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Review Article

Quality Assessment and Comparison of 3D-Printed and Milled Zirconia Anterior Crowns and Veneers: In Vitro Pilot Study

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Abstract

The esthetic rehabilitation of a patient is a demanding yet rewarding procedure, improving the form, function, and well-being of a patient. Three-dimensional (3D) printed, or additive manufactured, zirconia has recently entered the dental space, but without a thorough assessment or comparison. This pilot study utilized digital impressions of two demonstration casts: Cast 1 prepared both central incisors for full ceramic crown coverage, while cast 2 had a lateral incisor (#22) prepared for a ceramic veneer. Both casts underwent digital scanning (Straumann CARES 3, Straumann, Basel, Switzerland) to create virtual STL models. Cast 1 had two full zirconia anterior crowns digitally designed, and Cast 2 had a zirconia veneer digitally designed, using Exocad GmbH software by a certified dental technician at Schulich Dentistry. The STL files were used for fabricating six milled zirconia crowns for central incisor (#21) and six 3D-printed zirconia crowns for the other central incisor (#11). Similarly, for Cast 2, milled and 3D-printed zirconia veneers were made for the prepared lateral incisor (#22). Statistical analysis employed Minitab 16.1.0 software to construct a 2 × 2 table for cross-tabulation and chi-squared analysis. This statistical approach assessed the relationship between restoration design and processing method. Cochran–Mantel–Haenszel test evaluated categorical variables considering different classification variables. Milled restorations showed minor variations, while 3D-printed units displayed consistency. Statistical tests found no significant associations. This in vitro study suggests 3D-printed zirconia for crowns and veneers meets precementation standards akin to conventionally milled restorations. Further research can assess its potential benefits for dentistry's efficiency, cost, and sustainability.

Keywords
- 3D-printing
- additive manufacturing
- zirconia
- materials
- dental materials
- prosthodontics
- restorative dentistry
- sustainability

Introduction

The association of oral health to total health has become well documented in the literature[1–3] and the form and function of a patient's dentition have a profound impact on speech, mastication, appearance, confidence, and well-being.[3,4] Therefore, the esthetic restorative rehabilitation of a patient is challenging, complex, and highly dependent on meeting or exceeding the patient's expectations.[5,6] Although there are

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suitable dental materials available for success, certain clinical situations present demanding challenges, such as severely discolored dentin or excessive occlusal forces.[7] For these cases, zirconia seems to be the material of choice.[8] Unfortunately, zirconia has several disadvantages, which reduce the predictability and success of cases, even with its brief history.[9]

Zirconia or zirconium oxide (ZrO_2) is a ceramic material that has been widely used in prosthodontics. It has desirable mechanical properties due to transformation toughening, improved appearance, and biocompatibility.[6,10] However, chipping of the veneering[11] and its insufficient translucency[10,12] have been reported as major complications of this material. The success rate and clinical outcome of zirconia have been shown in a systematic review conducted by Bidra et al,[13] indicating a very low failure rate for zirconia in the short term, with limited history, but chipping was reported as the main complication. Using an alternative technique, employing computer-aided design/computer-aided manufacturing (CAD/CAM),[14] selecting an optimized core design,[15] and modifying the firing protocol[16] have overcome the disadvantages and may improve clinical outcomes. Monolithic zirconia, through CAD/CAM subtractive manufacturing, has shown improved fracture resistance and wear,[17] although long-term clinical evidence is still required.

Three-dimensional-printed zirconia has been presented in the literature,[18,19] but there has yet to be a detailed precementation assessment that evaluates anterior zirconia crowns and veneers. CAD/CAM milling systems offer swift, personalized fabrication of zirconia dental restorations.[19] According to the literature, 3D-printing shows promise in crafting customized zirconia implants with acceptable dimensional precision and comparable flexure strength to traditional ceramics.[18] Yet, drawbacks include accuracy limitations, potential microscopic cracks, and material wastage from the subtractive manufacturing method.[19] Enhancing 3D-printing parameters remains crucial for refining the microstructure of printed objects. This investigation addressed that shortcoming and a gap in the research.

The purpose of this investigation was to explore novel 3D-printed (additive manufactured) anterior crowns and veneers in zirconia and compare them to conventional milled (subtractive manufactured) zirconia. The hypothesis was to determine if 3D-printed zirconia may be a viable option for esthetic procedures in restorative dentistry.

Methods

Digital impressions of two (2) different demonstration casts were utilized. Cast 1 had both centrals incisors prepared for full ceramic crown coverage (►**Fig. 1**). Cast 2 had a lateral incisor (#22) prepared for a ceramic veneer (►**Fig. 2**). Both casts were digitally scanned (Straumann CARES 3, Straumann, Basel, Switzerland), and virtual STL models were produced.

Cast 1 had two (2) full zirconia anterior crowns digitally designed (►**Figs. 3** and **4**) and cast 2 had a zirconia veneer digitally designed (►**Fig. 5**). Digital design was completed using dental software (Exocad GmbH, Darmstadt, Germany) and was performed by a certified dental technician at Schulich Dentistry.

