Clinical Oral Investigations (2024) 28:543
https://doi.org/10.1007/s00784-024-05940-8

RESEARCH

An innovative evaluation method for clinical comparative analysis of occlusal contact regions obtained via intraoral scanning and conventional impression procedures: a clinical trial

Donghao Wei[1] **· Xiaosong Yi**[1] **· Ye Lin**[1] **· Ping Di**[1]

Received: 5 June 2024 / Accepted: 14 September 2024

Abstract

Objectives To compare the occlusal contact regions (OCRs) obtained through an intraoral scanning system and conventional impression procedures via an innovative evaluation method.

Materials and methods Fifteen participants with complete dentitions and stable centric occlusion were included. Three groups were created based on the technique used to obtain the OCRs of quadrant posterior teeth at the maximal intercuspal position: 100 μm articulating paper (Control), an intraoral scanner (Test 1, T1) and conventional impression procedure (Test 2, T2). OCRs of control group were digitized by the intraoral scanner, while all conventional impressions were cast and digitized by an extraoral scanner. The virtual occlusal records of the 2 test groups were obtained by buccal bite registration. The OCRs within 100 μm in the 3 groups were three-dimensionally superimposed based on the tooth surfaces and the area of OCRs (S_C, S_{T1}, S_{T2}) was calculated. The area of overlapping OCRs (S_O) between the test groups and the control group was calculated. In the two test groups, the consistency rate of OCRs (S_O/S_C) and the positive rate of OCRs (S_O/S_T) were calculated and compared. For occlusal tightness evaluation, the mean occlusal clearances (OC) as well as minimum OC between the upper and lower models were calculated and compared.

Results The consistency rate of OCRs was 0.73 ± 0.17 for T1 group and 0.23 ± 0.13 for T2 group ($p < 0.001$). The positive rate of OCRs was 0.67 ± 0.15 for T1 group and 0.56 ± 0.23 for T2 group ($p = 0.143$). The mean OC was 51.32 ± 16.04 μm for T1 group and 68.20 ± 18.15 μm for T2 group ($p = 0.024$). The minimum OC was -61.74 ± 35.38 μm for T1 group and 4.09 ± 27.15 μm for T2 group ($p < 0.001$).

Conclusions For obtaining occlusal records in the quadrant posterior region, the tested intraoral scanning system was more reliable for recording occlusal contact regions and showed higher occlusal tightness compared with conventional impression procedures.

Clinical relevance (1) The evaluation method can assist clinicians in making more objective analysis and comparisons among different sources of virtual occlusal records. (2) Occlusal tightness is a key and indispensable indicator in the evaluation of virtual occlusal records, and it can be quantified by measuring the occlusal clearance utilizing the current evaluation method.

Keywords Interocclusal records · Intraoral scans · Dental impression technique · Virtual occlusion · Quantitative occlusal analysis

Introduction

Accurate occlusal records are crucial for the successful delivery of fixed prostheses according to the desired occlusal scheme. With the development of digital technology, the fabrication process of dental restorations based on digital occlusal records is becoming increasingly widespread. In current clinical practice, there are two main procedures for obtaining digital occlusal records. The first procedure

Donghao Wei and Xiaosong Yi contributed to the work equally and should be regarded as co-first authors

✉ Ping Di
diping@bjmu.edu.cn

[1] Department of Oral Implantology, National Clinical Research Center for Oral Disease & National Engineering Laboratory for Digital and Material Technology of Stomatology & Beijing Key Laboratory of Digital Stomatology, Peking University School and Hospital of Stomatology, 22 Zhongguancun South Avenue, Haidian District, Beijing 100081, China

involves conventional impression taking, plaster cast pouring, mounting on an articulator, and the cast digitizing using extraoral scanners. The second procedure utilizes intraoral scanning technology to directly capture the three-dimensional information of the upper and lower dental arches as well as occlusal registration information simultaneously, which eliminates errors associated with impression making, plaster cast fabrication, and external occlusal registration. Moreover, the intraoral scanning procedure allows for occlusal recording of natural teeth under different occlusal forces, which provides a potential advantage in obtaining accurate impressions for restorations. Several studies [1–4] have revealed that short-span tooth-supported fixed dental prostheses and single-tooth implant crowns manufactured using a fully digital workflow involving intraoral scanning plus computer-assisted design and computer-assisted manufacturing (CAD/CAM) demonstrated higher clinical fitness and less occlusal adjustments compared to those using conventional impression taking and laboratory scanning procedures. These findings suggested that occlusal records obtained through intraoral scans may be more accurate than those obtained through conventional impressions followed by laboratory scans.

Several studies have investigated the accuracy and reliability of intraoral scanning technique for capturing occlusal records in vivo using different evaluation methods, however the relevant results are contradictory. Fraile et al. [5] employed sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) to compare the accuracy of intraoral and extraoral scanning systems in obtaining the occlusal contacts in vivo. The results revealed that the occlusal records obtained with extraoral scanning system were more reliable than those with the intraoral scanning system. While two studies [6, 7] using different evaluation methods showed clinically acceptable accuracy and reliability of intraoral scanning occlusal records, without employing conventional procedure for comparative analysis. Another two studies [8, 9] suggested that intraoral scans may provide more accurate occlusal records than conventional impressions through either average occlusal clearance or occlusal contact area.

The inconsistency of evaluation methods and parameters is one of the possible reasons contributing to the heterogeneity and disparate results among studies. In previous studies, the consistency of occlusal contacts determined by observers or the comparison of the area of occlusal contacts has been commonly used to compare the occlusal records obtained by different procedures [6, 10–13]. However, when comparing the consistency of occlusal contact distribution, it relies on visual observation and manual counting by the observers, and the subjectivity of the observers cannot be ignored in affecting the results [6, 11–13]. While measuring the area of OCRs fails to assess the consistency of occlusal contact distribution [14, 15]. Therefore, it is necessary to improve the existing evaluation methods.

The ideal evaluation method should be able to quantitatively and objectively compare the distribution of occlusal contact points (OCPs) or occlusal contact regions (OCRs) obtained by different techniques in a three-dimensional manner. With the continuous development of color rendering techniques for intraoral scanning images [16] and the increasing application of reverse engineering technology in digital dentistry, it is feasible to digitize OCRs obtained by various techniques and compare their distributions without involving observers [14]. Additionally, new quantifiable objective evaluation indicators should be introduced. Similar to the sensitivity and PPV indicators [6], one important indicator is the consistency rate of OCRs between the tested technique and standard, which demonstrated the consistency of OCR distribution between the groups [14]. The other indicator is the positive rate of OCRs, which evaluate the proportion of true OCRs among the tested OCRs.

