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Effect of a novel interocclusal recording method on occlusal accuracy of implant-supported fixed prostheses: A randomized clinical trial

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Abstract

Objectives: To investigate the effect of a novel interocclusal recording method on the occlusal accuracy of implant-supported fixed prostheses for partially dentate patients with distal extension.

Materials and Methods: Twenty patients with two or more adjacent teeth missing in the distal extension and scheduled to receive implant-supported fixed prostheses were enrolled. Two interocclusal recording methods were used: placing polyvinyl siloxane (PVS) on the interocclusal recording caps (test), and placing PVS on healing abutments (control). The intraoral occlusal contacts in maximal intercuspal position (MIP) were compared with those in the mounted casts to calculate sensitivity and positive predictive value (PPV). Then, patients were randomly allocated into two groups to determine which interocclusal record would be used. The implant prostheses' evaluations mainly included occlusal adjustment height, volume, and time, occlusal contact score based on articulating paper examination. Paired-samples *t*-test, Mann–Whitney *U* test, and least squares regression analyzed the statistic differences.

Results: The test method had higher sensitivity to detect intraoral occlusal contacts than the control method ($p = .002$), but similar PPV ($p = .10$). During the prostheses' evaluations, the occlusal adjustment height in the test group was significantly lower than that in the control group [99.4 (53.2, 134.2) vs. 159.0 (82.3, 247.8) μm, $p = .03$], while the occlusal contact score before adjustment was higher ($p = .006$). The groups had similar occlusal adjustment volume and time.

Conclusions: The novel interocclusal recording method for implant-supported fixed prostheses was more accurate and could reduce the occlusal adjustment.

KEYWORDS

bite registration, clinical effectiveness, dental implant therapy, implant-supported dental prosthesis, jaw relation record, occlusion

Clinical trial registration: This study was registered in the Chinese Clinical Trial Registry (ChiCTR2000041154).

1 | INTRODUCTION

Occlusion is a key factor affecting the clinical outcome of implant prostheses (Kim et al., 2005; Koyano & Esaki, 2015). In the absence of the periodontal ligament, osseointegrated implants' active and passive tactile sensibility threshold levels are higher than natural teeth (Song et al., 2022). Consequently, dental implants might experience occlusal overload and the resultant mechanical complications that may eventually compromise their longevity (Sheridan et al., 2016; Stoichkov & Kirov, 2018). Therefore, implant-supported fixed prostheses require high occlusal accuracy.

Accurate recording and transferring of the interocclusal relationship can help achieve good occlusion for prostheses, reducing the need for clinical occlusal adjustment (Ries et al., 2021). There are two commonly used methods for interocclusal recording of implant-supported fixed prostheses in the distal extensions. One is to fabricate record bases and occlusion rims, which is time-consuming and might require an additional visit. The other is to use polyvinyl siloxane (PVS), acrylic resin, wax or other interocclusal recording materials directly on the healing abutments to determine the interocclusal relationship (Park et al., 2017; Tejo et al., 2012). The compression resistance of most interocclusal recording materials was found to decrease with increase in thickness, and the 2 mm thickness material showed the least compression and negligible error (Dua et al., 2007; Nagrath et al., 2014). However, the distance between the healing abutment and the opposite teeth is usually larger than 2 mm, additionally, the simple healing abutment shape lacks supporting and retaining structures. Therefore, the method of using interocclusal recording materials directly on the healing abutments may lack accuracy and stability. Few studies have focused on interocclusal recording methods and investigating the accuracy of transferring interocclusal relationship and clinical occlusion for implant-supported fixed prostheses.

In this study, a series of 3D-printed caps was developed in order to improve the interocclusal recording stability and efficiency of implant-supported fixed prostheses for partially dentate patients with distal extension; and a clinical trial was conducted to investigate their accuracy in transferring interocclusal relationship to working casts and the finished prostheses' occlusion, comparing with a conventional method. The null hypotheses were: (1) the novel and conventional methods have similar occlusal registration accuracy; and (2) the implant prostheses fabricated using the two recording methods are similar in occlusal contacts and the amount and time required for occlusal adjustments.

2 | MATERIALS AND METHODS

2.1 | Design and prefabrication of the interocclusal recording caps

Scanned three-dimensional (3D) data of healing abutment types from different implant systems were imported into a 3D data processing software program (Geomagic Studio 2014; 3D Systems). The bottom of the interocclusal recording caps was cone-shaped and intersected with the top of the healing abutment (Figure 1a,b), and their top was shaped as a hexagonal prism with grooves to facilitate the supporting and retention of interocclusal recording materials. The hexagonal prism height (1–8 mm) and width (4–10 mm) matched the occlusogingival and mesiodistal dimensions in the edentulous area, respectively (Figure 1c,d). The designing data were exported as standard triangulation language (STL) files and 3D-printed using a stereolithography (SLA) 3D printer (Objet30 Pro, Stratasys Ltd., Rehovot, Israel) and photopolymer resin (VeroClear, Stratasys Ltd.). Thus, a series of interocclusal recording caps with various sizes, matching different types of healing abutments were prefabricated (Figure 2). Appropriate caps could be selected according to the prosthetic space, and directly installed, and retained on the corresponding healing abutments by a snap-on connection.