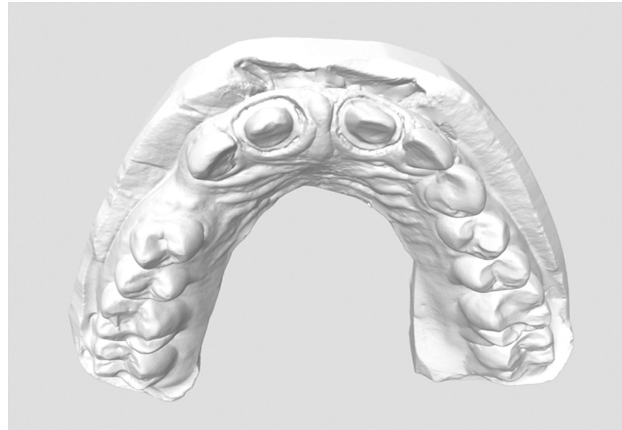


Fig. 1 Virtual Impression of cast 1—prepped central incisors (#11 & #21) for zirconia crowns.

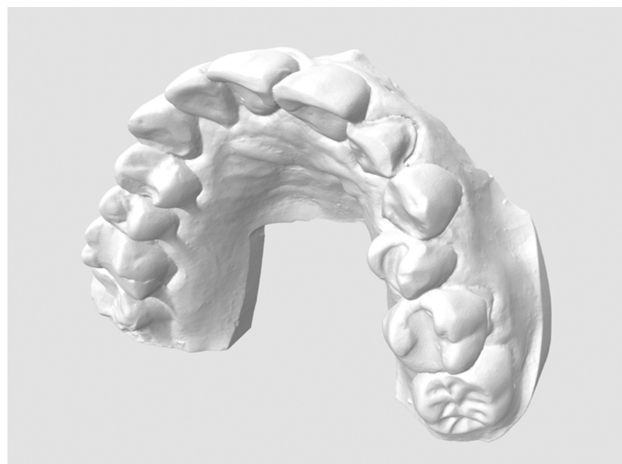


Fig. 2 Virtual impression of cast 2—prepped lateral incisor (#22) for zirconia veneer.

The STL digital files were electronically sent to a commercial dental laboratory (Glidewell, Newport Beach, California, United States) for the fabrication of six (6) identical milled zirconia (BruxZir full strength) crowns for one of the prepared central incisors (tooth #21). The same STL digital files were electronically sent to a ceramic printing company (Lithoz, Austria) for the fabrication of six (6) identical 3D-printed zirconia crowns for the other prepared central incisor (tooth #11). The virtual models were 3D-printed in standard resin (►**Fig. 6**) from a commercial dental laboratory (Glidewell, Newport Beach, California, United States; ►**Flowchart 1**).

Cast 2 had a full zirconia veneer digitally designed. The STL digital file was electronically sent to a commercial dental laboratory (Glidewell, Newport Beach, California, United States) for the fabrication of six (6) identical milled zirconia veneers (BruxZir esthetic veneer) for the prepared lateral incisor (tooth #22). The same digital file was electronically

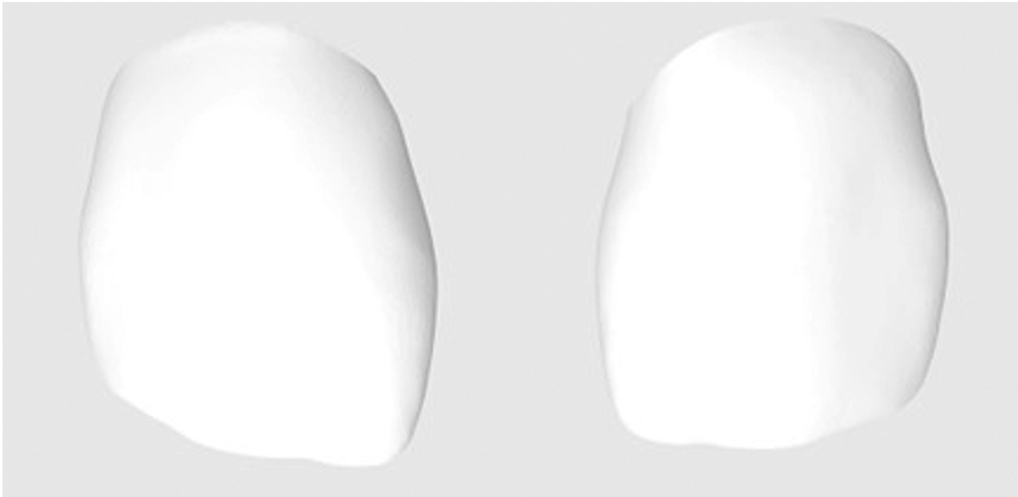


Fig. 3 Digital design (#11 left; #21 right) of anterior crowns.

