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Evaluation of Digital Versus Conventional Workflows for Full-Arch Implant-Supported Zirconia Prostheses: A Clinical and In Vitro Study

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ABSTRACT:

Background: Digital workflows have increasingly transformed implant prosthodontics by integrating digital data acquisition, virtual prosthetic planning, and computer-aided design and computer-aided manufacturing (CAD/CAM). However, comparative evidence regarding their clinical efficiency, prosthetic accuracy, and patient-related outcomes in full-arch implant-supported zirconia rehabilitation remains limited. The present study compared conventional and digital workflows with respect to clinical, time-related, and in vitro prosthetic outcomes.

Materials and Methods: A comparative study involving 60 participants was conducted, with 30 participants managed using a conventional workflow and 30 using a digital workflow for full-arch implant-supported zirconia prostheses. Demographic characteristics, total workflow time, chairside time, occlusal adjustment time, clinical prosthesis fit, patient satisfaction, prosthetic complications, three-dimensional (3D) deviation, implant positional deviation, and marginal and internal gaps were evaluated. Continuous variables were analyzed using the independent-samples Student's t-test, categorical variables using the chi-square test, and the relationship between 3D deviation and clinical fit was assessed using Pearson's correlation coefficient. Statistical significance was established at $p < 0.05$.

Results: The two groups were comparable in terms of age, sex, and arch distribution. The digital workflow significantly reduced total workflow time compared with the

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conventional approach (133.24 ± 17.97 vs. 189.09 ± 16.30 minutes; $p < 0.001$), as well as chairside time (96.82 ± 12.31 vs. 132.31 ± 10.90 minutes; $p < 0.001$) and occlusal adjustment time (10.27 ± 4.01 vs. 18.43 ± 5.95 minutes; $p < 0.001$). Clinical fit scores were significantly higher with the digital workflow (4.16 ± 0.51 vs. 3.67 ± 0.51; $p < 0.001$), as were patient satisfaction scores (4.41 ± 0.50 vs. 3.51 ± 0.55; $p < 0.001$). A significantly greater proportion of digital prostheses required no occlusal adjustment (60.0% vs. 30.0%; $p = 0.020$), and a higher proportion of patients reported satisfaction scores of ≥4/5 (86.7% vs. 63.3%; $p = 0.037$). The digital workflow demonstrated significantly lower 3D deviation (49.54 ± 11.87 vs. 84.96 ± 15.39 μm), implant positional deviation (46.32 ± 9.63 vs. 82.96 ± 20.05 μm), marginal gap (58.45 ± 14.92 vs. 89.71 ± 20.10 μm), and internal gap (96.20 ± 24.04 vs. 119.36 ± 27.70 μm) compared with the conventional workflow (all $p < 0.001$). Implant positional deviation was significantly lower with the digital workflow in the anterior, premolar, and molar regions. A moderate negative correlation was observed between 3D deviation and clinical fit score ($r = -0.577$, $p < 0.001$).

Conclusion: The digital workflow demonstrated significant advantages over the conventional approach in terms of procedural efficiency, clinical prosthesis fit, patient satisfaction, and prosthetic accuracy. Reduced 3D and implant positional deviations, along with smaller marginal and internal gaps, indicate improved precision of digitally fabricated full-arch zirconia prostheses. The findings suggest that digital integration may provide a more efficient and predictable approach to full-arch implant-supported rehabilitation, although larger multicenter studies with extended follow-up are required to confirm its long-term clinical benefits.

INTRODUCTION

Full-arch implant-supported prostheses represent a predictable treatment modality for the rehabilitation of patients with extensive tooth loss, offering improvements in oral function, esthetics, phonetics, and overall prosthetic comfort. The clinical success of these restorations is influenced by several factors, including implant positioning, prosthetic accuracy, framework adaptation, occlusal harmony, and the mechanical properties of the definitive restorative material. With the advancement of computer-aided design and computer-aided manufacturing (CAD/CAM), conventional prosthodontic procedures have increasingly evolved toward digitally planned and digitally manufactured rehabilitation protocols [1].

Digital dentistry has facilitated the integration of intraoral scanning, implant-level digital impressions, three-dimensional (3D) virtual planning, and CAD/CAM. Such workflows can simplify communication between the clinician and dental laboratory, improve digital data management, reduce the number of conventional impression-related procedures, and potentially shorten laboratory and clinical processing times. Nevertheless, the reliability of a complete-arch digital workflow is influenced by multiple factors, including the number and distribution of implants, interimplant distances, scan-body characteristics, intraoral scanner performance, scanning pathway, and operator-related variables [2].

Accurate recording of implant positions is particularly important in full-arch rehabilitation because scanning errors can accumulate over the length of the dental arch. Even minor discrepancies in the spatial registration of individual implants may become clinically significant when transferred to a definitive prosthesis supported by multiple implants. Studies evaluating complete-arch digital impressions have reported variations in trueness and precision among different scanners and clinical conditions, indicating that the accuracy achieved with digital impressions may depend considerably on the specific workflow employed [3].

The introduction of modified digital scanning techniques has attempted to address these limitations. Strategies involving scan-body splinting, optimized scanning sequences, and improved digital registration methods have been investigated to minimize cumulative deviations and enhance the reproducibility of full-arch implant scans. Such approaches may be particularly

relevant when multiple implants are distributed across an edentulous arch, where errors generated at one region can potentially influence the accuracy of subsequent regions [4].

