Journal of Dentistry 132 (2023) 104503

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Digital evaluation of the effect of nanosilica-lithium spray coating on the internal and marginal fit of high translucent zirconia crowns

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A R T I C L E I N F O

Keywords:
Zirconia
Silica coating
Surface treatment
Fit
Adaptation

A B S T R A C T

Objectives: To evaluate the effect of a nanosilica–lithium spray coating on the internal and marginal fit of high translucent zirconia crowns using a digital evaluation method.

Methods: A three-dimensional analysis model of a zirconia abutment was digitally scanned using a dental scanner, and 30 monolithic high translucent zirconia crowns were designed and fabricated. They were divided into groups ($n = 10$) according to the surface treatment method: (1) no treatment: as-sintered zirconia; (2) airborne-particle abrasion with 50 µm Al_2O_3 particles; and (3) nanosilica–lithium spray coating. Three-dimensional data for the abutment, crown, and crown seated on the abutment were obtained using a dental scanner. The three-dimensional seated fit between the crown and abutment was reconstructed using registration technology, and a three-dimensional (3D) deviation analysis was used to evaluate the effect of different modification methods on the internal and marginal fit of the crowns using root mean square (RMS) values.

Results: The 3D deviation analysis of all groups conformed to a normal distribution ($P > 0.05$), and the variance was homogeneous ($P > 0.05$). The different surface treatments had no significant effect on the RMS values in the occlusal, axial, and marginal regions of the high translucent zirconia crowns ($P > 0.05$).

Conclusions: Nanosilica-lithium spray coating for the modification of as-sintered zirconia is clinically feasible and does not affect the internal or marginal fit of high translucent zirconia crowns.

Clinical significance: Nanosilica–lithium spray coating does not affect the adaptation of zirconia crowns and is a clinically feasible surface treatment method for zirconia. It is unnecessary to add the setting values of the internal and marginal fit when fabricating nanosilica–lithium-sprayed zirconia crowns.

1. Introduction

High translucent zirconia, a material with both mechanical strength and esthetic properties [1], can be used to make monolithic zirconia restorations. Its clinical application has gradually increased in the esthetic field [2], making high-translucent zirconia restorations one of the most promising alternatives to zirconia-veneer porcelain restorations [1]. Given the dense crystal-phase structure of zirconia, it is not conducive to micromechanical retention, concurrently, it does not contain silica and has no glass-phase composition [3]. Therefore, the durability of bonding to high translucent zirconia is an important issue affecting the clinical application [4,5].

To improve the bonding strength between zirconia and resins, several studies have attempted to perform mechanical surface treatments, chemical modifications, and other methods [6–11]. Surface treatment methods for zirconia ceramics include airborne-particle abrasion [6], acid etching [7], plasma technology [8], laser etching [9], fusion sputtering [10], chemical pretreatment [11], silica coating [6], and combinations of these technologies. Methacryloyloxydecyl dihydrogen phosphate (MDP) is an efficient chemical surface pretreatment for zirconia ceramics [11]. Recently, in order to prepare silica coating on the surface of zirconia, several studies have attempted to use

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https://doi.org/10.1016/j.jdent.2023.104503
Received 12 October 2022; Received in revised form 13 March 2023; Accepted 28 March 2023
Available online 29 March 2023

different methods, including tribochemical silica coating [12], sol-gel silica coating [13], selective infiltration etching [14], internal silica coating [15], high-temperature chemical silica coating [16], chemical vapor deposition [17], and nanosilica coating [18], among others.

Internal silica coatings involve the application of silica-containing ceramic components to the intaglio surface of zirconia-fixed restorations and sintering to improve the bonding of zirconia resins [15,19]. Sawada et al. recently utilized a silica-containing surface conditioner on the surface of pre-sintered zirconia to create a silica coating with a graded structure of zirconia, which did not affect the biaxial flexural strength and crystal phase stability of zirconia [20]. However, controlling the coating thickness and uniformity is challenging [19]. Kitayama et al. reported that this method achieved a coating thickness of 200 μm, and this thickness of the coating may affect the placement and fit of clinical restorations [16]. In addition, the process must be further simplified to increase its clinical applicability.

In particular, a novel silica-lithium spray coating technique was developed to create a glass-ceramic coating with uniform thickness on the surface of zirconia [21,22]. This technology is easy to operate, and the silica coating is stable after ultrasonic cleaning with organic and inorganic solvents [21,22]. Recently, this spray method was reported to improve the bonding strength and durability [22]. Several studies have reported that ceramic coatings that can simulate the bonding performance of conventional glass ceramics [23,24], yield high long-term bond strength [22,24,25]. Ceramic coatings combined with MDP-containing primers effectively increase the durability of bonded zirconia resins [4]. This is a potential alternative method for improving the bonding effect of zirconia [21,22]. However, there is no conclusive evidence that a nanosilica coating influences the seating and adaptation of fixed restorations.