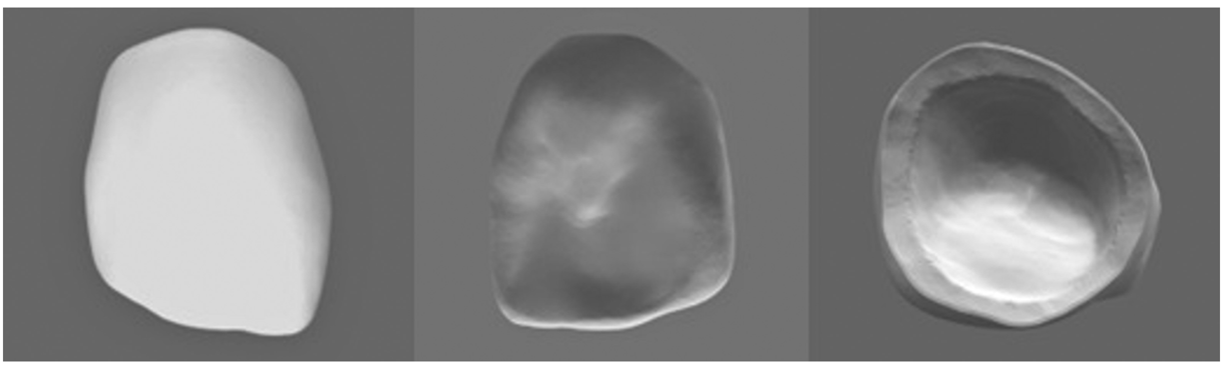


Fig. 4 Facial, lingual, and internal view of the central incisor (#11) digital design.

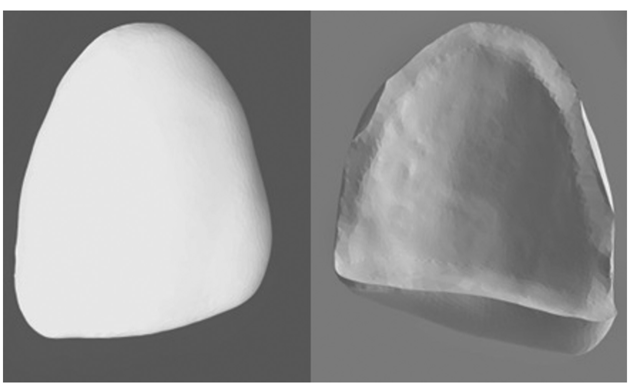


Fig. 5 Facial and lingual view of the lateral incisor (#22) veneer digital design.

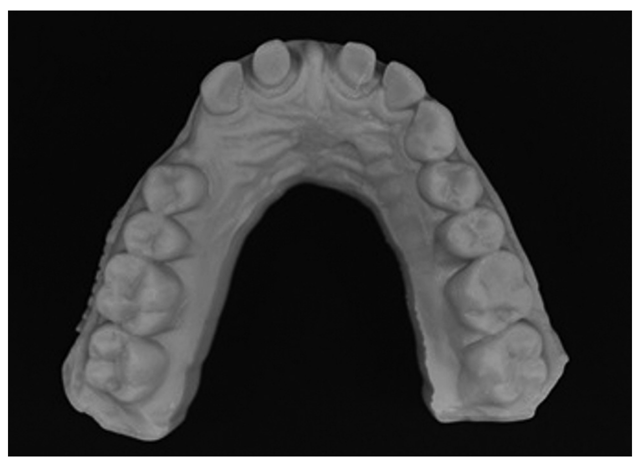
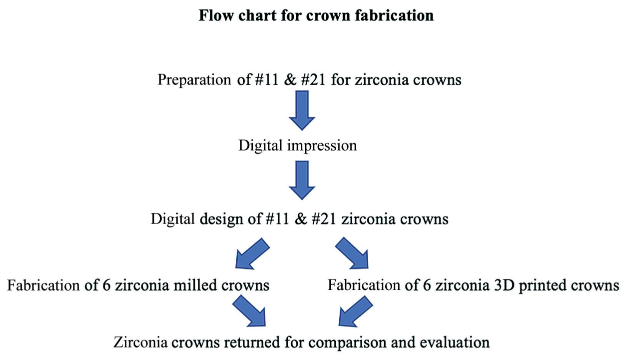


Fig. 6 Three-dimensional-printed model of simulated patient case for the central incisor anterior crowns.

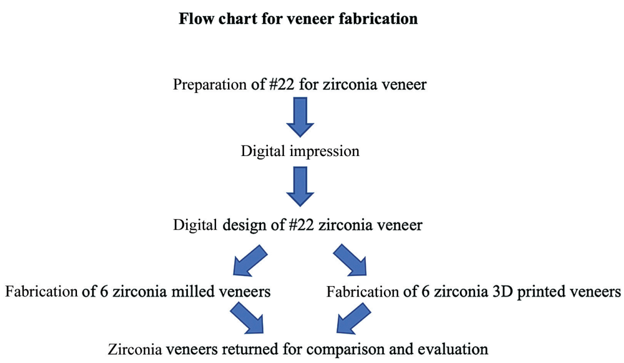
sent to a ceramic printing company (Lithoz, Austria) for the fabrication of six (6) identical 3D-printed zirconia veneers (►**Flowchart 2**). The virtual model was also 3D-printed in standard resin (►**Fig. 7**) from a commercial dental laboratory (Glidewell, Newport Beach, California, United States).

The STL files that were electronically sent to a commercial dental laboratory (Glidewell, Newport Beach, California, United States) contained no direction to alter the digital design. However, it was evident that design edits were implemented. The crowns and veneers were milled with BruxZir monolithic esthetic zirconia, with a reported flexural strength of 870 MPa. The crowns and veneers were arbitrarily stained and glazed and were delivered for in vitro evaluation.[20]

The STL files that were electronically sent to a ceramic printing company (Lithoz, Austria) were not subject to digital modification; they were printed directly from the STL file. The crowns and veneers were printed with a lithography-



Flowchart 1 Flowchart for crown fabrication.