The transfer of accurate implant information into the CAD/CAM environment is essential for obtaining an appropriate prosthetic fit. A discrepancy between the actual implant positions and their digitally reproduced locations can result in misadaptation at the implant–prosthesis interface. Inadequate adaptation may increase the possibility of technical complications such as screw loosening, component fracture, framework distortion, and unfavorable stress transmission. Therefore, achieving a passive or clinically acceptable fit remains an important objective during the fabrication of full-arch implant-supported restorations [5].

Zirconia has emerged as an increasingly used material for implant-supported full-arch prostheses because of its favorable mechanical strength, fracture resistance, biocompatibility, and esthetic potential. The development of monolithic zirconia has further expanded its application by reducing dependence on veneering ceramics and consequently minimizing certain complications associated with porcelain chipping or delamination. Available evidence indicates that zirconia-based full-arch prostheses can provide satisfactory clinical outcomes, although the incidence of mechanical complications and the limited duration of some follow-up studies warrant continued investigation [6].

Clinical evaluations of full-arch implant-supported zirconia restorations have demonstrated encouraging survival and complication profiles, supporting their use as an alternative to conventional metal-based restorative approaches in appropriately selected patients. However, restoration design, framework configuration, manufacturing method, implant distribution, and occlusal factors may influence the long-term behavior of these prostheses. Consequently, careful assessment of both the restorative material and the manufacturing protocol is required when evaluating the overall performance of full-arch zirconia rehabilitation [7].

The incorporation of a completely digital protocol has further enhanced the potential of zirconia for full-arch implant rehabilitation. A workflow incorporating digital implant impressions, virtual prosthesis design, CAD/CAM manufacturing, and definitive zirconia fabrication can provide a standardized pathway from clinical data acquisition to prosthesis delivery. Recent evidence suggests that such digitally fabricated full-arch zirconia restorations can demonstrate favorable clinical performance; however, variations in digital acquisition methods and manufacturing procedures may influence the final accuracy and prosthetic adaptation [8].

Although digital workflows are increasingly utilized in implant prosthodontics, assessment of their effectiveness should extend beyond the clinical appearance and short-term survival of the definitive restoration. In vitro evaluation can provide quantitative information regarding dimensional deviations, implant-position transfer, and prosthetic fit that may not be readily detected during routine clinical examination. Recent prospective evidence on digitally fabricated full-arch monolithic zirconia prostheses has further emphasized the clinical potential of integrated digital workflows while highlighting the importance of continued evaluation of their accuracy and long-term performance [9].

Therefore, there is a need for systematic evaluation of digital protocols that integrate implant scanning, virtual prosthesis design, CAD/CAM manufacturing, and zirconia fabrication within a single workflow. Combining clinical assessment with an in vitro evaluation may provide a more comprehensive understanding of the accuracy, efficiency, and clinical applicability of such protocols. The present study was therefore undertaken to evaluate a digital workflow for the fabrication of full-arch implant-supported zirconia prostheses, with specific emphasis on clinical performance, dimensional accuracy, prosthetic fit, fabrication efficiency, and associated technical complications.

MATERIALS & METHODS

Study Design and Participants

A comparative clinical study was conducted at a single tertiary care centre from January to March 2026 to evaluate and compare the accuracy, clinical efficiency, prosthetic fit, and patient-related outcomes associated with conventional and digital workflows for the fabrication of full-arch implant-supported zirconia prostheses. The study included 60 participants, who were divided equally into two groups, with 30 participants in each group. Participants were allocated to either the conventional workflow group or the digital workflow group according to the predetermined study protocol. All participants underwent a comprehensive clinical and radiographic assessment before initiation of prosthetic treatment. The treatment

procedures were performed following a standardized clinical protocol to minimize variations related to implant positioning, impression or scanning procedures, prosthetic fabrication, and clinical evaluation.

Group Allocation

- **Group I – Conventional workflow:** 30 participants received full-arch implant-supported zirconia prostheses fabricated using conventional clinical and laboratory procedures.
- **Group II – Digital workflow:** 30 participants received full-arch implant-supported zirconia prostheses fabricated using an intraoral digital scanning and CAD/CAM-based workflow.

The same general prosthetic principles and clinical criteria were followed for both groups, while the impression acquisition, prosthetic design, and fabrication procedures differed according to the assigned workflow.

Inclusion Criteria

Participants were eligible for inclusion when they fulfilled the following criteria:

- Adults requiring rehabilitation with full-arch implant-supported zirconia prosthesis
- Presence of adequately osseointegrated implants suitable for definitive prosthetic rehabilitation
- Sufficient implant distribution and prosthetic space to permit fabrication of a full-arch restoration
- Adequate residual bone and soft-tissue conditions around the implants
- Absence of active peri-implant infection or other pathological conditions affecting the implant sites
- Participants with adequate oral hygiene and willingness to comply with the prescribed maintenance protocol
- Participants who were able to understand the study procedures and provide informed consent
- Participants willing to attend the required clinical and follow-up appointments

Exclusion Criteria

Participants were excluded when any of the following conditions were present:

- Presence of active peri-implantitis or significant peri-implant bone loss
- Implants showing clinical mobility or inadequate osseointegration
- Severe systemic or local conditions that could adversely affect implant or prosthetic treatment
- Inadequate restorative space or unfavorable implant positioning that prevented fabrication of the planned prosthesis
- Severe parafunctional habits, such as uncontrolled bruxism, that could compromise the prosthetic restoration
- Poor oral hygiene that could not be adequately controlled before prosthetic rehabilitation
- Patients unwilling or unable to comply with follow-up requirements
- Incomplete clinical or radiographic records
- Participants who declined informed consent or requested withdrawal from the study

