± 11 μm, MO: 97 ± 12 μm) have similar marginal adaptation while knife-edge shows smaller marginal gap (AMO: 87 ± 10 μm, MO: 68 ± 9 μm). Cetik (Cetik et al., 2017) revealed that chamfer and knife-edge finishing lines appear to offer better adaptation than shoulder. In a systematic review and meta-analysis, Yu (Yu et al., 2019a) reported that ceramic crowns with rounded shoulder exhibit significantly better marginal adaptation than those with chamfer ($P < 0.001$; mean difference: -7.8 μm; 95% confidence interval: -11.6 to -4.1 μm), but inferior internal adaptation ($P = 0.020$; mean difference: 35.0 μm; 95% confidence interval: 6.5 to 63.5 μm). The seating process, which may involve inadequate escaping of cement, could partially account for the difference among studies (Quintas et al., 2004; Yu et al., 2019a). In this study, fabrication accuracy, other than the seating adaptation, was evaluated. The RMS value in external area of knife-edge design was higher than that of chamfer design ($P < 0.05$). Yet, the clinical significance of such a small difference in mean RMS value (less than 7 μm) is supposed to be low.

Milled crowns with different finish line designs showed chippings of various numbers and severity. This result was consistent with previous investigations (Schriwer et al., 2017; Skjold et al., 2019). Schriwer (Schriwer et al., 2017) investigated monolithic zirconia crowns milled from blanks of six brands and all of the soft-machined crowns show margin flaws. Skjold (Skjold et al., 2019) graded margin quality by the same scale and the soft-machined copings with chamfer margin were rated at 2.5 while those with knife-edge margin at 3. Such crowns are milled from pre-sintered blanks and clusters of zirconia particles are at risk of chipping under machining stress. The margin quality is determined by milling parameters, brittleness of the materials, and shape of the specimen (Kastyl et al., 2020; Tsitrou et al., 2007). Large margin defect is more likely to occur when manufacturing specimens with thin structure (Kastyl et al., 2020), such as knife-edged restorations.

In SLA group, no small flaws were observed but large chipping also occurred in knife-edged crowns. The crowns were fabricated by polymerizing the suspension using ultraviolet-laser scanning (Dehurtevent et al., 2017). Rounded line angle presented in the obtained margin area was ascribed to the light scattering phenomenon (Mitteramskogler et al., 2014). No machining stress was involved and thus the fabricated crowns showed smooth edges with no small flaws. However, the as-printed green bodies were fragile. Thin margins of knife-edged crowns were at risk of chipping during manual handling.

Although zirconia restorations with knife-edge finish line were reported to show good performance in vitro studies and several clinical studies (Mitov et al., 2016; Monaco et al., 2013; Reich et al., 2008; Serra-Pastor et al., 2019), it is worth noting that higher processing difficulty exists when fabricating knife-edged restorations. The milling strategies, such as milling burs, feed rates and depths of the cut, must be properly designed to reduce machining-induced chippings. As for SLA-printed restorations, careful and skillful manual operation is needed

**Table 2**
The influence of fabrication method and finish line design on RMS using two-way ANOVA.

| Source of variation | Type III sum of squares | *df* | Mean square | F | *P* |
|---|---|---|---|---|---|
| **External surface** | | | | | |
| Method | 41.301 | 1 | 41.301 | 3.239 | .084 |
| Design | 107.325 | 2 | 53.662 | 4.209 | .027 |
| Method*design | 69.069 | 2 | 34.534 | 2.709 | .087 |
| **Intaglio surface** | | | | | |
| Method | 2.080 | 1 | 2.080 | .174 | .680 |
| Design | 81.961 | 2 | 40.980 | 3.423 | .049 |
| Method*design | 35.089 | 2 | 17.544 | 1.466 | .251 |