Flowchart 2 Flowchart for veneer fabrication.

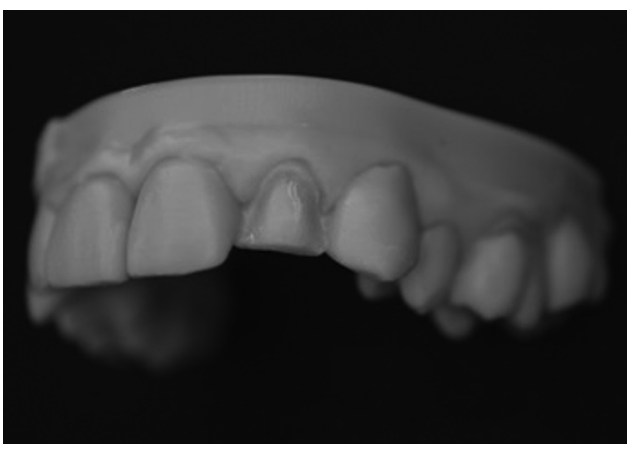


Fig. 7 Three-dimensional-printed model of simulated patient case for the lateral incisor veneer.

based ceramic technology that employed LithaCon 3Y 210 ceramic material. Lithoz CeraFab printers use the STL files as inputs and produce a ceramic slurry to produce a green ceramic part. Powder composition was 3 Mol% Y2O3 stabilized ZrO2, with a reported 4-point bending strength of 935 MPa and a surface roughness (Ra) < 1.0 µm.[21]

The samples were then printed using a CeraFab 7500 system with an in-layer pixel size of 40 µm and a layer thickness of 25 µm. The crown and veneer units underwent debinding and sintering. The zirconia shrinkage was approximately 20% linearly during sintering, which was compensated for by Lithoz Data Pre-processing software. The units were delivered for in vitro evaluation.[21] The assessor examining the restorations possessed significant expertise in restorative dentistry.

The restorations were evaluated by a precementation checklist (►**Fig. 8**). The prostheses were blindly evaluated by a full-time prosthodontic faculty member, under magnification, and deemed unacceptable (with a score of 0) or acceptable (with a score of 1) for the relevant criteria. Digital macrophotography was employed for visualization.

The statistical package software (Minitab 16.1.0, State College, Pennsylvania, United States) was used to design a

Areas to assess	*Clinically unacceptable (0)*	*Clinically acceptable (1)*
Structural detail		
Porosity		
Internal blebs, roughness		
Surface inclusions		
Surface finish		
Margin integrity		
Overextension		
Bulk		
Under extension		
Over finishing		
Roughness, curled		
Design factors		
Axial contours		
Proximal contacts-adequacy, location		
Embrasures-occlusal, incisal, facial, lingual, gingival		
Connector adequacy		
Pontic form-tissue contact, convex tissue surface		
Aesthetic factors		
Tooth bulk/shape		
Tooth orientation		
Tooth length		
Attention to detail		
Followed work authorization		
Conditions of dies, casts, etc.		
Restoration/Prosthesis fit		
Rocking on dies; in mouth		
Loose on dies; in mouth		
Not seating on dies; in mouth		

Fig. 8 Precementation checklist used for prosthesis assessment.

2×2 table, constructed for cross-tabulation and chi-squared analysis. This table consisted of two rows and two columns, providing a clear framework for organizing and analyzing categorical data. Each cell within the table represented a unique combination of variables, allowing for a comprehensive examination of the relationship between the two variables (restoration design and processing method) being studied. This analytical approach facilitated the calculation of chi-squared statistics enabling to assessment of the significance of association differences between the variables. For the analysis of the categorical variables, a comparison was performed using the Cochran–Mantel–Haenszel (CMH) test ($\alpha = 0.05\%$). The CMH test considers that three or more classification variables exist, and the first two variables have two pares each. All variables beyond the first two are treated as a single variable Z for the CMH test, with each combination of levels treated as a level of Z. The test is defined according to the following the nation:

$$A = \frac{(\mathrm{I}\sum_K(n_{11k} - n_1 + {}_k n + {}_{1k} n + {}_k{}^{-1})\mathrm{I} - 0.5)^2}{\sum_k n_1 + {}_k n_2 + {}_k n + {}_{1k} n\, n + +k - 1)^{\ \ -1}}$$

Where k is level of Z, $n11k$ is the number of observations in the first row, first column; $n1 + \mathrm{k}$ is the number of observations in the first row; $n + 1\mathrm{k}$ is the number of observations in the first column; $n + +\mathrm{k}$ is the total number of observations; $n2 + \mathrm{k}$ is the number of observations in the second row; $n + 2\mathrm{k}$ is the number of observations in the second column.

Results

►**Fig. 9** depicts the facial, lingual, and internal view of the milled zirconia crown, and ►**Fig. 10** depicts the facial, lingual, and proximal view of the milled zirconia veneer. There were minor variations observed between these units due to morphology, margin ex-tension, and esthetic characterization (staining and glazing).