Clinical and Prosthetic Procedures

For the conventional workflow group, implant-level impressions were obtained using a standardized conventional impression technique. The resulting casts were used for laboratory fabrication and prosthetic framework design. The zirconia prostheses were subsequently fabricated using established laboratory procedures and evaluated clinically before definitive placement. For the digital workflow group, implant positions were recorded using an intraoral scanning procedure. The digital data were

transferred to the CAD/CAM software for virtual prosthetic planning and design. The definitive full-arch zirconia prostheses were manufactured using a computer-controlled milling and fabrication process. The prostheses were subsequently evaluated intraorally for passive fit, marginal adaptation, occlusion, and overall clinical acceptability.

Evaluation of Prosthetic Accuracy

The accuracy of the two workflows was assessed using 3D digital comparison methods. The definitive prosthetic data were compared with the reference implant or master dataset to determine the magnitude of spatial discrepancies.

The following parameters were evaluated:

- **3D deviation**, expressed in micrometres (µm)
- **Implant positional deviation**, expressed in micrometres (µm)
- **Marginal gap**, expressed in micrometres (µm)
- **Internal gap**, expressed in micrometres (µm)

Lower deviation and gap values were considered indicative of greater accuracy and improved prosthetic adaptation.

Clinical Evaluation

The completed prostheses were clinically examined for marginal adaptation, seating, occlusal contacts, and overall prosthetic fit. Any necessary chairside adjustments were recorded. The total workflow time, chairside time, and occlusal adjustment time were documented for comparison between the two treatment approaches.

Patient Satisfaction

Patient satisfaction was assessed following delivery of the definitive prosthesis using a standardized patient-reported assessment method. Participants evaluated relevant aspects of the prosthesis, including comfort, function, appearance, and overall satisfaction. Higher scores indicated greater patient satisfaction.

Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS), IBM SPSS Statistics for Windows, version 26.0 (IBM Corp., Armonk, NY, USA). Appropriate descriptive and inferential statistical methods were applied according to the type and distribution of the data. Continuous variables such as age were expressed as mean ± standard deviation (SD), while categorical variables were summarized as frequencies and percentages. For comparison of continuous variables between the conventional and digital workflow groups, an independent-samples Student's t-test was used, including comparisons of total workflow time, chairside time, occlusal adjustment time, clinical prosthesis fit, patient satisfaction, 3D deviation, implant positional deviation, and marginal and internal gaps. Categorical variables, including sex distribution, arch evaluated, acceptable prosthesis fit, occlusal adjustment requirement, patient satisfaction category, and prosthetic complications, were compared using the Chi-square (χ^2) test. The association between 3D deviation and clinical prosthesis fit was evaluated using Pearson's correlation coefficient (r). A two-tailed p-value <0.05 was considered statistically significant, while $p<0.001$ was considered highly statistically significant.

RESULTS

Table 1 & Figure 1 summarize the baseline demographic characteristics of the participants enrolled in the clinical evaluation. The study included 60 participants, with 30 individuals allocated to each study group. The mean age was 56.34 ± 8.63 years in the conventional workflow group and 55.84 ± 7.08 years in the digital workflow group. No statistically significant difference in age was observed between the groups ($p = 0.806$), suggesting adequate comparability at baseline. In terms of sex distribution, the conventional workflow group included 18 males (60.0%) and 12 females (40.0%), while the digital workflow group comprised 17 males (56.7%) and 13 females (43.3%). The difference in sex distribution was not statistically significant ($p = 0.793$). Overall, the two groups demonstrated comparable baseline demographic profiles with respect to both age and sex.

Table 1: Demographic characteristics of clinical participants

Variable	Conventional workflow (n=30)	Digital workflow (n=30)	p-value
Age (years), Mean ± SD	56.34 ± 8.63	55.84 ± 7.08	0.806
Male, n (%)	18 (60.0%)	17 (56.7%)	0.793
Female, n (%)	12 (40.0%)	13 (43.3%)	0.793

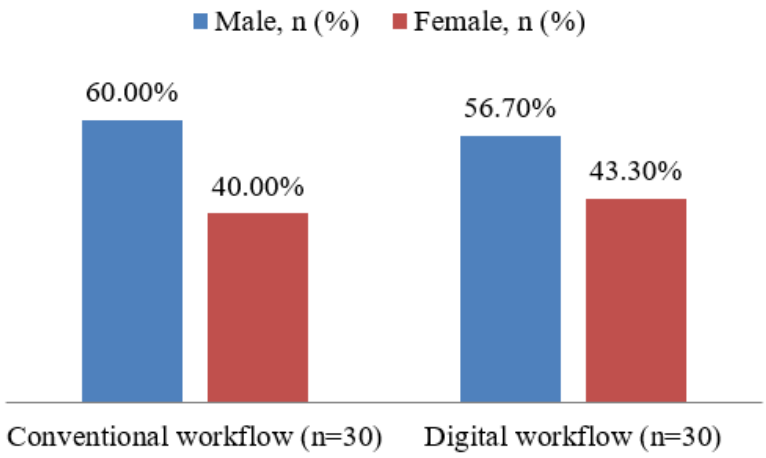

Figure 1: Comparative assessment of age and sex distribution across the two study groups

Table 2 & Figure 2 illustrate the distribution of the maxillary and mandibular arches across the two workflow groups. In the conventional workflow group, the maxillary arch was assessed in 16 participants (53.3%), while the mandibular arch was evaluated in 14 participants (46.7%). In the digital workflow group, 15 participants (50.0%) were assessed for the maxillary arch and 15 participants (50.0%) for the mandibular arch. The difference in arch distribution between the conventional and digital workflow groups was not statistically significant (p = 0.793). These findings indicate that the two groups were well balanced with respect to the distribution of maxillary and mandibular arches included in the evaluation.