Studies on the digital occlusal records reported a phenomenon of interocclusal perforations [6] or intersections [11], which does not occur in vivo or in physical casts. The interocclusal perforations may lead to inaccuracies in restorations and intraoral scanning procedure seems to be more affected by this phenomenon. Therefore, the occlusal clearance (OC) is another indispensable indicator for evaluating digital occlusal records, as it describes the occlusal tightness between the upper and lower teeth.

Therefore, the primary aim of this clinical study was to propose an innovative method for quantitative and objective evaluation of occlusal records obtained through intraoral scanning procedure and conventional procedures (impression taking and laboratory scanning), with the articulating paper marks used as control. This was achieved by evaluating the consistency rate and positive rate of OCRs. The secondary aim was to assess the occlusal tightness by calculating mean OC and minimum OC. The study hypotheses postulated that the intraoral scanning procedure would achieve comparable consistency of OCRs distribution and occlusal tightness to that of the conventional procedure.

Materials and methods

Participant enrollment

The study was a comparative clinical study and fifteen participants were enrolled. The study was conducted in accordance with the 1975 Declaration of Helsinki, as revised in 2000. The study protocol was approved by the local ethics committee (Approval Numbers: PKUSSIRB-202054037).

Participants provided written informed consent after a comprehensive consultation.

Inclusion criteria were as follows:

1) Participants had a complete dental arch in both jaw from the left second molar to the right second molar, with only permanent teeth present.

2) Participants exhibited a stable maximal intercuspal position (MICP), biting stably in a single position during habitual opening and closing movements, without any other jaw position.

3) Participants had normal overbite and overjet, meaning the overbite relationship did not affect the buccal bite scan and registration, and the overjet met the cusp-to-fossa occlusal relationship of the maxillary and mandibular teeth.

4) The occlusal table of the posterior teeth was intact.

5) Participants had a normal degree of mouth opening (37–45 mm).

Exclusion criteria were as follows:

1) Participants with incomplete dentures with missing teeth (excluding the third molars).

2) Participants with unstable occlusal relationships or jaw relations.

3) Participants with malocclusion situations, such as open bite, premature contact, occlusal interference, scissors-bite, or buccal crossbite.

4) Participants with severe tooth abrasion, characterized by the absence of grooves and fossae on the occlusal table.

5) Participants with limited mouth opening, preventing them from undergoing intraoral scanning and photography.

6) Participants who were currently receiving or had previously received orthodontic treatment.

7) Participants with metal restorations or fillings causing abnormal occlusal contact.

8) Participants with loose teeth.

9) Participants with temporomandibular disorders.

Sample size calculation

In this study, the consistency rate of occlusal contact regions (OCRs) was proposed as the primary outcome. To the best of our knowledge, no relevant results were found in previous studies. Therefore, the most commonly used evaluation parameter in previous research, the sensitivity of occlusal contact points, was used to calculate the sample size. The sensitivity results of an in vivo study using the same intraoral scanning system (3Shape Trios) were referred to calculate the sample size [9]. The reported sensitivity values of the intraoral scanner group and the conventional impression group were 0.8382 and 0.9080, respectively. A minimum sample size of 15 cases in each group was calculated according to the paired t-test for non-inferiority formula ($\alpha = 0.05$, $\beta = 0.20$, and an estimated standard deviation of the paired differences of 0.20). The issue of loss to follow-up did not need to be considered in this study design.

Acquisition of occlusal records

All participants underwent three rehearsals of heavy bites at MICP to ensure they understood the instructions clearly. Heavy biting was verified by palpating the evident contraction of the temporalis and masseter muscles by the clinicians. Unilateral posterior teeth were randomly selected as the regions for obtaining occlusal records.

Each participant underwent occlusal record acquisition during a single visit using a single layer of articulating paper (Control), an intraoral scanner (3Shape TRIOS 4, wireless, v. 21.2.0; 3Shape A/S) (Test 1, T1), and conventional impression procedure (Test 2, T2), following a standardized protocol. The occlusal records obtained by the three procedures were completed in a specific sequence as follows:

1) Acquisition of occlusal records via articulating paper.

After the surfaces of the posterior teeth were cleaned and dried, the occlusal records at MICP of the participants' unilateral posterior regions were obtained using a 100 μm single layer articulating paper on each side by the same experienced prosthodontic clinician (Dr. Yi). Each participant kept single heavy bites at MICP to obtain occlusal records.

2) Intraoral scanning procedure for acquiring the upper and lower quadrant dentitions.

After completing the occlusal records using the articulating paper, intraoral scan (3Shape TRIOS 4, wireless, v. 21.2.0; 3Shape A/S) was taken to acquire the quadrant dentition from the canine tooth to the second molar. The tooth surfaces as well as the articulating paper marks were digitized (Fig. 1). The scanning sequence involved capturing the occlusal surfaces, followed by the buccal surfaces and finally the lingual/palatal surfaces.

3) Acquisition of occlusal records at MICP via intraoral scanning procedure.

After removing the articulating paper marks from the occlusal surfaces, participants were instructed to maintain a heavy biting force at MICP. The buccal surfaces of the upper and lower teeth were scanned from the first premolars to the first molars. All intraoral scans were performed by the same experienced operator (Dr. Wei). In the software (3Shape TRIOS 4, wireless, v. 21.2.0; 3Shape A/S), the digital models of the upper and lower dentitions were aligned with the buccal scans automatically, and the aligned digital models were exported as Polygon (PLY) file format (Fig. 2).

4) Conventional procedure.

After intraoral scanning procedure, the conventional impressions of upper and lower dentitions were taken using vinyl polysiloxane material (Silagum MixStar Putty Soft, DMG, Hamburg, Germany) by the same prosthetist (Dr. Yi).

Fig. 1 Intraoral scanning procedure. The occlusal records acquired by articulating paper on the tooth surfaces were thus digitized

The quality of the impressions was checked meticulously. Impressions without deformations, defects and air bubbles on occlusal surfaces were suitable for subsequent casting. After disinfection, all impressions were stored at ambient room temperature for 24 h before being poured with type IV dental stone (Die-stone, Heraeus Kulzer, South Bend, USA) by the same technician. The impression trays were removed from the stone models after a setting time of 40 min. After being stored at ambient room temperature for 24 h, the upper and lower casts were scanned separately using a laboratory scanner (LS 3 scanner, Kavo). Subsequently, the upper and lower models were articulated by hand [17] and mounted on an articulator (SAM 3, GmbH, Germany). The articulated models were then fixed under a load of 400 N using a universal testing machine (Instron, Canton, MA, USA) to simulate heavy bite forces. Buccal scans from the first premolars to the first molars were performed using the intraoral scanner (3Shape TRIOS 4, wireless, v. 21.2.0; 3Shape A/S)