►**Fig. 11** depicts the facial, lingual, and internal view of the 3D-printed zirconia crown and ►**Fig. 12** depicts the facial, lingual and proximal view of the 3D-printed zirconia veneer. There were no noticeable variations observed between these units, either in terms of morphology, margin extensions, or characterization (there was no staining and glazing employed). Please note that shade was removed as a variable in the evaluation of the prostheses and was not a request in the laboratory prescription.

►**Table 1** illustrates the summary of unacceptable and acceptable criteria. The anterior zirconia crowns that were milled had a total of 42 unacceptable criteria and 72 acceptable criteria, respectively. The anterior zirconia crowns that were 3D-printed had a total of 24 unacceptable criteria and 90 acceptable criteria, respectively. The anterior zirconia veneers that were milled had a total of 54 unacceptable criteria and 60 acceptable criteria, respectively. The anterior zirconia veneers that were 3D-printed had a total of 41 unacceptable criteria and 73 acceptable criteria, respectively.

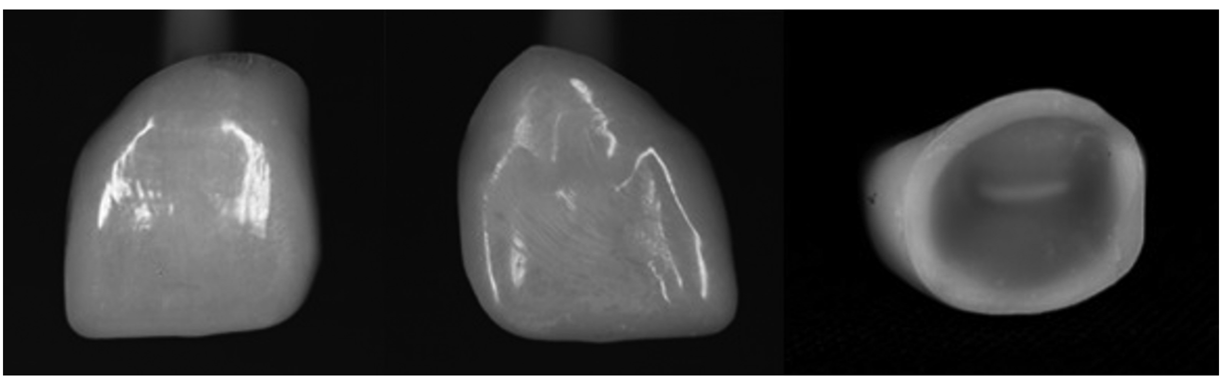


Fig. 9 Facial, lingual, and internal view of milled zirconia crown (#21).

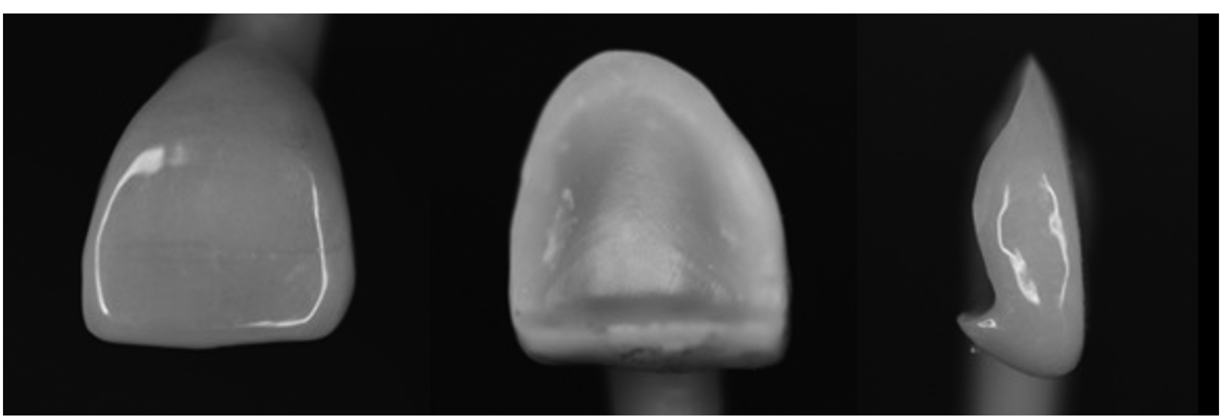


Fig. 10 Facial, lingual, and proximal view of milled zirconia veneer (#22).

