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RESEARCH AND EDUCATION

Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns

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ABSTRACT

Statement of problem. Stereolithography (SLA) additive manufacturing (AM) technologies can be selected to fabricate zirconia crowns; however, the internal and marginal discrepancies associated with these new technologies remain unclear.

Purpose. The purpose of this in vitro study was to measure and compare the marginal and internal discrepancies of milled and AM zirconia crowns by using the silicone replica technique.

Material and methods. An implant custom abutment was manufactured and scanned by using a laboratory scanner (CARES Software; Straumann). An anatomic contour crown was digitally designed, and the standard tessellation language (STL_C) file was obtained. The STL_C file was splinted into 2 pieces, simulating the parts of the crown that would replace the enamel (STL_{G1} file) and dentin (STL_{G2} file) structures. Three groups were determined: anatomic contour zirconia milled (CNC group), AM anatomic contour zirconia (AM group), and AM splinted zirconia (SAM group). For the CNC group, the STL_C file was used to manufacture milled (CARES zirconium-dioxide crown; Straumann) zirconia specimens. For the AM group, the STL_C file was used to additively fabricate (CERAMAKER 900; 3DCeram Co) the zirconia (3DMix ZrO_2 paste; 3DCeram Co) specimens. For the SAM group, the STL_{G2} file was selected to AM (CERAMAKER 900; 3DCeram Co) the zirconia (3DMix ZrO_2 paste; 3DCeram Co) specimens. Ten specimens per group were manufactured. The silicone replica technique was used to measure the marginal and internal discrepancies. The cement gap was measured on images captured by using a digital microscope at ×100 magnification. For the internal gap, 50 measurements were made for each specimen, and for the marginal gap, 25 measurements were made for each specimen. The normality test, Shapiro-Wilk test, was conducted. The results indicated that the distributions were not normal; therefore, nonparametric Kruskal-Wallis H and pairwise Mann-Whitney U-tests were used to analyze the data. The Spearman correlation coefficient was used to determine the correlation between marginal and internal discrepancies in all 3 groups.

Results. Significant differences were found in marginal and internal discrepancies among the groups. The CNC group had the least marginal and internal discrepancies compared with the AM and SAM groups. The SAM group had significantly lower values for marginal and internal discrepancies than the AM group. The AM group showed the highest marginal and internal discrepancies. The CNC group had a weak correlation coefficient of 0.13 (P=.046), the AM group had a moderate correlation coefficient of 0.32 (P<.001), and the SAM group had a nonsignificant correlation coefficient of 0.12 (P=.051).

Conclusions. CNC and SAM groups had clinically acceptable marginal and internal discrepancies, while the AM group had a clinically unacceptable marginal and internal crown discrepancies. Furthermore, a weak correlation was encountered between the marginal and internal discrepancies measured in all groups. (J Prosthet Dent 2019;■:■-■)

Computer-aided design and computer-aided manufacturing (CAD-CAM) technologies involve processes whereby the design and the subtractive and/or additive fabrication of a prostheses are guided by computers.[1-5] Advancements in subtractive technologies have enabled fabrication of ceramic dental restorations exhibiting a clinically acceptable fit[6-13] while reducing the influence of the dental laboratory technician in the

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Clinical Implications

The stereolithography AM technology tested is able to provide zirconia crowns with clinically acceptable marginal and internal accuracy; however, the total volume of the digital design of the restoration significantly influences the manufacturing outcome.

production process.[13] However, such technologies present a number of manufacturing limitations, including considerable wastage of the unused parts of the milled blocks, the constant need for replacement of the milling tools after a number of cycles, limited reproduction of surface geometry as dictated by the size of the milling burs and the axis of the computer numerical controlled (CNC) machine, and the risk of introducing microscopic cracks while milling the ceramic materials.[14-18]

The American Society for Testing and Materials (ASTM) has defined additive manufacturing (AM) as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[19] The ASTM has determined seven AM categories: stereolithography (SLA), material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition.[19] Current AM methods that can be used to manufacture zirconia materials are SLA, material jetting, material extrusion, SLS, selective laser melting (SLM) technologies from the PBF technologies family, direct energy deposition, sheet lamination, and binder jetting technologies.[20]

Several research groups have developed photopolymerizable ceramic suspensions by using photopolymerizable resin loaded with ceramic powder[21-24] for the fabrication of fully dense SLA AM materials. To obtain a homogeneous green part and promote binder removal and sintering, highly concentrated resins are used.[25] A liquid resin is mixed in a ceramic suspension and selectively solidified through controlled photopolymerization. Consequently, green parts with different shapes can be fabricated from a mixture of ceramic powders and photosensitive resin. Postprocessing of the fabricated green parts is necessary to eliminate the photosensitive resin, fuse ceramic particles together, and obtain a dense ceramic component.[21-25]

Advantages of AM technologies over subtractive methodologies include saving material and the versatility to manufacture complex geometries.[26-28] Factors that can affect the accuracy of a printed object include laser speed, intensity, angle and building direction,[29-33] number of layers,[29] software,[33] shrinkage between layers,[32] amount of supportive material,[31] and postprocessing procedures.[34-36]

Marginal fit is an important factor in the clinical success and longevity of indirect restorations. Minimizing the marginal discrepancy between the prepared tooth structure and the restoration minimizes the exposure of the luting material to the oral environment, thus reducing cement dissolution, microleakage, inflammation of the periodontal tissues, and the risk of pulpal inflammation.[37-41] The American Dental Association (ADA) in its specification N.8 indicates that the thickness of the luting cement for a dental crown should not exceed 25 μm when using a Type I luting cement or 40 μm when using a Type II luting agent.[42] Even though a consensus as to the ideal maximum marginal gap width of a dental restoration is lacking, a marginal gap between 50 to 120 μm has been considered clinically acceptable.[9,10,43-48] The most referenced study pertaining to clinically acceptable marginal discrepancy was conducted by McLean and Von Fraunhofer in 1971,[43] where the authors concluded that a marginal opening of no more than 120 μm was clinically acceptable after a clinical examination of more than 1000 crowns at 5 years.