Various methods have been proposed to measure marginal adaptation and internal fit [26–30], each with its own advantages and disadvantages. However, there is no uniform standard [27,28]. Currently, the replica technology is the most commonly used quantitative analysis method [28]. The light body of the polysiloxane impression material was injected into the intaglio surface of the prosthesis to prepare a replica of the gap between the prosthesis and the abutment and then measured with a microscope. However, polysiloxane materials may contain bubbles or defects in the key viewing areas [29]. The measurement sites were limited and some positions may not have been correctly observed. Sectioning may also lead to the deformation of the replica [30].

With improvements in the scanning accuracy of intraoral scanners and the optimization of reverse engineering software, the advantages of using digital methods to analyze the adaptation of crowns have become more obvious in recent years [31]. This study aimed to evaluate the effect of nanosilica-lithium spray coating on the internal and marginal fit of high-translucent zirconia crowns using a digital evaluation method based on a three-dimensional (3D) model of the abutment.

2. Materials and methods

2.1. Abutment model for 3D analysis of adaptation of crowns

The upper right first molar (Type 1 Advance; Nissan Chemical, Tokyo, Japan) was scanned using an intraoral scanner (Trios 4; 3Shape, Copenhagen, Denmark) to acquire 3D data. Based on the data, the abutment was designed using the full crown preparation computer-aided design software, and the digital design method of the crown abutment has been described in detail [32]. The parametric design of full crown abutments included the following four steps: acquisition of clinical crown 3D data, generation of the shoulder, occlusal, and axial surface to be prepared [32]. The abutment design parameters were as follows: occlusal preparation depth, 1.5 mm; degree of convergence, 10°; and a chamfer with a shoulder width of 0.5 mm. Four feature markers suitable for the registration analysis were designed. The markers were designed as triangular prisms, cuboids with rectangular bases, cuboids with square bases, and hexagonal prisms, and were located around the preparation. Finally, a digital model integrating the abutment, base, and markers was obtained and used for the 3D analysis of the adaptation of the crowns. As shown in Fig. 1, the crown abutment model was fabricated from pre-sintered 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) (APW; Aidite, Qinghuangdao, China) using a five-axis computerized numerical control (CNC) cutting device (AMD-500; Aidite) and was fully sintered according to the manufacturer's instructions (Fig. 2).

The 3D model of the zirconia abutment was scanned using an intraoral scanner (Trios 4, 3Shape). The crown was designed using 3Shape design software (Dental System, 3Shape) based on the scanning data of the crown morphology. The virtual cement gap was set to 40 μm. All 30 high translucent zirconia crowns were fabricated by a five-axis CNC cutting device (AMD-500, Aidite) using pre-sintered zirconia (3D Pro, Aidite) containing 4-5 mol% Y_2O_3 and were fully sintered according to the manufacturer's instructions. The zirconia specimens were divided into three equal groups ($n = 10$ each) for surface treatment. The sample size ($n = 10$) was determined from pilot studies with power analysis to provide statistical significance (α=0.05) at 80% power. The surface treatment was as follows: (1) no treatment group (NT), as-sintered high translucent zirconia crown with no surface treatment on the intaglio surface; (2) airborne particle abrasion group (APA), as-sintered high-translucent zirconia crowns with the intaglio surface abraded with 50 μm Al_2O_3 particles (COBRA; Renfert GmbH, Hilzingen, Germany) using a sandblasting machine (Basic classic, Renfert GmbH) under a pressure of 0.2 MPa (perpendicular to the intaglio surface of crowns, the distance was kept at 10 mm and abraded uniformly for 15 s); (3) nanosilica–lithium spraying group (SC), based on the transformation of the surface treatment patent [21], the zirconia treatment spray (SiO_2 55–75%; Li_2O 5–16%; Al_2O_3 1.2–6%; Na_2O 1.4–11%; Nb_2O_5 6–19.8%) was manufactured. Ten fully sintered, high translucent zirconia crowns were sprayed uniformly on intaglio surfaces and then subjected to low-temperature sintering. The nanosilica–lithium zirconia treatment agent was shaken and sprayed evenly on the surface of zirconia in a Z-shape, spraying twice for each specimen (Fig. 3). The agent was sprayed 10 cm away and perpendicular to the intaglio surface of the crowns. After the first spraying, the zirconia crown was rotated 90° clockwise before the second spraying. The crown was then placed in a zirconia sintering furnace (AGT-L, Aidite) under the following conditions: 30% vacuum, 1 min of predrying, initial temperature of 450 °C, and heating rate of 80 °C/min. The temperature was then raised to 890 °C for 1.5 min; thereafter, the crown was naturally cooled to room temperature. Finally, a nanosilica-lithium-sprayed high translucent zirconia crown was obtained. The surface-treated zirconia crowns were ultrasonically cleaned in 75% alcohol and distilled water for 10 min, and then dried for later use.

