

Original Article

Influence of a digital versus a conventional workflow on occlusal contacts of posterior implant-supported single crowns based on digital occlusal analysis: a retrospective study

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Abstract: Objectives: To compare the effects of a digital workflow versus a conventional workflow on occlusal contacts of posterior implant-supported single crowns using digital occlusal analysis. Methods: This retrospective study included 239 patients with single posterior implant-supported monolithic zirconia crowns, comprising a digital workflow group (DWG, n = 101) and a conventional workflow group (CWG, n = 138). In the DWG, intraoral scanning with an auxiliary occlusal device and computer-aided design/computer-aided manufacturing (CAD/CAM) were performed without using stone casts, while the CWG used polyether impressions and stone cast fabrication. Occlusal deviation parameters, relative occlusal force (ROF) measured by the T-Scan III system, time efficiency, and clinical adjustments were evaluated at crown insertion and at 6-month follow-up. Results: Compared to the CWG, the DWG showed significantly lower maximum occlusal deviation, mean occlusal deviation, occlusal adjustment area, and occlusion time ratio (all $P < 0.001$). The ROF of the implant crown was lower ($P = 0.004$), whereas the ROF of the adjacent natural tooth was higher ($P = 0.002$) in the DWG. In addition, the DWG showed significantly shorter total laboratory time ($P < 0.001$) and impression/scan time ($P < 0.001$), as well as fewer crowns requiring occlusal adjustment ($P = 0.012$). Conclusions: A digital workflow incorporating intraoral scanning and an auxiliary occlusal device was associated with improved occlusal accuracy, optimized occlusal force distribution, reduced laboratory time, and fewer occlusal adjustments compared to a conventional workflow for posterior implant-supported single crowns.

Keywords: Digital workflow, conventional workflow, occlusal contacts, intraoral scanning, implant-supported single crown

Introduction

Posterior dental implants play an essential role in restoring oral function and aesthetics in patients with missing teeth. Implant-supported monolithic zirconia crowns have become increasingly popular due to their excellent durability, esthetic outcomes, and biocompatibility. However, achieving optimal occlusal contacts remains crucial for the success of these restorations [1-3]. Inadequate occlusion can lead to complications such as excessive wear, crown fracture, discomfort, and even implant failure [4, 5]. Conventional workflows for fabricating implant-supported crowns involve multiple steps, each of which may introduce inaccuracies and inefficiencies, thereby affecting the

final outcome. With the rapid development of digital technologies, dental workflows have gradually shifted towards more streamlined and precise approaches, which may offer significant advantages in terms of occlusal accuracy and time efficiency.

The conventional workflow for fabricating implant-supported crowns typically begins with obtaining a polyether impression of the patient's oral cavity. This physical impression is then used to fabricate a stone cast, which serves as the foundation for subsequent restorative steps. A wax-up is performed on the stone cast to replicate the desired crown shape, followed by investing and casting or milling processes. Finally, the crown is fabricated using

computer-aided design/computer-aided manufacturing (CAD/CAM) technology based on the stone cast model. While this workflow has been widely used and refined over many years, it remains susceptible to errors introduced during each step, particularly during impression acquisition and stone cast fabrication. These inaccuracies may lead to suboptimal occlusal contacts, necessitating additional chair-side adjustments and thus compromising the overall quality and longevity of the restoration [6-8].

In contrast, the digital workflow offers a more integrated and efficient approach for fabricating implant-supported crowns. Intraoral scanning replaces conventional impression procedures by enabling direct digital acquisition of the patient's dentition and occlusal surfaces. The use of an auxiliary occlusal device during scanning further enhances the accuracy of occlusal contact registration [9-11]. The digital data are then transferred to CAD software, allowing precise crown design and optimization of occlusal morphology and fit. The CAM process then enables crown fabrication without the need for physical stone casts. This streamlined workflow reduces errors associated with conventional impressions and stone cast fabrication, potentially improving occlusal accuracy. Furthermore, digital workflows allow real-time modification and virtual simulation, enhancing the predictability and precision of the final restoration [12, 13].