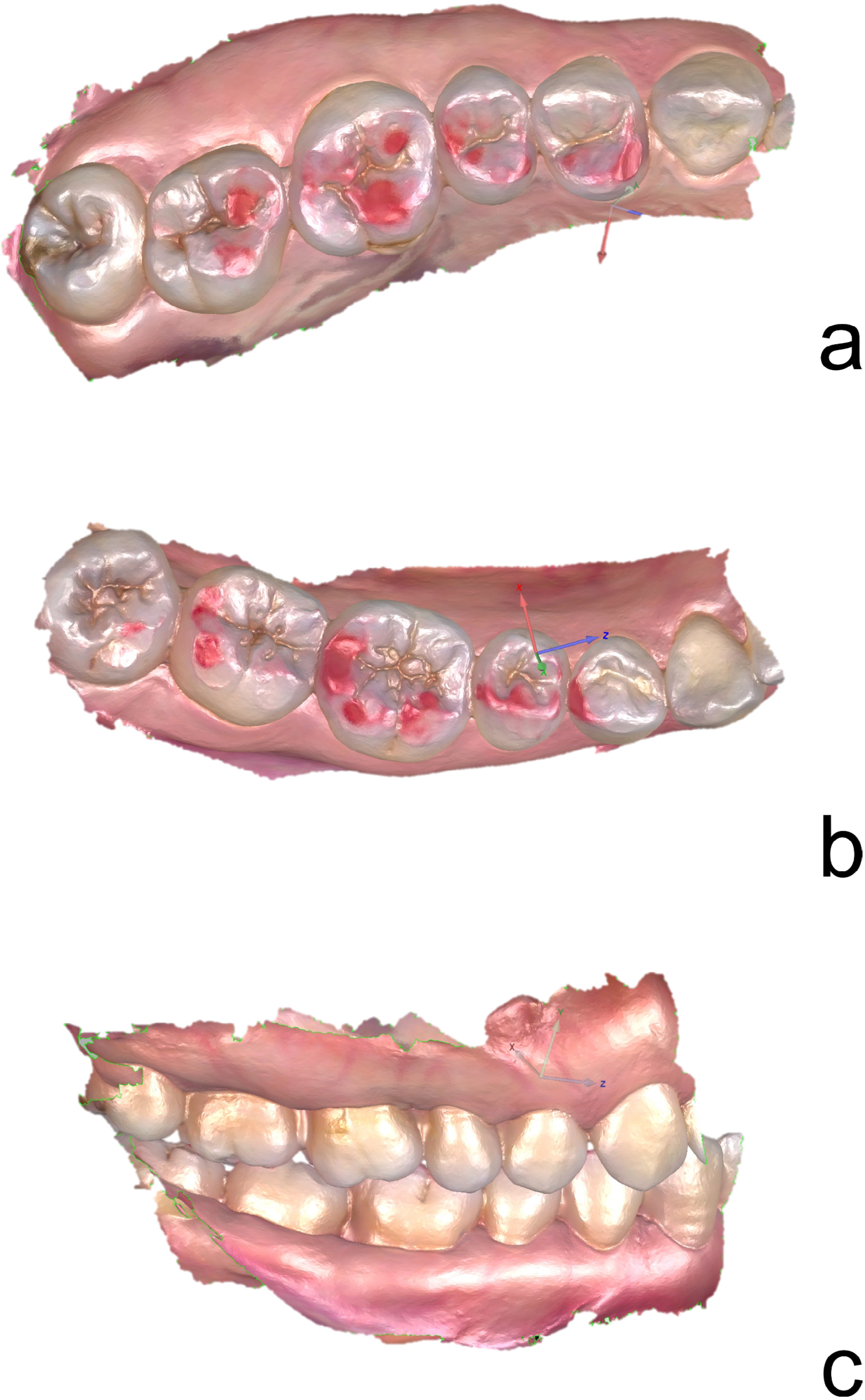

Fig. 2 Digital models obtained from the intraoral scanning procedure. The articulating paper markings on the tooth surfaces were digitized. **a** Upper model, **b** Lower model, **c** Upper and lower models were aligned using buccal bite registration

(Fig. 3). The digitized models of the upper and lower dentitions were aligned with buccal scans automatically in software (Exocad Dental CAD; Exocad, GmbH), and exported as Standard Tessellation Language (STL) format.

Three-dimensional analysis of the occlusal contact regions

All data were imported into reverse engineering software (Geomagic Control 2017, Geomagic, USA) and trimmed to include only the teeth from the first premolars to the second molars (Fig. 4a). In order to visually compare the occlusal records obtained through different techniques for each participant, the digital models obtained by different techniques were superimposed via "best-fit alignment" algorithm based on the tooth surfaces to align the three-dimensional coordinate systems of the digital models (Fig. 4b).

To compare with the occlusal contact regions (OCRs) of control group, the distances within 100 μm between the upper and lower digital models were calculated and presented in the form of a three-dimensional (3D) spectrum in the two test groups. For each pair of digital models, the calculation process and the generation of the spectrum were performed via the following steps:

1) The lower model was set as the Reference Model, while the upper model was set as the Test Model. Distances between the upper and lower models were calculated automatically by the software.

2) Distances within 100 μm were visualized in the 3D spectrum using the "3D Compare" function.

3) The colored regions in the spectrum represented the OCRs within 100 μm. If the distances in any regions were beyond 100 μm, those regions were not displayed in color on the spectrum.

The OCRs on the lower models were selected for analysis and comparison. The digital models were extracted by manually trimming along the borders of OCRs in the control group, while OCRs were automatically extracted by the software in the two test groups (Fig. 4c). Since the three groups of digital models for each participant have been three-dimensionally aligned, the overlapping ratio of OCRs among groups can be visually compared to each other.

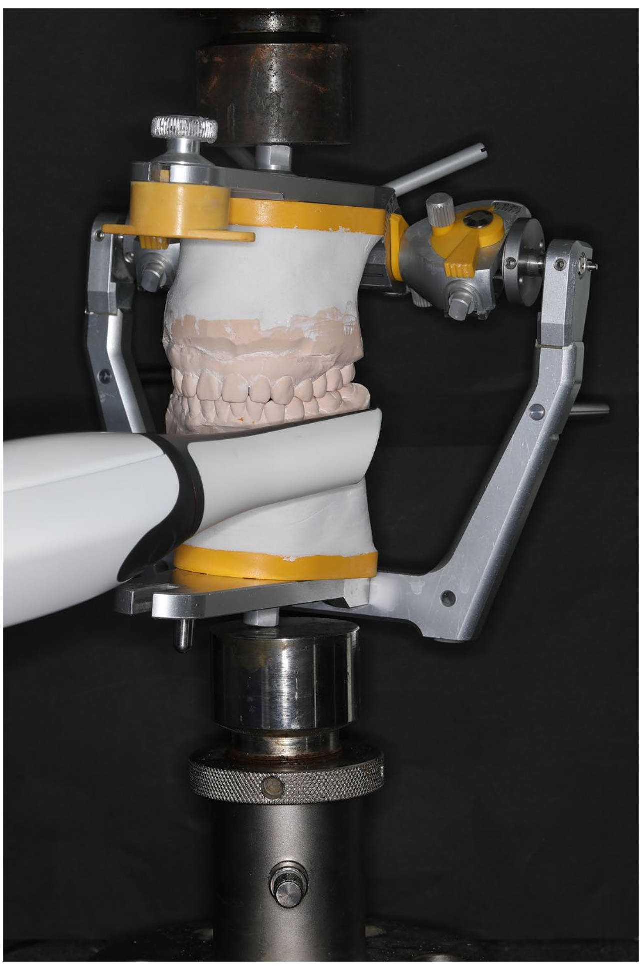

Fig. 3 The articulated upper and lower models were mounted to an articulator and then fixed under a pressure of 400 N. The buccal surfaces of the models were scanned subsequently by the intraoral scanner for interocclusal registration