Table 2: Distribution according to arch evaluated

Arch	Conventional workflow n (%)	Digital workflow n (%)	p-value
Maxillary	16 (53.3%)	15 (50.0%)	0.793
Mandibular	14 (46.7%)	15 (50.0%)	0.793

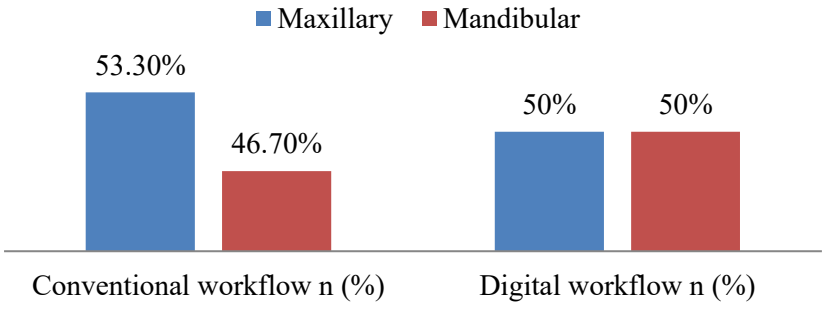

Figure 2: Comparative distribution of maxillary and mandibular arch assessments between the two study groups

Table 3 & Figure 3 present a comparative analysis of the time requirements associated with the conventional and digital workflows. The total workflow time was considerably greater in the conventional workflow group (189.09 ± 16.30 minutes) than in the digital workflow group (133.24 ± 17.97 minutes). The mean difference between the groups was 55.85 minutes, with a t-value of 12.61, and this difference was statistically significant ($p < 0.001$). The mean chairside time was 132.31 ± 10.90 minutes for the conventional workflow group and 96.82 ± 12.31 minutes for the digital workflow group. The digital workflow therefore resulted in a mean reduction of 35.50 minutes in chairside time. This difference was statistically significant ($t = 11.82$, $p < 0.001$). Similarly, the mean occlusal adjustment time was significantly shorter in the digital workflow group (10.27 ± 4.01 minutes) than in the conventional workflow group (18.43 ± 5.95 minutes). The mean difference was 8.16 minutes, with a t-value of 6.22, and the difference was statistically significant ($p < 0.001$). Overall, the findings indicate that the digital workflow substantially improved time efficiency by significantly reducing total workflow time, chairside time, and occlusal adjustment time compared with the conventional workflow.

Table 3: Comparison of workflow and clinical time

Outcome	Conventional Mean ± SD	Digital Mean ± SD	Mean difference	t-value	p-value
Total workflow time (min)	189.09 ± 16.30	133.24 ± 17.97	55.85	12.61	<0.001
Chairside time (min)	132.31 ± 10.90	96.82 ± 12.31	35.50	11.82	<0.001
Occlusal adjustment time (min)	18.43 ± 5.95	10.27 ± 4.01	8.16	6.22	<0.001

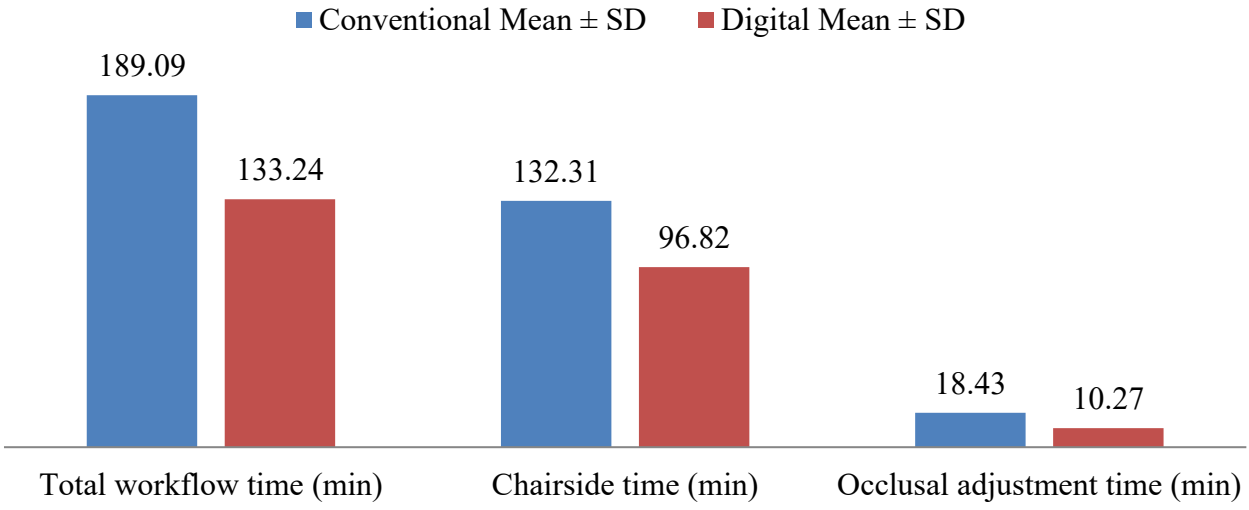

Figure 3: Comparative evaluation of total workflow, chairside, and occlusal adjustment times between the two study groups