Digital occlusal analysis plays a critical role in optimizing occlusal contacts within digital workflows. By using advanced software systems, clinicians can analyze and modify occlusal contacts in a virtual environment before crown fabrication. This allows for more precise control of occlusal force distribution and may reduce the risk of complications, such as excessive wear or fracture. Additionally, digital occlusal analysis facilitates better communication between clinicians and dental laboratory technician by providing a clear understanding of the desired occlusal outcomes. The ability to simulate various occlusal conditions and perform immediate adjustments may further improve the overall quality, consistency, and predictability of the final restoration [5, 14].

With the increasing adoption of digital technologies in dentistry, it is important to investigate their effects on occlusal contacts compared to

conventional methods. Therefore, this study aimed to compare digital and conventional workflows regarding occlusal accuracy and related clinical outcomes in posterior implant-supported crowns. Through systematic evaluation, this study may provide further evidence supporting the integration of digital workflows into routine clinical practice and contribute to improved functional and esthetic outcomes for patients receiving implant-supported restorations.

Materials and methods

Patient selection and group allocation

The study population consisted of patients who received a single implant-supported monolithic zirconia crown in the posterior region (first premolar, second premolar, or first molar) between July 2020 and July 2025 at the Peking University First Hospital (Ethics No: 2025R0582-0002). Patients were identified through the hospital's electronic medical record system. This retrospective study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Peking University First Hospital (Approval No. 2025R0582-0002). Given the retrospective design and use of anonymized clinical data, the requirement for written informed consent was waived by the IRB.

Inclusion criteria: (1) Presence of a single osseointegrated implant with a diameter of ≥ 3.75 mm restored with a screw-retained or cement-retained monolithic zirconia crown; (2) Implant placement in a posterior region (premolar or molar) with a natural opposing tooth and natural adjacent teeth; (3) Availability of high-quality intraoral scan data (for the digital workflow group) or stone cast models (for the conventional workflow group) suitable for digital occlusal analysis; (4) Complete clinical records including occlusal examination at the time of crown insertion (baseline) and at the 6-month follow-up; and (5) Absence of prosthetic complications before the 6-month follow-up.

Exclusion criteria: (1) Documented parafunctional habits (e.g., bruxism, clenching, nail biting) in the medical chart; (2) Requirement for a fixed partial denture in the same arch; (3) Active untreated periodontitis (defined as clini-

cal attachment loss ≥ 3 mm and bleeding on probing at $\geq 30\%$ of sites); (4) Temporomandibular joint disorders diagnosed by a specialist; (5) Inadequate quality of occlusal records or missing data at the required time points; (6) Use of crown materials other than monolithic zirconia (to minimize material-induced confounding effects); and (7) History of orthodontic treatment within the past 2 years.

According to the treatment workflow, patients were categorized into two groups: a digital workflow group (DWG) and a conventional workflow group (CWG). The DWG comprised patients who underwent a fully digital workflow consisting of intraoral scanning with an auxiliary occlusal device and computer-aided design/computer-aided manufacturing (CAD/CAM) crown fabrication without physical stone casts. The CWG included patients who underwent a conventional workflow involving polyether impression acquisition, stone cast fabrication, conventional wax-up and investing procedures, followed by CAD/CAM milling based on the stone cast.

Group allocation was determined by routine clinical decision-making based on clinical preference and equipment availability during the study period. A total of 281 patients were initially screened. After applying the inclusion and exclusion criteria, 239 patients (239 implant crowns) were retained for the final analysis, including 101 crowns in the DWG and 138 crowns in the CWG.

Workflow protocols

Conventional workflow group: For patients in the CWG, implant-level impressions were obtained using polyether (Impregum Penta, 3M ESPE, Seefeld, Germany) with a custom tray. Type IV dental stone casts (Fujirock EP, GC, Tokyo, Japan) were fabricated and mounted on a semi-adjustable articulator using face-bow transfer. Monolithic zirconia crowns were designed based on scanned stone casts, milled from pre-sintered yttria-stabilized zirconia blocks (Katana, Kuraray Noritake, Tokyo, Japan), sintered, finished, and cemented using a self-adhesive resin cement (RelyX Unicem, 3M ESPE). Occlusal contacts were evaluated using articulating paper (12 μm and 40 μm).

