Journal of Dental Sciences 18 (2023) 715–721

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.e-jds.com

Original Article

Clinical evaluation of 3D-printed zirconia crowns fabricated by selective laser melting (SLM) for posterior teeth restorations: Short-term pilot study

Chia-Tze Kao [a,b], Sze-Han Liu [a,b], Chuan-Yi Kao [c], Tsui-Hsein Huang [a,b*]

[a] School of Dentistry, College of Oral Medicine, Chung Shan Medical University, Taichung, Taiwan
[b] Dental Department, Chung Shan Medical University Hospital, Taichung, Taiwan
[c] School of Medicine, Chung Shan Medical University, Taichung, Taiwan

Received 10 November 2022; Final revision received 14 November 2022
Available online 26 November 2022

KEYWORDS
Three dimension printing;
Zirconia crown;
Periodontal status;
Plaque index;
Gingival index

Abstract *Background/purpose:* Zirconia crowns (ZrC) without veneering porcelain have become an effective alternative in clinical practice. Monolithic zirconia restorations fabricated by the dry milling method do not have acceptable clinical properties. This study evaluated the periodontal qualities of three-dimensional printed ZrC using the modified United States Public Health Service (USPHS) criteria.
Materials and methods: A total of 15 patients who required dental crowns were recruited, and all 15 teeth were restored with digital 3D-printed ZrC. All crowns were assessed at the time of crown placement and 2, 6, and 24 weeks post-placement. Clinical parameters, including plaque index, gingival index, probing depth, crown marginal integrity, and attrition of the antagonist's teeth, were evaluated and recorded.
Results: According to the Modified California Dental Association quality evaluation system, 100% of the crowns received satisfactory grades. Despite the significant increase in plaque index and gingival index at two weeks post-ZrC placement, there was no deterioration in probing depth. Moreover, there was discard usage of ZrC on the antagonist's teeth at 24 weeks post-treatment. Of the 15 crowns, one tooth had to be extracted due to a vertical root fracture. Overall, the digital 3D-printed crowns showed no adverse effects on periodontal tissues after 24 weeks of follow-up.

* Corresponding author. School of Dentistry, College of Oral Medicine, Chung Shan Medical University, Dental Department, Chung Shan Medical University Hospital, No. 110, Chien Kuo N. Road, Taichung, 00407, Taiwan.
E-mail address: thh@csmu.edu.tw (T.-H. Huang).

https://doi.org/10.1016/j.jds.2022.11.017

Conclusion: The 3D-printed ZrC showed no periodontal problems. It can serve as an alternative for patients, particularly those with high esthetic expectations.

Introduction

Metal-ceramic crowns have been the gold standard for prostheses for more than 50 years due to their high mechanical strength.[1] The opacity of the metal, on the other hand, may be revealed over time near the gingival margin and affect patient aesthetics. As patients currently have increasing aesthetic demands, all-ceramic crowns are becoming more popular as they mimic the appearance of natural-looking prosthetic restorations. In 1990, zirconia was introduced as a superior option because it provides additional mechanical properties while still maintaining the visual benefits of all ceramic crowns.[1–7] The addition of yttria to zirconia, known as yttria-stabilized tetragonal zirconia polycrystals (Y-TZPs), has strong mechanical properties of 1200 HV hardness, 900—1200 MPa flexural strength, and fracture toughness of 6—8 MPa $m^{1/2}$.[7]

Zirconia restorations can be fabricated by CAD-CAM technology or 3-D printing techniques. One may order the material in a laboratory or in a milling center and be self-produced chair-side in the office. The zirconia restoration success is dependent on the marginal fit. Poor marginal adaptation of zirconia restoration causes microleakage, easy plaque retention and induced secondary caries, pulp infection, periodontal problems, and alveolar bone loss.[8,9] The comparisons of zirconia copings and ceramic restorations shows higher accuracy for zirconia copings.[10] The ZrC fabrication showed a clinically acceptable marginal discrepancy range between the CAD-CAM CEREC in the LAB system and the LAVA system milling center.[11] When comparing the trueness and precision of 3D-printed versus milled monolithic zirconia crowns (MZCs), it was shown that milled MZCs had a statistically higher trueness than 3D-printed ones, and both were compatible with clinical use.[12]

Reviewing the literature, most studies discussed the 3D printing of zirconia in vitro.[13–16] There have been fewer reports of periodontal effects of 3D printing zirconia crowns in vivo. The aim of this study was to evaluate the clinical performance of zirconia crowns fabricated by selective laser melting (SLM) on posterior teeth restorations.