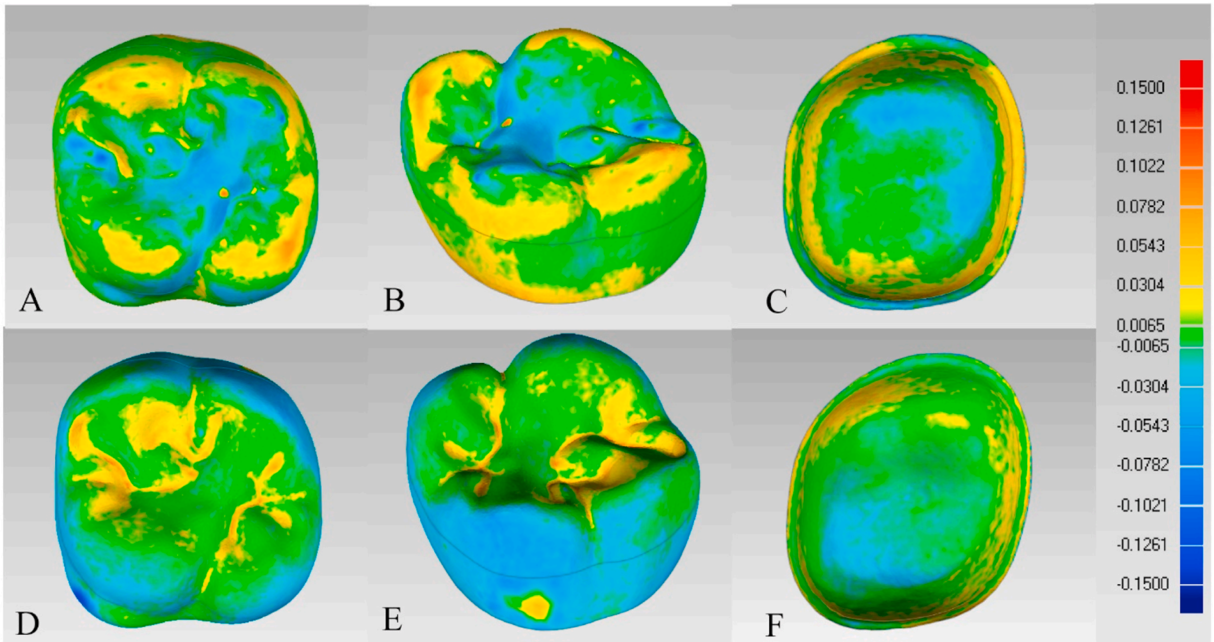


**Fig. 2.** Representative color-difference map of crowns with chamfer. SLA: (A, B) external (C) intaglio; Milling: (D, E) external (F) intaglio. Red indicates a positive error, blue indicates a negative error, and green indicates good trueness.

**Table 3**
Margin quality evaluation: the number of every grade, N = 30.

| Grade | Chamfer | | Rounded shoulder | | Knife-edge | |
|---|---|---|---|---|---|---|
| | SLA | Milling | SLA | Milling | SLA | Milling |
| 1: Smooth edge with no defects | 5 | 5 | 5 | 5 | 1 | 0 |
| 2: Smooth edge with few, small separate defects | 0 | 0 | 0 | 0 | 2 | 2 |
| 3: Several small defects | 0 | 0 | 0 | 0 | 0 | 0 |
| 4: Rough edge with continuous defects | 0 | 0 | 0 | 0 | 0 | 0 |
| 5: Large defects | 0 | 0 | 0 | 0 | 2 | 3 |

when cleaning them in a green state.

## 5. Conclusions

This preliminary study investigated the performance of SLA and milling in fabricating monolithic zirconia crowns with different finish line designs by characterizing the fabrication accuracy and margin quality. The results indicate that SLA and milling can fabricate monolithic zirconia crowns of comparable accuracy and knife-edged crowns are prone to large margin chippings by either of the two manufacturing methods. Further investigations on optimizing the milling strategies are needed to improve the margin integrity. Moreover, the intraoral occlusal and interproximal contacts of the SLA-printed restorations and their long-term performance remain to be studied.

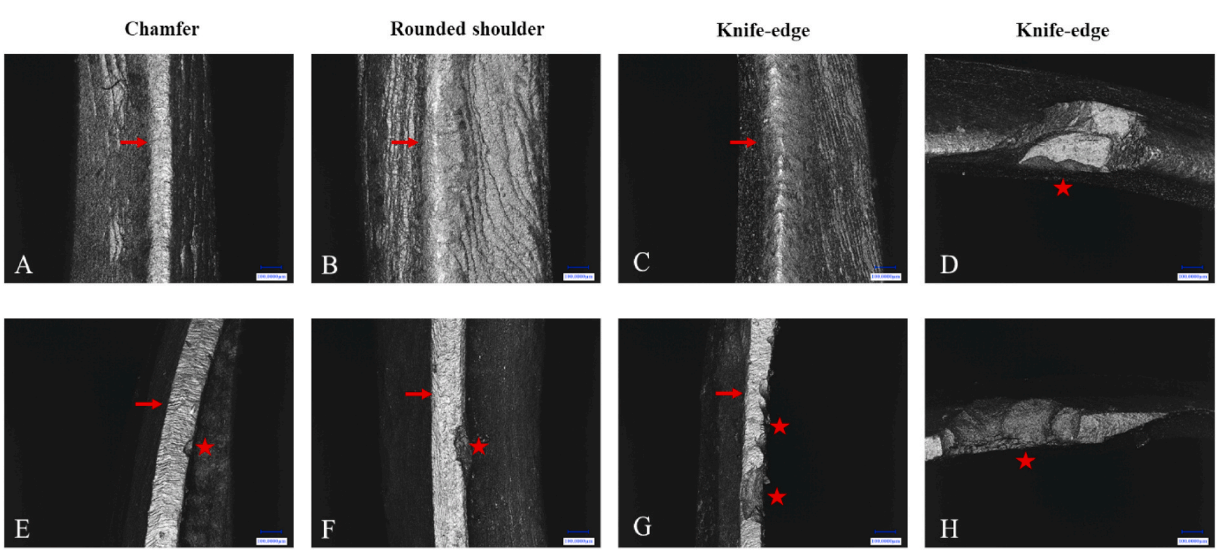


**Fig. 3.** Margins of the fabricated crowns with different finish lines under 3D laser scanning microscope, 200 × magnification. SLA: (A, B, C) margins of rounded line angle showed a smooth contour without small flaws (D) large chippings; Milling: (E, F) margins of sharp line angle showed separate chippings (G, H) more and larger chippings were found in knife-edged crowns. (Arrows: contour line, stars: flaws and chippings).

## CRediT authorship contribution statement

**Rong Li:** Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Hu Chen:** Methodology, Writing - review & editing. **Yong Wang:** Supervision, Writing - review & editing, Funding acquisition. **Yuchun Sun:** Conceptualization, Writing - review & editing, Funding acquisition.

## Declaration of competing interest

None.

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