Outcome measurements

1) The consistency rate and the positive rate of OCRs between the test groups and control group.

The area of OCRs in the three groups (S_C, S_{T1}, S_{T2}) was directly calculated by the software, respectively. Subsequently, the overlapping OCRs between the test groups and control group were visually displayed and the area of the overlapping OCRs (S_O) was calculated via the following process:

In three-dimensional space, to evaluate the overlapping area of two complex surfaces, the directional plane must first be determined, which means identifying the direction from which the observation will be made. In the study, a single defined direction was set as perpendicular to the mandibular occlusal plane, which aligned with clinical practices. On the digitized plaster models, the occlusal plane was determined by the incisal edge of the lower central incisor and the mesiobuccal cusps of the left and right first lower molars (Fig. 5a and b). Since the digital models from intraoral scanning were already aligned with the digitized plaster models, the occlusal plane determined on the digitized plaster models also served as the occlusal plane for the digital models from the intraoral scans.

The OCRs of the control group were set as the Reference Model, and the OCRs of the test group were set as the Test Model. Subsequently, directional deviations were analyzed in "3D Compare" function. The directional deviation

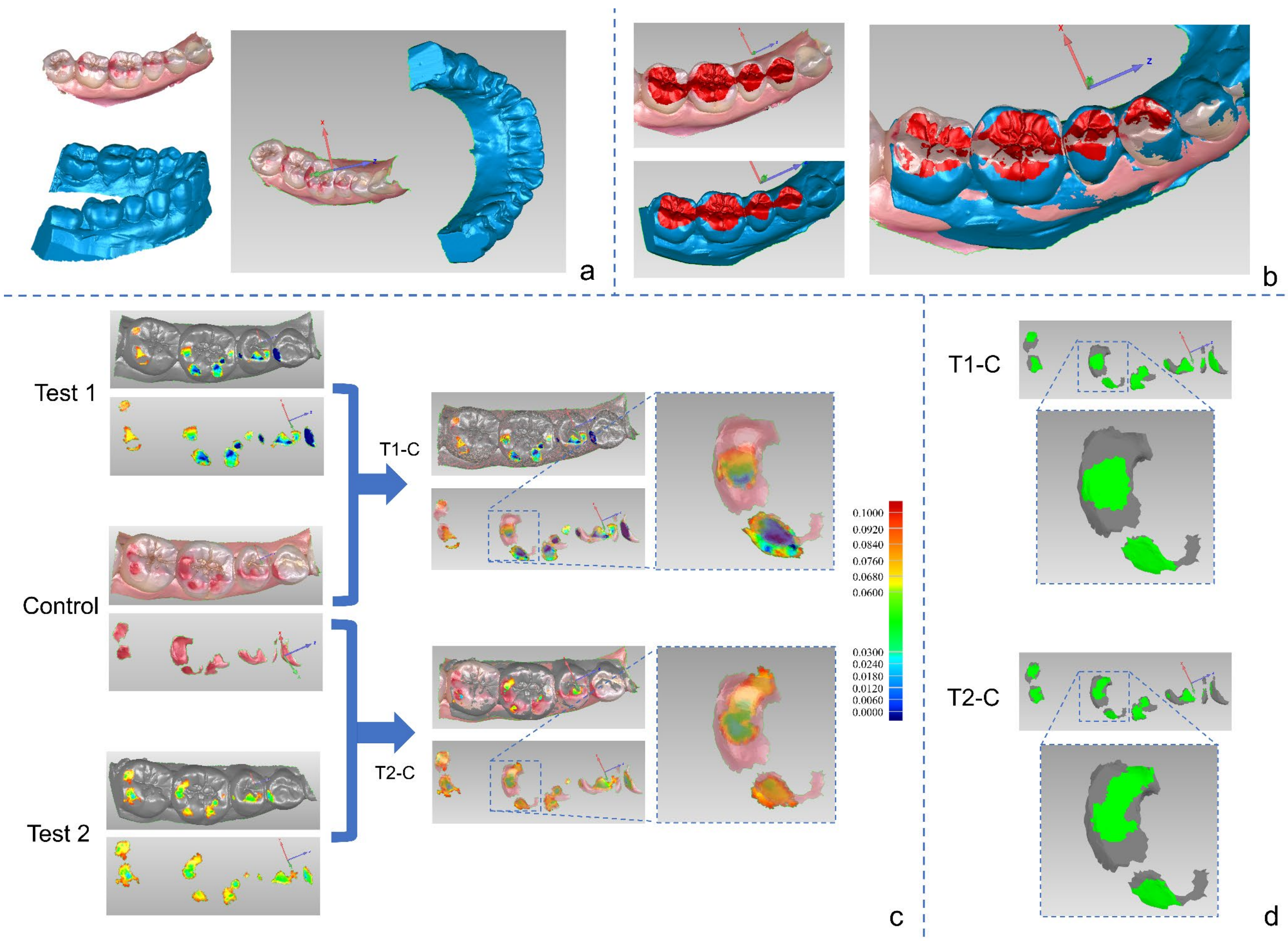

Fig. 4 Three-dimensional superimposition of occlusal contact regions (OCRs) between the control and test groups. **a** The digital models were imported into the reverse engineering software. The occlusal records obtained by articulating paper were visualized on the digital models obtained from intraoral scans. **b** The digital models of control group and test groups were superimposed using "best-fit alignment" based on the tooth surfaces. **c** The distances from 0 to 100 μm between the upper and lower models were calculated and displayed on the spectrum. The three sets of images on the left side, from top to bottom, represented the OCRs of the T1 group, control group, and T2 group, respectively. The two sets of images on the right side, from top to bottom, depicted the three-dimensional comparison of OCRs between the T1 group and control group, as well as between the T2 group and control group. **d** The overlapping OCRs were displayed in green color. The two sets of images, from top to bottom, respectively depicted the overlapping OCRs between the T1 group and control group, and the overlapping OCRs between the T2 group and control group