Previous studies have reported a marginal discrepancy of milled zirconia restorations between 17 μm and 118 μm.[6-11,46,49-57] In a systematic review based on 54 articles, the marginal gap for ceramic crowns was identified as ranging from 7.6 μm to 206.3 μm.[48]

A consensus as to the best methodology for evaluating the fit accuracy of prosthetic restorations is lacking.[44,48] The outcome variations between different studies can be attributed to heterogeneous study designs with varying definitions of the marginal discrepancy, direct and indirect evaluation methods, measurements per specimen, sample size, finish line, and the stage at which the marginal gap was measured.[48] The silicone replica technique is the most extensively used nondestructive tool for analyzing the marginal and internal areas with direct microscopic examination.[48]

Limited information is available regarding the marginal and internal discrepancies of zirconia crowns manufactured by using SLA AM technologies.[56] The purpose of the present study was to compare the marginal and internal discrepancies of anatomically contoured milled zirconia crowns and additively manufactured, anatomically contoured and splinted zirconia crowns by using the silicone replica technique. The null hypotheses were that no significant difference in marginal discrepancy would be found between the milled and additively manufactured groups and that no significant difference would be found in the internal discrepancy between the milled and additively manufactured groups.

MATERIAL AND METHODS

A maxillary definitive cast with a dental implant (Bone level RC implant; Straumann) in the right first premolar

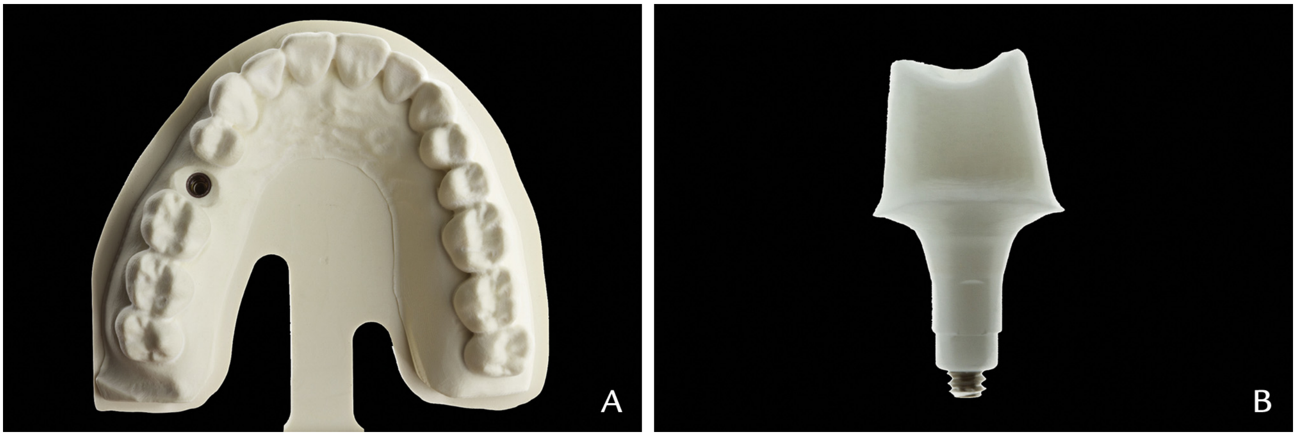

Figure 1. A, Maxillary master cast with dental implant in right first premolar position. B, Zirconia abutment manufactured for cemented crown restoration.

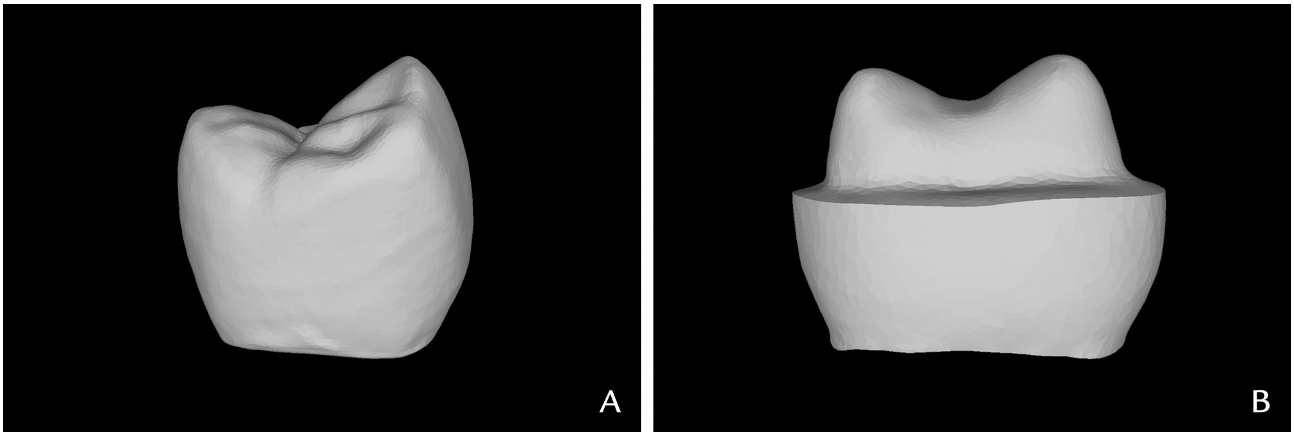

Figure 2. Digital design of specimens. A, Anatomically contoured crown digital design for specimen fabrication in milled and additive manufactured groups. B, Splinted additive manufactured crown digital design.