Digital workflow group: For patients in the DWG, treatment followed a complete digital

protocol. Before final data acquisition, a full-arch intraoral scan was obtained using an intraoral scanner (i500, Medit, Seoul, South Korea) with an auxiliary occlusal device. The auxiliary device consisted of a custom-made acrylic resin wafer (2.0 mm in thickness) fabricated from clear heat-polymerized polymethyl methacrylate (Vertex Rapid Model, Vertex-Dental, Soesterberg, Netherlands), which was used to record the maximal intercuspal position. The wafer covered the entire occlusal surfaces of the posterior teeth and was scanned together with the dental arches to provide a reference for virtual interocclusal registration. The scanning procedure was performed by two calibrator prosthodontists following the manufacturer's recommended scanning sequence (lingual roll, occlusal, buccal). The crown was designed using CAD software (Medit Link) without a physical stone cast, milled from the same zirconia material, and cemented using the same protocol as that in the CWG.

In both groups, crown insertion and all clinical adjustments were performed by two prosthodontists, each with more than 5 years of clinical experience in implant prosthodontics. The cementation procedure for cement-retained crowns followed a standardized protocol, including rubber dam isolation, cleaning of the abutment surface, application of the self-adhesive resin cement, seating of the crown under finger pressure, removal of excess cement, and light curing for 3 seconds on each surface.

Occlusal deviation and contact parameters

For each crown, intraoral scans of the entire dental arch were obtained using the same intraoral scanner (i500, Medit, Seoul, South Korea) before any clinical occlusal adjustment and after the final adjustment. Scanning was performed under standardized ambient lighting and humidity conditions. The distance between the corresponding surfaces was computed point-by-point across the entire occlusal table of the implant crown. Maximum occlusal deviation was defined as the largest single distance value recorded, with deviations > 100 μm considered clinically relevant. Mean occlusal deviation was calculated as the arithmetic mean of all distance values across the occlusal surface. The occlusal adjustment area was defined as the area of the occlusal surface

where the distance exceeded 100 μm . The number of occlusal contacts in the maximum intercuspal position was determined using a virtual articulator. Overlapping areas with a distance of $< 20 \mu\text{m}$ were considered occlusal contacts. The occlusion time ratio was defined as the percentage of total occlusal contact time attributed to the implant crown during a 5-second clenching task.

T-scan analysis of relative occlusal force

Relative occlusal force (ROF) was assessed at the 6-month follow-up using a T-Scan III system (Tekscan, Boston, MA, USA). After calibration, patients were instructed to perform maximum voluntary clenching for 2 seconds. The ROF of the implant crown was defined as the percentage of force exerted on the implant crown relative to total occlusal force of the arch. The ROF of the adjacent natural tooth was defined as the percentage of force exerted on the natural tooth immediately mesial or distal to the implant crown. When both adjacent teeth were present, the tooth with the higher ROF was selected for analysis. The ROF of the contralateral homologous tooth was defined as the percentage of force exerted on the corresponding natural tooth (first premolar, second premolar, or first molar) on the opposite side of the same arch.

Time efficiency and clinical adjustment indicators

Time efficiency indicators were measured using a stopwatch. Total laboratory time was defined as the interval from impression/scan acquisition to crown delivery at the clinic. Impression/scan acquisition time was recorded separately. Total chair-side time was defined as the total time that the patient spent in the dental chair, from entering the treatment room to leaving the room during the crown insertion appointment. The duration of anesthesia administration was recorded separately. Proximal contact adjustment (yes/no) was documented when dental floss passed through the proximal contact without resistance, versus with excessive resistance. The requirement for occlusal adjustment (yes/no) was recorded when any occlusal surface material removal was performed after verification with articulating paper.

Post-insertion complications within 6 months

All technical and biological complications recorded in the electronic medical chart during the 6-month follow-up period were documented. Technical complications included screw loosening (defined as clinically or radiographically confirmed screw loosening by the dentist), crown fracture (defined as any visible crack or complete fracture of the monolithic zirconia crown), and crown decementation (defined as loss of retention requiring recommendation). Biological complications included peri-implant mucositis (defined as bleeding on probing at the implant site with probing depth $\leq 4 \text{ mm}$ and no radiographic bone loss beyond baseline levels), peri-implantitis (defined as bleeding on probing, probing depth $\geq 5 \text{ mm}$, and radiographic marginal bone loss $\geq 2 \text{ mm}$ compared to baseline), and fistulation (defined as the presence of an intraoral fistula communicating with the peri-implant region). Patients experiencing multiple complications were counted once in the "any complication" category, while each individual event was recorded separately.