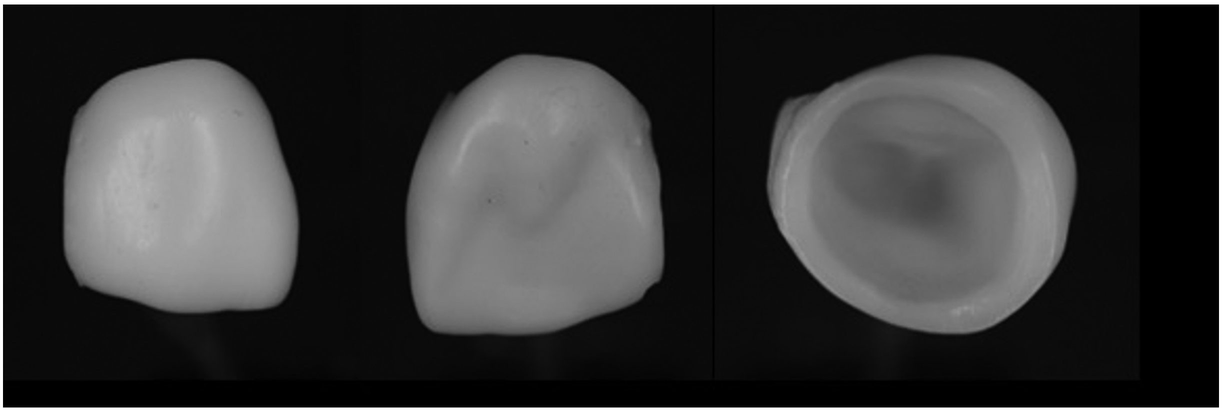


Fig. 11 Facial, lingual, and internal view of three-dimensional-printed zirconia crown (#11).

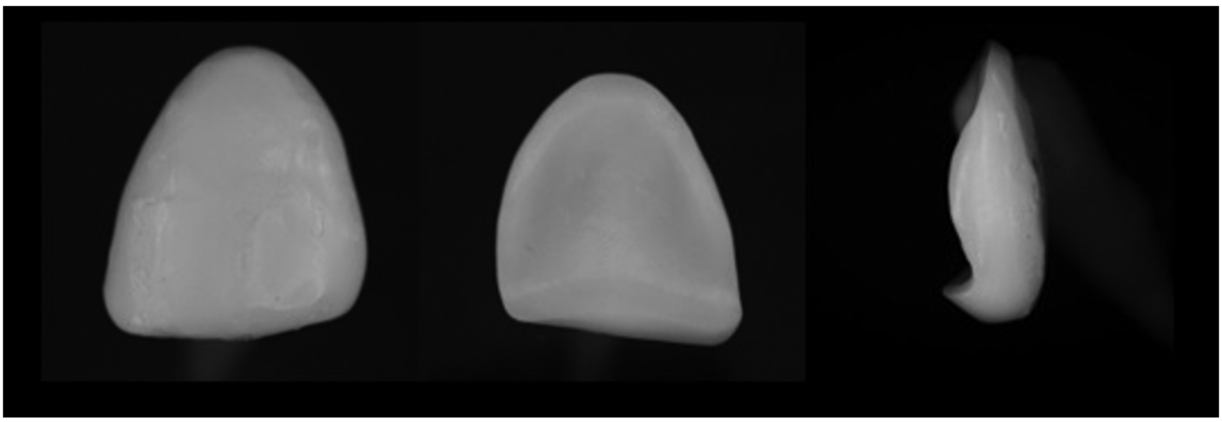


Fig. 12 Facial, lingual, and proximal view of three-dimensional-printed zirconia veneer (#22).

Table 1 Summary of unacceptable and acceptable criteria and contribution to chi-squared test group

	Unacceptable		Acceptable	
	3D Printed	Milled	3D Printed	Milled
Crown (count)	24	42	90	72
Contribution to chi-square	0.2627	0.1779	0.002662	0.003287
Veneer (count)	41	54	73	60
Contribution to chi-square	0.1825	0.1236	0.003242	0.004004
All	65	96	163	132

Abbreviation: 3D, three-dimensional.

A chi-squared test was conducted to examine the association between the factors of design and processing method about clinically unacceptable specimens. The Pearson chi-squared statistic was calculated to be 0.747, with a corresponding *p*-value of 0.387. Additionally, the Likelihood Ratio chi-squared statistic was found to be 0.750, with a *p*-value of 0.386. These results indicate that there is no statistically significant association between the factors of design and processing method concerning clinically unacceptable specimens. Therefore, based on the chi-squared test results, there is insufficient evidence to conclude that design or processing method significantly impacts the likelihood of obtaining clinically unacceptable specimens.

In the sequence, the chi-squared test was used to evaluate the relationship between design and processing methods concerning clinically acceptable specimens. The Pearson chi-squared statistic yielded a value of 0.013, accompanied by a corresponding *p*-value of 0.909. Similarly, the Likelihood Ratio chi-squared statistic produced a value of 0.013, with a *p*-value of 0.909. These findings indicate that there is no significant association between the design and processing method when it comes to clinically acceptable specimens.

Finally, the CMH test was conducted to examine the relationship between variables. The calculated odds ratio was found to be 0.924320, indicating that there is a slightly lower likelihood of the occurrence of the outcome variable

