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ORIGINAL ARTICLE

Clinical evaluation and quantitative occlusal change analysis of posterior implant-supported all-ceramic crowns: A 3-year randomized controlled clinical trial

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Abstract

Objectives: To compare the survival and complication rates of posterior screw-retained monolithic lithium disilicate (LS_2)/veneered zirconia (ZrO_2) single implant crowns (SICs), as well as analyze the occlusal changes observed during a 3-year follow-up period.

Materials and Methods: Thirty-three patients were included and randomly divided into two groups. The test group consisted of 17 patients who received monolithic-LS_2–SIC, while the control group consisted of 16 patients who received veneered-ZrO_2-SIC. Implant/prosthesis survival rates, technical complications, peri-implant soft tissue conditions, and quantitative occlusal changes of SIC (obtained by the intra-oral scanner and analyzed in reverse software Geomagic Control 2015) were assessed at 1- and 3-year follow-ups. Bone loss and Functional Implant Prosthodontic Score (FIPS) were evaluated at a 3-year follow-up.

Results: After a 3-year follow-up period, one patient dropped out of the follow-up. No implant loss was observed. One crown was fractured, resulting in prosthesis survival rates of 93.75% for the monolithic group and 100% for the veneered group. A technical complication rate of 25% (4/16) was observed in the veneered group ($p = .333$). No significant differences in the marginal bone loss were observed at the 3-year follow-up (0.00 (−0.22, 0.17) mm versus 0.00 (−0.12, 0.12) mm, $p = .956$). The total FIPS scores for the test group were 9.0 (9.0, 9.0), while the control group received scores of 9.0 (8.0, 10.0) ($p = .953$). The changes in mean occlusal clearance were 0.022 ± 0.083 mm for the test and 0.034 ± 0.077 mm for the control group (at 3 years, $p = .497$). The changes in occlusal contact area were $1.075 \pm 2.575\,mm^2$ for the test and $1.676 \pm 2.551\,mm^2$ for the control group (at 3 years, $p = .873$).

Conclusion: After a 3-year follow-up, screw-retained monolithic LS_2 and veneered ZrO_2 SIC demonstrated similar survival rates. The occlusal performance of implant prostheses needs to be closely examined during follow-up, and appropriate occlusal adjustments need to be considered.

KEYWORDS
complications, digital workflow, implant crown, monolithic, occlusal, screw-retained, survival, veneered

1 | INTRODUCTION

Continuous digital systems and materials improvements have revolutionized dentistry, offering alternative pathways to conventional manufacturing processes. This technological advancement brings multiple benefits, not only for dentists and technicians but also for patients seeking efficient and high-quality dental treatment. The indications for all-ceramic restorations have expanded due to digital procedures' improved efficiency and effectiveness (Muhlemann et al., 2018). Currently, the effects of crown material and design (monolithic/micro-veneered/veneered) on the clinical outcomes of single implant crowns (SICs) have recently garnered attention and generated discussions (Abou-Ayash et al., 2017; Rabel et al., 2018). A recent systematic review by Pjetursson et al. (2021) analyzed the survival, failure, and complication rates of monolithic/micro-veneered and conventionally veneered all-ceramic SIC. The findings revealed that both veneered and monolithic SIC had favorable short-term survival and complication rates.

The residual cement excess is a typical biological complication in the treatment of cement-retained implant-supported prosthesis. Recently, the emergency of titanium-based materials has allowed for the effective and extra-oral removal of spilled cement. In addition, bonding the superstructure with the crown can be easily secured onto the implant using screws, allowing for convenient repair (Pamato et al., 2020). The feasibility of utilizing a titanium base in conjunction with a monolithic ceramic crown has been evaluated in several clinical studies, demonstrating similar outcomes in the short to medium term (Guncu et al., 2022; Wolfart et al., 2021). There is insufficient evidence regarding the long-term clinical performance (especially for technical complications and peri-implant soft conditions) of ceramic crowns bonded to titanium bases.

Proper occlusion is essential for the functioning of dental implants and for preventing potential complications, such as implant overloading. The distribution of occlusal contact and the extent of occlusal force are critical indicators for evaluating the function of implant prosthesis (Koyano & Esaki, 2015). Currently, occlusal analysis and evaluation methods can be divided into qualitative and quantitative analyses. Standard tools commonly used for qualitative occlusion analysis in a clinical setting include articulating paper, film, soft wax, silicone rubber, and other occlusal recording materials. The quantitative methods of occlusion analysis reported in the literature mainly included the image processing and measurement of occlusal records (Lepley et al., 2011), T-scan system (CotruTa et al., 2015), and Dental Prescale System (Sondang et al., 2003). All of the occlusal analysis methods mentioned above rely on the detecting medium, the presence of which alters the initial occlusion relationship to some extent (Forrester et al., 2011). Recently, the introduction and improvement of the intraoral scanner (IOS) have made it possible to record the static interocclusal relationship without any detection materials, illustrating occlusal contacts in different colors and offering useful information for reverse engineering software (Lee et al., 2018; Wong et al., 2018), which provides a novel and reliable method for quantitative analysis of occlusal change in restorations (Fraile et al., 2022; Iwauchi et al., 2022).