Periodontal and peri-implant indicators at 6-months

Periodontal and peri-implant indicators at the 6-month follow-up were measured using a manual periodontal probe (UNC-15, Hu-Friedy, Chicago, IL, USA). Probing pocket depth (PPD) was calculated as the mean value of four sites (mesial, distal, buccal, lingual). Bleeding on probing (BOP) was expressed as the percentage of positive sites. The modified plaque index (m-PI) was assessed at four sites and scored from 0 to 3 according to the following criteria: 0 = no plaque; 1 = plaque detectable only by running a probe across the surface; 2 = plaque visible to the naked eye; and 3 = abundant soft deposits. Gingival recession (yes/no) was recorded when the distance from the cemento-enamel junction (or implant abutment margin) to the gingival margin was $\geq 1 \text{ mm}$ on the buccal or lingual aspect.

Radiographic marginal bone level (MBL) changes

Intraoral periapical radiographs were obtained at crown insertion and at the 6-month follow-up using a standardized paralleling technique with a digital X-ray unit (Heliodont Plus, Sirona,

Table 1. Comparison of demographic and baseline clinical characteristics between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	t/ χ^2	P
Age (years)	52.18 $\pm$ 11.73	53.72 $\pm$ 13.71	0.912	0.363
Sex (female/male) [n (%)]	45 (44.55%)/56 (55.45%)	63 (45.65%)/75 (54.35%)	0.028	0.866
BMI (kg/m ²)	23.54 $\pm$ 3.21	23.81 $\pm$ 3.45	0.619	0.537
Smoking status [n (%)]	28 (27.72%)	50 (36.23%)	1.921	0.166
Jaw location (maxilla/mandible) [n (%)]	43 (42.57%)/58 (57.43%)	59 (42.75%)/79 (57.25%)	0.001	0.978
Implant location (premolar/molar) [n (%)]	41 (40.59%)/60 (59.41%)	62 (44.93%)/76 (55.07%)	0.447	0.504
Implant length ($\geq$ 10 mm/< 10 mm) [n (%)]	67 (66.34%)/34 (33.66%)	89 (64.49%)/49 (35.51%)	0.087	0.767
Implant diameter (mm)	4.32 $\pm$ 0.55	4.29 $\pm$ 0.58	0.363	0.717
Time from implant placement to impression (months)	4.25 $\pm$ 0.87	4.18 $\pm$ 0.92	0.551	0.582
Opposing dentition (natural/restored) [n (%)]	87 (86.14%)/14 (13.86%)	118 (85.51%)/20 (14.49%)	0.019	0.890
Retention type (screw-retained/cemented) [n (%)]	66 (65.35%)/35 (34.65%)	89 (64.49%)/49 (35.51%)	0.019	0.891

Notes: DWG, digital workflow group; CWG, conventional workflow group; BMI, body mass index.

Bensheim, Germany) at 70 kVp, 7 mA, and 0.12 s exposure time. The radiographs were analyzed using imaging software (ImageJ 1.53, National Institutes of Health, Bethesda, MD, USA). Marginal bone level (MBL) was defined as the vertical distance from the implant shoulder (the most coronal part of the implant body) to the most coronal bone-to-implant contact, measured separately on the mesial and distal aspects.

Prosthetic technical quality and patient-reported outcomes

Prosthetic technical quality and patient-reported outcomes were evaluated. Marginal fit was assessed using the replica technique, and the maximum marginal discrepancy (μ m) was measured under a microscope. The number of occlusal contacts before adjustment was recorded using articulating paper (12 μ m). The esthetic outcome of the crown was evaluated using a 10-point visual analog scale (VAS), ranging from 0 (extremely poor esthetics) to 10 (excellent esthetics). The assessment was based on standardized intraoral photographs obtained at the 6-month follow-up, including frontal, right buccal, and left buccal views. At the 6-month follow-up, patients were asked to rate their overall satisfaction with the implant crown using a 10-point Likert scale (1 = completely dissatisfied, 10 = completely satisfied).