All 30 crowns were fabricated by the same dental technician (who has more than 10 years of work experience) to minimize errors in the production of crowns and ensure consistency of the samples. The zirconia crowns with different surface treatments were tried individually, and they were all fully seated. The crowns were checked using a dental probe to ensure the absence of visible overhangs or gaps. The crown restoration was examined using an optical stereomicroscope (SZX7; Olympus, Tokyo, Japan) at 10× magnification to ensure visible margins, no obvious defects, and smooth and continuous chamfer shoulders.

2.2. Data acquisition

First, an intraoral scanner (Trios 4, 3Shape) was used to scan the abutment and base parts with the markers of the 3D analysis model of the abutment, which were saved as abutment data (Data A), as shown in Fig. 4. Then, the intaglio and external surfaces of the high translucent zirconia crown were scanned and saved as crown data (data C), as shown in Fig. 5. Finally, a light-body vinyl polysiloxane impression material

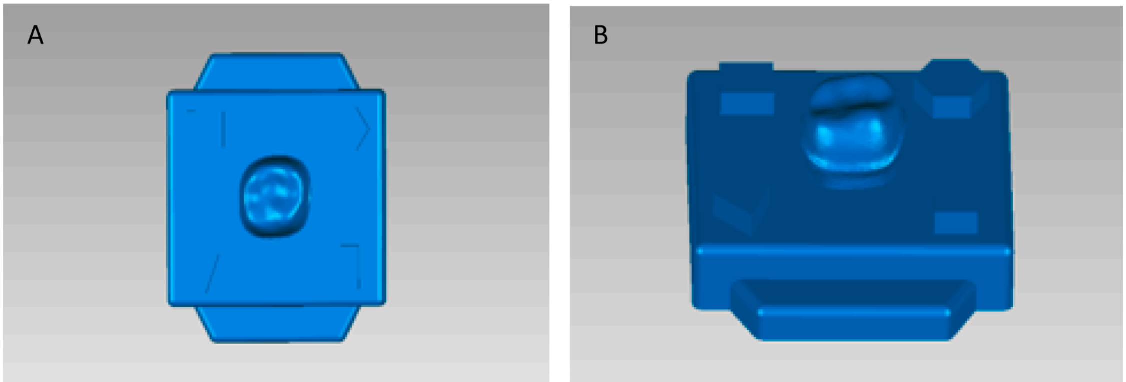

Fig. 1. Digital design of the three-dimensional analysis model of the crown abutment. (A) Vertical view. (B) Lateral view.

Fig. 2. Three-dimensional analysis model of computerized numerical control-cut zirconia crown abutment.

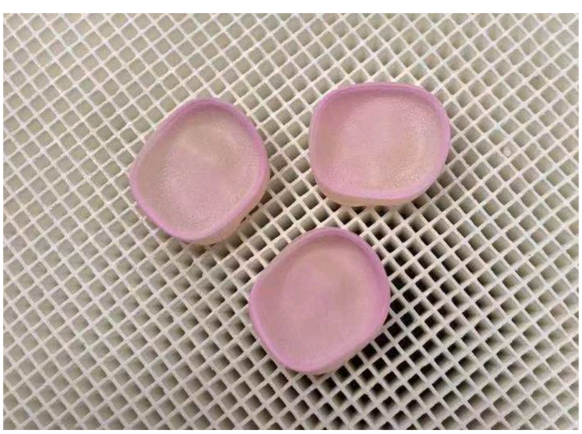

Fig. 3. Nano-silica–lithium coating on the internal surface of zirconia crowns.

(Type 3, Meijiayin; Huge Dental, Shandong, China) was injected into the intaglio surface of the zirconia crown, and the crown was placed on the zirconia abutment. A 500-g weight was used to press vertically on the occlusal surface for 5 min until the vinyl polysiloxane impression was completely polymerized. Excess impression material on the margins of the crowns was removed, the intaglio surface of the zirconia crown was seated, and the base with markers was scanned. This was saved as seated data (data S), as shown in Fig. 6. The measurements were performed to obtain clear scanning results without dusting. The above three datasets were stored in STL format for 3D point cloud data.