Materials and methods

Study protocol

The study protocol was approved by the Ethics and Clinical Trials Committee of Chung Shan Medical University Hospital (Taiwan) (registration number: 212250-028-F-008-1). Patients were provided with complete information about the study protocol, procedures, follow-up visits, potential risks, and alternative treatment options before obtaining informed consent. The subjects could leave the trial at any time for any reason. The patient authorized the use of personal medical records (including pictures and measurement data) for research purposes, and the personal data will never be connected in any manner.

Sample selection criteria

A total of 15 patients (7 males and 8 females) were selected at Chung-Shan Medical University Dental Hospital (Taiwan) from March 2021 to July 2022 who needed dental crowns for the premolars or molars. The age of the subjects ranged from 23 to 66 years old with an average age of 44 years old. All received 3D-printed ZrC (n = 15) were fabricated by selective laser melting technology from Taiwan Innovative Biomedical company (TIB Co., Kaohsiung, Taiwan).

The patient inclusion criteria were as follows: 1) patients aged ≥20 years old, 2) patients who required a premolar or molar crown restoration, and 3) patients with no history of allergies to medications or materials. The patient exclusion criteria were as follows: 1) untreated parafunction, such as TMJ disorder or sleep bruxism, 2) systemic disease, including hypertension or diabetes, 3) periodontal problems, 4) history of allergy to medications or materials, and 5) pregnancy.

Tooth preparation

All restorative procedures were performed by the same dentist, including preparation of abutment teeth, digitalization, temporization, and cementation. The tooth distribution for 3D-printed ZrC is shown in Table 1. For tooth preparation, 1.5—2.0 mm of the occlusal surface was removed. The axial surface was reduced 1.0—1.5 mm with circumferential deep chamfer margins located subgingivally and axial wall taper degrees of 6—10°. A 3Shape TRIOS 3(3Shape A/S Co., Copenhagen, Denmark) intraoral scanner was used to scan directly on the patient's mouth to produce digital impressions. The scanning digital data were sent to the TIB company for fabricating 3D-printed ZrC (Fig. 1).

Table 1 The tooth distribution of the tested 3D-printed crowns.

Regions	Maxilla	Mandible
First premolar	3	1
Second premolar	2	1
First molar	1	2
Second molar	1	4