Statistical analysis

All statistical analyses were performed using SPSS software (version 25.0, IBM Corp., Armonk, NY, USA). Continuous variables were tested for normality using the Shapiro-Wilk test.

All continuous variables were normally distributed and expressed as mean $\pm$ standard deviation (SD). Comparisons between groups for continuous variables were performed using the independent two-sample Student's t-test. Categorical variables (n, %) were analyzed using the chi-square (χ^2) test.

No adjustment for multiple comparisons were performed because this retrospective study was exploratory in nature. The sample size was not pre-calculated and was determined by the number of eligible patients identified during the study period. All analyses were conducted using a complete-case approach, as only patients with complete clinical records were included and no missing data imputation was performed. A two-sided *P* value < 0.05 was considered significant.

Results

Baseline demographic and clinical characteristics

Table 1 summarizes the baseline demographic and clinical characteristics of the two groups. No significant differences were observed between the DWG and CWG for any of the variables, including age, sex, body mass index, smoking status, jaw location, implant location, implant length, implant diameter, time from implant placement to impression, opposing dentition, or retention type (all *P* > 0.05).

Primary outcomes

Table 2 presents the occlusal deviation and contact parameters. The maximum occlusal

Table 2. Comparison of occlusal deviation and contact parameters between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	t	P
Maximum occlusal deviation (μm)	163.47 $\pm$ 61.89	291.23 $\pm$ 110.56	11.359	< 0.001
Mean occlusal deviation (μm)	55.78 $\pm$ 22.96	102.63 $\pm$ 38.77	11.673	< 0.001
Occlusal adjustment area (mm^2)	7.96 $\pm$ 4.31	15.88 $\pm$ 8.64	9.303	< 0.001
Number of occlusal contacts in MIP	3.19 $\pm$ 1.04	2.98 $\pm$ 1.09	1.533	0.127
Occlusion time ratio (%)	14.21 $\pm$ 5.37	23.05 $\pm$ 7.49	10.632	< 0.001

Notes: DWG, digital workflow group; CWG, conventional workflow group; MIP, maximum intercuspal position.

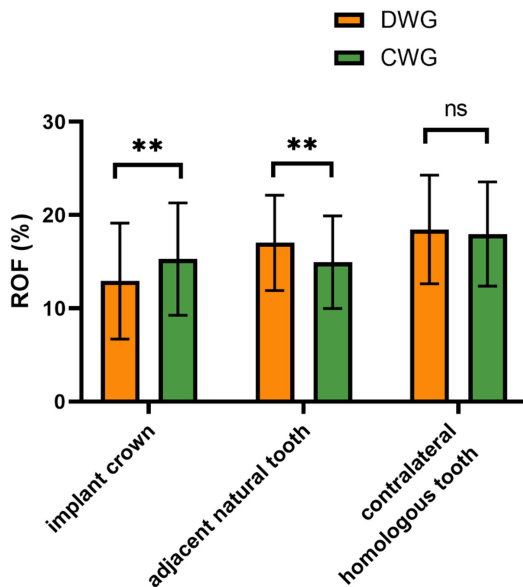


Figure 1. Comparison of relative occlusal force distribution between the two groups 6 months after insertion. Notes: DWG, digital workflow group; CWG, conventional workflow group; ROF, relative occlusal force; **, $P < 0.01$; ns, no significant difference.

deviation was significantly lower in the DWG than in the CWG (163.47 ± 61.89 vs. 291.23 ± 110.56 , $P < 0.001$). Similarly, the mean occlusal deviation (55.78 ± 22.96 vs. 102.63 ± 38.77 , $P < 0.001$) and occlusal adjustment area (7.96 ± 4.31 vs. 15.88 ± 8.64 , $P < 0.001$) were significantly smaller in the DWG. The occlusion time ratio was also significantly lower in the DWG (14.21 ± 5.37 vs. 23.05 ± 7.49 , $P < 0.001$). However, the number of occlusal contacts in maximum intercuspal position (MIP) did not differ significantly between the two groups ($P = 0.127$).