Table 4 & Figure 4 compare the clinical prosthesis fit and patient satisfaction scores between the conventional and digital workflow groups. The mean clinical fit score was 3.67 ± 0.51 in the conventional workflow group, compared with 4.16 ± 0.51 in the digital workflow group. The mean difference was −0.48, with a corresponding t-value of −3.65. This difference was statistically significant ($p < 0.001$), indicating a significantly superior clinical fit in the digital workflow group. The mean patient satisfaction score was 3.51 ± 0.55 in the conventional workflow group, whereas the digital workflow group recorded a higher mean score of 4.41 ± 0.50. The mean difference between the groups was −0.90, with a corresponding t-value of −6.66. This difference was statistically significant ($p < 0.001$), demonstrating significantly greater patient satisfaction with the digital workflow. Overall, both clinical prosthesis fit and patient satisfaction were significantly improved in the digital workflow group compared with the conventional workflow group. These findings suggest that the digital workflow facilitated better clinical adaptation of the full-arch zirconia prostheses and contributed to a more favorable treatment experience for patients.

Table 4: Clinical assessment of prosthesis fit and patient satisfaction

Outcome	Conventional Mean ± SD	Digital Mean ± SD	Mean difference	t-value	p-value
Clinical fit score (1–5)	3.67 ± 0.51	4.16 ± 0.51	-0.48	-3.65	<0.001
Patient satisfaction (1–5)	3.51 ± 0.55	4.41 ± 0.50	-0.90	-6.66	<0.001

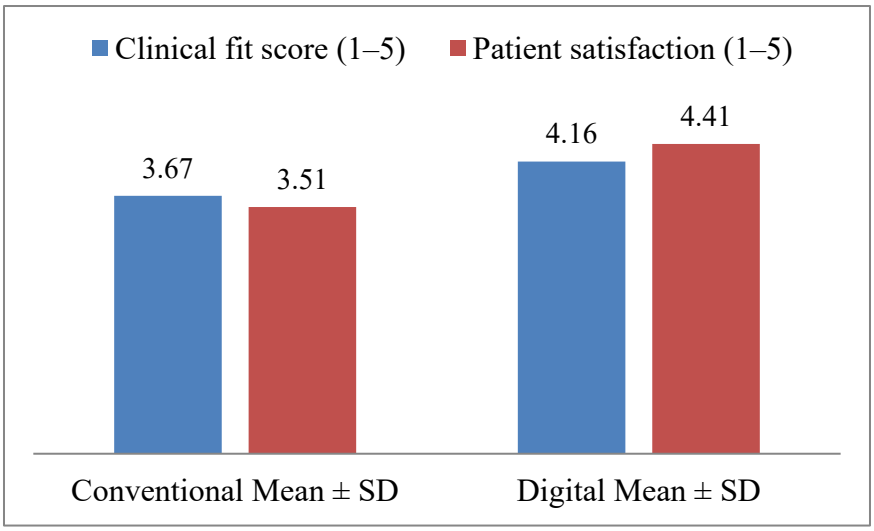

Figure 4: Comparative assessment of clinical prosthesis fit and patient satisfaction between the two study groups

Table 5 & Figure 5 summarize the categorical clinical outcomes observed in the conventional and digital workflow groups. An acceptable prosthesis fit was achieved in 24 cases (80.0%) in the conventional workflow group, compared with 28 cases (93.3%) in the digital workflow group. Despite the higher proportion of acceptable prosthesis fits in the digital workflow group, the difference was not statistically significant ($\chi^2 = 2.31$, $p = 0.129$). With respect to occlusal adjustment requirements, no adjustment was necessary in 9 cases (30.0%) in the conventional workflow group, whereas 18 cases (60.0%) in the digital workflow group required no occlusal adjustment. The difference was statistically significant ($\chi^2 = 5.45$, $p = 0.020$), indicating that prostheses fabricated using the digital workflow were significantly more likely to require no occlusal adjustment. The absence of major complications was observed in 27 cases (90.0%) in the conventional workflow group and 29 cases (96.7%) in the digital workflow group. However, this difference was not statistically significant ($\chi^2 = 1.07$, $p = 0.301$), suggesting comparable rates of major complications between the two workflows. A patient-rated satisfaction score of ≥4/5 was reported by 19 participants (63.3%) in the conventional workflow group and 26 participants (86.7%) in the digital workflow group. This difference was statistically significant ($\chi^2 = 4.36$, $p = 0.037$), demonstrating a significantly greater proportion of highly satisfied participants in the digital workflow group. Overall, the digital workflow demonstrated more favorable categorical clinical outcomes, particularly in terms of reduced occlusal adjustment requirements and higher patient satisfaction. Although acceptable prosthesis fit and freedom from major complications were more frequently observed with the digital workflow, the differences in these outcomes were not statistically significant.