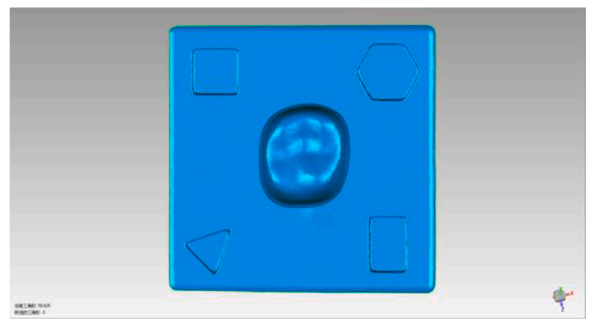

Fig. 4. Abutment data (Data A).

2.3. *Data registration*

The scanned datasets were analyzed using 3D reverse engineering software (Geomagic Studio 2013; 3D Systems, Rock Hill, SC, USA). Based on the characteristics of the tooth model, data registration was performed as follows: The corresponding feature points of Data A and S were selected interactively, and the two data points were preliminarily registered using the registration module. Then, the area where the marker was located was selected as the common area, based on the iterative closest point algorithm calculation, and data A and data S were accurately registered by "Best Fit Alignment," as shown in Fig. 7. Through the same alignment strategy, the relative positions of data C and data S were obtained in the same coordinate system, using "virtual seating."

2.4. *Measurement of internal and marginal fit*

After the relative positions of the crown and abutment were reconstructed using the software (Fig. 8), the intaglio surface of the crown and corresponding external surface of abutment were kept, and the other areas were selected and removed. Then, the Normal of the crown intaglio surface area was fliped and the seated fit was divided into three regions: the occlusal surface region (OR), axial surface region (AR), and marginal region (MR) (Fig. 9), using the "draw curves" module. Finally, the corresponding region was selected for 3D deviation analysis, and the average distance between the two surfaces in this region was obtained, that is, the average value of the seated fit.

2.5. *Statistical analysis*

Root mean square (RMS) values were statistically analyzed using SPSS (version 20.0; IBM, Armonk, NY, USA), and the data were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene tests. A one-way analysis of variance (ANOVA) was used to

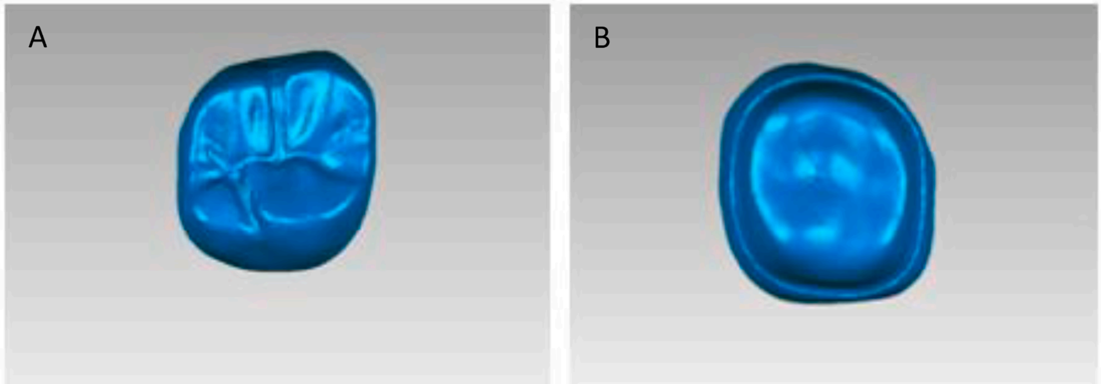

Fig. 5. Crown data (Data C). (A) External surface of crowns. (B) Intaglio surface of crowns.