As there is still a lack of medium- to long-term randomized comparative studies that provide detailed outcomes for different types of veneered and monolithic ceramics (Jokstad et al., 2021), as well as insufficient information regarding the occlusal change of posterior implant-supported all-ceramic crowns, the primary objective of this 3-year follow-up randomized controlled trial (RCT) was to clinically evaluate the survival, and complication rates of monolithic lithium disilicate (LS_2)/veneered zirconia (ZrO_2) SIC. The secondary objective was to quantitatively analyze the occlusal change of SIC for both groups during a 3-year follow-up.

2 | MATERIALS AND METHODS

2.1 | Study participants

The present material comprised the 3-year follow-up data from a previously published RCT (Zhang et al., 2019). The original design was a parallel RCT including 33 patients provided with monolithic LS_2–SICs (test group = 17) and veneered ZrO_2 SICs (control group = 16) as initial restoration. Inclusion criteria encompassed individuals between 18 and 70 years old, in good medical health, with no contraindications for implant treatment, no history of poor oral habits, including smoking or bruxism, and proper treatment compliance. The individuals required single-tooth replacement using screw-retained implant crowns from the specific implant system (CAMLOG® SCREW-LINE, Promote Plus, Camlog Biotechnologies AG) in premolar or molar sites with interproximal and antagonistic contacts. Randomization occurred at the time when patients initially received restoration treatment. They were randomly distributed into two groups using the envelope technique. The different workflow made it impossible to blind clinicians and patients. Therefore, blind procedures are only applied to the assessor during evaluation. Regarding sample size calculation, the present material is the second report from 3-year follow-up data of a previously published RCT (Zhang et al., 2019). The primary objective of the previous study was to compare the clinical adjustment time and quantitative feedback between the complete and hybrid digital workflows. A significant difference in try-in time between the test (7.4 min ± 0.2) and control (10.5 min ± 1.7) groups (Joda & Bragger, 2016) was utilized based on a preliminary assessment to calculate sample size under conditions of $\alpha = 0.05$, $\beta = 0.10$ and statistical power = 0.9. A minimum sample size of 12 implant restorations was required for each group.

This RCT complied with the Helsinki Declaration, which was updated in 2008. The research was officially approved by the local ethical committee (Institutional Review Board of Peking University School and Hospital of Stomatology, Approval Number: PKUSSIRB-201736075) and registered on the Chinese Clinical Trial Registry (Registration number: ChiCTR1800015285; http://www.chictr.org.cn/listbycreater.aspx). The research protocol followed the Helsinki Declaration of 1975, revised in 2000 and 2008, and

patients provided informed consent to participate in the study. This RCT followed the CONSORT 2010 statement.

2.2 | Intervention and follow-up

The enrolled patients received transocclusal screw-retained implant crowns produced either through a chairside or hybrid digital workflow. In total, 17 participants were carried to a chairside digital workflow. Their restorations ($n=17$) were designed and produced using a complete digital CAD/CAM system (CEREC, Sirona Dentsply). A quadrant-like IOS (CEREC Omnicom, Sirona Dentsply) was used to capture the 3D implant position, antagonistic dentition, and bite registration. Following the completion of the design process, the virtual design file was transferred to the milling unit (CEREC MC XL Premium, Sirona Dentsply) for the milling of a monolithic LS_2-crown (IPS e.max CAD, Ivoclar Vivadent). After staining and crystallization (Programmat 700, Ivoclar Vivadent), the monolithic restoration was adhesively luted extra-orally to the prefabricated titanium base (Camlog Titanium base CAD/CAM crown, Camlog, Ivoclar Vivadent). Before bonding, the bonding surface of the titanium base was sandblasted with a maximum of 50 μm of aluminum oxide. A pressure of 2.0 bar is applied to enhance the bonding strength of the interface. Then, the intaglio surface of the crown was etched with 5% hydrofluoric acid and the titanium base was treated with silanated (Monobond Plus, Ivoclar Vivadent). Finally, the crown was cemented extra-orally using Multilink Implant (Ivoclar Vivadent). The remaining 16 participants were fitted with CAD/CAM-fabricated zirconia superstructures (Zenostar, Wieland) with hand-layered ceramic (IPS e.max Ceram, Ivoclar Vivadent) veneering crowns and prefabricated titanium bonding bases (Camlog Titanium base CAD/CAM crown, Camlog, Ivoclar Vivadent) in a hybrid digital workflow. The zirconia inner crown was fabricated by outsourcing the milling and sintering process. The thickness of the veneered ceramic was about 2–2.5 mm. Considering enhancing bonding strength, both the intaglio surface of the zirconia inner crown and the bonding surface of the titanium base were sandblasted with aluminum oxide. Then, the crown was cemented extra-orally as same as monolithic LS_2-crown group. Differently, no process of etching or silylanization agent was needed in the control group. The restorations in both groups were installed onto the implants using a manual torque control ratchet (25–30 N/cm). Clinical adjustments were made using diamond burs and silicone polishers. The screw access was sealed with Teflon and composite.