position was obtained (Fig. 1A). A dental laboratory scanner (DWOS 7 Series scanner; Straumann) was used to digitize the definitive cast. A dental CAD software program (CARES Software; Straumann) was used to design a custom abutment, the STL_A file was used to manufacture a zirconia implant abutment (CARES zirconium-dioxide abutment; Straumann) with a chamfer finishing line, and the cervical preparation line followed a representative gingival margin contour to simulate clinical conditions. The preparation of the abutment had a total convergence angle of 10 to 12 degrees and a circumferential chamfer margin of 1 mm (Fig. 1B).

The same dental laboratory scanner and CAD software were used to digitize the zirconia custom abutment and design a cemented crown, the thickness of which ranged from 1.0 to 2.0 mm. The digital design of the anatomically contoured crown (STL_C file) was obtained (Fig. 2A). The STL_C file was divided into 2 pieces, simulating the parts of the crown that would replace the enamel (STL_{G1} file) and dentin (STL_{G2} file) structures (Fig. 2B). Three groups were determined: milled anatomically contoured zirconia (CNC group), additively manufactured anatomically contoured zirconia (AM group), and splinted additively manufactured zirconia (SAM group) crowns (Table 1 and Table 2). The STL_C file was used to manufacture the specimens of CNC and AM groups, while the STL_{G2} file was used to fabricate the SAM group specimens.

For the CNC group, the STL_C file was used to manufacture 10 anatomically contoured zirconia crowns (CARES zirconium-dioxide crown; Straumann). All the AM specimens were produced by the same manufacturer (Straumann). For the AM group, the same STL_C file was used to manufacture 10 anatomically contoured zirconia crowns by using a zirconia paste (3DMix ZrO_2 paste; 3DCeram Co) mixed with liquid photosensitive resin in a ceramic 3D printer (CERAMAKER 900; 3DCeram Co). After the AM process was completed, the binder was removed thermally, and the ZrO_2 was sintered. No additional processing, including finishing or polishing, was

Table 1. Characteristics of milled and stereolithography (SLA) additive manufactured zirconia specimens

Group	Material	Technology	Composition
Anatomically contoured milled (CNC group)	CARES Zirconia-dioxide (Straumann)	Milling 5-axis	NP
Anatomically contoured additively manufactured (AM group)	3DMix ZrO_2 (3DCeram)	Laser, stereolithography (SLA)	Zirconia stabilized with 3% yttria
Splinted additively manufactured (SAM)	3DMix ZrO_2 (3DCeram)	Laser, stereolithography (SLA)	Zirconia stabilized with 3% yttria

NP, not provided.

performed. All the AM specimens were produced by the manufacturer 3DCeram Co.

For the SAM group, the STL_{G2} file was used to manufacture the 10 AM zirconia (3DMix ZrO_2 material; 3DCeram Co) specimens by using the same ceramic 3D SLA printer (CERAMAKER 900; 3DCeram Co). All the AM specimens were produced by the manufacturer 3DCeram Co. The thickness of the restorative material ranged from 0.5 to 1.0 mm. The specimens of the SAM group were manufactured following the same protocol as the AM group.

Thirty specimens were obtained (Fig. 3). For the marginal and internal discrepancy measurement, the silicone replica technique was used.[43] A white silicone indicator material (Fit Checker Advanced; GC Corp) was used to simulate the cement space. The intaglio surface of the crown was coated and placed on the implant abutment by using firm hand pressure from the occlusal surface to simulate a clinical situation until complete polymerization of the silicone material. Subsequently, the crown was removed from the implant abutment. The silicone cement film was stabilized with a light-body type A silicone material (Extrude VPD impression material light body; Kerr) before removal and sectioned by using a scalpel in a buccolingual direction and subsequently in a mesiodistal direction (Fig. 4). This procedure was repeated with each specimen.

The cement gap was measured on images recorded by using a digital microscope (VHX-2000 series digital microscope; Keyence America) at ×100 magnification. For the internal gap, 50 measurements were made for each specimen, and for the marginal gap, 25 measurements were made for each specimen (Fig. 5). The same person performed all measurements to minimize variation in the measured values.

A statistical software program (IBM SPSS Statistics, v22; IBM Corp) was used to calculate the means and standard deviations of the internal and marginal discrepancies for each group. To investigate significant differences among the 3 groups, the normality Shapiro-Wilk test was conducted. The results indicated that the distributions were not normal. Therefore, measurement data were assessed by the nonparametric Kruskal-Wallis H test and pairwise Mann-Whitney U-test (α=.05). Furthermore, as the data were not normally distributed, the Spearman correlation coefficient was used to determine the correlation between marginal and internal discrepancies in all 3 groups.

Table 2. Mechanical properties of stereolithography additive manufactured zirconia material

Mechanical Property	3DMix ZrO_2 3D Ceram
Grade	700
Particle size (μm)	0.1-0.8
Density (g/cm^3)	5.97
Vickers hardness (GPa)	12.6
Young's modulus (GPa)	209.4
Weibull modulus	NP
Shear modulus (GPa)	79.8
Flexural strength (MPa)	1088
Compressive strength (MPa)	2070
Coefficient thermal expansion (K^{-1})	12.4

NP, not provided. Information provided by manufacturer.