2.2 | Participants

A randomized controlled clinical trial was designed to investigate the accuracy of transferring interocclusal relationships for implant prostheses using a novel recording method. The trial was registered in the Chinese Clinical Trial Registry (ChiCTR2000041154). The study followed the principles of the Declaration of Helsinki and the Good Clinical Practice guidelines. The Biomedical Institutional Review Board of Peking University School of Stomatology approved this study (No. PKUSSIRB-202059176). We consecutively recruited patients with two or more adjacent missing posterior teeth in the distal extension (Kennedy Class I and II) scheduled to receive implant-supported fixed prostheses. Written informed consent was obtained from all participants before their inclusion in the study. All surgical and restorative phases were performed by dentists at the Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China, between December 2020 and December 2021. The Consolidated Standards of Reporting Trials (CONSORT) guidelines were used as the framework of this study.

The inclusion criteria were: aged over 20 years; absence of uncontrolled or untreated periodontal disease; two or more missing adjacent posterior teeth in the distal extension and had received implant placement three months before; with a repeatable and stable intraoral maximal intercuspal position (MIP) in the remaining dentition.

The exclusion criteria were: loss of intercuspal occlusion of the remaining teeth or completely edentulous dentition; had a local or systemic contraindication for implant treatment; smoked ≥10 cigarettes daily; had discomfort in the temporomandibular joint; and had parafunctional habits (clenching and/or bruxism) detected by inquiry and examination.

2.3 | Interocclusal recording

Open-tray impressions were taken at the implant level using a polyether impression material (Impregum Penta, 3M ESPE), so did the

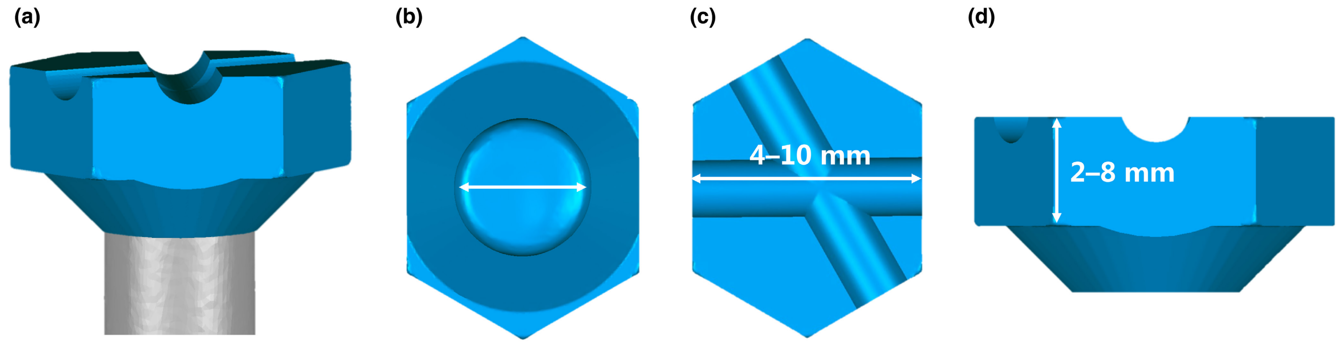

FIGURE 1 A digital model of the interocclusal recording cap. (a) the designed cap intersected with the top of the healing abutment (the gray cylinder below); (b) bottom view; the arrow marks the bottom, which was a negative mold of the healing abutment top; (c) top view; the arrow marks the width range; (d) lateral view; the arrow marks the height range.

FIGURE 2 Prefabricated interocclusal recording caps with various sizes, matching different types of healing abutments.

impressions of the opposing arch. The novel interocclusal recording method for implant-supported fixed prostheses is shown in Figure 3: after screwing the healing abutments, one or more appropriate prefabricated caps were selected according to the prosthetic space and healing abutment type, then installed and retained on the top of the healing abutments. After determining the MIP with PVS (TopasA85; Müller-Omicron GmbH & Co.KG) placed on the caps, the interocclusal record and caps were removed together and reset on healing abutments in the dental casts to transfer the interocclusal relationship. For each participant, two interocclusal records in MIP were acquired by one prosthodontist (Q.D.) using the following two methods, respectively: (i) test method: placing PVS on the interocclusal recording caps; and (ii) control method: placing PVS directly on the healing abutments in the edentulous area with distal extension (Figure 4).

2.4 | Accuracy of transferring MIP to the dental casts

To minimize possible bias, the accuracy of transferring the MIP to the dental casts using the two methods was evaluated in a self-controlled study design. One working cast set per patient was poured using type IV gypsum (Die stone; Heraeus Kulzer Gmbh) and mounted it on a mechanical articulator (PROTARevo 7; KaVo Dental GmbH) in MIP with low-expansion gypsum (ZERO-arti; Dentona AG) using the two interocclusal records, successively. The working casts were mounted and stored with a 3-kg weight placed on the articulator as a standardized force in each case.