Patients were recalled for follow-up visits annually. All clinical work steps and follow-up examinations were performed by a single qualified prosthodontist (PD). Implant loss, technical complications, peri-implant soft tissue conditions, such as probing pocket depths (PPD), modified plaque index (mPI), and modified bleeding index (mBI) (Mombelli et al., 1987) were assessed at follow-up visits (Figure 1).

2.3 | Radiographic assessment

Peri-apical radiographs were taken using paralleling technique after prosthetic delivery and at 3-year follow-up. The digital images were assessed using Planmeca Romexis software (Planmeca Dental Imaging Oy). The distance between the implant–titanium base platform and the most coronal level of implant–bone contact will be measured as marginal bone level using implant length as a calibration reference. The distances at the mesial and distal sites were averaged to obtain the final result. Marginal bone loss (MBL) was defined as the difference in the distance between the baseline and follow-up measurements. Each radiographic assessment at baseline and 3-year follow-up were examined twice for the mesial and distal sites by a single trained operator (YZ), with a 2-week interval between the assessments.

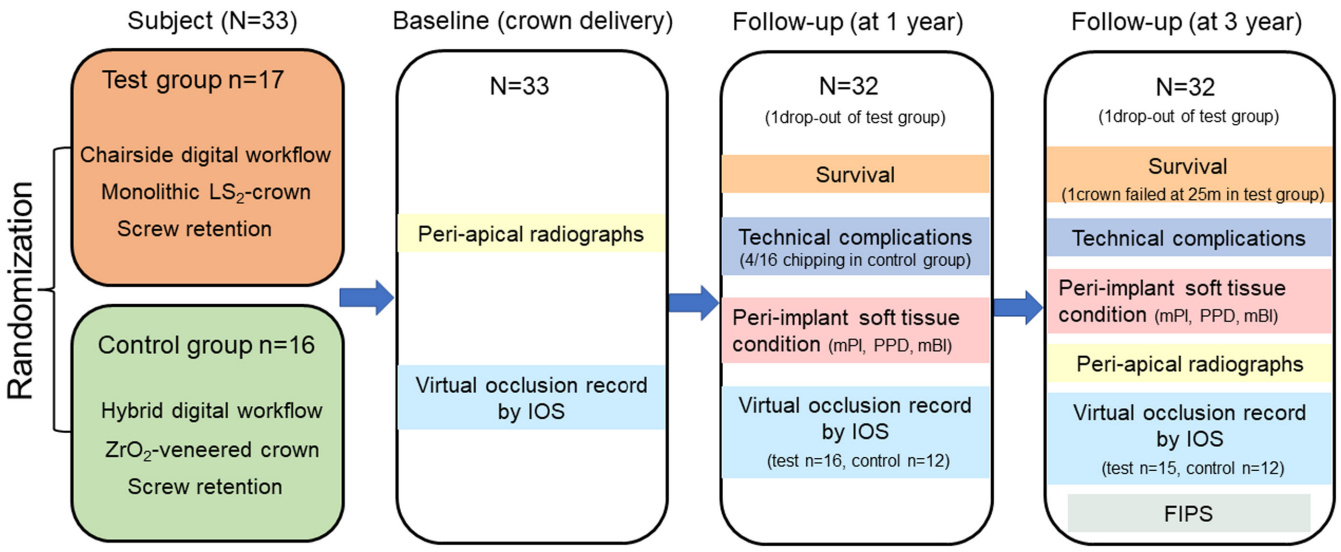

FIGURE 1 Study flowchart visualizing the baseline treatment and follow-up assessment for the test and control groups.

2.4 | Functional Implant Prosthodontic Score (FIPS)

Based on the Functional Implant Prosthodontic Score (FIPS) proposed by Joda et al. (2017), one operator (PD) applied the five defined variables of FIPS for the evaluation of fixed implant restorations at the time of the 3-year follow-up examination. Each variable is scored 2–1-0, as follows:

a. Interproximal: mesial-distal contact areas and the papillary presence of the adjacent dentition; scored as significant discrepancy (0), minor discrepancy (1), or no discrepancy (2).
b. Occlusion: including static and dynamic occlusion; scored significant discrepancy (0), minor discrepancy (1), or no discrepancy (2).
c. Design: including the shape and contour, as well as color and finish of the crown; any chipping or fracture scored as significant discrepancy (0), minor discrepancy (1), or no discrepancy (2).
d. Mucosa: Assessment of the quality and quantity of the peri-implant soft tissue conditions; scored as nonkeratinized/nonattached (0), nonkeratinized/attached (1), or keratinized + attached (2).
e. Bone: the radiographic level of the alveolar crest mesially and distally: scored as loss >1.5 mm (0), loss <1.5 mm (1), and no loss (2).