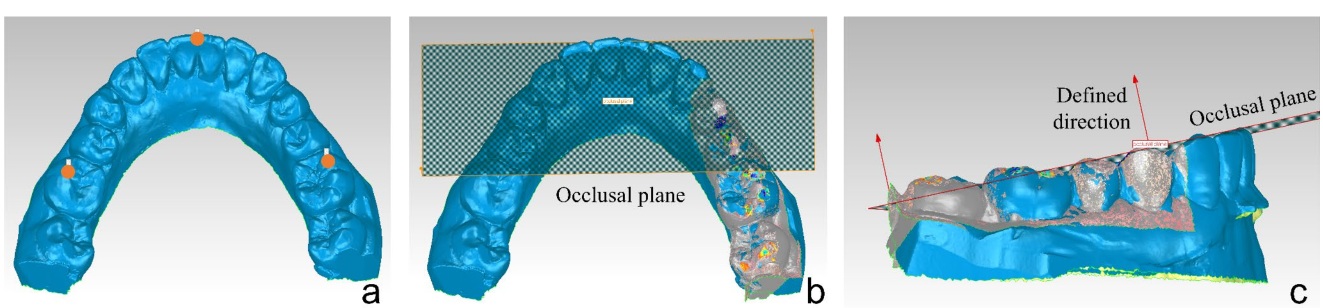

Fig. 5 The determination of the defined direction for the analysis of overlapping regions of OCRs between the test groups and control. **a**, **b** The mandibular occlusal plane was determined by the incisal edge of the lower central incisor and the mesiobuccal cusps of the left and right first lower molars. **c** The defined direction was set as perpendicular to the occlusal plane

analysis function allows reporting the distance from the Test to the Reference in the defined direction (Fig. 5c).

In the 3D spectrum (Fig. 4d), the green regions represented the overlapping regions of the OCRs, while the gray regions represented the non-overlapping area. The overlapping region was trimmed for area calculation (S_O).

The consistency rate of OCRs between the test groups and control group was assessed by calculating S_O/S_C, and the positive rate of OCRs in the test groups was assessed by calculating S_O/S_T.

2) The mean and minimum occlusal clearances (OC) between the upper and lower models.

The OC measures the degree of tightness between the upper and lower models. For each pair of upper and lower models, the distances between the upper and lower occlusal surfaces with 100 µm were calculated. This process was achieved by calculating each STL vertex point of triangle surface in the upper model to the nearest vertex point in the lower model [18, 19] (Fig. 6). All distance values of each paired upper and lower models were exported to Microsoft Excel 2022 (Microsoft, USA) and then arranged in ascending order. The mean and minimum values were calculated.

An overview of the study design and procedures was illustrated in form of a flow chart (Fig. 7).

Statistical analysis

All data were statistically analyzed in the SPSS software (SPSS 23.0, IBM). The Kolmogorov-Smirnov test evaluated continuous variables for normal distribution. Normally distributed data were presented as mean ± standard deviation, while non-normally distributed data were expressed as median (first quartile, third quartile). The differences in the consistency of OCRs, the positive rate of OCRs, the mean OC, and the minimum OC between the two test groups were analyzed using a paired-sample *t*-test. Statistical significance was set to $p < 0.05$.

Results

All data were normally distributed and the results of the descriptive statistical analysis are listed in Table 1.

1) The consistency rate of OCRs was 0.73 ± 0.17 in the T1 group and 0.23 ± 0.13 in the T2 group, with statistically significant differences between the two groups ($p < 0.001$). The positive rate of OCRs was 0.67 ± 0.15 in the T1 group and 0.56 ± 0.23 in the T2 group, with no statistically significant differences between the two groups ($p = 0.143$).

2) The mean OC values were 51.32 ± 16.04 µm for T1 group and 68.20 ± 18.15 µm for T2 group, with statistically significant differences between the two groups ($p = 0.024$). The minimum OC values were -61.74 ± 35.38 µm for the T1 group and 4.09 ± 27.15 µm for the T2 group, with statistically significant differences between the two groups ($p < 0.001$).

Screenshots of the occlusal records in control and test groups were displayed in Fig. 8.

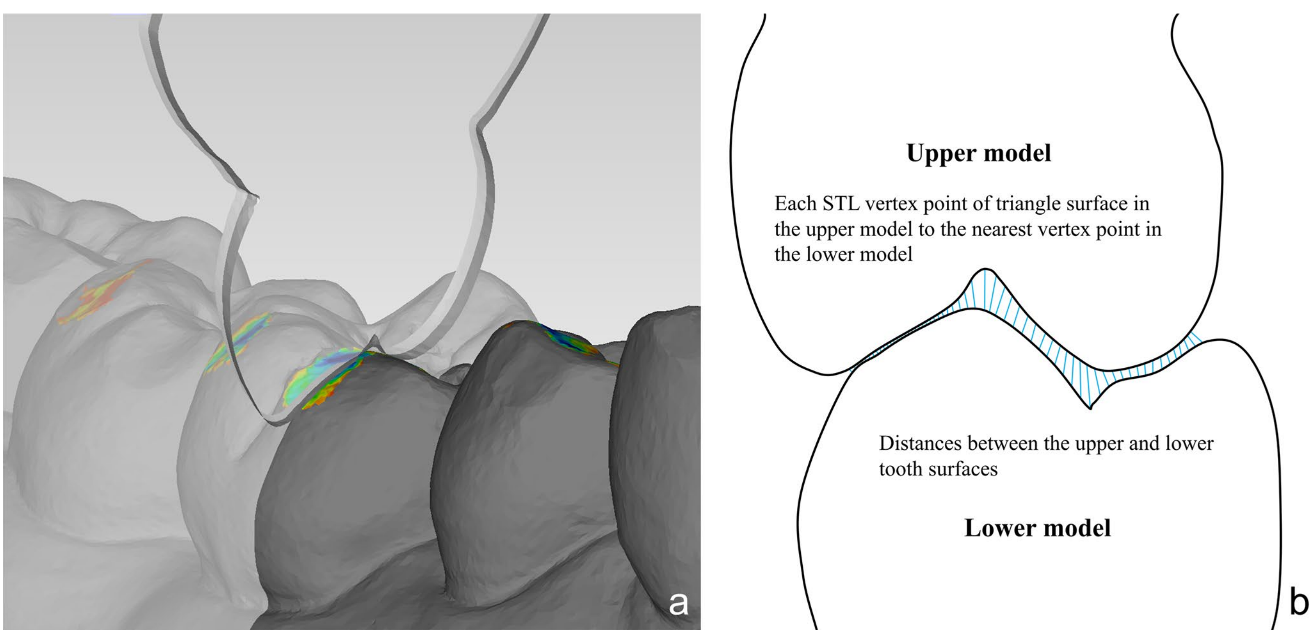

Fig. 6 Illustration of the occlusal clearance calculation between the upper and lower models. **a** The sectional view showed the occlusal clearance between the upper and lower models. **b** The schematic diagram illustrated the occlusal clearance calculation