After drying the occlusal surface of the remaining teeth, the participants were instructed to clench firmly in MIP on a 30-μm articulating paper (YAMAHACHI) for 3 times to achieve good staining. Intraoral photographs were taken immediately as a reference. The occlusal contacts on working casts were also marked with a 30-μm articulating paper, when a 3-kg weight was placed on the articulator. The casts would be remounted if obvious occlusal deviation was found, such as less than 3 occlusal contacts in the posterior teeth. Diagnostic test was used to detect the difference between the occlusal contacts in oral cavity and in mounted casts as previously described (Delong et al., 2002; Solaberrieta et al., 2015), where false positive (FP), true positive (TP), and false negative (FN) were obtained by counting and comparing the occlusal contact points in the mounted casts and the oral cavity, and

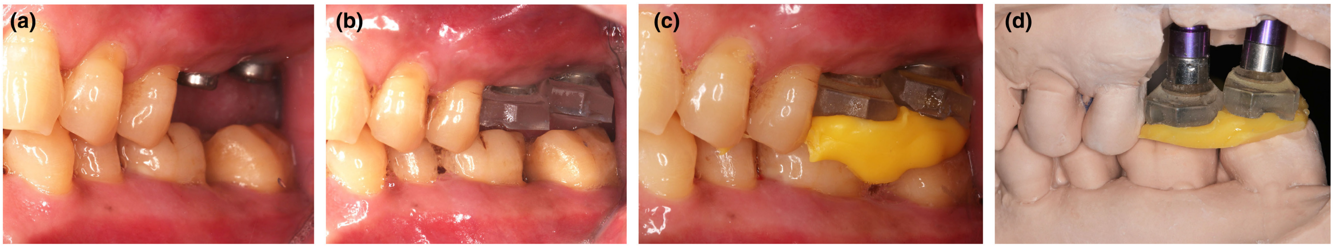

FIGURE 3 The interocclusal recording procedure with the caps. (a) healing abutments were screwed before interocclusal recording; (b) installing the appropriate interocclusal recording caps on the healing abutments; (c) determining the maximum intercuspal position with polyvinyl siloxane (the yellow part); (d) resetting the interocclusal record on a dental cast.

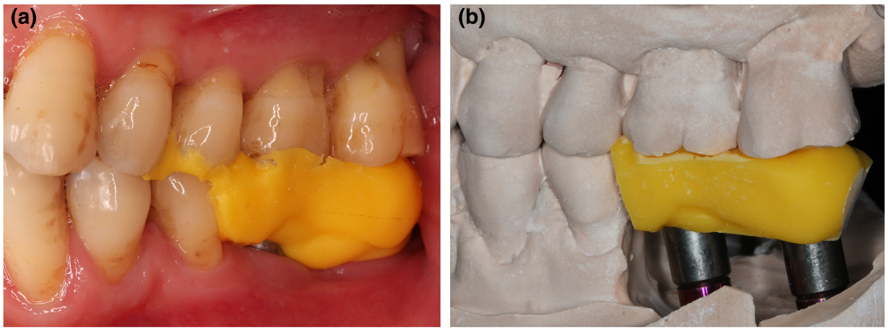

FIGURE 4 Interocclusal recording using the control method. (a) determining the maximum intercuspal position with polyvinyl siloxane (the yellow part) directly placed on the healing abutments; (b). resetting the interocclusal record on a dental cast.

the sensitivity and positive predictive value (PPV) were calculated as follows:

Sensitivity: the proportion of true occlusal contact points that are correctly identified, indicating the ability in detecting true occlusal contacts.

$$\text{Sensitivity} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

PPV, the probability of occlusal contacts truly existing when the diagnostic test was positive.

$$\text{PPV} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

Intraoral scan (3Shape Trios® Standard-P11, 3Shape A/S, Copenhagen, Denmark) including both jaws and a bite registration was acquired after taking the impression. All mounted cast sets were scanned in a laboratory scanner (3Shape D2000; 3Shape A/S) to obtain a virtual MIP. The intraoral and extraoral scanning data were imported into reverse engineering software (Geomagic Control 2014; 3D Systems). The mean occlusal clearances between the remaining posterior teeth (the left and right side were calculated separately), the implant's mesial adjacent tooth, the contralateral tooth and their opposite teeth were calculated by "3D compare." Then the differences between the occlusal clearance values of extraoral and intraoral scans were calculated as the occlusal clearance differences, and compared between the two interocclusal recording methods.