Table 5: Categorical Clinical Outcomes

Clinical outcome	Conventional n (%)	Digital n (%)	χ^2	p-value
Acceptable prosthesis fit	24 (80.0%)	28 (93.3%)	2.31	0.129
No occlusal adjustment required	9 (30.0%)	18 (60.0%)	5.45	0.020
No major complication	27 (90.0%)	29 (96.7%)	1.07	0.301
Patient-rated satisfaction ≥4/5	19 (63.3%)	26 (86.7%)	4.36	0.037

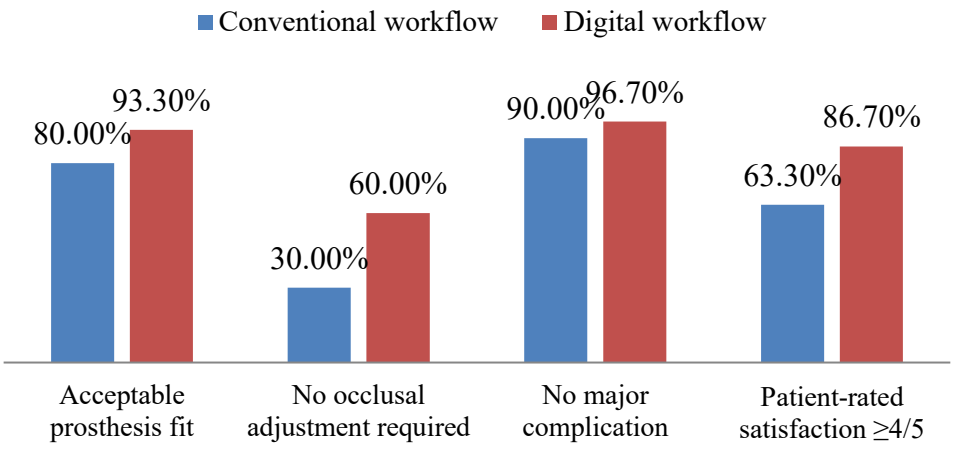

Figure 5: Comparative analysis of categorical clinical outcomes between the two study groups

Table 6 & Figure 6 present the distribution of prosthetic complications recorded during the clinical evaluation. The majority of prostheses in both workflow groups were completed without any prosthetic complications. No complications were reported in 27 cases (90.0%) in the conventional workflow group and 29 cases (96.7%) in the digital workflow group. Minor complications occurred in 2 cases (6.7%) in the conventional workflow group and 1 case (3.3%) in the digital workflow group. Major complications were identified in 1 case (3.3%) in the conventional workflow group, whereas no major complications were observed in the digital workflow group **(**0.0%**).**

Overall, prosthetic complications were uncommon in both groups. The digital workflow demonstrated a numerically lower incidence of both minor and major complications than the conventional workflow. Furthermore, the high proportion of complication-free cases in the digital workflow group indicates favorable clinical performance of the digitally fabricated prostheses during the evaluation period.

Table 6: Prosthetic complications during clinical evaluation

Complication status	Conventional workflow	Digital workflow
No complication	27 (90.0%)	29 (96.7%)
Minor complication	2 (6.7%)	1 (3.3%)
Major complication	1 (3.3%)	0 (0.0%)

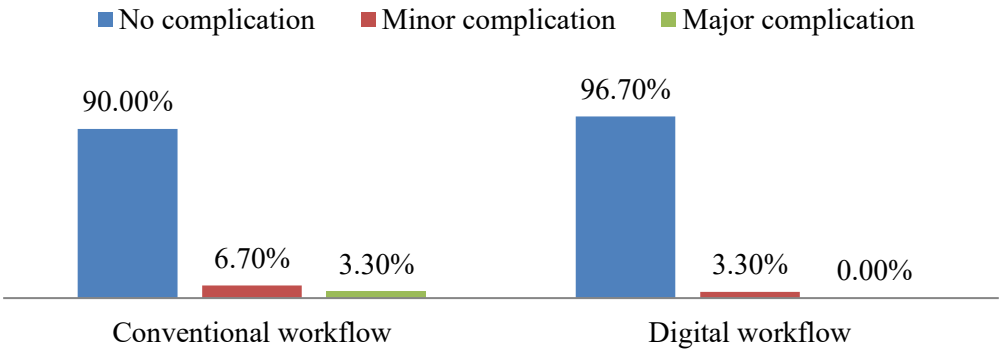

Figure 6: Comparative distribution of prosthetic complications between the two study groups

Table 7 & Figure 7 present the in vitro comparison of 3D accuracy and implant positional deviation between the conventional and digital workflows. The mean 3D deviation was 84.96 ± 15.39 µm in the conventional workflow group, whereas a considerably lower value of 49.54 ± 11.87 µm was recorded for the digital workflow group. The mean difference between the groups was 35.42 µm, with a corresponding *t*-value of 11.53. This difference was statistically significant ($p < 0.001$), demonstrating significantly greater 3D accuracy with the digital workflow.

The mean implant positional deviation was 82.96 ± 20.05 µm in the conventional workflow group and 46.32 ± 9.63 µm in the digital workflow group. The mean difference was 36.65 µm, with a corresponding *t*-value of 10.42. The difference was statistically significant ($p < 0.001$), indicating significantly lower implant positional deviation with the digital workflow.

Overall, the in vitro assessment demonstrated that the digital workflow achieved significantly higher 3D accuracy and greater implant positional accuracy than the conventional workflow. The lower deviation values observed in the digital group suggest a more precise transfer of the planned implant positions to the definitive full-arch zirconia prosthesis.