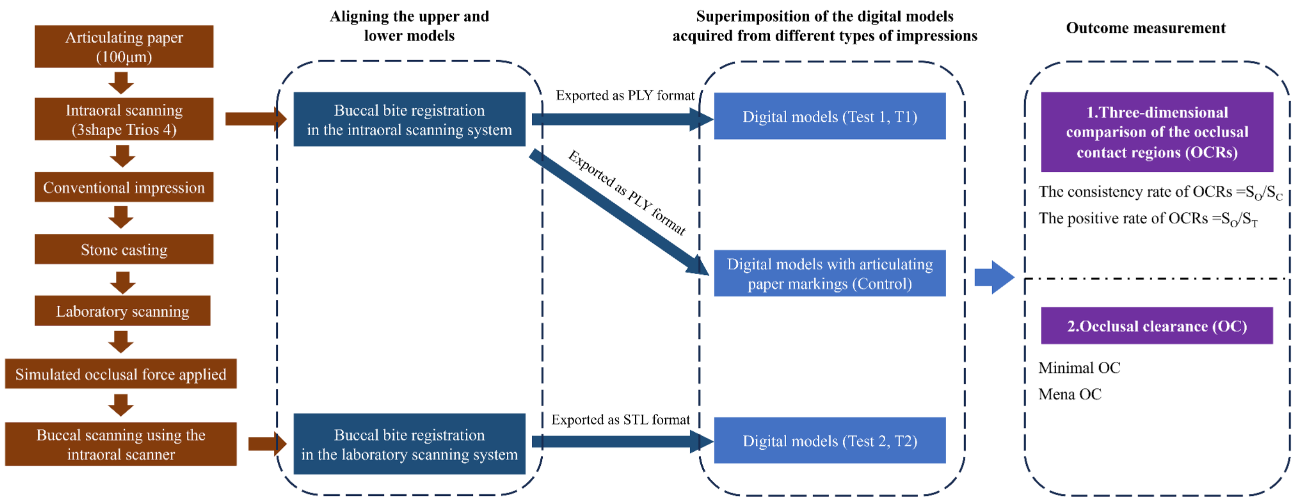

Fig. 7 The flow chart of the study design and procedures. S_C, the area of OCRs in the control group; S_T, the area of OCRs in the test groups; S_O: the overlapping OCRs between the control and test groups

Table 1 The comparative results of the two test groups

	Occlusal contract regions (OCRs)		Occlusal clearance OC (μm)	
	consistency rate	positive rate	Mean OC	Minimum OC
Intraoral scan (Test 1)	0.73 ± 0.17	0.67 ± 0.15	51.32 ± 16.04	-61.74 ± 35.38
Conventional impression (Test 2)	0.23 ± 0.13	0.56 ± 0.23	68.20 ± 18.15	4.09 ± 27.15
p value	< 0.001	0.143	0.024	< 0.001

Discussion

By means of an innovative evaluation method, the present clinical study compared quadrant interocclusal records acquired using intraoral scanning and conventional impression procedures with those obtained using articulating paper. The evaluation method achieved the three-dimensional superimposition and quantitative comparison of the OCRs obtained by different techniques. The null hypotheses that the intraoral scanning procedure would achieve comparable consistency of OCRs distribution and occlusal tightness to the conventional procedure were both rejected based on the results. The intraoral scanning procedure exhibited

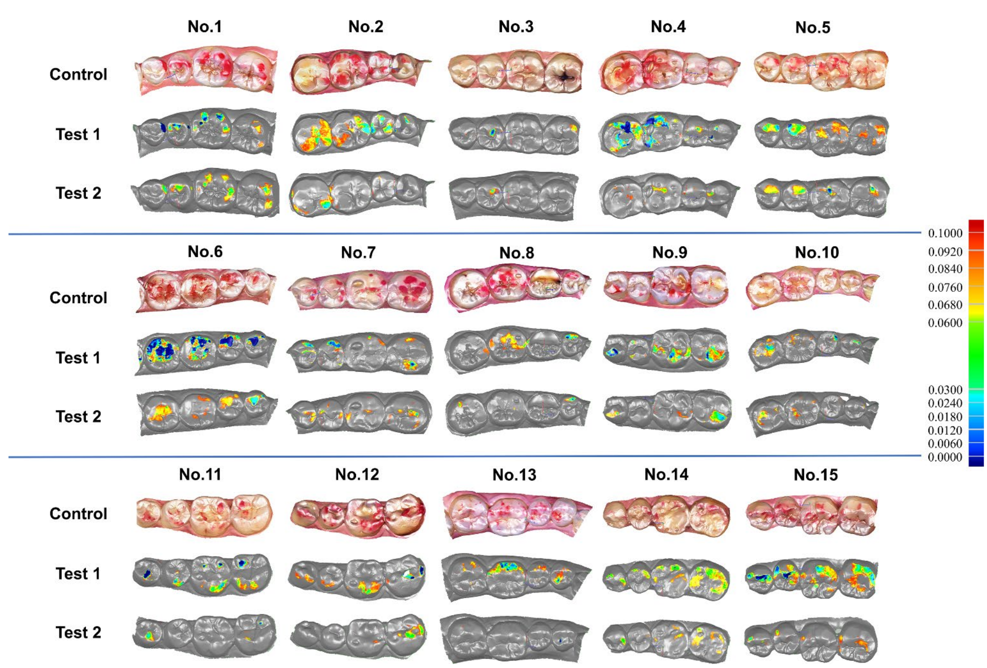

Fig. 8 Visual analysis results of the interocclusal records obtained using three techniques

significant higher consistency rate of OCRs and occlusal tightness compared with conventional procedure.

Prior to the digital occlusal records, various techniques including articulating paper [5, 7], Parkell [20], silicone transmission method [21], light transmission system [22], and T-scan system [23] are used to acquire the occlusal records in vivo. Among them, articulating paper technique is one of the most widely used techniques for occlusal contact recording and occlusal adjustments. To evaluate the reliability of digital occlusal contacts, a comparison with a gold standard or an established validated method is essential. However, there is currently no universally accepted gold standard method for identifying clinical occlusal contacts [6, 9, 24, 25]. The present study used the articulating paper technique as control technique for static occlusal recording evaluation in previous studies [5, 7, 9, 10, 17]. The use of the occlusion foil is particularly relevant and easy to implement in clinical application. Therefore, it makes sense that the two test groups were compared with it. Moreover, Wang et al. [7] found a strong reliability of the 100 µm articulating paper for measuring occlusal contact. In this study, the colored markings made by articulating papers on tooth surfaces were digitized through the use of intraoral scanning for quantitative analysis. This technique has also been reported in other studies [7, 17].