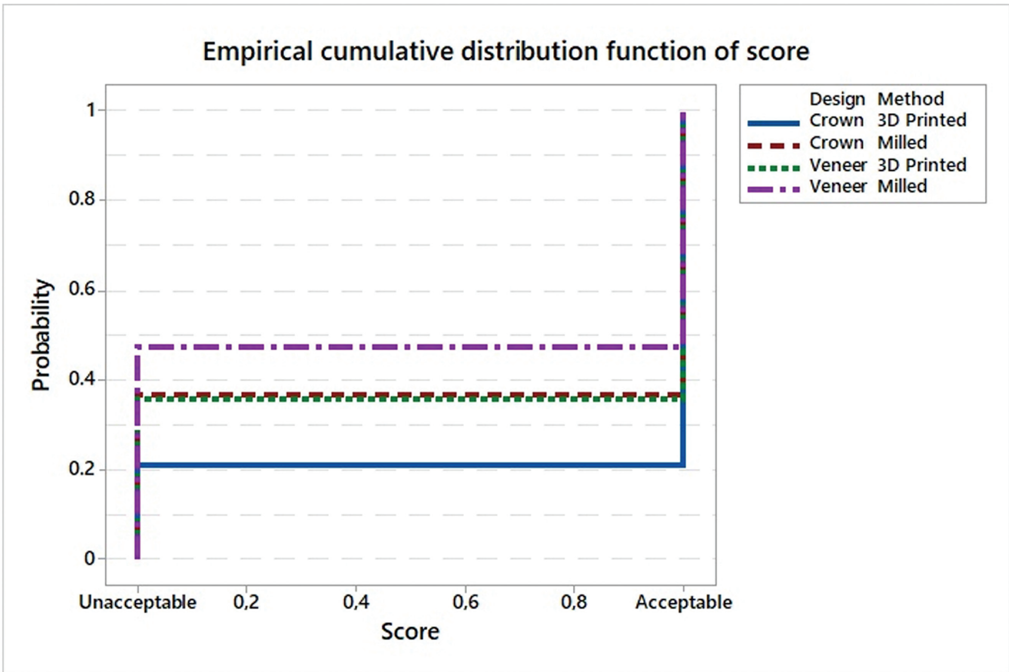


Fig. 13 Empirical cumulative distribution function graph, which illustrates the cumulative probabilities of observed data. The x-axis represents the possible outcome of the restorations being analyzed, while the y-axis indicates the cumulative probability associated with each group.

for the acceptable specimens compared to the unacceptable specimens. The CMH statistic was determined to be 0.0997501, with a corresponding *p*-value of 0.752130. These results suggest that there is no significant association between the variables being studied. ►**Fig. 13** shows the empirical cumulative distribution function graph that visually represents the distribution of data in the present dataset. It illustrates how the values in the dataset are spread or distributed across different levels or intervals. The groups showing curves that consistently lie above another indicate that the values in the first dataset are larger, or in this case there are more unacceptable specimen.

Discussion

The prostheses were assessed on a simulated patient case with the soft tissue removed, soft tissue intact, and a hybrid soft tissue model. The milled crowns were loose on the simulated patient model with little retention, while the 3D-printed crowns were too tight and required minor adjustments to properly fit. Both veneers fit well with the simulated model.

The milled crowns (►**Figs. 14** and **15**) had a morphology different than the digital design, possibly related to digital design modification before milling. The 3D-printed crowns were essentially identical to the digital design supplied. It is imperative to ensure that the digital design provided is ideal and the laboratory prescription should be followed regarding design modifications. This observation aligns with existing literature that suggests digital design modifications can affect the final restoration's form and fit.[22,23] It emphasizes the significance of ensuring that the digital design provided is optimal and accurately represents the desired clinical outcome.

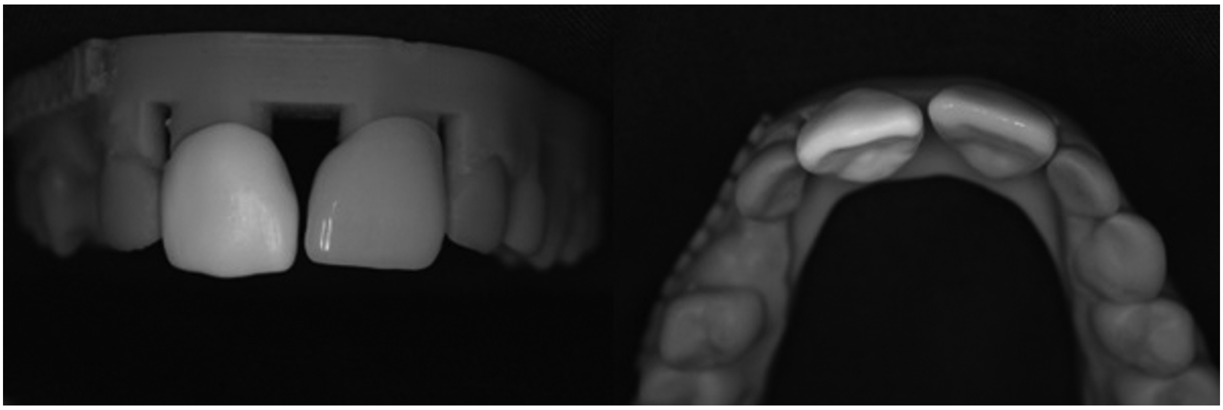


Fig. 14 Three-dimensional printed (#11) and milled (#21) anterior zirconia crowns on model.