Table 7: In vitro evaluation of 3D accuracy

Parameter	Conventional Mean ± SD	Digital Mean ± SD	Mean difference	t-value	p-value
3D deviation (µm)	84.96 ± 15.39	49.54 ± 11.87	35.42	11.53	<0.001
Implant positional deviation (µm)	82.96 ± 20.05	46.32 ± 9.63	36.65	10.42	<0.001

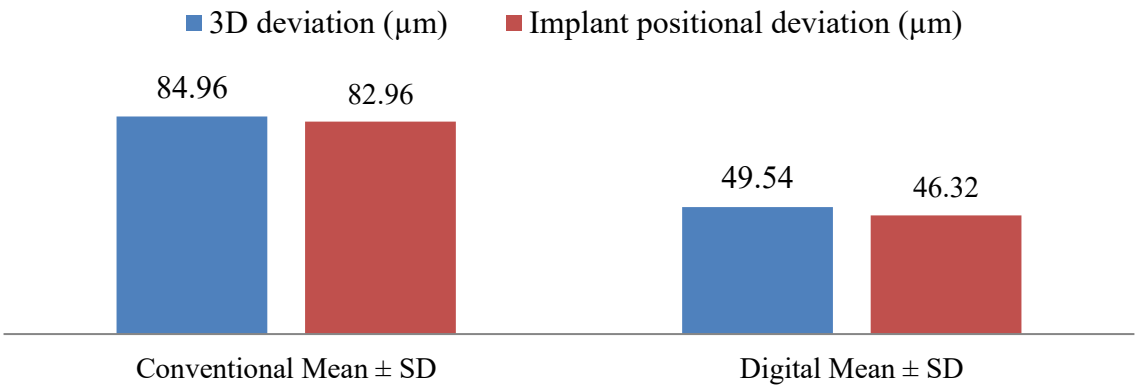

Figure 7: Comparative evaluation of 3D accuracy and implant positional deviation between the two study groups

Table 8 & Figure 8 present a comparative assessment of the marginal and internal fit of the prostheses fabricated using the conventional and digital workflows. The mean marginal gap measured 89.71 ± 20.10 µm in the conventional workflow group, while the digital workflow group showed a considerably smaller mean marginal gap of 58.45 ± 14.92 µm. The mean difference between the groups was 31.25 µm, with a corresponding *t*-value of 7.90. This difference was statistically significant ($p < 0.001$), demonstrating significantly better marginal adaptation in the digital workflow group. The mean internal gap was 119.36 ± 27.70 µm in the conventional workflow group and 96.20 ± 24.04 µm in the digital workflow group. The mean difference between the groups was 23.16 µm, with a corresponding *t*-value of 3.99. This difference was statistically significant ($p < 0.001$), indicating a significantly smaller internal gap with the digital workflow. Overall, both marginal and internal gap measurements were significantly lower in the digital workflow group than in the conventional workflow group. These findings indicate that the digital workflow provided superior marginal and internal adaptation of the full-arch implant-supported zirconia prostheses.

Table 8: Marginal and internal fit

Parameter	Conventional Mean ± SD	Digital Mean ± SD	Mean difference	t-value	p-value
Marginal gap (µm)	89.71 ± 20.10	58.45 ± 14.92	31.25	7.90	<0.001
Internal gap (µm)	119.36 ± 27.70	96.20 ± 24.04	23.16	3.99	<0.001

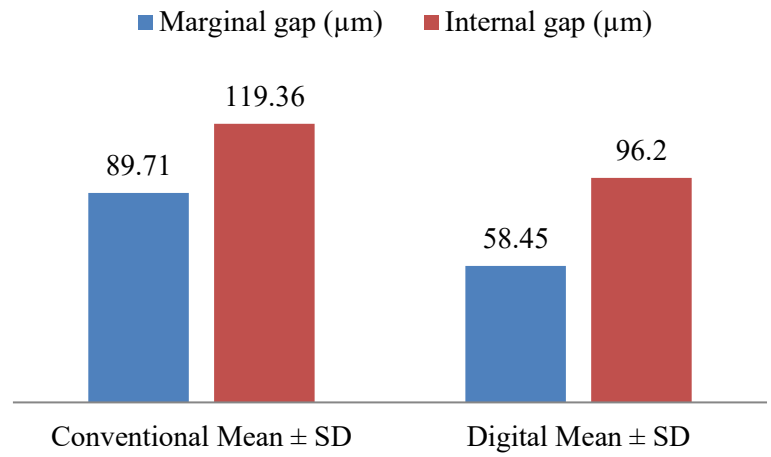

Figure 8: Comparative evaluation of marginal and internal fit of full-arch implant-supported zirconia prostheses fabricated between the two study groups

Table 9 & Figure 9 present a comparative evaluation of implant positional deviation across different implant locations in the conventional and digital workflow groups. In the anterior region, the mean positional deviation was 71.92 ± 11.06 µm for the conventional workflow and 43.91 ± 8.66 µm for the digital workflow. The difference was statistically significant ($t = 12.61$, $p < 0.001$), indicating significantly greater positional accuracy with the digital workflow. In the premolar region, the mean implant positional deviation was 82.05 ± 12.06 µm in the conventional workflow group, compared with 50.42 ± 9.65 µm in the digital workflow group. A statistically significant difference was observed between the groups ($t = 12.95$, $p < 0.001$), demonstrating superior positional accuracy with the digital workflow in the premolar region.

In the molar region, the conventional workflow group exhibited a mean positional deviation of 96.96 ± 12.88 µm, whereas the digital workflow group showed a considerably lower value of 54.68 ± 9.47 µm. This difference was statistically significant ($t = 16.73$, $p < 0.001$), further supporting the higher positional accuracy achieved with the digital workflow. Overall, implant positional deviation was significantly lower with the digital workflow across all three implant locations. In both groups, the deviation was lowest in the anterior region and increased progressively toward the molar region. Despite this regional variation, the digital workflow consistently demonstrated greater implant positional accuracy than the conventional workflow across the anterior, premolar, and molar regions.