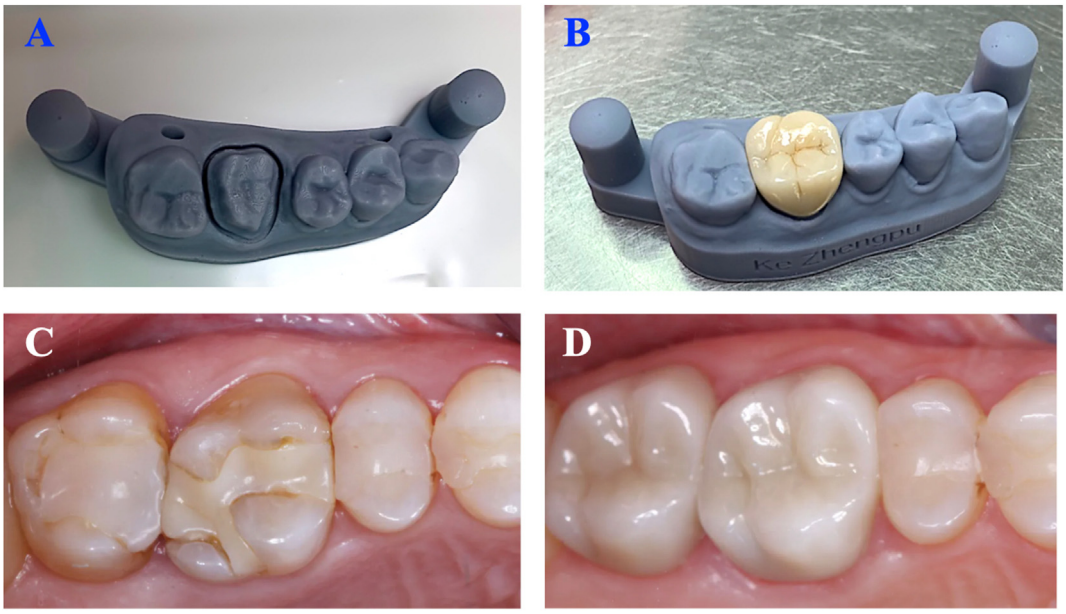

Figure 1 (A) The 3D printing resin model with crown preparation at the first molar. (B) The 3D-printed zirconia crowns fit on the prepared first molar. (C) The patient's maxilla right first molar showed a mesio-occlusal-disto composite restoration. (D) The status of the patient's maxilla right first molar placed a 3D-printed zirconia crown after 24 weeks. The periodontal tissue showed normal structure without inflammation.

The prepared teeth were protected by temporary restoration with Tokuso Curefast (Tokuyama Co., Tokyo, Japan) and cemented with eugenol-free temporary dental cement (Freegenol, GC International Co., Tokyo, Japan). After 2–3 weeks of temporization, interim crowns were removed, and ZrC was cemented with self-adhesive resin cement (RelyX U200, 3 M ESPE Co., Seefeld, Germany) (Table 2).

Study variables

The study variables were recorded: 1) age, 2) sex, 3) type of tooth (premolar or molar), 4) region of the tooth (maxillary or mandible), 5) condition of the antagonist tooth (natural tooth or types of restoration), 6) complications (mechanical or biological), 7) evolution of survival parameters (marginal adaptation, color match, marginal discoloration, crown margin integrity, anatomic form, gross fracture, and surface texture), 8) evolution of periodontal parameters (plaque index (PI), gingival index (GI), probing depth (PD), and 9) attrition grade of the antagonist tooth.

All crowns were assessed at the time of crown placement at 0 weeks (baseline) and 2 weeks, 6 weeks, and 24 weeks. The 3D-printed zirconia crowns were rated according to the modified California Dental Association (modified CDA criteria) quality evaluation system to assess marginal adaptation, color match, marginal discoloration, crown margin integrity, anatomic form, gross fracture, and surface texture. Each item was rated A (Excellent) in case of no problem, B (Acceptable) in case of minor problems, and C (Failure) in case of major complications. A crown score of A or B indicated success, whereas a score of C indicated failure.

Periodontal parameters such as plaque index, gingival index, and probing depth were evaluated in the following way: (1) PI, the amount and thickness of plaque were rated

Table 2 Materials used in the crown preparation procedures.

Procedure	Material	Proprietary Name	Company
Impression	Vinyl Polysiloxane	Epxress XT Putty Soft	**3M ESPE, Seefeld, Germany**
Temporary crown fabrication	Autopolymerizing resin	TOKUSO CUREFAST	**Tokuyama Co. Tokyo, Japan**
Temporary crown cementation	Eugenol free luting cement	FREEGENOL TEMPORARY PACK	**GC International Co., Tokyo, Japan**
Zirconia crown cementation	Self adhesive resin cement	RelyX U200	**3M ESPE, Seefeld, Germany Co.**
Retraction cord	Treated with aluminum sulfate	SilTrax AS	**Pascal, Safco Dental Supply LLC., Buffalo Grove, IL, USA**
Disclosing agents	Erythrosine	TRACE	**DentaKit Co., Belmont, CA USA**