T-scan analysis

Figure 1 shows the relative occlusal force distribution at the 6-month follow-up. The ROF

of the implant crown was significantly lower in the DWG than in the CWG (12.93 ± 6.21 vs. 15.28 ± 6.03 , $P = 0.004$), whereas the ROF of the adjacent natural tooth was significantly higher in the DWG (17.03 ± 5.11 vs. 14.95 ± 4.96 , $P = 0.002$). No significant difference was observed in the ROF of the contralateral homologous tooth between the two groups ($P = 0.518$).

Time efficiency and chair-side adjustment indicators

Table 3 summarizes the time efficiency and clinical adjustment indicators. The total laboratory time (44.82 ± 6.38 vs. 114.56 ± 8.27 , $P < 0.001$) and impression/scan acquisition time (12.73 ± 2.19 vs. 21.89 ± 3.75 , $P < 0.001$) were significantly shorter in the DWG than the CWG. The proportion of crowns requiring occlusal adjustment was also significantly lower in the DWG (31.68% vs. 47.83% , $P = 0.012$). However, no significant differences were observed in total chair-side time ($P = 0.209$) or proximal contact adjustment ($P = 0.757$) between the two groups.

Post-insertion complications

Table 4 summarizes post-insertion complications during 6-month follow-up period. The overall complication rate did not differ significantly between the DWG and the CWG (9.9% vs. 13.77% , $P = 0.366$). The recorded complications included screw loosening, crown fracture, crown decementation, peri-implant mucositis, fistulation, and peri-implantitis.

Periodontal and peri-implant parameters

Table 5 presents the periodontal and peri-implant parameters at the 6-month follow-up. No significant differences were observed between the DWG and the CWG in probing

Table 3. Comparison of time efficiency and chair-side adjustment indicators between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	t/ χ^2	P
Total laboratory time (min)	44.82 $\pm$ 6.38	114.56 $\pm$ 8.27	73.580	< 0.001
Impression/scan acquisition time (min)	12.73 $\pm$ 2.19	21.89 $\pm$ 3.75	23.677	< 0.001
Total chair-side time (min)	60.62 $\pm$ 12.96	58.55 $\pm$ 12.18	1.260	0.209
Proximal contact adjustment [n (%)]	26 (25.74%)	38 (27.54%)	0.096	0.757
Occlusal adjustment required [n (%)]	32 (31.68%)	66 (47.83%)	6.282	0.012

Table 4. Comparison of post-insertion complications between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	χ^2	P
Any complication [n (%)]	10 (9.9%)	19 (13.77%)	0.818	0.366
Screw loosening	2 (2.0%)	5 (3.6%)		
Crown fracture	1 (1.0%)	2 (1.4%)		
Crown decementation	1 (1.0%)	1 (0.7%)		
Peri-implant mucositis	5 (5.0%)	9 (6.5%)		
Fistulation	1 (1.0%)	1 (0.7%)		
Peri-implantitis	0 (0%)	1 (0.7%)		

Notes: DWG, digital workflow group; CWG, conventional workflow group.

pocket depth ($P = 0.581$), bleeding on probing ($P = 0.114$), modified plaque index ($P = 0.267$), or gingival recession ($P = 0.899$).

Radiographic marginal bone level changes

Figure 2 shows the radiographic marginal bone level outcomes. Baseline MBL values were comparable between the two groups (0.48 ± 0.23 vs. 0.51 ± 0.25 , $P = 0.343$). Similarly, no significant difference was observed in MBL values at the 6-month follow-up (0.72 ± 0.28 vs. 0.77 ± 0.31 , $P = 0.180$).

Prosthetic technical quality and patient-reported outcomes

Table 6 summarizes prosthetic technical quality and patient-reported outcomes. No significant differences were found between the DWG and the CWG regarding marginal fit ($P = 0.193$), number of occlusal contacts before adjustment ($P = 0.424$), restoration esthetics ($P = 0.203$), or patient satisfaction ($P = 0.187$).