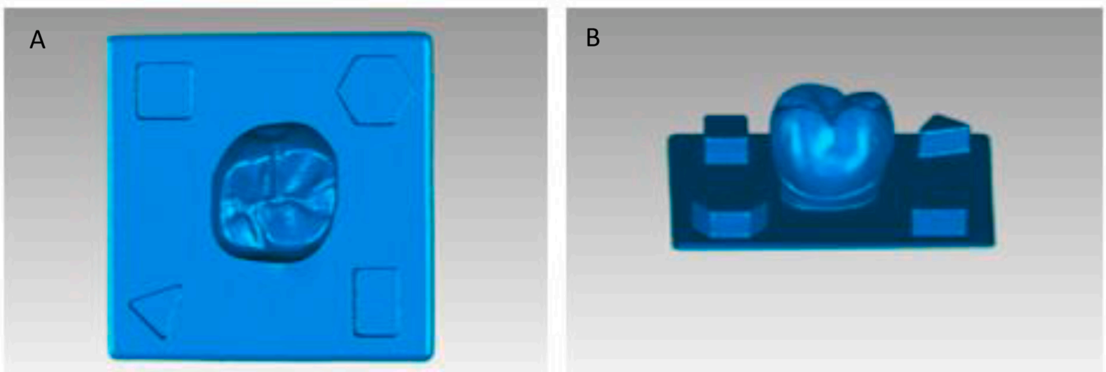

Fig. 6. Data with the crowns seated on three-dimensional analysis model for the abutment (Data S). (A) Vertical view. (B) Lateral view.

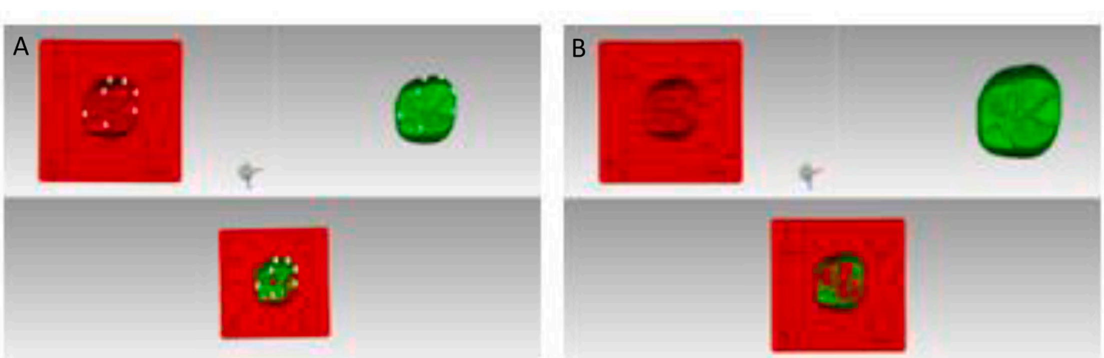

Fig. 7. Registration of Data A and Data S. (A) Preliminary registration by the registration module.
(B) Data A and Data S were finally registered by “Best Fit Alignment”.

evaluate whether the different surface treatment methods influenced the RMS value of the seated fit of the high translucent zirconia crown. The sample size (n = 10) was determined from pilot studies with a power analysis to provide statistical significance (α=0.05) at 80% power. Multiple comparisons of the RMS values of the seated fit among the different surface treatment groups were performed, with statistical significance defined as α=0.05.

3. Results

The high translucent zirconia crowns in the NT, APA, and SC groups were successfully seated without intaglio surface adjustments. The relative positions of the crown and abutment were obtained through registration using a reverse engineering software. The overall and partial enlargements of the reconstructed 3D seated fit are shown in Fig. 10. The seated fit was divided into OR, AR, and MR, as shown in Fig. 11. A 3D deviation analysis was conducted on these three regions, a chromaticity diagram was created (Fig. 12), and the average RMS value of the area was obtained.

The results of the 3D deviation analysis of the fit of zirconia crowns in the NT, APA, and SC groups (n = 10 each) are shown in Table 1. The RMS values in each group showed a normal distribution ($P > 0.05$) with homogeneous variance ($P > 0.05$). There were no significant differences in the RMS values of OR, AR, and MR among the NT, APA, and SC

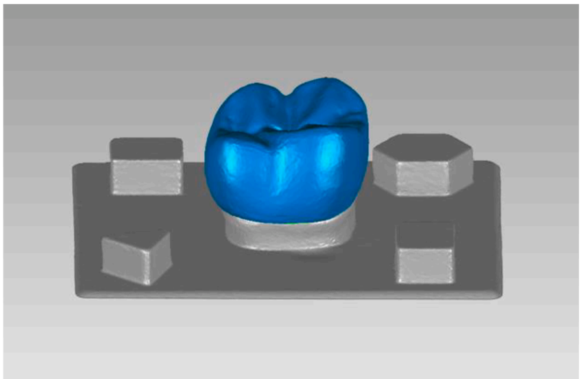

Fig. 8. Reconstructed relative position of the crown and abutment.

groups.

The results of one-way ANOVA of the RMS values of the zirconia crowns subjected to different surface treatments are shown in Table 2. The RMS values in all three regions were not significantly different among the three treatment groups ($P > 0.05$).