2.5 | Quantitative occlusal change analysis of SIC

2.5.1 | Virtual occlusion record acquisition

The occlusal relationships of patients, including the restoration and mesial/distal adjacent teeth, were captured using an intraoral scanner (3Shape TRIOS Color, 3Shape). The same trained operator (Y.Z) performed the scans on the day of prosthetic delivery and during the 1- and 3-year follow-up visits. While scanning the buccal occlusal relationship, the patient was instructed to maintain a stable intercuspal position (ICP) with the maxillary and mandibular teeth. The scanning path followed the instructions provided by the manufacturer. The software automatically aligned the previously scanned maxillary and mandibular dentition with the occlusal relationship data upon completion. For patients requiring additional clinical adjustment due to chipping or occlusal overloading during follow-up, the occlusion was scanned and recorded before and after the appropriate treatment, respectively.

2.5.2 | Quantifiable occlusal indicators

The virtual occlusion records obtained on the day of prosthetic delivery and during the follow-up were imported into the reverse engineering software Geomagic Control 2015 (Geomagic 2015, 3D Systems). The records were then trimmed to retain only the occlusal surfaces of the restorations and the antagonist's teeth. The jaw position of the restoration is set as the reference, with the antagonist jaw serving as the test. The test model was selected, and the "Analysis" – "Calculate surface area" function was used to calculate the area of the test model as S_{total}. After a 3D comparison for deviation, a color-coded occlusal contact result was displayed for visual analysis (Figure 2).

a. Mean occlusal clearance of the restoration
   After "3D comparison", the software could automatically calculate the average value d (mm) of the distance between the upper and lower occlusal surfaces, considering the average occlusal clearance between the prosthesis and opposing teeth. The clearances on the day of prosthetic delivery (d_0) and at the 1 – (d_1) and 3-year (d_3) follow-up visits were recorded. The change of mean occlusal clearance (Δd) could be acquired from the subtraction of baseline distance (d_0) and the follow-up one (d_1 or d_3).
b. Occlusal contact area of the restoration
   After performing the "3D comparison", we selected the "Export deviation table" to save the results and opened them using Microsoft Excel 2019 software. The total number of points (N_{total}) and the number of points within 0.1 mm of the deviation ($N_{occlusal}$) in the list were counted. The occlusal contact area of the restoration ($S_{occlusal}$) was calculated according to the formula:

$$S_{occlusal} = S_{total} \times \frac{N_{occlual}}{N_{total}}$$

The occlusal contact areas on the day of prosthetic delivery (S_0) and at the 1 – (S_1) and 3-year (S_3) follow-up visits were recorded and subtracted to obtain the changes in occlusal contact area (ΔS).

2.6 | Statistical analysis

Statistical analysis was conducted using SPSS 26.0 software (BM SPSS) with a significance level set at $p = .05$. Descriptive statistics were conducted to obtain an overview of the data. For data following a normal distribution (change of mean occlusal clearance and occlusal contact area), mean ± standard deviation (Mean ± SD) was used to express. Median (Q25, Q75) was utilized to represent non-normally distributed data. The generalized linear mixed models were used to compare data within and across groups over time (peri-implant soft tissue parameters at 3 years and mean occlusal clearance and occlusal contact area at 1 and 3 years). The results that showed no variation over time have been described in detail. A two-sample *t*-test was performed to compare normal data (baseline and change of occlusal clearance and contact area). Non-parametric Mann–Whitney test was employed to assess the differences in MBL, FIPS, and peri-implant soft tissue parameters between two groups at 1 year. The Chi-squared test was used to compare the proportion of technical complications between the two groups.