2.5 | Randomized grouping in clinical evaluation

The participants were randomly allocated into two groups using a computer-generated randomization list, and an envelope technique was used to hide the grouping. A researcher who was not involved in enrolling or treating the patients performed the randomized allocation and unblinding. After unblinding, the working cast set mounted with the randomly assigned interocclusal record (test or control) was transformed to dental lab. The participants, technician, and prosthodontists who involved in enrolling and treating were blinded to the grouping. The prosthodontists who performed the treatments including interocclusal recording and casts mounting were different from the researchers who made the measurements and the technician who made the prostheses.

The sample size calculation was based on a superior assumption. A mean occlusal adjustment height difference of ≥50 μm between the test and control groups was considered clinically significant. To maintain a significance level of 0.025 and power of 80%, with a common standard deviation of 46.0 μm based on pretest results, a minimum of nine patients per group had to be enrolled. We enrolled ten as this study required no follow-up measurements.

2.6 | Clinical evaluation of the implant prostheses

After evaluation of transferring MIP to dental casts, wax patterns of screw-retained implant-supported fixed prostheses were made by one technician (T.P.) in the same mechanical articulator with the working casts mounted with the interocclusal record randomly-allocated as above. Considering the physiologic mobility of natural teeth when occluding (Li et al., 2021; Miura et al., 1998), the implant prostheses' occlusal clearance in working casts was designed to achieve light contact by extracting a 38-μm articulating paper (SHOFU) with light resistance in MIP. The implant prostheses' occlusal contacts in both MIP and eccentric position were detected using a 100-μm articulating paper (BK-51 Blue and BK-52 Red; Dr.

Jean Bausch GmbH) in working casts. The eccentric occlusion was adjusted on the mechanical articulator using mean condylar guidance values (protrusive condylar inclination, 35°; Bennett angle, 15°). The wax pattern was scanned, and the data were sent to a 5-axis milling machine (Zenotec T1; Wieland Dental Technik GmbH & Co. KG). Monolithic zirconia (3 mol% yttria-stabilized tetragonal zirconia polycrystal, 3Y-TZP; Ideal Zirconia; RK) prostheses were milled and sintered following the manufacturer's recommendations. Subsequently, the crown's axial surface was colored and glazed. Pits and fissures in the crown's occlusal surface were colored, while other areas were highly polished. The above procedures were kept consistent in the two groups.

After interproximal and internal fitting, the prosthesis occlusion was evaluated using articulating papers before and after occlusal adjustment. To evaluate the degree of supra- or infra-occlusion on the prosthesis, the occlusal contacts in MIP were checked and marked using 100-μm (BK-52 Red; Bausch) and 30-μm (Yamahachi Dental) articulating papers, respectively. Clinical photographs were taken immediately. A prosthodontist blinded to the grouping scored the occlusal contacts and distribution based on a modified criterion (Hickel et al., 2010; Zhang et al., 2021) (Table 1). The two groups were compared for occlusal evaluation scores of implant prostheses.

The occlusal adjustment was standardized to achieve even and equally strong contacts with the adjacent teeth, evaluated on both a 30-μm and a 100-μm articulating papers during forceful occlusion (Rilo et al., 2008). The premature contacts were interpreted by visual confirmation and by asking the patient for his or her perception of whether the teeth contact evenly or meet on one side first. Two different colored articulating papers (BK-51 Blue and BK-52 Red, Bausch) were used to identify and adjust lateral interference (Okeson, 2019). The occlusal adjustment was completed with a diamond bur, and the adjustment time was recorded. The same prosthodontist performed intraoral scans of the implant prostheses before (BEFORE) and after (AFTER) occlusal adjustment. The scans' STL files were exported to Geomagic Control 2014 and trimmed to remain the prosthesis only. The BEFORE and AFTER scans were superimposed using "best fit alignment" to obtain a color-coded 3D deviation map. The occlusal adjustment height perpendicular to the occlusal plane and occlusal adjustment volume were calculated as shown in Figure 5. The patients were asked to evaluate the prostheses' occlusal comfort after fitting using a 100-mm visual analog scale (VAS).

2.7 | Statistical analysis

As the occlusal adjusted volume and time included adjustments for premature contact and lateral interference, occlusal adjustment height was set as the primary outcome measure. Data were analyzed using IBM SPSS Statistics for Macintosh, Version 20.0 (IBM Corp.). The Shapiro–Wilk test assessed continuous variables for normal distribution. Normally distributed data are presented as mean ± standard deviation; non-normally distributed data are expressed as median (first quartile, third quartile). Paired-samples *t*-test or Mann–Whitney *U* test evaluated the sensitivity, PPV, and occlusal clearance differences between the two interocclusal recording methods.

The independent-samples *t*-test compared the VAS scores of the two patient groups. Other data were measured and analyzed in implant prosthesis units to ensure between-group comparability. Clustered standard errors (CSEs) manipulated the within-patient correlation to make the results more robust as most patients had two or more implant prosthesis units, which were inter-related. Least squares regression and clustering analyzed differences in occlusal contact and distribution scores, lateral interference, and volume, height, and time of occlusal adjustment. Statistical significance was set to $p < .05$.