on a scale of 0—3, with 0 indicating no plaque on the gingival margin, 1 indicating fine film of plaque that can be seen using a probe, 2 indicating moderate plaque on the gingival margin, and 3 indicating abundant plaque on the gingival margin. (2) GI, a periodontal probe, was gently inserted 1 mm below the gingival margin and slid along the margin to observe any gingival bleeding. The result was rated on a scale of 0—3, with 0 indicating healthy gingiva, 1 indicating mild gingival inflammation and no bleeding on probing, 2 indicating moderate gingival inflammation, and 3 indicating severe gingival inflammation and tendency for spontaneous bleeding. (3) PDs, the gingival pocket depth of abutment tooth at 6 gingival sites (mesiobuccal, mid-buccal, distobuccal, mesiolingual, mid-lingual, and distolingual), were measured. The average value was rated on a scale of 0—3, with 0 indicating healthy gingiva with a probing depth $<$3 mm, 1 indicating mild gingivitis with a probing depth $<$4 mm, 2 indicating moderate gingivitis with a probing depth 4—5 mm, and 3 indicating severe gingivitis with a probing depth $>$6 mm. (4) The attrition grades were evaluated in the following way: 0 indicated no enamel wear, 1 indicated only enamel wear, 2 indicated mild dentin wear, 3 indicated severe dentin wear, and 4 indicated pulp exposure.

After crown placement, follow-up visits were performed at 0 weeks, 2 weeks, 6 weeks, and 24 weeks. Data were collected by a single examiner.

Statistical analysis

The data were analyzed with JMP® 16.0 (Student Edition 16.0 for Mac OX, SAS Institute, Cary, NC, USA). Descriptive analysis was performed for evaluation of the crown restorations according to the modified CDA criteria. The Wilcoxon signed-rank test was used to compare differences in periodontal parameters at various follow-up time points. The level of significance was set at 0.05.

Results

In total, 15 3D-printed ZrC were produced by the SLM machine. Seven (47%) crowns were placed in the maxilla, and 8 (53%) were placed in the mandible (Table 1). All patients were successfully followed for 24 weeks. Only 1 patient was excluded due to a vertical root fracture at the 6th week.

Evaluation of survival parameters

According to the modified CDA quality evaluation system, with the exception of two crowns that were rated as acceptable for marginal adaptation from the 2nd to 24th week, all other crowns were evaluated as excellent for color match, marginal discoloration, crown margin integrity, anatomic form, gross fracture, and surface texture after placement (Fig. 1). Crowns with excellent and acceptable rates were considered successful. The results in a success rate of 100% (Table 3).

Survival parameters such as marginal adaptation, color match, marginal discoloration, crown margin integrity, anatomic form, gross fracture, and surface texture were not significantly different at the different time points ($P > 0.05$) (Table 4).

Table 3 Quality of zirconia crowns based on the Modified California Dental Association (CDA) criteria.

Modified CDA criteria	Success Excellence (A)	Success Acceptable (B)	Failure Unacceptable (C)
Marginal adaptation			
O Week	14	0	0
2 weeks	13	1	0
6 weeks	12	2	0
24 weeks	12	2	0
Color match			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0
Marginal discoloration			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0
Corwin margin integrity			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0
Automatic form			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0
Gross fracture			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0
Surface texture			
O Week	14	0	0
2 weeks	14	0	0
6 weeks	14	0	0
24 weeks	14	0	0

Each item was rated A (Excellent) in case of no problem, B (Acceptable) in case of minor problems, and C (Failure) in case of major complications.

Evaluation of periodontal parameters

The 3D-printed ZrC periodontal analyzed parameters are shown in Fig. 2. The results of periodontal parameter comparisons are shown in Table 5. The PI and GI score at the abutment teeth were significantly increased ($P < 0.05$) after 2 weeks. There were significant deteriorations in both PI and GI in patients during the follow-up after crown placement (all $P < 0.05$). However, there was no statistically significant difference in GI score between 0 and 24

Table 4 Quality assessment of the ZrC at 0 weeks, 2 weeks, 6 weeks, and 24 weeks.

	0 week			2 weeks			6 weeks			24 weeks		
	A	B	C	A	B	C	A	B	C	A	B	C
Marginal adaptation	100%	0	0	92.9%	7.1%	0	85.8%	14.2%	0	85.8%	14.2%	0
Color match	100%	0	0	100%	0	0	100%	0	0	100%	0	0
Marginal discoloration	100%	0	0	100%	0	0	100%	0	0	100%	0	0
Crown margin integrity	100%	0	0	100%	0	0	100%	0	0	100%	0	0
Anatomy from	100%	0	0	100%	0	0	100%	0	0	100%	0	0
Gross fracture	100%	0	0	100%	0	0	100%	0	0	100%	0	0
Surface texture	100%	0	0	100%	0	0	100%	0	0	100%	0	0

Each item was rated A (Excellent) in case of no problem, B (Acceptable) in case of minor problems, and C (Failure) in case of major complications.

weeks ($P > 0.05$). The 3D-printed ZrC showed good periodontal status (Fig. 2 A, B, C).