Discussion

The present study aimed to evaluate the effects of digital and conventional workflows on occlusal contacts in patients receiving single implant-supported monolithic zirconia crowns in the posterior region. Our findings revealed

several key differences between the two workflows, suggesting associations between the fully digital workflow and improved occlusal accuracy and greater time efficiency.

Regarding occlusal deviations, the DWG exhibited better outcomes compared to the CWG. This suggests that intraoral scanning combined with an auxiliary occlusal device and CAD/CAM technology may be

associated with more accurate occlusal design and adjustment. The improved accuracy observed in the digital workflow may be attributed to the ability of digital scanning to capture detailed occlusal information while avoiding potential distortions associated with conventional impressions [15, 16]. Additionally, CAD/CAM systems can simulate occlusal adjustments more precisely, leading to fewer discrepancies between planned and actual occlusal contacts [17, 18].

Another notable finding was the reduction in occlusal adjustment area and occlusion time ratio in the DWG. These improvements suggest that digital workflows not only improve initial occlusal accuracy but also reduce the extent of chair-side adjustments required after crown insertion. This could be attributed to the higher reproducibility of digital data acquisition, which facilitates more accurate crown fabrication and minimizes additional adjustments during clinical fitting [19, 20]. The streamlined workflow in the digital group reduces the likelihood of human errors during impression taking and stone cast fabrication, which are common sources of inaccuracy in traditional methods [21-23].

The ROF analysis provided further insight into the potential biomechanical effects of the two

Table 5. Comparison of periodontal and peri-implant parameters between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	t/ χ^2	P
Probing pocket depth (PPD, mm)	2.92 $\pm$ 0.65	2.97 $\pm$ 0.69	0.553	0.581
Bleeding on probing (BOP, %)	13.51 $\pm$ 6.72	14.98 $\pm$ 7.33	1.586	0.114
Modified plaque index (m-PI)	0.75 $\pm$ 0.34	0.81 $\pm$ 0.4	1.112	0.267
Gingival recession (≥ 1 mm) [n (%)]	13 (12.87%)	17 (12.32%)	0.016	0.899

Notes: DWG, digital workflow group; CWG, conventional workflow group; PPD, probing pocket depth; BOP, bleeding on probing; m-PI, modified plaque index.

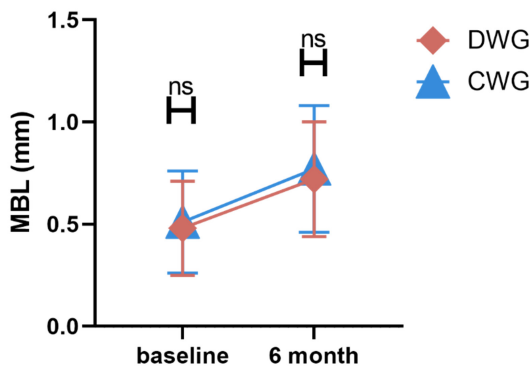


Figure 2. Comparison of radiographic MBL changes between the two groups. Notes: DWG, digital workflow group; CWG, conventional workflow group; MBL, marginal bone level; ns, no significant difference.

workflows. The lower ROF of the implant crown and higher ROF of the adjacent natural tooth observed in the DWG may indicate a more balanced occlusal force distribution, thus reducing excessive loading on the implant restoration [24, 25]. The increased ROF of adjacent natural teeth in the DWG indicates a redistribution of occlusal forces, possibly due to the enhanced precision in digital occlusal adjustment procedures [26-28]. These findings highlight the importance of evaluating occlusal relationships at the level of the entire dental arch, as subtle occlusal modifications can influence overall biomechanical behavior.

Time efficiency represents another important advantage of digital workflows. In this study, both total laboratory time and impression/scan acquisition time were notably shorter in the DWG. This improvement may be attributed to the elimination of conventional procedures, such as polyether impression acquisition and stone cast fabrication, which are time-consuming. Furthermore, the reduced requirement for occlusal adjustments in the digital group may contribute to additional time savings, supporting the potential efficiency benefits of digital

workflows in implant prosthodontics [29-31]. It is noteworthy that anesthesia time, although included in the measurement of total chair-side time, did not differ between groups and thus was unlikely to affect the between-group comparison. The absence of significant difference in total chair-side time suggested that the time savings achieved during laboratory procedures and digital data acquisition were offset by other clinical procedures required in both workflows, resulting in comparable overall chair-side experiences for patients.