3 | RESULTS

A series of interocclusal recording caps with various heights and widths were successfully prefabricated, showing good retention

TABLE 1 Evaluation criteria of occlusal contacts and occlusal contact distribution in MIP.[a]

Score	Occlusal contacts	Occlusal contact distribution
4 (Clinically good)	Occlusal contact points on the prostheses and adjacent teeth; equally strong contacts (both 100-μm and 30-μm articulating paper imprints exist on the prostheses and adjacent teeth); no supra- or infra-occlusion.	Good occlusal contact distribution. Occlusal contacts between supporting cusps and opposing fossa or ridge.
3 (Clinically satisfactory)	Occlusal contact points on the prostheses and adjacent teeth; unequally strong contacts (only 100-μm articulating paper imprints exist on the prostheses and adjacent teeth, and 30-μm articulating paper imprints exist only on adjacent teeth, with no imprints on the prostheses).	Individual occlusal contact points are missing or deviated; occlusal contacts on the main supporting cusp are still functional.
2 (Clinically unsatisfactory)	Contact points only on the prostheses (supra-occlusion) as indicated by 30-μm articulating paper.	No occlusal contacts on the supporting cusps; contacts are present on other parts of the occlusal surface.
1 (Clinically poor)	No occlusal contact points on the prostheses (infra-occlusion) as indicated by 100-μm articulating paper.	No occlusal contacts or the distribution is detrimental to the prostheses' stability.

[a]Maximum intercuspal position.