Evaluation of antagonist tooth attrition

There was no significant attrition found in the wear of the antagonist teeth at different follow-up time points (Fig. 2D).

Discussion

In the present study, despite the marginal adaptation of one crown and two crowns, they were graded as acceptable at the 2nd and 6th weeks, respectively. Overall, the survival parameters of all crowns resulted in a 100% success rate. Therefore, the 3D-printed ZrC had adequate clinical qualities. The 3D-printed ZrC survival rate results were similar to those of other studies.[12]

The marginal adaptation of 3D-printed ZrC is influenced by several factors, such as fabrication method, material composition of zirconia crowns, finishing line design, accuracy of the scanner, and cement type. The present study showed that 3D-printed ZrC had a 100% success rate.

One study demonstrated that the 3D additive technique had better margin quality compared to those fabricated by subtractive milling soft-machined blanks,[17] while another study showed that both had similar accuracy.[6] Schriwer et al. found that the production method and material composition of monolithic ZrC affected internal fit, crown margin quality, and load at the crown fracture.[18] Schmitz et al. found that monolithic lithium disilicate crowns with knife-edged margins yielded clinical outcomes similar to other margin designs, and knife-edged crowns were prone to large chipping.[19] Mangano et al. compared 12 intraoral scanners (IOS) and found that statistically significant differences in trueness were found among the intraoral scanners.[20] The digital impression of the crown was directly

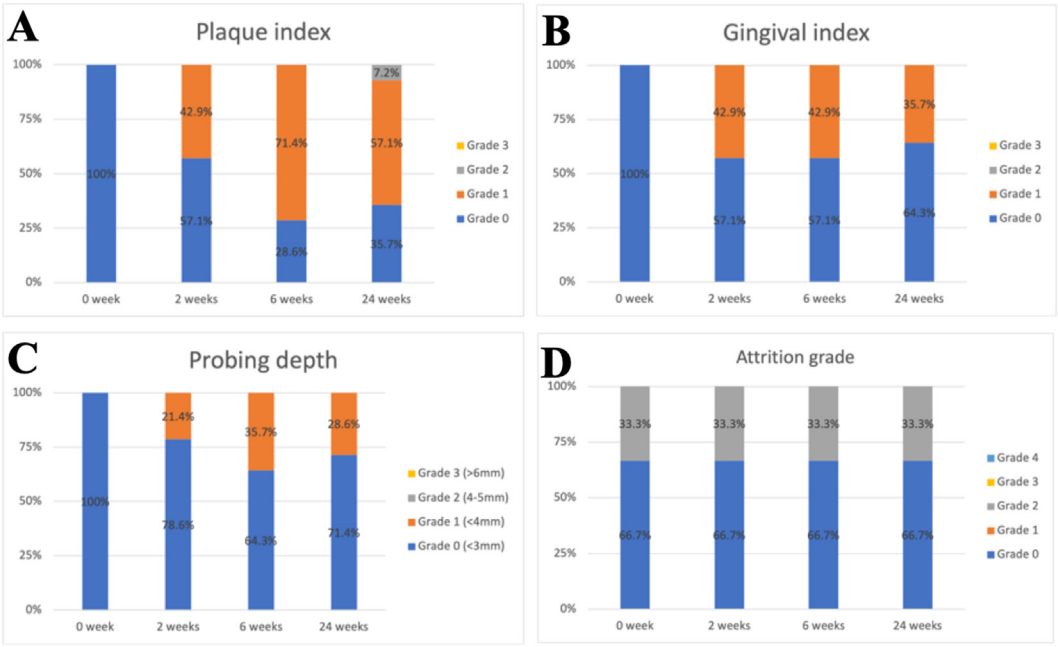

Figure 2 The analytic periodontal parameters of the 3D-printed zirconia crown. (A) Plaque index. (B) Gingival index. (C) Probing depth. (D) Attrition grade.