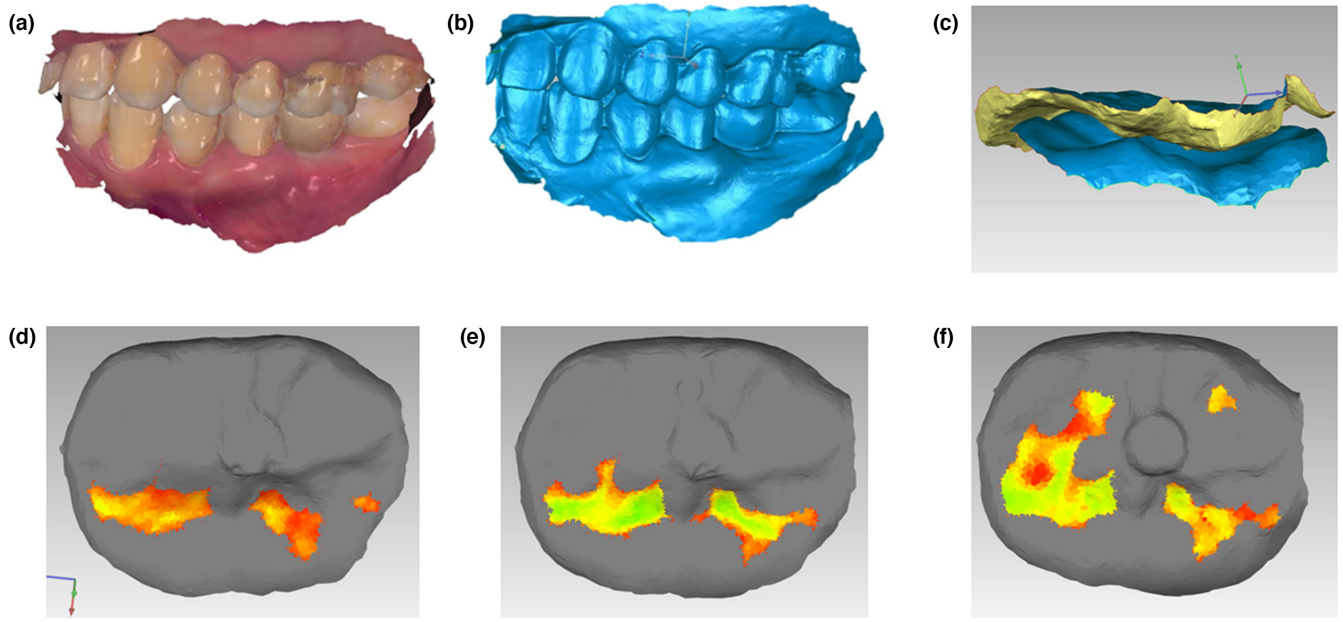

FIGURE 2 Quantitative occlusal change analysis of the prosthesis: (a) virtual maxillary and mandibular dentation with occlusal relationship aligned automatically in the software of IOS. (b) digital occlusal data in the form of standard tessellation language (STL). (c) the occlusal surfaces of the restorations and antagonist's teeth for quantitative analysis. (d) Occlusal contact area in color after "3D comparison" on the day of prosthetic delivery. (e) Occlusal contact area in color after 1 year of prosthetic delivery. The increased area and light green part represent the closer occlusal contact. (f) Occlusal contact area in color after 1 year of prosthetic delivery. In this case, obvious closer occlusal contact area and interference points were observed, and necessary occlusal adjustments were needed.

TABLE 1 Baseline demographic characteristics for included study participants.

Demographic data	Total	Test	Control
Study participants	$n=33$	$n=17$	$n=16$
Mean age	46.8 years	44.4 years	49.4 years
Gender ratio	36% females	24% females	50% females
Implant sites			
Molar	$n=25$	$n=12$	$n=13$
Premolar	$n=8$	$n=5$	$n=3$

3 | RESULTS

3.1 | Patient information

Thirty-three (12 females and 21 males) with a mean age of 46.8 years (range of 25–69 years) were included in the study. Table 1 summarizes the baseline demographic patient data of the original RCT. One patient in the test group was pregnant and declined further follow-up. The remaining 32 patients completed the following 1- and 3-year studies. One restoration in the test group fractured after 25 months of loading and was replaced with a monolith zirconia crown. Therefore, the 3-year results of FIPS and virtual occlusion records were obtained from 31 examinations (15 for the test group and 16 for the control group).

3.2 | Implant survival, technical complications, and peri-implant soft tissue condition

No implant failed in both groups. In the test group, one patient experienced a crown fracture and subsequently suffered crown loss after 25 months of prosthetic loading. At the 1-year follow-up, four patients in the control group experienced minor chipping, addressed through clinical polish. These incidents were deemed acceptable by both the patients and the prosthodontist. No chipping occurred in the test group. Thus, 93.75% (15/16) of the restorations in the test group and 75% (12/16) in the control group were free of any technical complications ($p=.333$).

Examination of peri-implant soft tissue condition at 1- and 3-year follow-up revealed that the mPI increased from 0.25 (0.25, 0.50) to 0.50 (0.25, 0.69) in the test group and remained 0.50 (0.25, 0.50) in the control group. In the test group, the PPD increased from 3.00 (2.25, 4.00) mm to 3.50 (3.00, 4.00) mm, while in the control group, it increased from 3.00 (3.00, 4.00) mm to 3.50 (3.00, 4.00) mm. The mBI remained at 0 (0, 0) for both groups throughout the follow-up. No significant differences were found between the two groups both at 1- and 3-year follow-ups (Table 2).

3.3 | Radiographic assessment

At the 3-year follow-up examination, the mean marginal bone levels in the test and control groups were 0.00 (0.00, 0.44) mm and 0.00 (0.00, 0.12) mm, respectively. During the 3-year observation, the

TABLE 2 Summary of peri-implant soft tissue parameters with median (Q25, Q75).

	1 year	3 years
mPI		
Test group ($n=16$)	0.25 (0.25, 0.50)	0.50 (0.25, 0.69)
Control group ($n=16$)	0.50 (0.25, 0.50)	0.50 (0.25, 0.50)
p-Value	.980[a]	.605[b]
PPD		
Test group ($n=16$)	3.00 (2.25, 4.00) mm	3.50 (3.00, 4.00) mm
Control group ($n=16$)	3.00 (3.00, 4.00) mm	3.50 (3.00, 4.00) mm
p-Value	.453[a]	1.000[b]
mBI		
Test group ($n=16$)	0 (0, 0)	0 (0, 0)
Control group ($n=16$)	0 (0, 0)	0 (0, 0)
p-Value	.346[a]	.754[b]

[a]Non-parametric the Mann–Whitney test was used.
[b]A linear regression mode was used.

mean MBL in the test group and control group were 0.00 (−0.22, 0.17) mm and 0.00 (−0.12, 0.12) mm, respectively. Most of the implants in both groups exhibited MBL within 1 mm. No peri-implantitis was observed during the follow-up in both groups. No significant differences were found in the MBL between the groups at the 3-year follow-up visit ($p=.956$).