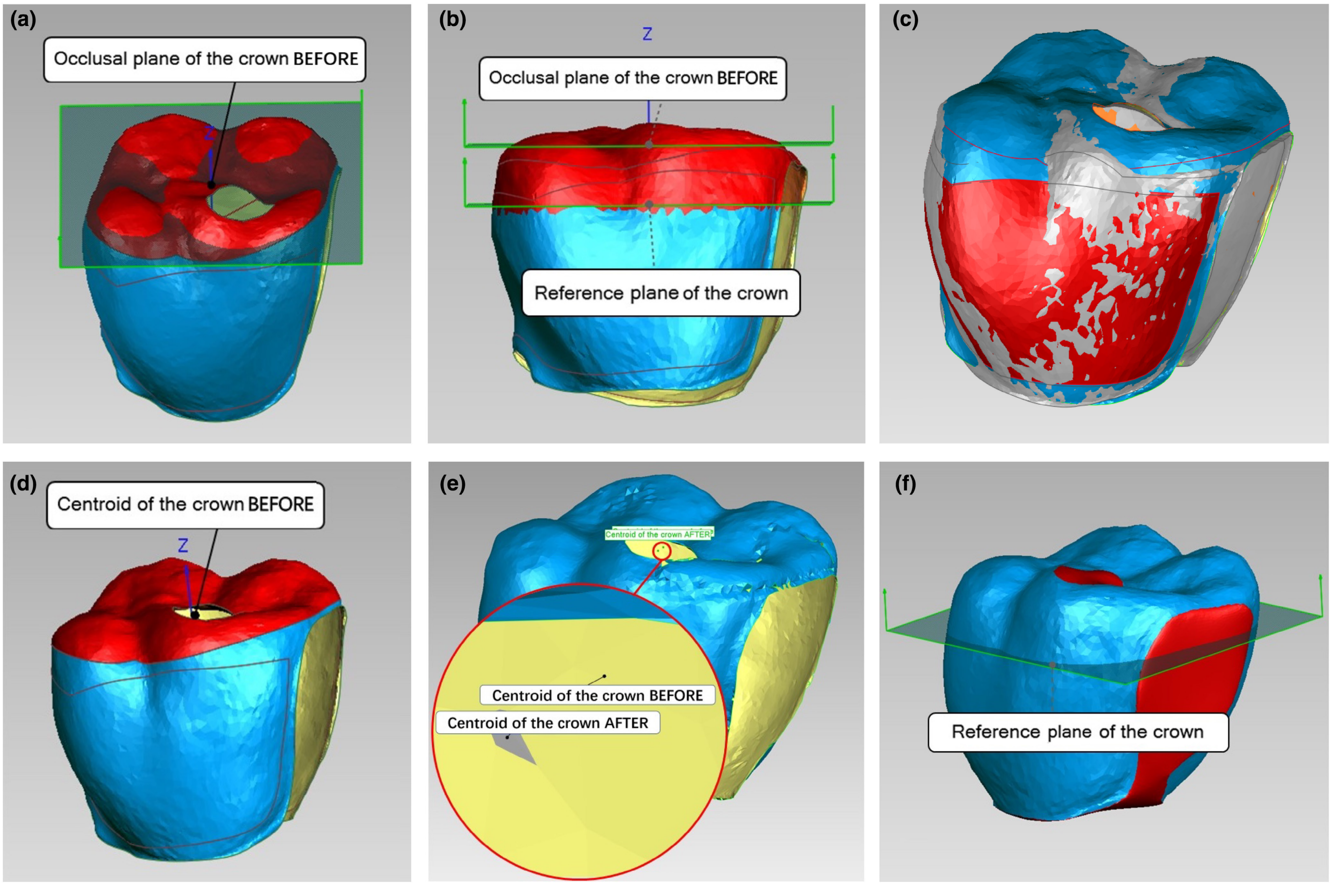

FIGURE 5 Procedure for occlusal adjustment volume and height calculation. (a) fitting the occlusal surface of the crown before occlusal adjustment (BEFORE) into a plane by the "best fit" method; (b) using "plane shift" to build a reference plane parallel to the occlusal plane; (c) superimposing the crowns' data after occlusal adjustment (AFTER) with the BEFORE; (d) establishing the crown centroid; (e) the BEFORE and AFTER crown centroids' distance perpendicular to the reference plane was defined as the occlusal adjustment height; (f) calculating the occlusal adjustment volume as the volume difference between the BEFORE and AFTER data over the reference plane.

TABLE 2 Baseline demographic data in the test and control group.

Demographic data	Total	Test group	Control group
Participants	$n = 20$	$n = 10$	$n = 10$
Age (mean ± standard deviation)	55.3 ± 11.2 years	59.0 ± 10.9 years	52.5 ± 8.6 years
Gender ratio (females/males)	7/13	5/5	2/8
Missing teeth site	49	21	28
Premolars	11	3	8
Molars	38	18	20

and stability on the corresponding healing abutments. This study recruited 20 patients (seven females, 13 males) aged 55.3 ± 11.2 years. Table 2 includes baseline demographic patient data. Forty-six Straumann SLA bone level or soft tissue level implants (Straumann AG, Basel, Switzerland) were inserted. The healing abutments were cylindrical or conical in shape. Forty implant-supported single-unit crowns and three three-unit implant-supported fixed prostheses were fabricated to restore 49 missing teeth, including two first premolars, nine second premolars, 22 first molars, and 16 second molars. In some cases, a missing second molar was not restored. After randomization, the test group included 10 patients with 21 prosthesis units, and the control group included 10 patients with 28 prosthesis units. Most of the cases restored missing posterior teeth in unilateral distal extension. One case in test group and two cases in control group were bilateral distal extension.

3.1 | Accuracy of transferring MIP to the dental casts

The sample size of in casts' evaluation included all the 20 sets of working casts. The test method (0.75 ± 0.15) showed significantly higher sensitivity to identify the intraoral occlusal contacts than the control method (0.66 ± 0.13, p = .002), while both methods had similar PPV (0.77 ± 0.13 vs. 0.74 ± 0.09, p = .10). The differences in the occlusal clearance values between the extraoral and intraoral scans are summarized in Table 3. The mean occlusal clearance difference of the contralateral tooth in the test method was significantly smaller than in the control method (p = .03). Similar mean occlusal clearances differences of the remaining posterior teeth in both sides were noted between two methods, and the differences between left and right posterior teeth were also similar within each method (p > .05).

3.2 | Clinical evaluation of the implant prostheses

3.2.1 | Time, volume, and height of the occlusaladjustment

As the primary outcome measure, the occlusal adjustment height of the test group was 99.8 (47.5, 134.5) μm, significantly lower than that of the control group [159.0 (82.3, 247.8) μm, p = .03]. The median adjusted height difference between the control and test groups was 59.2 μm. The test and control groups had similar occlusal adjustment times [58.0 (34.3, 100.5) s vs. 68.5 (36.7, 112.0) s, p = .48] and volumes [7.93 (4.90, 12.38) mm^3 vs. 7.52 (5.31, 12.69) mm^3, p = .83]. The need for additional porcelain because of infra-occlusion occurred only in one prosthesis in the control group. This prosthesis was excluded from the occlusal adjustment comparisons.

3.2.2 | Lateral interference and the occlusal evaluation scores

The occlusal evaluation scores of the two groups before and after occlusal adjustment are shown in Table 4. Before occlusal adjustment, the occlusal contact score in the test group was significantly higher than that in the control group (p = .006), but both groups had similar occlusal contact distribution scores (p = .23), and the number of prostheses with lateral interference (p = .39). After occlusal adjustment, the groups had similar VAS (p = .32) and occlusal evaluation scores (p = .06 and .16).

4 | DISCUSSION

This study evaluated the effect of a novel interocclusal recording method on the occlusal accuracy of implant-supported fixed prostheses for partially dentate patients with distal extension, using a series of prefabricated interocclusal recording caps. Compared to the conventional method, this method partly improved the accuracy of transferring the MIP to the working casts, reduced the occlusal adjustment needed, and achieved better occlusal fitting. The null hypothesis that the interocclusal registration was equally accurate in both methods was rejected. The other hypothesis should be partially rejected because the groups deferred significantly in the occlusal adjustment height and occlusal contact score before adjustment.