Table 5 Clinical assessment of plaque index, ginvial index, probing depth, and attrition grade.

	Abutment teeth				
	0	1	2	3	*P*-value
Plaque index					
0 week	14	0	0	0	
2 weeks	8	6	0	0	0.031*
6 weeks	4	10	0	0	0.002*
24 weeks	5	8	1	0	0.004*
Gingival index					
0 week	14	0	0	0	
2 weeks	8	6	0	0	0.031*
6 weeks	8	6	0	0	0.031*
24 weeks	9	5	0	0	0.062
Probing index					
0 week	14	0	0	0	
2 weeks	11	3	0	0	0.050
6 weeks	9	5	0	0	0.125
24 weeks	10	4	0	0	0.125
	Antagonist teeth				
	0	1	2	3	*P*-value
Attrition grade					
0 week	2	0	1	0	1.000
2 weeks	2	0	1	0	1.000
6 weeks	2	0	1	0	1.000
24 weeks	2	0	1	0	1.000

scanned from the patient's mouth in the present study. Digital duplication is more accurate from the direct oral scan method than from the indirect model scan method. It is suggested that better marginal adaptation may be attributed to a deep chamfer margin design, such as knife-edged crowns in the present study.[6]

The preparation of the margin, contour, and emergence profile of the prosthesis can influence the periodontal response to the prosthesis. The rough and irregular surfaces of restorative materials can affect biofilm formation for bacterial colonization. Conventional CAD/CAM zirconia all-ceramic crown restoration is more favorable to the health of periodontal tissues.[21] Successful restorative materials with accurate marginal and internal fit are essential to maintain longevity.[22] As reported, zirconium did not affect soft periodontal tissues or stimulate the protective mechanisms of the periodontium, and ZrC showed less microbial adhesion than the base metal crown.[23,24] In the present study, 3D-printed ZrC showed similar periodontal characteristics.

In the present study, PI and GI were significantly increased after 2 weeks. On the other hand, probing depth did not differ between different time periods. However, this finding was not in line with other previous studies, which found a stable PI score during the whole observation period.[1,4] A patient's unstable PI score may have been due to improper oral hygiene during the observation period. Patient compliance with good hygiene was also essential for ZrC survival.

In the present study, there was one incidence of vertical root fracture in one of the abutment teeth over the course of the 24-week follow-up. A possible explanation for this case might be that the tooth became fragile after receiving root canal therapy, and the 3D ZrC was at the high occlusal pressure posterior region.

The limitations of this pilot study were that the sample size was small, and the observation period was short. It would be more conducive to having more participants, stricter oral hygiene regimes, and a longer follow-up period in future research.

It is concluded that the 3D-printed ZrC showed no detectable adverse effects on the periodontal tissues, and antagonist tooth attrition was invisible. It could serve as an alternative to patients, particularly those with high esthetic expectations.

Declaration of competing interest

All authors have no conflicts of interest relevant to this article.

Acknowledgments

This project was supported by grants from the Chung Shan Medical University Hospital (CS19047) and Taiwan Innovative Biomedical Co.