3.4 | Functional implant prosthodontic score

At the 3-year follow-up, a skilled prosthodontist (PD) did all FIPS evaluations for participating study patients. There were no significant differences in the total FIPS scores between the test group (9.0, 9.0, 9.0) and the control group (9.0, 8.0, 10.0) ($p=.953$). Table 3 presents the detailed results for each FIPS variable, including medians (minimum–maximum) and mean (SD) values.

3.5 | Quantitative occlusal change analysis

Of the 33 patients, intraoral scanning (IOS) was performed on 32 patients to obtain occlusal data records at the 1-year follow-up, while 31 patients were recorded at the 3-year follow-up. One patient dropped out after 1 year post-delivery, and another experienced a crown fracture after 25 months post-delivery. Four crowns in the control group suffered chipping on the occlusal surface during the 1-year follow-up period and were subsequently excluded due to their inability to pass the "3D comparison" in the software. Therefore, all indicators of occlusal changes of prostheses are based on the occlusal records of 27 patients (15 in the test group and 12 in the control group) after prosthetic delivery and at 1- and 3-year follow-ups.

At the 1-year follow-up, the changes in mean occlusal clearance (Δd) were 0.009 ± 0.052 mm for the test group and 0.007 ± 0.067 mm for the control group. The changes in occlusal contact area (ΔS) were $0.909 \pm 2.842\,mm^2$ for the test group and $0.812 \pm 1.808\,mm^2$ for the control group. At the 3-year follow-up, the changes in mean occlusal clearance (Δd) were 0.022 ± 0.083 mm for the test group and 0.034 ± 0.077 mm for the control group. The changes in occlusal contact area (ΔS) were $1.075 \pm 2.575\,mm^2$ for the test group and $1.676 \pm 2.551\,mm^2$ for the control group. No significant differences were found between the two groups at 1- and 3-year follow-up. Detailed data are shown in Table 4.

4 | DISCUSSION

The current 3-year follow-up of RCT investigated clinical outcomes and quantitative occlusal changes in posterior monolithic LS_2–SIC (test group) and veneered ZrO_2 SIC (control group). As demonstrated, the implant survival rates in both groups were 100%. One crown was lost after 25 months of prosthetic loading in the test group due to ceramic fracture, leading to a 93.75% (15/16) survival rate for monolithic-LS_2-crown compared with a 100% survival rate for veneered-ZrO_2-crown. Our results are consistent with the conclusions reported in a recent systematic review by Pjetursson et al. (2021), showing that the estimated 3-year survival rates were 97.0% (95% CI: 94.0%–98.5%) for monolithic-reinforced glass–ceramic implant-supported single crowns (SC) and 96.3% (95% CI: 93.9%–97.7%) for veneered zirconia SCs. The lost crown occurred to a 45-year-old male patient (FDI i24), who denied experiencing bruxism but habitually consuming nuts. The overload experienced by the crown due to biting nuts was identified as the primary cause of core fracture. Therefore, we opted for a monolithic zirconia design as a substitute for the crown due to its superior fracture strength.

The overall technical complication rates were 6.25% for monolithic-LS_2 SIC and 25% for veneered zirconia SIC after 3-year prosthetic loading. A randomized controlled clinical trial observed 28 screw-retained monolithic LS_2 implant-supported posterior single crowns for comparison. The study reported a 100% survival rate, with mucositis occurring in 14.2% of cases after 12 months and only one incident of screw loosening observed over 24 months (Wolfart et al., 2021). A retrospective study was conducted on 182 implant-supported zirconia single crowns with titanium-base abutments. The study revealed a cumulative implant survival rate of 100% and a restoration survival rate of 98.9%, with a mean follow-up of 32 ± 18 months (24–60 months). The MBL was 0.7 ± 0.5 mm, and no peri-implantitis was diagnosed (Guncu et al., 2022). In addition to the high-chipping rate caused by the veneered design, our results demonstrate that the Ti-base plus ceramic crown may serve as a feasible restoration for SIC.

TABLE 3 Analysis of FIPS with summarized medians, minimum–maximum (Min–Max), mean FIPS scores including standard deviations (SDs) values for each variable after 3 years.