4. Discussion

In this study, the effect of nanosilica–lithium spraying on the fit of crowns was quantitatively evaluated, and the results of the 3D deviation analysis are presented as RMS values and color scales. The RMS value reflects the deviation of each position in the two datasets, and the chromaticity diagram visually shows the 3D morphological deviation [33]. When the fixed restoration and abutment data models were analyzed, the results indicated that the smaller the RMS value, the smaller the seating fit between the restoration and abutment [34]. Jang et al. reported the average RMS values of the marginal and internal fit of computer-aided designed/manufactured (CAD/CAM) ceramic crowns

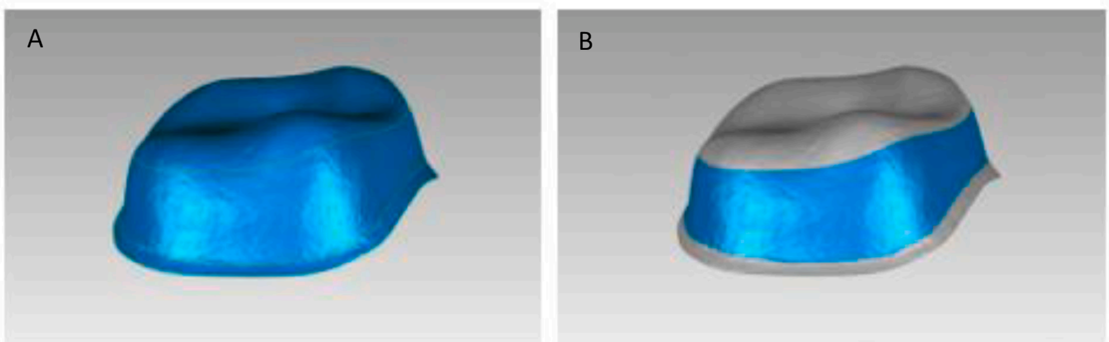

Fig. 9. Drawing curves to divide the three-dimensional seated fit of crowns.
(A) Drawing curves. (B) The three-dimensional seated fit was divided into three regions.

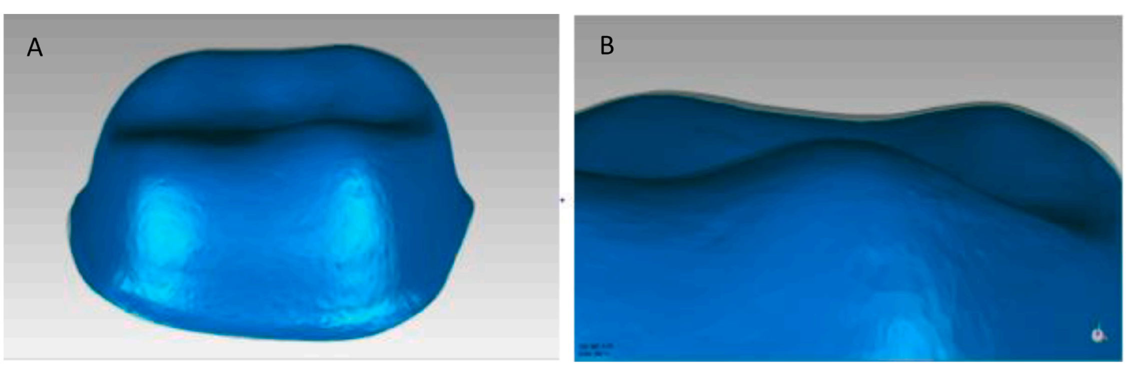

Fig. 10. Reconstructed three-dimensional seated fit of crowns
(A) Overall picture. (B) Partially enlarged picture.

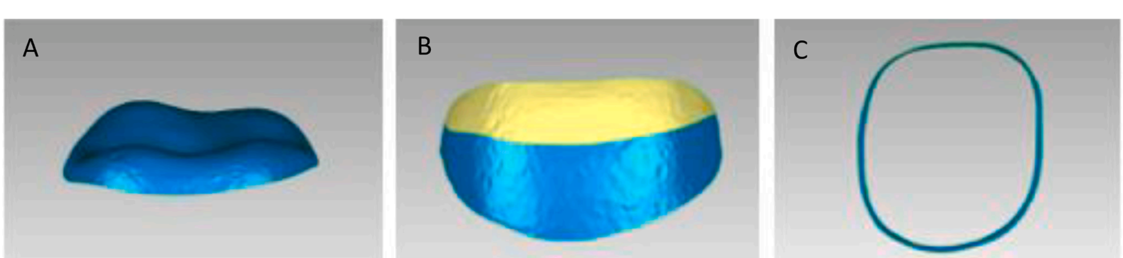

Fig. 11. Three regions of the three-dimensional seated fit.
(A) Occlusal region. (B) Axial region. (C) Marginal region.