The results of this study showed that the consistency rate of OCRs in intraoral scanning group was approximately triple that of the conventional impression group, indicating that the tested intraoral scanning system is reliable for recording occlusal contacts than the conventional procedure. The findings of this study contradict a previous study [5] in which reported the conventional procedure had better reliability for recording occlusal contact than the intraoral scanner. The discrepancies can be attributed to the advancement in scanning accuracy of the intraoral scanning system and the different scanning regions. Although the same intraoral scanning system was used, the rapid updates and development in intraoral scanning devices and software may have led to an improvement in scanning accuracy. Meanwhile, the larger the scanning regions, the lower the scanning accuracy. Two studies reported a clinical acceptable accuracy of occlusal recording using intraoral scanning technique [6, 9], however, the conventional impression procedure was not included. The findings were in accordance with the findings in two studies [8, 9] revealed that intraoral scans provided more accurate occlusal records than conventional impression procedure.

In addition to evaluation methods, multiple factors can influence the accuracy of occlusal records in vivo [26]. An in vivo study reported that the occlusal contact area increased under heavy occlusal forces regardless of tooth mobility [27]. Similar findings were also observed in another study that occlusal contact area increased ranging from 9 to 16% in vivo when applying maximum bite force, as compared to moderate forces [10]. These findings demonstrated that the occlusal contact regions can vary under different occlusal forces. In the present study, all occlusal records were obtained under conditions where occlusal forces or simulating forces were applied. Since heavy bites at MICP can be easily determined by a significant contraction of the masseter muscles, such as bite and temporal muscles, participants are more likely to close near this position [10, 28]. Laboratory scanning was used to digitized the upper and lower casts as it is the most commonly used method for cast digitization and provides the highest accuracy. To ensure the rigor of the study design, obtaining buccal scans of the upper and lower models under a simulated pressure was necessary. However, the fixture in laboratory scanners cannot apply constant and quantifiable pressure to the upper and lower models. Lee et al. reported using a universal testing machine to fix the articulated upper and lower models and apply a specific pressure (600 N) to simulate occlusal force, followed by buccal scanning with an intraoral scanner [29]. This study adopted the same method, while the articulated upper and lower casts during buccal scanning were loaded a pressure force of 400 N to simulate intraoral occlusal forces. Currently, there is no universally established standard for applying pressure force to stone casts to simulate occlusal force. Ayuso-Montero et al. reported changes in maximum bite force during the growth and development period of 15 subjects (3 males and 12 females). Upon completion of growth and development (at age 29), the average maximum bite force of the first permanent molar was 424.4 N, and the average bite force of the second permanent molar was 405 N [10]. Luraschi et al. [30] reported an average maximum voluntary bite force of 378.8 N in elderly fully dentate subjects. Another multicenter study [31] reported a similar result to Luraschi et al., with a value of 350 N, also based on an elderly population. Taking into account the maximal occlusal force levels of healthy adults with complete dentition [30, 31] and the load-bearing capacity of stone casts, a relatively smaller force was applied. Excessive force has the potential risk of fractures and wear on the cusps of the plaster models. Given that plaster models are rigid and lack periodontal membrane structures, a smaller force might be equally effective, though this requires further exploration. Experiments were conducted on a universal testing machine and revealed that a 400 N force did not cause fractures or wear on the cusps of the plaster models.

This study investigated only the unilateral side of the posterior teeth primarily to control for the interference of confounding factors on the results. Currently, intraoral scanning systems show high accuracy for the posterior teeth region in a single quadrant, with minimal cumulative errors due to image stitching and less influence from different systems, scanning strategies, and dental arch morphology [19, 32, 33]. Considering that the main aim of this study was to explore an innovative evaluation method for the three-dimensional quantitative comparison of occlusal records, rather than to investigate the factors affecting the accuracy of occlusal record acquisition, the scanning regions were restricted to a single posterior quadrant to better illustrate the evaluation method.

According to previous studies on the digital fabrication process of either tooth or implant restorations, restorations fabricated through a fully digital workflow involving intraoral scans exhibited significantly higher precision on the occlusal surface, requiring fewer clinical occlusal adjustments compared to the conventional impression procedures [1, 2, 4, 34]. The results of the mean OC revealed that the occlusal tightness in the intraoral scanning group was significantly higher compared to the conventional impression group. This may be one of the reasons why restorations fabricated through the intraoral scanning technique require less clinical occlusal adjustment.

Theoretically, the values of the minimum OC should be greater than or equal to zero. However, negative values of minimum OC were observed in both test groups, indicating the occurrence of intersections between the surfaces of the maxillomandibular dental arches on the digital models. This phenomenon was also observed in several studies [6, 11]. In the intraoral scanning group, the minimum OC values were significantly lower than those in the conventional group, which was consistent with previous research findings that the alignments of intraoral scanners were more affected by intersections compared with extraoral scanners [11]. However, this study differs from Beck et al.‘s study [11] in terms of metrics. In this study, intersections were evaluated by measuring the minimum distance between upper and lower models, whereas Beck et al. primarily assessed intersections based on the area where intersections occurred. The intersections could attribute to scanning errors and the limitations of the alignment algorithm. However, it seems that virtual intersections do not result in more errors on the occlusal surface of restorations fabricated by a fully digital workflow. Further research is needed to investigate the relationship between the degree of intersections and the amount of clinical adjustment of restorations.

The study results should be considered in light of certain limitations. Despite being regarded as a gold standard or validated method, the articulating paper technique has its own limitations. The staining capacity of articulating paper impacts the results. As the study conducted with only one intraoral scanner, general statements should therefore be formulated with caution as the accuracy of the scanner is also decisive. Numerous and complex factors can affect the accuracy of occlusal records. To ensure standardized occlusal guidance and clinical procedures for all participants, all procedures were performed by the same clinicians. This design inevitably introduced observer bias during data acquisition. Studies with larger sample sizes and multiple blinded operators are needed to verify the conclusions of this study. Additionally, although participants were instructed to occlude in MICP with maximum bite force, the force was not measured quantitatively, and its reproducibility remains uncertain.

Conclusions

Within the limitations of the present study, the following conclusions may be drawn:

1) For obtaining occlusal records in the quadrant posterior region, the tested intraoral scanning system was more reliable for recording occlusal contact regions and showed higher occlusal tightness compared with conventional impression procedures.

2) The evaluation method can assist clinicians in making more objective analysis and comparisons among different sources of virtual occlusal records.

3) Occlusal tightness is a key and indispensable indicator in the evaluation of virtual occlusal records, and it can be quantified by measuring the occlusal clearance utilizing the current evaluation method.