The methods commonly used for interocclusal recording of implant-supported fixed prostheses primarily include using record bases and occlusion rims, and using PVS, wax, or flowable composite resin placed directly on the healing abutments. These methods still have a deficiency in clinical convenience, efficiency, and lack the accuracy and stability needed to transfer the interocclusal relationship to the dental casts (Nagrath et al., 2014; Park et al., 2017). Park et al. (2017) evaluated the accuracies of seven bite registration techniques for implant-fixed prostheses using 3D analysis of reference points. The smallest distance discrepancy was observed when using the Blu-Mousse record on temporary copings (34.78 μm), while the largest discrepancies were noted when the healing abutment held the Aluwax (148.32 μm) or pattern resin (169.76 μm) record. Therefore, using the healing abutment to directly hold the interocclusal recording material lacks accuracy. Temporary copings used for interocclusal recording increase the costs and usually require

TABLE 3 The mean occlusal clearance differences between the extraoral and intraoral scans (μm; median [first quartile, third quartile]).

Interocclusal recording method	Left posterior teeth	Right posterior teeth	Mesial adjacent tooth	Contralateral tooth
Test	50.1 (28.3, 90.5)	35.3 (23.0, 83.1)	38.1 (19.0, 65.5)	31.2 (8.4, 86.5)
Control	74.0 (30.7, 111.6)	33.4 (18.9, 58.0)	29.1 (12.7, 54.4)	48.2 (21.9, 130.5)

TABLE 4 Occlusal evaluation scores before and after occlusal adjustment.

Group	Occlusal adjustment	Occlusal contact score				Occlusal contact distribution score				Sum of prostheses
		1	2	3	4	1	2	3	4	
Test	Before	1	2	15	3	1	5	12	3	21
	After	0	0	2	19	2	4	16	1	21
Control	Before	4	13	10	1	4	7	15	2	28
	After	1	0	7	20	1	0	19	8	28

adjustments to fit into the occlusogingival space in edentulous area. Besides, bite registration aids lacking supporting and retaining structures should be splinted for two or more adjacent posterior implants in the distal extension to enhance the interocclusal record stability, which is a time-consuming procedure difficult to complete in one visit.

Kokubo and Ohkubo (2006) proposed a stainless steel device fixed in the implant with a guide pin but without a screw. The MIP is recorded using auto-polymerizing acrylic resin placed on the device table. However, whether the device could damage the internal implant structure and how accurate and stable are the occlusal records remain unknown. Another study used acrylic resin copings for interocclusal recording on prepared teeth with auto-polymerizing acrylic resin (Stamoulis, 2009). However, this method is only applicable to conventional fixed prostheses.

The advocated interocclusal recording caps used in this study evolved from previous interocclusal recording methods of implant-supported fixed prostheses. The interocclusal recording caps were prefabricated by 3D-printing, and could be transformed into products easily with low costs. The caps were shaped as hexagonal prisms with different widths and heights to fit the prosthetic space, with retaining grooves on the top, thus, it can reduce the distance between healing abutments and antagonists, and improve the supporting and stability of the interocclusal recording materials, which is important for improving the accuracy of interocclusal records. The prefabricated caps with various types could adapt to the corresponding healing abutments of commonly used implant systems, and fit into the prosthetic space, with no need of chair-side adjustment in most cases. It is clinically convenient and effective, avoids a second appointment. The interocclusal recording method using the caps can be commonly used in implant-supported prosthetic treatment, particularly needed in the situation with a large prosthetic space in distal extension.

The adjustment time in this study was shorter than reported for implant-supported crowns produced using digital and conventional workflows (Haghi et al., 2022; Joda et al., 2016). However, the adjustment time is inevitably affected by operating and subjective factors. Digital scanning and dedicated software for superimposition of the STL datasets were shown to efficiently measure and compare occlusal accuracy (Ries et al., 2021; Ury et al., 2020). Zhang et al. (2019) evaluated the clinical adjustment change of implant-supported single crowns by superimposing the STL data before and after adjustment using "3D compare" to detect deviations in the maximum adjustment amount. Their results were $237 \pm 112\,\mu m$ and $485 \pm 195\,\mu m$ when using two digital workflows. However, deviations in the maximum adjustment could result from lateral interference rather than premature contact. The occlusal adjustment time and volumes were similar in the test and control groups in our study, possibly because the adjustments result from both the lateral interference and premature contact that were included, and the two groups had similar lateral interference rates. The occlusal contact distribution score was mainly related to the occlusal design of the technician and the implant position. And the VAS score was mainly determined by subjective factors. Therefore, the above measurements were all set as secondary outcomes.