RESULTS

The internal and marginal adaptation measurements of the study groups are shown in Table 3. For the marginal discrepancy analysis, significant differences were found in the marginal gap among the CNC, AM, and SAM groups (P<.001). Pairwise testing indicated that the AM group had a significantly higher marginal discrepancy than the CNC and SAM groups (P<.001) and that the SAM group had a significantly higher marginal discrepancy than the CNC group (P<.001) (Fig. 6A).

For the internal discrepancy examination, a significant difference was found in the internal discrepancy among the CNC, AM, and SAM groups (P<.001). Pairwise testing indicated that the SAM group had a significantly higher internal discrepancy than the CNC group (P<.001), the SAM group had a significantly lower internal discrepancy than the AM group (P=.001), and the AM group had a significantly higher internal discrepancy than the CNC group (P<.001) (Fig. 6B).

The Spearman correlation coefficient between the marginal and internal discrepancies was 0.24 (P<.001). The CNC group had a weak correlation coefficient of 0.13 (P=.046), the SAM group had a nonsignificant correlation coefficient of 0.12 (P=.051), and the AM group had a moderate correlation coefficient of 0.32 (P<.001). This meant that a significant weak association was encountered between the marginal and internal discrepancies measured in all groups.

Superficial manufacturing defects encountered on specimens are shown in Figure 7. The majority of manufacturing defects were found in the AM group, which corresponded with the group that obtained the highest marginal discrepancy values.

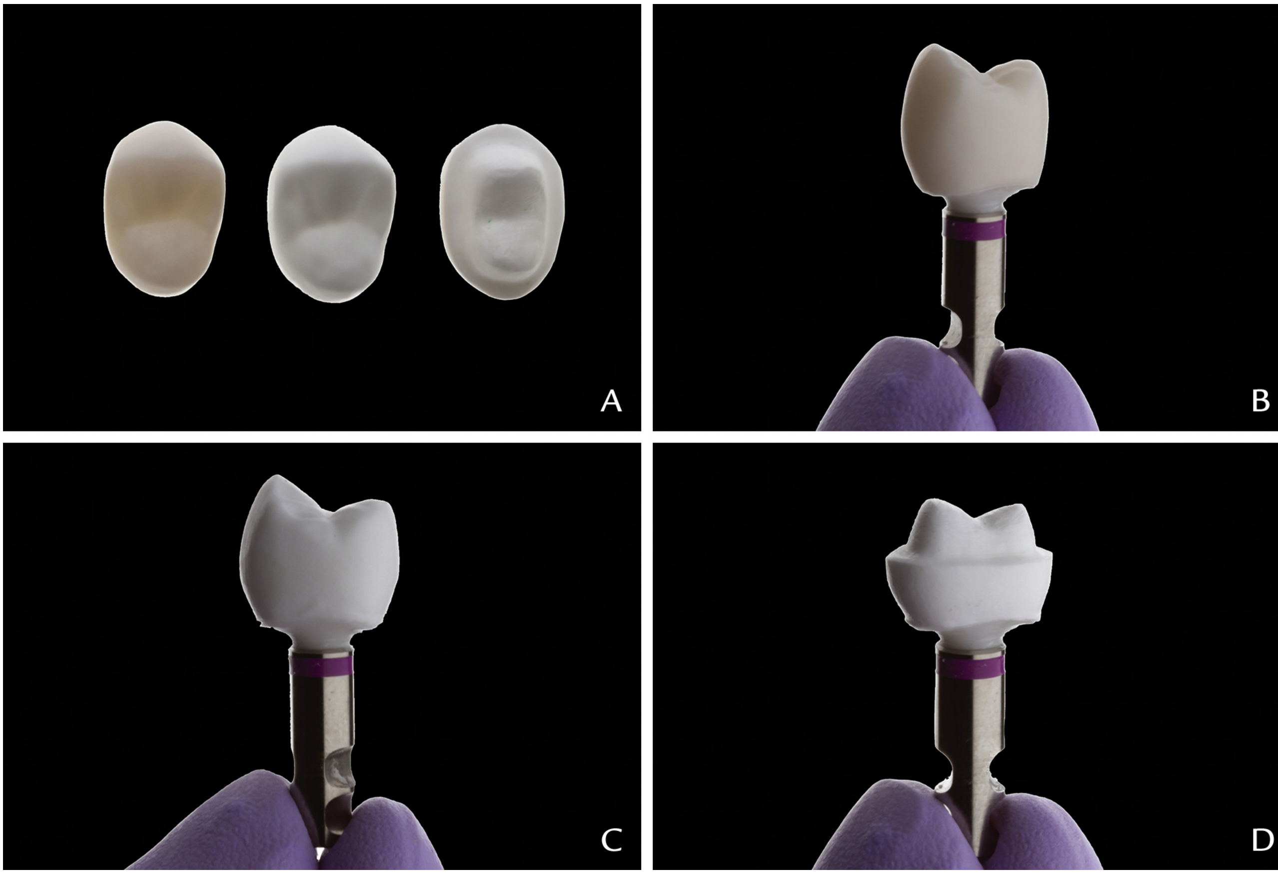

Figure 3. A, Specimens of CNC, AM, and SAM groups. B, Milled anatomically contoured specimen of CNC group. C, Anatomically contoured additively manufactured zirconia crown. D, Splinted zirconia additively manufactured crown.