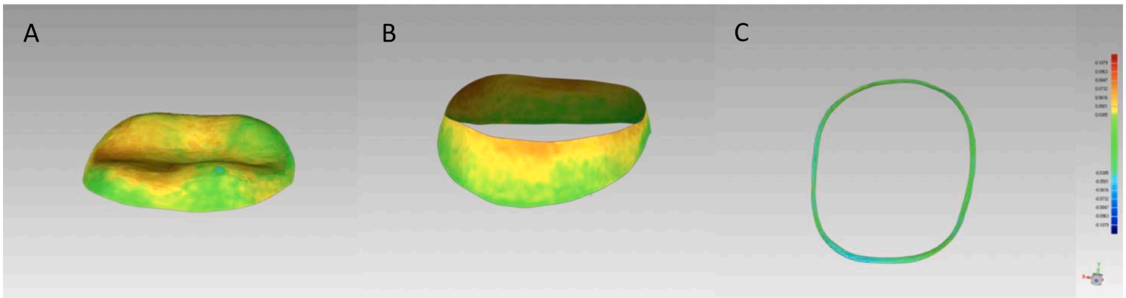

Fig. 12. Color scale diagram of the three-dimensional deviation analysis of crowns. (A) Occlusal region. (B) Axial region. (C) Marginal region.

Table 1
Three-dimensional deviation analysis of the adaptation of zirconia crowns by different surface treatment methods ($n = 10$).

Group	NT (μm)	APA (μm)	SC (μm)
OR	57.35 ± 1.10	58.25 ± 1.30	58.54 ± 1.18
AR	48.88 ± 0.82	49.51 ± 1.01	49.38 ± 1.35
MR	44.46 ± 1.93	45.19 ± 1.13	45.29 ± 1.10

NT, no treatment; APA, airborne particle abrasion; SC, nanosilica-lithium spray; OR, occlusal region; AR, axial region; MR, marginal region. Data are presented as mean ± standard deviation.

Table 2
One-way analysis of variance of root mean square values of zirconia crowns with NT, APA, and SC.

		Sum of squares	*df*	Mean square	F	*P*
OR	Between groups	7.701	2	3.850	2.681	0.087
	Within group	38.774	27	1.436		
	Total	46.475	29			
AR	Between groups	2.213	2	1.106	0.942	0.402
	Within group	31.721	27	1.175		
	Total	33.934	29			
MR	Between groups	4.106	2	2.053	0.992	0.384
	Within group	55.902	27	2.070		
	Total	60.008	29			

NT, no treatment; APA, airborne particle abrasion; SC, nanosilica-lithium spray; OR, occlusal region; AR, axial region; MR, marginal region.

ranged from 30.9 to 52.6 μm [34], which is consistent with the results of this study. In this study, the average RMS value of marginal and internal regions ranged from 58.54 ± 1.18 μm to 44.46 ± 1.93 μm.

The fit of fixed prostheses is usually evaluated using the marginal discrepancy and internal fit [35]. Excessive marginal discrepancies may lead to plaque accumulation and microleakage, affect periodontal health, and increase the risk of secondary caries [36]. Therefore, it is important to clinically evaluate the marginal discrepancy of fixed restorations [35,36]. Studies have shown that the clinically acceptable range for margin discrepancy in CAD/CAM crowns is 30–150 μm [37, 38]. McLean et al. conducted a 5-year clinical study on the adaptation of more than 1000 intra-oral fixed restorations and found that a marginal discrepancy <120 μm was clinically acceptable [39]. Despite the lack of sufficient scientific evidence, marginal discrepancy <120 μm has been considered by most studies as clinically acceptable [26,40,41]. In this study, the RMS values of the MR indicated that the marginal fit was within this range.

Internal fit is also crucial for the long-term stability of restorations [34,37]. Internal fit is related to the retention and fracture resistance of the prosthesis [42]. Excessive internal fit and uneven cement thickness may lead to insufficient retention force, prosthesis falling off, or restoration fracture [43]. However, the maximum value of internal fit for clinically acceptable fixed restorations has not been clear until now [41]. In a previous literature review, the internal fit values for CAD/-CAM restorations ranged from 23 to 230 μm [41]. The review reported that ceramic restorations have internal fit ranging from 29 to 195 μm [37]. In this study, the RMS values of the internal fit of the three groups for the OR and AR were within this range, indicating that they were clinically acceptable.