This study focused on the interocclusal record in MIP, rather than in eccentric position. A new effective method to calculate the occlusal surface height change following occlusal adjustment (occlusal adjustment height) of posterior implant-supported prosthesis was presented in this study, which was caused mainly by supra-occlusion perpendicular to the occlusal plane. Before occlusal adjustment, the test method caused significantly less supra-occlusion in MIP and led to less occlusal adjustment than the control method. A supra-occlusion difference of $\geq 50\,\mu m$ is clinically relevant due to it can be both perceived by patients and detected clinically by using articulating paper (Gonzalez-Gil et al., 2022). And the prosthodontist conducting occlusal adjustment in this study is experienced, but for non-specialists, an occlusal adjustment height difference of $59\,\mu m$ may take longer adjustment time. The occlusal contact score can reflect the degree of occlusal fitting by detecting supra- or infra-occlusion on the prosthesis (Zhang et al., 2021). Before occlusal adjustment, the occlusal contact score of the test group was significantly higher than that of the control, in agreement with the lower occlusal adjustment height required for the test group. These results demonstrated that using the interocclusal recording caps could improve the occlusal fitting of implant prostheses. The improved fitting is especially beneficial for monolithic zirconia (3Y-TZP) prostheses due to their high strength, hardness, and Young's modulus values (Shelar et al., 2021; Zhang & Lawn, 2018), making them difficult to adjust clinically.

To quantitatively evaluate the difference in occlusal contacts, diagnostic test was introduced in the 2000s and be commonly used in previous studies to evaluate the accuracy of transferring interocclusal position by different methods, including occlusion obtained by intraoral or extraoral digital scanning, dental casts mounted in articulator (Abdulateef et al., 2020; Fraile et al., 2018; He et al., 2022; Solaberrieta et al., 2015). And intraoral occlusal contact marks are the common gold standard (as reference) which the newer methods are compared to (Sharma et al., 2013). In this study, the diagnostic test was the interocclusal recording methods, and the reference diagnostics were the intraoral occlusal contacts obtained with the articulating paper. It can indicate the consistency between occlusal contacts in the oral cavity and in the mounted casts. Delong et al. (2002) compared occlusal contacts using virtual casts aligned by various methods and reported sensitivities of 0.76–0.89 and PPVs of 0.67–0.90. Sensitivity >0.7 was considered acceptable for clinical use (Ogawa et al., 2000). The sensitivity of the novel method proposed in this study was clinically acceptable and significantly higher than that of the control method. However, the results should be considered cautiously, as articulating papers might produce false-positive marks (Brizuela-Velasco et al., 2015). Thus, digital occlusal analysis and measurement were performed to assist in the evaluation of occlusal accuracy.

The natural teeth prone to contact more closely than dental casts when occluding in MIP due to their physiologic mobility (Li et al., 2021). Therefore, this study compared the mean occlusal clearance differences between the casts and intraoral scans in the two methods. The less mean occlusal clearance difference indicates the closer occlusal contact in the mounted casts. The mean occlusal clearance difference of the contralateral tooth using the test method was significantly lower than using the control method, suggesting that the test method resulted in closer contact than the control on the contralateral side of the implants. The same working casts were mounted and assessed using both interocclusal recording methods and compared with the same intraoral scan data. And instead of calculating the complete-arch occlusal data, only the mean occlusal clearances in the remaining posterior teeth, the implant's mesial adjacent tooth and the contralateral tooth were calculated. Therefore, the influence of errors generated during the impression process, casts making, and intraoral scanning could be eliminated. However, the results are still affected by mounting errors, extraoral scanning, and occlusal registration errors of the software (Edher et al., 2018; Tomita et al., 2018). The differences between the extraoral and intraoral scans in the mean occlusal clearances ranged from 29.1 to 74.0 μm, indicating a relatively good precision of mounting casts. The occlusal design and fabrication of implant prostheses in working casts mounted on the same mechanical articulator was finished by the same technician who was blinded to the grouping. Therefore, the fabrication procedure was supposed to have little influence on the results.

This study had several limitations, including the small sample size, no long-term follow-up result, and not including eccentric interocclusal records. Our results should be considered within the confounding bias limitations, including the difference in the number and position of the missing teeth between participants, the inevitable error caused by milling and sintering the prostheses, and the technician's operating factors. A further study with a large sample is needed to explore the outcomes based on different numbers and positions of the missing teeth and compare the interocclusal recording cap method with other interocclusal recording methods for implant-supported fixed prostheses.

5 | CONCLUSION

Compared with the conventional method, the novel interocclusal recording method for implant-supported fixed prostheses that uses advocated interocclusal recording caps can improve the accuracy of transferring the MIP to the dental casts, reduce the occlusal adjustment to some extent, and achieve better occlusal fitting of the implant prostheses, with good clinical convenience. Future, standardized mass production of the interocclusal recording caps could further improve the accuracy and reduce the costs to the benefit of patients.

AUTHOR CONTRIBUTIONS

Q.D. conducted the prosthetic treatments, collected and analyzed the data, and led the writing; T.P. fabricated all the implant prostheses and collected the data; Y.T. and M.H. analyzed the 3D data and interpreted the results; S.W. assisted in the design of the interocclusal recording caps. L.Z. directed the study design, revised and approved the manuscript; and J.L. assisted in the prosthetic treatments and collected the data; Y.Z. contributed to conception, revised and approved the manuscript. All authors gave their final approval and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflicts of interest related to this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

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