The overall complication rates within 6 months after crown insertion were comparable between the DWG and CWG, indicating that the digital workflow did not appear to increase the risk of early complications compared with conventional methods. Implant-related complications are multifactorial and can be influenced by patient-specific factors, implant placement conditions, surgical procedures, and maintenance protocols, which may have a more significant effect than the workflow method itself. Future studies with longer follow-up periods are warranted to determine whether digital workflows offer additional benefits in reducing long-term complications. The comparable complication rates observed in this study suggest that digital workflows may represent a safe alternative to conventional methods in implant prosthodontics.

Periodontal and peri-implant parameters, radiographic marginal bone level changes, prosthetic technical quality, and patient-reported outcomes showed no significant differences between the two groups. These findings indicate that both workflows achieved comparable outcomes in terms of peri-implant tissue health, osseointegration, and stability, suggesting that the choice of workflow does not inherently affect the biological response of peri-implant tissues. Both workflows produce

Table 6. Comparison of prosthetic technical quality and patient-reported outcomes between the two groups

Variable	DWG (n = 101)	CWG (n = 138)	t	P
Marginal fit (max discrepancy, μm)	98.46 $\pm$ 29.12	103.79 $\pm$ 32.54	1.306	0.193
Occlusal contacts before adjustment (number)	3.51 $\pm$ 1.18	3.39 $\pm$ 1.23	0.800	0.424
Restoration esthetics (VAS 0-10)	8.08 $\pm$ 0.81	7.93 $\pm$ 0.94	1.277	0.203
Patient satisfaction (1-10 Likert)	9.01 $\pm$ 0.38	8.84 $\pm$ 0.42	1.324	0.187

Notes: DWG, digital workflow group; CWG, conventional workflow group; VAS, visual analog scale.

restorations of comparable quality and patient satisfaction. Nevertheless, patient-related factors, including oral hygiene maintenance and individual anatomical characteristics, remain important determinants of periodontal health and esthetic outcomes.

Several limitations should be acknowledged. First, the retrospective design may have introduced inherent limitations, including potential selection bias and the inability to establish causal inference. Group allocation was based on clinical preference rather than randomization, and clinicians may have preferentially selected the digital workflow for patients with more favorable anatomical conditions or better oral hygiene. Although no significant differences were identified in measured baseline characteristics, residual confounding from unmeasured variables cannot be excluded. Therefore, our findings should be interpreted as associations rather than causal effects. Second, the two workflows differed not only in scanning method but also in occlusal registration protocols. The custom-made acrylic resin wafer used in the digital workflow was not employed in the conventional workflow, in which face-bow transfer and articulator mounting were performed. This methodologic difference may have contributed to the observed outcomes and limits direct comparison between the two workflows. Future prospective studies should consider using comparable occlusal registration approaches in both groups to isolate the specific contribution of digital scanning technology. Third, the relatively short follow-up period restricts our ability to assess long-term clinical outcomes. Future prospective studies with larger sample sizes and extended follow-up periods are needed to validate these findings and further evaluate the long-term clinical performance of digital workflows in implant dentistry. Despite these limitations, our study provides clinically relevant insight into the advantages of digital work-

flows, particularly in improving occlusal accuracy and time efficiency, and contributes to the ongoing development of digital approaches in implant prosthodontics.

Conclusion

Our findings suggest that digital workflows were associated with improved occlusal accuracy and greater time efficiency compared to conventional workflows for posterior implant-supported monolithic zirconia crowns. Specifically, the digital workflow was associated with reduced maximum and mean occlusal deviations, smaller occlusal adjustment areas, and lower occlusion time ratios, without an apparent increase in early post-insertion complications. In addition, digital workflows resulted in shorter laboratory and impression/scan acquisition times, as well as a reduced need for occlusal adjustments. Further prospective studies with a larger sample size and extended follow-up periods are required to confirm these findings and further evaluate the long-term clinical benefits of digital workflows. Overall, digital workflows show potential for enhancing the precision, predictability, and efficiency of implant-supported restorative treatment.

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Disclosure of conflict of interest

None.

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