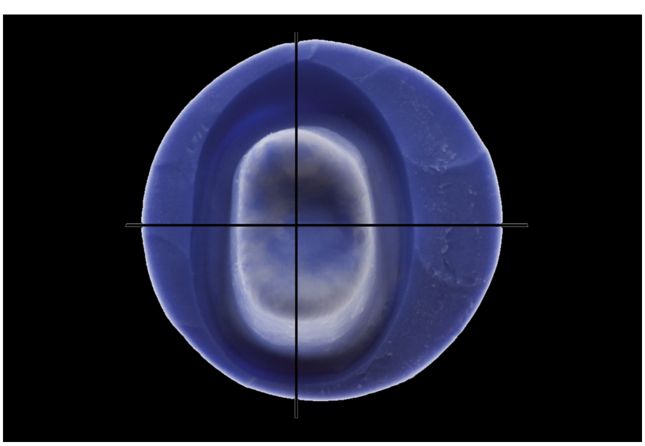

Figure 4. Marginal and internal discrepancies measured by using silicone replica technique. Silicone replicas sectioned by using scalpel in buccolingual direction and subsequently in mesiodistal direction.

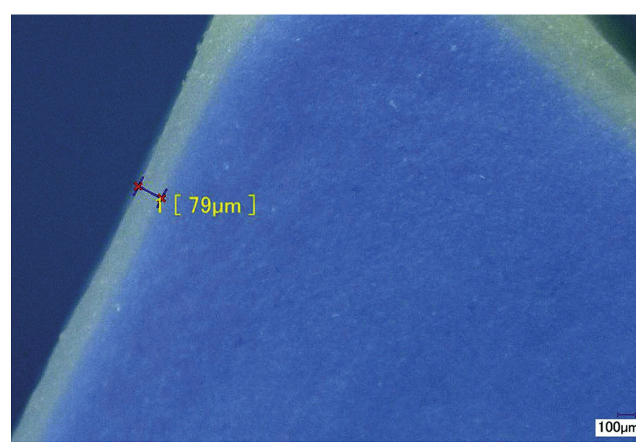

Figure 5. Discrepancy measurement made by using digital microscope (VHX-2000 series digital microscope; Keyence America) under ×100 magnification.

DISCUSSION

The null hypotheses were rejected as significant differences were found both in the marginal and internal discrepancies between the milled (CNC group) and the additively manufactured (AM and SAM) groups. Based on the results of this study, subtractive or additive technologies do seem to influence the marginal and internal discrepancies of a zirconia crown. Anatomically contoured zirconia milled crowns had significantly lower values for

Table 3. Descriptive statistics of the CNC, AM, and SAM groups for the marginal and internal discrepancy data (μm)

Group	Measurement	CNC	AM	SAM
Marginal discrepancy (N=250)	Median ±IQR	37.5 ±50	146.0 ±103.2	79.5 ±49.2
	Percentile 25	25.0	97.0	59.0
	Percentile 75	75.0	200.2	108.2
Internal discrepancy (N=500)	Median ±IQR	73.0 ±44.7	79.0 ±46	85.0 ±48
	Percentile 25	54.0	64.0	67.0
	Percentile 75	98.7	110.0	115.0

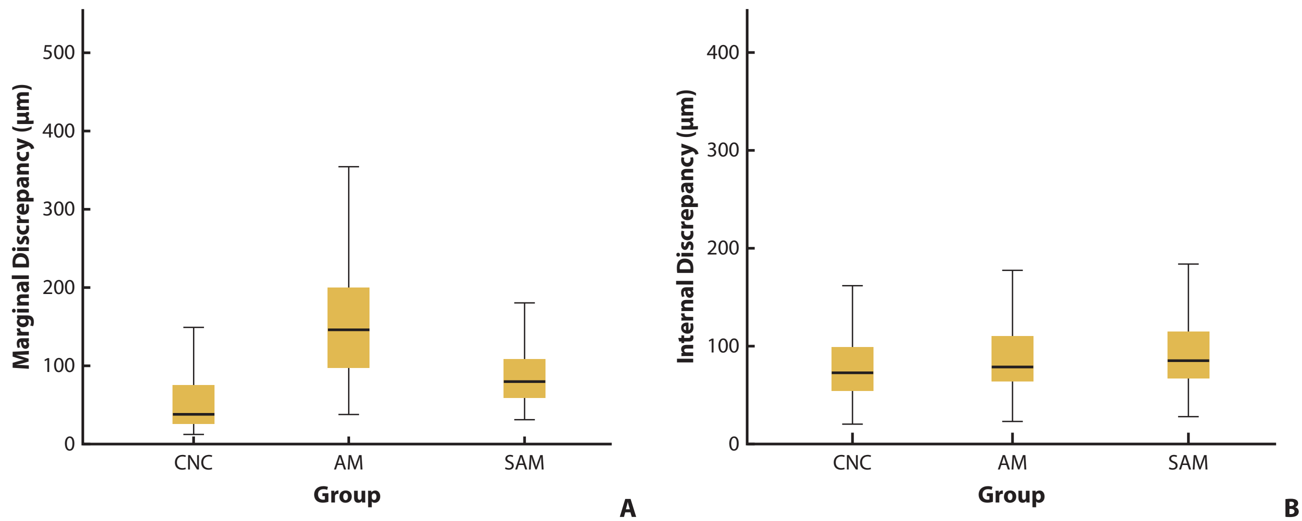

Figure 6. A, Marginal discrepancy. B, Internal discrepancy.

marginal and internal discrepancies than AM specimens. However, a wide range of variables in both manufacturing processes, including calibration, scanning process, software design, milling technology, milling strategy, AM technology, printing parameters, postprocessing procedures, and shrinkage after final firing of the restoration, can affect the marginal and internal accuracy of a restoration.[49,58] Nevertheless, specimens in one of the AM groups (SAM) demonstrated a marginal discrepancy that could be considered clinically acceptable.