The distribution and size of the 3D deviation between the abutment and crowns were more vividly represented by the color-scale map, which was useful in the evaluation of crown adaptation. The color-scale diagram shows that the deviation distributions of the entire crown in the OR, AR, and MR were relatively uniform and small, with similar distribution characteristics. This was consistent with the RMS values. Currently, there are few reports on the effect of silica coatings on the adaptation of zirconia crowns [44–46]. Bottino et al. reported that silica coating with a thickness of 12 μm had no effect on the seating and marginal fit of zirconia crowns [45]. The results of the present study are consistent with those of previous studies. Toyama et al. reported a silica-infiltrated layer of approximately 6 μm on the zirconia surface, which was not expected to affect restoration seating and fit [46]. However, they only investigated the effect of silica coating on the flexural strength and crystal-phase structure of zirconia [46]. The effect of silica coating on the internal and marginal fit of zirconia crowns was limited to speculation, and no conclusive evidence was obtained. Contrary to the results of this study, Vanderlei et al. reported that the application of low-melting glass-ceramic powder increased the marginal fit of zirconia crowns but remained within the clinically acceptable range [44]. This may be attributed to the large thickness of the porcelain coating prepared by this method, which affected the seating of the crown and resulted in a significant difference in the marginal fit of the crowns between the porcelain-coated and untreated groups [44]. In the current study, the results of the color scale, average RMS value, and one-way ANOVA showed that the nanosilica–lithium spray coating did not affect the fit of zirconia crowns. These findings support the clinical feasibility of nanosilica-lithium spray coating technology.

The RMS results have good reproducibility and comprehensively reflect the adaptation of the fixed restorations [47]. However, it was difficult to directly compare the RMS values of this experiment with the measured discrepancy data from previous studies because of differences in the measurement methods and principles. Several studies proved the feasibility of digital evaluation methods for the adaptation of crowns and fixed bridge restorations [45–47]. Liang et al. [46] reported that the relative positions of restorations and abutments could be obtained through three optical scans and data registrations. Furthermore, 360-degree visualization was used to measure the marginal discrepancy of the fixed prosthesis, providing more comprehensive measurement data [46]. Li et al. [47] compared the measurement results of the above digital method with those of the replica method, and the results showed no significant difference between the two methods, verifying the reliability of the dental scanner as a digital method for evaluating the fit of the crown [47]. It is important to note that the accuracy of the scan data and the registration technique are critical when assessing the adaptation of fixed restorations using 3D deviation analysis. These factors directly affect the accuracy of the digital design of the crown and that of the 3D deviation analysis of crown adaptation.

Silica-lithium spray coating technology has been proven to increase the wettability of zirconia and effectively improve its bonding strength and durability [22]. As the coating is rich in silica, it can simulate the bonding of conventional glass-ceramics, and its bonding performance is better than that of the conventional sandblasting method when a silane pretreatment agent is used [19]. Moreover, the surface roughness of zirconia was improved through this method without transformation from the tetragonal to monoclinic phase, and this technique did not affect the mechanical strength, surface damage, or microcrack formation [20,22,24]. The modification of densely sintered zirconia via silica–lithium spray coating combined with low-temperature sintering is a potential alternative method for improving the bonding durability between zirconia and resins [21,22].

A limitation of this study is that the measurement process involved many human-computer interaction operations and required personnel with software operation skills. These are the learning curves for most dentists. With the development and application of computer analysis, such as 3D image analysis systems, measurement methods have become increasingly nondestructive, high-resolution, and automatic, and digital 3D deviation analysis methods are expected to be further optimized. Future directions include the development of software and the integration of functional modules to facilitate convenient and swift clinical evaluations of the quality of fixed prostheses.

5. Conclusions

Nanosilica–lithium spraying does not affect the marginal fit or internal fit of high translucent zirconia crowns and is a clinically feasible surface treatment method for zirconia. It is unnecessary to add the setting values of the internal and marginal fit when fabricating nanosilica–lithium-sprayed zirconia crowns.

Funding

This research was funded by the National Key R&D Program of China [52035001], and the Capital Science and Technology Leading Talent Project [Z191100006119022].

CRediT authorship contribution statement

Shanshan Liang: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Fusong Yuan:** Methodology, Software, Formal analysis, Resources, Data curation, Writing – review & editing. **Hu Chen:** Validation, Visualization, Supervision, Project administration, Writing – review & editing. **Yuchun Sun:** Conceptualization, Investigation, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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