	Test group ($n=15$)		Control group ($n=16$)		
	Median (min–max)	Mean (SD)	Median (min–max)	Mean (SD)	*p*-Value
Interproximal	2 (1–2)	1.8 (0.4)	1 (1–2)	1.8 (0.4)	.164
Occlusion	2 (1–2)	1.8 (0.4)	2 (1–2)	1.7 (0.5)	.482
Design	2 (1–2)	1.7 (0.5)	2 (1–2)	1.8 (0.5)	.917
Mucosa	2 (1–2)	1.7 (0.5)	2 (1–2)	1.8 (0.4)	.362
Bone	2 (2–2)	2 (0)	2 (2–2)	2 (0)	1.000

TABLE 4 Quantitative occlusal change analysis of two groups.

	Baseline	1 year	3 years	Change from baseline to 1 year	Change from baseline to 3 years
Mean occlusal clearance (mean ± SD, mm)					
Test group ($n=15$)	0.813 ± 0.132	0.804 ± 0.124	0.789 ± 0.104	0.009 ± 0.052	0.022 ± 0.083
Control group ($n=12$)	0.818 ± 0.106	0.812 ± 0.089	0.785 ± 0.081	0.007 ± 0.067	0.034 ± 0.077
p-Value	.616[a]	.883[b]	.984[b]	.401[a]	.497[a]
Occlusal contact area (mean ± SD, mm^2)					
Test group ($n=15$)	6.989 ± 2.561	7.898 ± 2.283	8.064 ± 1.975	0.909 ± 2.842	1.075 ± 2.575
Control group ($n=12$)	5.960 ± 2.456	6.772 ± 2.991	7.636 ± 3.806	0.812 ± 1.808	1.676 ± 2.551
p-Value	.872[a]	.291[b]	.497[b]	.268[a]	.873[a]

[a]Two-sample *t*-test was used.

[b]A linear regression mode was used.

Numerous studies have demonstrated significantly higher rates of ceramic chipping in veneered ceramic SCs than in monolithic ceramic SCs (Bösch et al., 2018; Guljé et al., 2019; Pjetursson et al., 2018). Nevertheless, the chipping rate of veneered zirconia (25%, 4/16, FDI i16, i26, i36, i46) in this study was higher than that reported in other studies (Kraus et al., 2019; Spies et al., 2017; Wittneben et al., 2020). A long-term clinical result of 652 SICs by Rammelsberg et al. (2020) revealed that avoiding the use of full-coverage veneers significantly decreased the occurrence of chipping. Our study utilized veneered zirconia SCs comprising a CAD/CAM zirconia inner crown and an occlusal–buccal feldspathic layer. The veneering thickness ranged from 2–2.5 mm, which could result in a primarily elevated chipping rate. Furthermore, all the chipping occurred on the first molar position, and the sites were distributed at the mesial marginal ridge (2/4), nonfunctional cusp (1/4), and distal marginal ridge (1/4). When the fragile-veneered area, such as the marginal ridge and cusp, are subjected to increased bite force (often occurring on the position of the first molar), chipping is more likely to occur with greater frequency and ease. Considering aesthetics and function, it is suggested that partial veneers retaining the functional occlusal area as zirconia may be a better option than conventional full-coverage ones (Zhang et al., 2023).

Innovatively, this study utilized IOS to obtain static interocclusal records of the quadrants. These records were then analyzed using reverse engineering software to quantitatively assess occlusal changes in 27 subjects over a 3-year follow-up period. The advancement in scanner resolution has made it possible to perform three-dimensional (3D) analyses of digital interocclusal registration. Scanning the buccal bite part with the mandibular and maxillary teeth in the ICP records the static interocclusal relationship intraorally. This technique depicts occlusal contacts in different colors and provides quantitative information for further analysis. Recent studies have consistently shown that digital scans of the intermaxillary relationship obtained by IOSs exhibit higher precision than those achieved through conventional methods using a silicone impression material and a gypsum cast (Fraile et al., 2022; Iwauchi et al., 2022; Lee et al., 2018; Stück et al., 2022). Morsy and El Kateb (2022) assessed the precision of digital interocclusal registration compared with conventional registration in an RCT and revealed that quadrant arch interocclusal registration obtained by IOS exhibited significantly higher precision, with a mean value of 18 ± 6 μm compared with 255 ± 136 μm for conventional registration ($p=.0009$). The main error in this approach stems from the buccal bite registration (BBR) method used in the IOS software program (Li et al., 2021).

Although the evidence showed current IOS could accurately capture quadrant static interocclusal records, its accuracy for occlusal change analysis has yet to be verified. The large standard deviations were observed in the present study as the changes in mean occlusal clearance (Δd) and occlusal contact area (ΔS) were calculated by subtracting the baseline (the day of the final prosthesis delivery) from the last follow-up measurement. Considering that the same trained operator conducted IOS, the procedure of dentition alignment was automatically achieved in the 3Shape software.