The virtual crown design of the AM and SAM groups was identical on their cervical parts but not the total volume of the crown design. Furthermore, significant differences were found in the marginal and internal gaps between both groups. Material bulk difference or volume design of the STL files used to manufacture the specimens may imply a different direction and volumetric shrinkage behavior during the binder elimination and/or the sintering process, which could explain the differences encountered. Having transitioned through the learning curve and improvements during the last few decades, milling has evolved to be a more mature technology. Similarly, improvements in AM technologies could enable the control of direction and shrinkage behavior at different thicknesses.

The manufacturing and postprocessing procedures involved in the SLA AM technology evaluated appear to limit the accuracy to which it could reproduce the digital design of the specimens. Also, the green structures formed by additive technology were subjected to physical handling, postprocessing, debinding, and sintering. Cumulatively, these factors accounted for the large variability in the gap measurements which were observed with the AM group. Moreover, manufacturing defects were encountered mostly on the intaglio marginal area in the AM group, which obtained the highest marginal discrepancy and were deemed clinically unacceptable.

The trueness of the zirconia crowns fabricated with the same SLA AM technology used in the present study was analyzed.[56] A typodont tooth was prepared for a ceramic crown, and a digital crown was designed by using the CAD software. The STL_C file of the digital crown was either milled by using a dental 5-axis milling system or additively manufactured. The CAM crowns were scanned by using a laboratory scanner, and the trueness of each part was analyzed by superimposition onto the STL_C file. The authors reported that the trueness of the AM specimens was not significantly different from that of the corresponding milled specimens. Owing to the lack of standardization and differences in methodology encompassing tooth

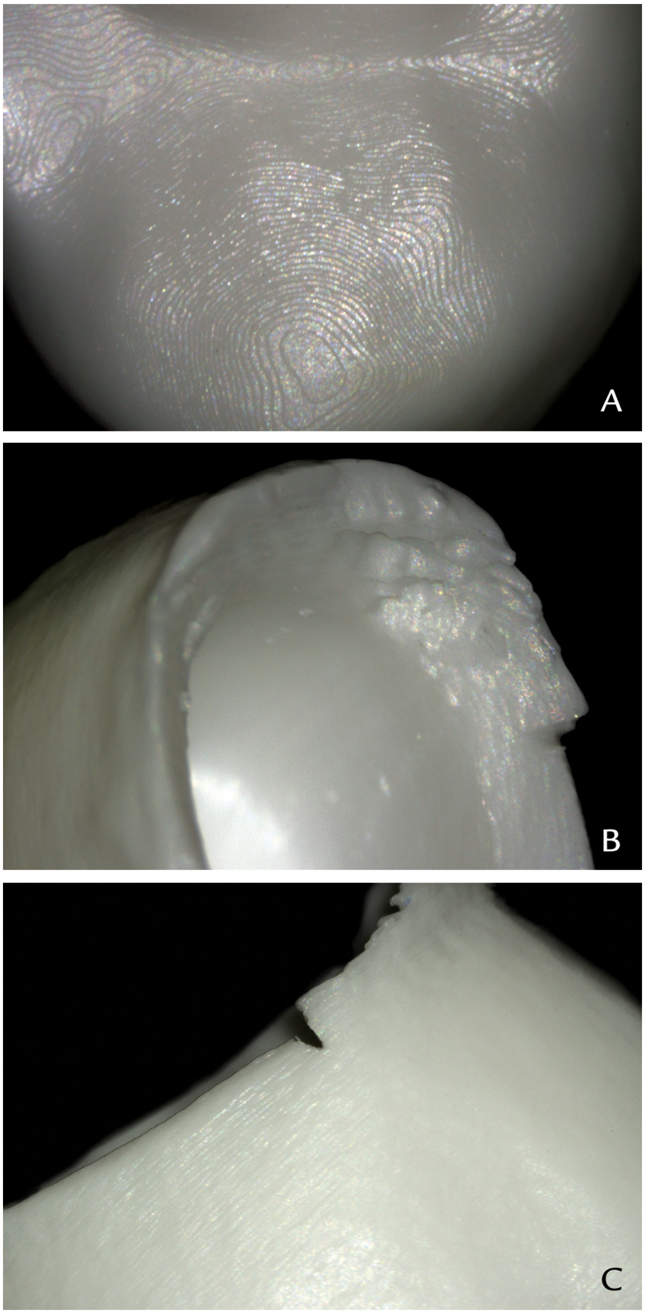

Figure 7. Manufacturing defects. A, Characteristically superficial texture of AM specimen. B, Manufacturing defect on intaglio surface of anatomically contoured additively manufactured zirconia crown. C, Manufacturing defect on marginal portion of anatomically contoured additively manufactured zirconia crown.

preparation, thickness differences in the crown design, and the measurement method selected, it was difficult to make a comparison with the present study. Moreover, the authors did not report the thickness of the digital crown design, a variable that might have contributed to the differences obtained in the present study on the AM group.