Acknowledgements The authors thank dental technicians including Qiang Hao, Zhichun Zhang and Tong Zhao from the Department of Oral Implantology at Peking University School and Hospital of Stomatology in Beijing for their support in the laboratory workflow.

Author contributions Donghao Wei: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original drafting.Xiaosong Yi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Writing – original drafting.Ye Lin: Resources, Supervision, Validation, Visualization, Writing – review & editing.Ping Di: Project administration, Supervision, Validation, Visualization, Writing – review & editing.

Funding This study was funded by Youth Research Fund of Peking University School and Hospital of Stomatology (PKUSS20200103).

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the Institutional Review Board of Peking University School and Hospital of Stomatology (Approval Numbers: PKUSSIRB-202054037).

Consent to participate Informed consent was obtained from all individual participants included in the present study. They were informed verbally and in writing of the advantages and disadvantages of participating in the study.

Competing interests The authors declare no competing interests.

References

1. Joda T, Bragger U (2016) Patient-centered outcomes comparing digital and conventional implant impression procedures: a randomized crossover trial. Clin Oral Implants Res 27(12):e185–e189
2. Zhang Y et al (2019) Quantitative clinical adjustment analysis of posterior single implant crown in a chairside digital workflow: a randomized controlled trial. Clin Oral Implants Res 30(11):1059–1066
3. Zhang Y et al (2023) Clinical evaluation and quantitative occlusal change analysis of posterior implant-supported all-ceramic crowns: a 3-year randomized controlled clinical trial. Clin Oral Implants Res 34(11):1188–1197
4. Karasan D et al (2023) Occlusal adjustment of 3-unit tooth-supported fixed dental prostheses fabricated with complete-digital and -analog workflows: a crossover clinical trial. J Dent 128:104365
5. Fraile C et al (2018) Intraoral versus extraoral digital occlusal records: a pilot study. Int J Comput Dent 21(4):329–333
6. Abdulateef S et al (2020) Clinical accuracy and reproducibility of virtual interocclusal records. J Prosthet Dent 124(6):667–673
7. Wang Q et al (2022) In vivo evaluation of the reliability and validity of three digital occlusion analysis methods. J Dent 127:104355
8. Cheng MX, Sun TJYC, Zhang HY (2018) Influence of intraoral scan and dental cast scan on occlusal quantitative analysis of virtual dental model. Beijing Da Xue Xue Bao Yi Xue Ban 50(1):136–140
9. Fraile C et al (2022) Clinical study comparing the accuracy of interocclusal records, digitally obtained by three different devices. Clin Oral Investig 26(2):1957–1962
10. Ayuso-Montero R et al (2020) Reliability and validity of T-scan and 3D Intraoral scanning for measuring the Occlusal Contact Area. J Prosthodont 29(1):19–25
11. Beck F et al (2023) Comparison of virtual intersection and Occlusal contacts between Intraoral and Laboratory scans: an In-Vivo study. J Clin Med, 12(3)
12. Fraile C, Solaberrieta AFE, Pradíes G (2018) Intraoral versus extraoral digital occlusal records: a pilot study. Int J Comput Dent 21(4):329–333
13. Xiao N et al (2020) [Preliminary study on three digital analysis methods for analyzing the distribution and area of occlusal contacts]. Beijing Da Xue Xue Bao Yi Xue Ban 52(1):144–151
14. Li L et al (2021) Construction of virtual intercuspal occlusion: considering tooth displacement. J Oral Rehabil 48(6):701–710
15. Zhao Z et al (2022) Reliability and validity of two computerised occlusion analysis systems. J Dent 118:104051
16. Deferm JT et al (2018) Validation of 3D documentation of palatal soft tissue shape, color, and irregularity with intraoral scanning. Clin Oral Investig 22(3):1303–1309
17. Solaberrieta E et al (2015) Comparison of a conventional and virtual occlusal record. J Prosthet Dent 114(1):92–97
18. Wei D et al (2020) Evaluation of intraoral digital impressions for obtaining gingival contour in the esthetic zone: accuracy outcomes. Clin Oral Investig 24(4):1401–1410
19. Ender A et al (2016) In vivo precision of conventional and digital methods for obtaining quadrant dental impressions. Clin Oral Investig 20(7):1495–1504
20. Forrester SE et al (2011) Occlusal measurement method can affect SEMG activity during occlusion. J Oral Rehabil 38(9):655–660
21. Thanabalan N et al (2019) Interocclusal Records in fixed prosthodontics. Prim Dent J 8(3):40–47
22. Makino S et al (2013) Evaluation of the occlusal contact of crowns fabricated with the bite impression method. J Med Dent Sci 60(3):73–81
23. Velasquez B et al (2023) Occlusal Analysis in Natural Dentition: systematic review. Eur J Dent 17(3):615–622
24. van den Bergh HT, Owen CP, Howes DG (2022) A comparison of different methods and materials for establishing maximal intercuspal position: a clinical study. J Prosthet Dent
25. Revilla-Leon M et al (2023) Differences in maxillomandibular relationship recorded at centric relation when using a conventional method, four intraoral scanners, and a jaw tracking system: a clinical study. J Prosthet Dent
26. Velasquez B et al (2022) Occlusal Analysis in Natural Dentition: systematic review. Eur J Dent
27. Lu B, Shao L, Yu Q (2023) Effect of different occlusal forces on the accuracy of interocclusal records of loose teeth. J Oral Rehabil
28. Hoshino K et al (2004) Influence of occlusal height for an implant prosthesis on the periodontal tissues of the antagonist. J Med Dent Sci 51(4):187–196
29. Lee H et al (2018) Comparison of the occlusal contact area of virtual models and actual models: a comparative in vitro study on Class I and Class II malocclusion models. BMC Oral Health 18(1):109
30. Luraschi J et al (2012) Mechanosensation and maximum bite force in edentulous patients rehabilitated with bimaxillary implant-supported fixed dental prostheses. Clin Oral Implants Res 23(5):577–583
31. Mericske-Stern R et al (1995) Occlusal force and oral tactile sensibility measured in partially edentulous patients with ITI implants. Int J Oral Maxillofac Implants 10(3):345–353
32. Afrashtehfar KI, Alnakeb NA, Assery MKM (2022) Accuracy of Intraoral scanners Versus Traditional impressions: a Rapid Umbrella Review. J Evid Based Dent Pract 22(3):101719
33. Latham J et al (2020) Effect of scan pattern on complete-arch scans with 4 digital scanners. J Prosthet Dent 123(1):85–95
34. Ren S et al (2022) Crown Accuracy and Time Efficiency of Cement-Retained Implant-supported restorations in a complete Digital Workflow: a Randomized Control Trial. J Prosthodont 31(5):405–411