References

1. Solá-Ruiz MF, Baixauli-López M, Roig-Vanaclocha A, Amengual-Lorenzo Jm Agustín-Panadero R. Prospective study of monolithic zirconia crowns: clinical behavior and survival rate at a 5-year follow-up. *J Prostho Res* 2021;65:284—90.
2. Baig MR, Tan KBC, Nicholls JI. Evaluation of the marginal fit of a zirconia ceramic computer-aided machined (CAM) crown system. *J Prosthet Dent* 2010;104:216—27.
3. Kitaoka A, Akatsuka R, Kato Hiroaki, Yoda N. Clinical evaluation of monolithic zirconia crowns: a short-term pilot report. *Int J Prosthod* 2018;31:124—6.
4. Konstantinidis I, Trikka D, Gaparatos S, Mitsias ME. Clinical outcomes of monolithic zirconia crowns with CAD/CAM technology. a 1-year follow-up prospective clinical study of 65 patients. *Int J Environ Res Publ Health* 2018;15:2523—9.
5. Kunrath MF, Gupta S, Lorusso F, Scarano A, Noumbissi S. Oral tissue interactions and cellular response to zirconia implant-prosthetic components: a critical review. *Materials* 2021;14:2825—34.
6. Li R, Chen H, Wang CY, Sun Y. Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. *J Mech Behav Biomed Mater* 2021;115:104255—69.
7. Tang Z, Zhao X, Wang H, Liu B. Clinical evaluation of monolithic zirconia crowns for posterior teeth restorations. *Medicine* 2019;98:e17385.
8. Sorensen JA. A rationale for comparison of plaque-retaining properties of crown systems. *J Prosthet Dent* 1989;62:264—9.
9. Kashani HG, Khera SC, Gulker IA. The effects of bevel angulation on marginal integrity. *J Am Dent Assoc* 1981;103:882—5.
10. Piccitiello F, Amato M, Leone R, Spagnuolo G, Sorrentino R. In vitro evaluation of the marginal fit and internal adaptation of zirconia and Lithium Disilicate single crowns: micro-CT comparison between different manufacturing procedures. *Open Dent J* 2018;12:160—72.
11. Meirowitz A, Bitterman Y, Levy S, Mijiritsky E, Dolev E. An in vitro evaluation of marginal fitzirconia crowns fabricated by

a CAD-CAM dental laboratory and a milling center. *BMC Oral Health* 2019;19:103—9.
12. Lernera Henriette, Nagya Katalin, Prannob Nicola, Zaronec Fernando, Admakind Oleg. Francesco Mangano Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: an in vitro study. *J Dent* 2021;113:103792—807.
13. Revilla-León M, Methani MM, Morton D, Zandinejad A. Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. *J Prosthet Dent* 2020;124:730—7.
14. Galante R, Figueiredo-Pina CG, Serro AP. Additive manufacturing of ceramics for dental applications: a review. *Dent Mater* 2019;35:825—46.
15. Schweiger J, Edelhoff D, Güth JF. 3D printing in digital prosthetic dentistry: an overview of recent developments in additive manufacturing. *J Clin Med* 2021;10:2010—21.
16. Methani MM, Revilla-Leon M, Zandinejad A. The potential of additive manufacturing technologies and their processing parameters for the fabrication of all-ceramic crowns: a review. *J Esthetic Restor Dent* 2020;32:182—92.
17. Li R, Chen H, Wang Y, Zhou Y, Shen Z, Sun Y. Three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition. *J Prosthodont Res* 2020;64:478—84.
18. Schriwer C, Skjold A, Gjerdet NR, Øilo M. Monolithic zirconia dental crowns. Internal fit, margin quality, fracture mode and load at fracture. *Dent Mater* 2017;33:1012—20.
19. Schmitz JH, Beani M. Effect of different cement types on monolithic lithium disilicate complete crowns with feather-edge preparation design in the posterior region. *J Prosthet Dent* 2015;115:678—83.
20. Mangano FG, Admakin O, Bonacina M, Lemer H, Rutkunas V, Mangano C. Trueness of 12 intraoral scanners in the full-arch implant impression: a comparative in vitro study. *BMC Oral Health* 2020;20:1—21.
21. Shang LJ, Wu Y, Xu YJ. Effect of the CAD/CAM zirconia all-ceramic crown restoration on periodontal tissue. *J Clin Rehabilitative Tissue Eng Res* 2014;18:4804—9.
22. Heboyan AG, Marya A, Syed AUIY, et al. Marginal and internal fit of fixed prosthodontic constructions:a literature review. *Int J Dent Res Rev* 2019;2:19—25.
23. Zarone F, Di Mauro MI, Spagnuolo G, Gherlone E, Sorrentino R. Fourteen-year evaluation of posterior zirconia-based three-unit fixed dental prostheses: a prospective clinical study of all ceramic prosthesis. *J Dent* 2020;101:103419—30.
24. Nakamura K, Kanno T, Milleding P, Ortengren U. Zirconia as a dental implant abutment material: a systematic review. *Int J Prosthodont* 2010;23:299—309.