The anatomically contoured milled zirconia specimens demonstrated a mean marginal discrepancy of 65.0 μm, which was consistent with that found in previous studies reporting the marginal discrepancy of milled zirconia restorations to range from 17 to 118 μm.[6-11,46,49-57] The outcome variations between different studies can be attributed to heterogeneous study designs, inconsistent definitions of marginal discrepancy, direct and indirect evaluation methods, measurements per specimen, sample size, finish line, scanning procedures, digital design of the restoration, milling technology used, and the stage at which the marginal gap was measured.[48]

In the present study, marginal adaptation of the specimens obtained by using the silicone replica technique was evaluated by direct visual examination under a digital microscope at ×100 magnification, representing a nondestructive technique. A limitation of the technique, however, was the ideal positioning and identical angle for direct measurements.[58] Nevertheless, these aspects were minimized by positioning the specimens in relation to a base, such that measurements were always made at the same points,[58] and by increasing the number of measurements per specimen.[59]

Further studies accounting for the effect of variables including thickness of the restorative material, firing cycles effect, tooth type, tooth preparation, finishing line configuration, occlusal anatomy, and different measurement techniques are recommended. Furthermore, investigations analyzing the mechanical properties and clinical outcomes of zirconia AM restorations are needed.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Significant differences were found in the marginal and internal discrepancies between the 2 different manufacturing methods, namely subtractive and additive technologies. The anatomically contoured milled group demonstrated lower marginal and internal discrepancies than additively manufactured specimens.
2. The splinted zirconia AM group had significantly higher marginal and internal discrepancies than the anatomically contoured milled group. However, it can be considered to be within the clinically acceptable range.
3. Anatomically contoured AM crown specimens had the highest marginal and internal discrepancies, which were beyond the clinically acceptable range.
4. A significant weak correlation between the marginal and internal discrepancies was measured in all groups.