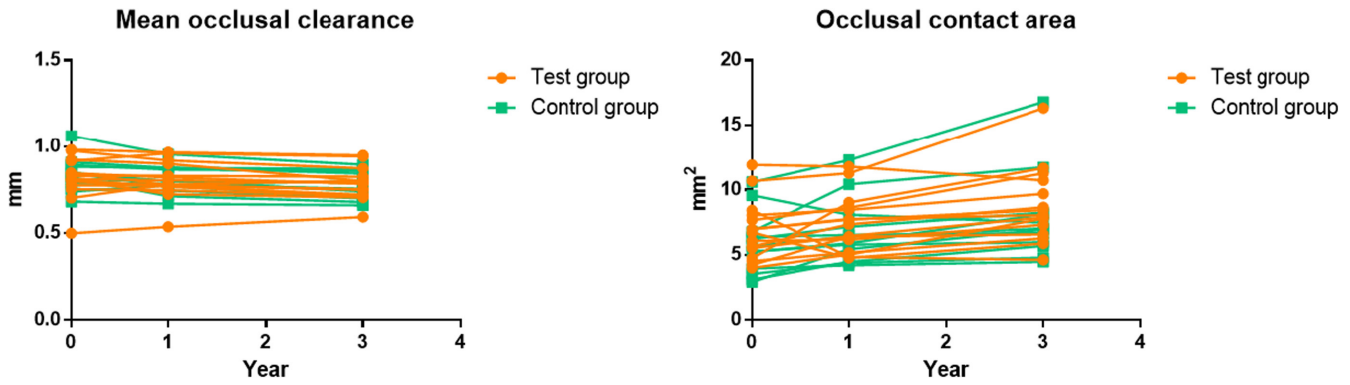

FIGURE 3 Spaghetti graphs plot longitudinal data (Left: mean occlusal clearance; Right: occlusal contact area), showing individual tracings over time for each crown at baseline, 1 year, and 3 years follow-up between test (yellow) and control (green) groups.

The software also automatically implemented the '3D comparison' and calculated distances and areas in the reverse software. The significant standard deviations observed can be attributed to the accuracy of the IOS and the BBR method used in the software program. Our quantitative occlusal change analysis showed that the value of mean occlusal clearance decreased while the occlusal contact area increased during the 3-year follow-up, indicating the intraoral occlusal contact tended to become closer (Figure 3). Due to the lack of periodontal membrane teeth, the occlusion of implant-supported prostheses may change over time. In a prospective 3-year follow-up study, Luo et al. (2019) analyzed changes in occlusal force distribution and contact in posterior partial fixed implant-supported prostheses using T-Scan. The results demonstrated a progressive increase in occlusal force and contact duration of implant prostheses over 3 years. In this study, we observed similar occlusal changes in both monolithic LS_2–SIC and veneered ZrO_2 SIC. However, it is not solely attributable to the abrasion of restorations. The continuous eruption of opposing teeth, mesial tooth movement, and other factors can cause changes in occlusal contacts (Bondevik, 1998; d'Incau et al., 2012; Heij et al., 2006). Interestingly, the occlusal contacts of 3 crowns (FDI i16, i16, i46) in the test group and 1 crown (FDI i46) in the control group tended to decrease in distance and size over time. Among them, two patients (one in the test group and one in the control group) discontinued orthodontic treatment before implant restoration and did not consistently wear their retainers. All antagonists were natural teeth. One possible explanation was that the occlusal contact was slightly altered due to the unstable periodontal conditions in the opposing teeth. The implication is that implant prostheses' occlusal performance should be carefully assessed during follow-up, and any necessary occlusal adjustments should be considered.

The limitations of the present study include small sample size, enrollment from a single center, and a need for long-term follow-up. The same clinician conducted the prosthodontic treatment and subsequent clinical examinations. The accuracy of using IOS for occlusal change analysis has yet to be confirmed. Further support for the pattern of occlusal change in implant prostheses is necessary through clinical studies with more stringent design specifications and extended observation periods.

5 | CONCLUSION

Based on the 3-year follow-up results of this RCT, both screw-retained monolithic LS_2–SIC and veneered ZrO_2 SIC showed comparable survival rates with a small sample size limitation. A technical complication rate of 25% (4/16) was observed on veneered ZrO_2 SIC after 1-year prosthetic loading. The occlusal performance of implant prostheses should be carefully evaluated during follow-up, and appropriate occlusal adjustments should be considered.

AUTHOR CONTRIBUTIONS

Yifan Zhang: Data curation; formal analysis; investigation; visualization; writing–original draft, review & editing. **Donghao Wei:** Methodology; technique support; validation. **Jiehua Tian:** Conceptualization; project administration. **Yijiao Zhao:** Technique support; software. **Ye Lin:** Funding acquisition; investigation; writing–review& editing. **Ping Di:** Concept; resources; investigation; supervision; writing–review& editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest with respect to the authorship and/or publication of this article.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

This study was officially approved by the local ethical committee (Institutional Review Board of Peking University School and Hospital of Stomatology, approval number: PKUSSIRB-201736075); all persons involved had provided their informed consent prior to inclusion in the study.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

This study did not include reproducing material from other sources.

CLINICAL TRIAL REGISTRATION

This study was registered on the Chinese Clinical Trial Registry (Registration number: ChiCTR1800015285; http://www.chictr.org.cn/listbycreater.aspx).

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