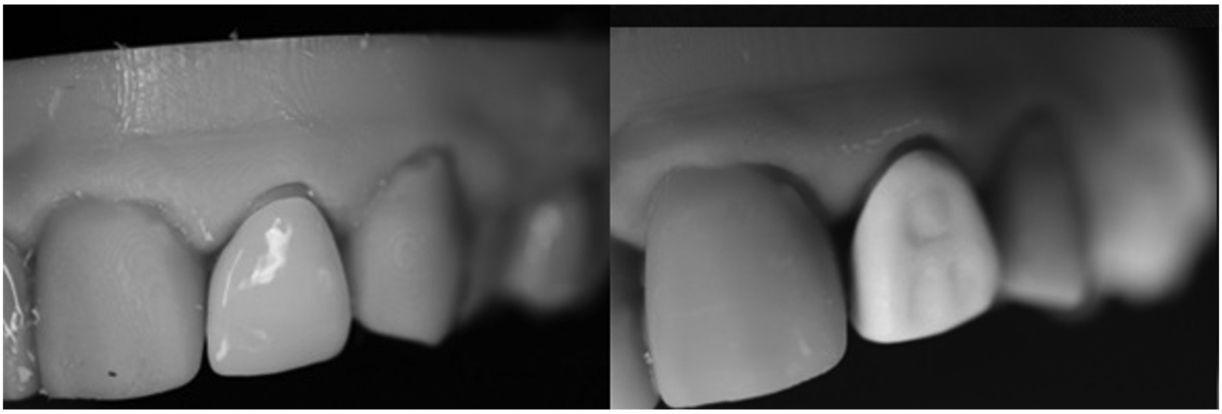


Fig. 15 Milled (left) and three-dimensional printed (right) zirconia veneer on simulated tooth #22.

A recent review provided an overview of the current state of additive manufacturing of zirconia-based materials for dental applications. According to them, vat polymerization techniques like stereolithography and digital light processing show promise in producing accurate dental crowns, bridges, implants, and abutments. However, material jetting and robocasting exhibit lower resolution and mechanical resistance, limiting their use in anterior tooth restorations. The authors also claimed that the research in zirconia-based AM materials is expanding, but more work is needed to ensure the safe and durable production of prostheses to mimic the complex properties of natural teeth in dental restorations.[23]

In general, 3D-printed zirconia exhibits varied mechanical properties depending on factors such as surface roughness and the presence of defects. When printing the zirconia restoration, the technician should align the printed layers with the expected load distribution, achieving improved strength and resistance to deformation.[24] After printing, the postprocessing step is crucial to minimize surface roughness through polishing techniques to enhance the overall mechanical performance of 3D-printed zirconia restorations.[24] This study can complement those findings, suggesting that an adequate misfit can be achieved with clinically acceptable quality for such restorations.

During this investigation, color was removed from the evaluation criteria as no shade was selected on the laboratory prescription. The milled crowns and veneers were characterized (at the discretion of the lab). The printed crowns and veneers were initially of a yellow hue, due to challenges with the sintering. Subsequent prostheses were delivered in an OM1 shade (at the discretion of the technician). Sintering 3D-printed zirconia presents challenges due to shrinkage and warping, as zirconia undergoes significant shrinkage during the process. Achieving full densification is difficult due to the presence of voids or porosity, and maintaining uniformity in microstructure and composition is crucial.[25–27] Determining the optimal sintering temperature is challenging, as it should promote densification without causing adverse effects. The design and capabilities of the sintering furnace also impact the process. Overcoming these challenges requires process optimization, material formulation, and advanced sintering techniques. Ongoing research aims to improve sintering methods for 3D-printed zirconia.[26–28]

Cost and fabrication time were not considered, as this was a pilot study. However, the 3D printing workflow can print multiple prosthodontic units at once, related to the size of the build plate. Based on this investigation and the work of Krishna and Srikanth,[22] the additive manufacturing workflow has shown to be more efficient, and cost-effective and demonstrates a reduced environmental impact, as the powder can be reused (recycled).

Shade characterization is an essential aspect of dental zirconia, as it directly influences the aesthetic outcome of restorations. However, achieving accurate shade matching with zirconia can be challenging. Various factors, including composition, sintering conditions, and translucency, affect the final shade of zirconia restorations. While extensive research has been conducted on shade characterization for traditional zirconia,[29,30] more investigation is needed specifically for 3D-printed zirconia. The unique properties of 3D-printed zirconia, such as different printing parameters and postprocessing techniques, may introduce additional complexities in achieving precise shade matching. Further research is necessary to explore and optimize shade characterization methods specifically tailored to 3D-printed zirconia, ensuring that dental restorations achieve optimal aesthetic outcomes.[31]

Previous work with metal AM has indicated significant physical performance, which could impact the material thickness and preparation requirements.[32] Further study is required to assess postprocessing (patient-specific stain and glaze—currently in progress), physical testing of the 3D-printed prostheses (planned), and clinical evaluation. Additionally, the effects of damage in mechanical properties, as well as the roughened surface, from grinding via an appropriate polishing treatment must be evaluated for such material.[33–36]

Conclusion

This preliminary in vitro investigation has demonstrated that 3D-printed or additive-manufactured zirconia, for anterior crowns and veneers, has similar clinically acceptable precementation criteria to those that have been conventionally milled.

This fabrication pathway may be considered a viable alternative for esthetic restorations, but the digital design must be ideal and supported with a very clear laboratory prescription.

Three-dimensional printing or additive manufacturing has started to have a significant impact on dentistry. More research is required to determine if 3D printing with zirconia is a suitable alternative manufacturing approach, which could predictably benefit the clinician, patient, and environment with improved efficiency, cost-effectiveness, and sustainability.

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Conflict of Interest
None declared.

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