REFERENCES

1. Singh V. Rapid prototyping, materials for RP and applications of RP. Int J Eng Res Sci 2013;4:473-80.
2. Young JM, Altschuler BR. Laser holography in dentistry. J Prosthet Dent 1977;38:216-25.
3. Kalpakjian S, Schmid SR. Manufacturing engineering and technology. 7th ed. New York: Addison-Wesley: New York; 2014. p. 1-10.
4. Horn TJ, Harrysson OLA. Overview of current additive manufacturing technologies and selected applications. Sci Prog 2012;95:255-82.
5. Al-Jubouri O, Azzari A. An introduction to dental digitizers in dentistry: systematic review. J Chem Pharm Res 2015;7:10-20.
6. Sulaiman F, Chai J, Jameson V, Wozniak WT. A comparison of the marginal fit of In- Ceram, IPS Empress, and Procera crowns. Int J Prosthodont 1997;10:478-84.
7. Bindl A, Mörmann WH. Marginal and internal fit of all-ceramic CAD/CAM crown copings on chamfer preparations. J Oral Rehabil 2005;32:441-7.
8. Baig MR, Tan KB, Nicholls JI. Evaluation of the marginal fit of a zirconia ceramic computer-aided machined (CAM) crown system. J Prosthet Dent 2010;104:216-27.
9. Grenade C, Mainjot A, Vanheusden A. Fit of single tooth zirconia copings: comparison between various manufacturing processes. J Prosthet Dent 2011;105:249-55.
10. Karataşli O, Kursoğlu P, Capa N, Kazazoğlu E. Comparison of the marginal fit of different coping materials and designs produced by computer aided manufacturing systems. Dent Mater J 2011;30:97-102.
11. Rinke S, Fornefett D, Gersdorff N, Lange K, Roediger M. Multifactorial analysis of the impact of different manufacturing processes on the marginal fit of zirconia copings. Dent Mater J 2012;31:601-9.
12. Ng J, Ruse D, Wyatt C. A comparison of the marginal fit of crowns fabricated with digital and conventional methods. J Prosthet Dent 2014;112:555-60.
13. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. J Am Dent Assoc 2006;137:1289-96.
14. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J 2008;204:505-11.
15. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations-dental milling machines from a mechanical engineering viewpoint. Part A: chairside milling machines. Int J Comput Dent 2016;19:45-62.
16. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations-dental milling machines from a mechanical engineering viewpoint. Part B: labside milling machines. Int J Comput Dent 2016;19:115-34.
17. Ebert J, Özkol E, Zeichner A, Uibel K, Weiss O, Koops U, et al. Direct inkjet printing of dental prostheses made of zirconia. J Dent Res 2009;88:673-6.
18. ISO/ASTM 52900:2015 [ASTM F2792]. Additive manufacturing – General principles – Terminology. Available at: https://www.iso.org/standard/69669.html.
19. Deckers J, Vleugels J, Kruth JP. Additive manufacturing of ceramics: A review. J Ceram Sci Tech 2014;05:245-60.
20. Griffith ML, Halloran JW. Freeform fabrication of ceramics via stereolithography. J Am Ceram Soc 1995;82:1653.
21. Himmer T, Nakagawa T, Noguchi H. In: Bourell DL, Beaman JJ, Crawford RH, Marcus HL, Barlow JW, editors. Proceedings of SFF Symposium 1997. p. 363.
22. Hinczewski C, Corbel S, Chartier T. Ceramic suspensions suitable for stereolithography. J Eur Ceram Soc 1998;18:583-90.
23. Doreau F, Chaput C, Chartier T. Stereolithography for manufacturing ceramic parts. Adv Eng Mater 2000;2:493-6.
24. Bertsch A, Jiguet S, Renaud P. Microfabrication of ceramic components by microstereolithography. J Micromech Microeng 2004;14:197-203.
25. Torabi K, Farjood E, Hamedani S. Rapid prototyping technologies and their applications in prosthodontics, a review of literature. J Dent (Shiraz) 2015;16:1-9.
26. Kyobula M, Adedeji A, Alexander MR, Saleh E, Wildman R, Ashcroft I, et al. 3D inkjet printing of tablets exploiting bespoke complex geometries for controlled and tune able drug release. J Control Release 2017;10:207-15.
27. Shan XF, Chen HM, Liang J, Huang JW, Cai ZG. Surgical reconstruction of maxillary and mandibular defects using a printed titanium mesh. J Oral Maxillofac Surg 2015;73:1437.e1-9.
28. Allen S, Dutta D. On the computation of part orientation using support structures in layered manufacturing. Proceedings of the Solid Free-form Fabrication Symposium, Austin, TX 1994:259-69.
29. Puebla K, Arcaute K, Quintana R, Wicker RB. Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. Rapid Prototyp J 2012;18:374-88.
30. Alharbi N, Osman R, Wismeijer D. Effect of build direction on the mechanical properties of 3D printed complete coverage interim dental restorations. J Prosthet Dent 2016;155:760-7.
31. Brain M, Jimbo R, Wennenberg A. Production tolerance of additive manufactured polymeric objects for clinical applications. Dent Mater 2016;32:853-61.
32. Ide Y, Nayar S, Logan H, Gallagher B, Wolfaardt J. The effect of the angle of acuteness of additive manufactured models and the direction of printing on the dimensional fidelity: clinical implications. Odontology 2017;105:108-15.
33. Plooji JM, Maal TJ, Haers P, Borstlap WA, Kuijpers-Jagtman AM, Berge SJ. Digital three-dimensional image fusion processes for planning and evaluating orthodontics and orthognathic surgery. A systematic review. Int J Oral Maxillofac Surg 2011;40:341-52.
34. Revilla-León M, Özcan M. Additive manufacturing technologies used for 3D metal printing in dentistry. Curr Oral Health Rep 2017;4:201-8.
35. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. J Prosthodont 2019;28:146-58.
36. Sorensen SE, Larsen IB, Jörgensen KD. Gingival and alveolar bone reaction to marginal fit of subgingival crown margins. Scand J Dent Res 1986;94:109-14.
37. Block PL. Restorative margins and periodontal health: a new look at an old perspective. J Prosthet Dent 1987;57:683-9.
38. Sorensen JA. A rationale for comparison of plaque-retaining properties of crown systems. J Prosthet Dent 1989;62:264-9.
39. Jacobs MS, Windeler AS. An investigation of dental luting cement solubility as a function of the marginal gap. J Prosthet Dent 1991;65:436-42.
40. Felton DA, Kanoy BE, Bayne SC, Wirthman GP. Effect of in vivo crown margin discrepancies on periodontal health. J Prosthet Dent 1991;65:357-64.
41. American Dental Association. ANSI/ADA Specification No. 8 for zinc phosphate cement. In: Guide to dental materials and devices (ed 5). Chicago: American Dental Association; 1970-1971.
42. White SN, Yu Z. Film thickness of new adhesive luting agents. J Prosthet Dent 1992;67:782-5.
43. McLean JW, Von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131:107-11.
44. Lofstrom LH, Barakat MM. Scanning electron microscopic evaluation of clinically cemented cast gold restorations. J Prosthet Dent 1989;61:664-9.
45. Nakamura T, Dei N, Kojima T, Wakabayashi K. Marginal and internal fit of CEREC 3 CAD/CAM all-ceramic crowns. Int J Prosthodont 2003;16:244-8.
46. Coli P, Karlsson S. Precision of a CAD/CAM technique for the production of zirconium dioxide copings. Int J Prosthodont 2004;17:577-80.
47. Kenyon BJ, Hagge MS, Leknius C, Daniels WC, Weed ST. Dimensional accuracy of 7 die materials. J Prosthodont 2005;14:25-31.
48. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: A systematic review. J Prosthet Dent 2013;110:447-54.e10.
49. May KB, Russell MM, Razzoog ME, Lang BR. Precision of fit: the Procera All Ceram crown. J Prosthet Dent 1998;80:394-404.
50. Beschnidt SM, Strub JR. Evaluation of the marginal accuracy of different all-ceramic crown systems after simulation in the artificial mouth. J Oral Rehabil 1999;26:582-93.
51. Boening KW, Wolf BH, Schmidt AE, Kästner K, Walter MH. Clinical fit of Procera AllCeram crowns. J Prosthet Dent 2000;84:419-24.
52. Yeo IS, Yang JH, Lee JB. In vitro marginal fit of three all-ceramic crown systems. J Prosthet Dent 2003;90:459-64.
53. Suárez MJ, González de Villaumbrosia P, Pradíes G, Lozano JF. Comparison of the marginal fit of Procera AllCeram crowns with two finish lines. Int J Prosthodont 2003;16:229-32.
54. Quintas AF, Oliveira F, Bottino MA. Vertical marginal discrepancy of ceramic copings with different ceramic materials, finish lines, and luting agents: an in vitro evaluation. J Prosthet Dent 2004;92:250-7.
55. Balkaya MC, Cinar A, Pamuk S. Influence of firing cycles on the margin distortion of 3 all-ceramic crown systems. J Prosthet Dent 2005;93:346-55.
56. Wang W, Yu H, Liu Y, Jiang X, Gao B. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. J Prosthet Dent 2019;121:285-91.
57. Beuer F, Aggstaller H, Edelhoff D, Gernet W, Sorensen J. Marginal and internal fits of fixed dental prostheses zirconia retainers. Dent Mater 2009;25:94-102.
58. Gassino G, Barone Monfrin S, Scanu M, Spina G, Preti G. Marginal adaptation of fixed prosthodontics: a new in vitro 360-degree external examination procedure. Int J Prosthodont 2004;17:218-23.
59. Groten M, Axmann D, Pröbster L, Weber H. Determination of the minimum number of marginal gap measurements required for practical in-vitro testing. J Prosthet Dent 2000;83:40-9.

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