Table 9: Implant positional deviation at different implant locations

Implant location	Conventional Mean ± SD (µm)	Digital Mean ± SD (µm)	t-value	p-value
Anterior	71.92 ± 11.06	43.91 ± 8.66	12.61	<0.001
Premolar	82.05 ± 12.06	50.42 ± 9.65	12.95	<0.001
Molar	96.96 ± 12.88	54.68 ± 9.47	16.73	<0.001

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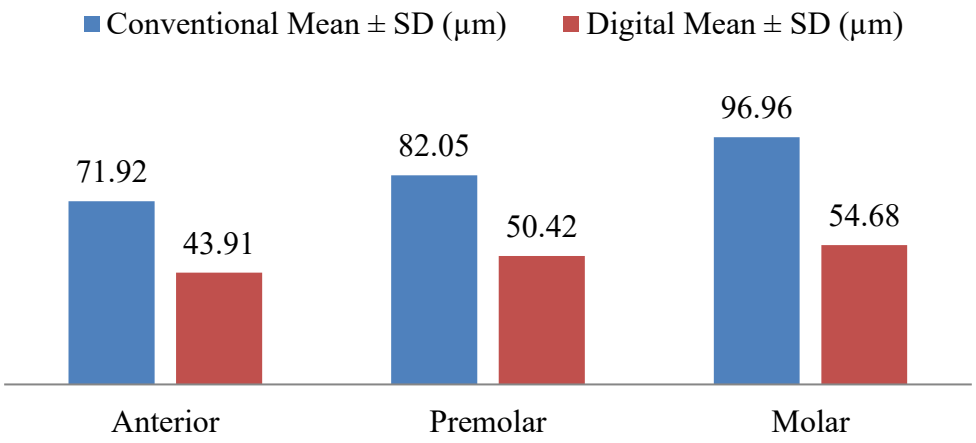

Figure 9: Comparative evaluation of implant positional deviation across anterior, premolar, and molar regions using the two study groups

Table 9 presents the correlation between 3D deviation and clinical prosthesis fit score, assessed using Pearson's correlation analysis. A statistically significant negative correlation was identified between 3D deviation and clinical fit score ($r = -0.577$, $p < 0.001$). The inverse relationship indicates that greater 3D deviation was associated with lower clinical fit scores, whereas smaller deviations corresponded to higher prosthesis fit scores. The correlation coefficient ($r = -0.577$) represents a moderate negative correlation between the variables. These findings indicate that greater 3D accuracy, reflected by lower deviation values, was associated with improved clinical adaptation and fit of the full-arch implant-supported zirconia prostheses. Nevertheless, the observed correlation represents an association between the variables and does not establish a causal relationship.

Table 10: Correlation between 3D deviation and clinical fit

Variables	Correlation coefficient (r)	p-value	Interpretation
3D deviation vs clinical fit score	-0.577	<0.001	Negative correlation; greater deviation was associated with lower fit score

DISCUSSION

Papaspyridakos et al. (2020) [10] demonstrated the clinical feasibility of a complete digital workflow for implant rehabilitation using double full-arch monolithic zirconia prostheses. Their approach integrated digital implant impressions, virtual prosthetic planning, CAD/CAM procedures, and zirconia prosthesis fabrication, thereby reducing dependence on conventional laboratory procedures. These findings support the concept that digital technologies can simplify the management of complex full-arch implant cases while maintaining an efficient and predictable restorative workflow. The present study similarly emphasizes the integration of digital data acquisition, virtual planning, and CAD/CAM fabrication for full-arch implant-supported zirconia prostheses.

Papaspyridakos et al. (2021) [11] further illustrated the potential of digital dentistry by describing a complete mandibular full-arch implant rehabilitation accomplished within three clinical appointments. Their workflow incorporated digital planning and fabrication techniques to streamline the transition from implant placement to definitive prosthetic restoration. The reduction in the number of clinical visits highlights an important advantage of digital workflows, particularly in terms of treatment efficiency, communication between clinical and laboratory teams, and patient convenience. The findings of the present study are consistent with this concept, indicating that a structured digital workflow can facilitate more efficient management of full-arch implant-supported prosthetic rehabilitation.

Chochlidakis et al. (2022) [12] evaluated the double digital scanning technique for fabrication of prosthesis prototypes in edentulous maxillary arches. Their prospective investigation demonstrated that digitally fabricated prototypes could achieve accurate adaptation to verified master casts. This finding is particularly relevant to full-arch rehabilitation because prototype verification provides an opportunity to identify discrepancies before fabrication of the definitive prosthesis. The use of digital scanning and virtual duplication may therefore contribute to improved predictability and reduce the risk of transferring errors to the final restoration. The present study similarly supports the importance of digital verification and intermediate evaluation in achieving accurate full-arch zirconia prosthesis.

Wadhawan et al. (2024) [13] discussed the expanding role of digital technologies and artificial intelligence (AI) in prosthodontics, particularly in diagnosis, treatment planning, virtual prosthetic design, and CAD/CAM-based fabrication. Their work highlighted how digital integration can improve workflow efficiency, enhance treatment planning, and facilitate more predictable prosthetic outcomes. Although their discussion extended beyond full-arch implant rehabilitation, the principles are directly applicable to digitally fabricated implant-supported restorations. The present study builds upon these concepts by evaluating a structured digital workflow specifically for full-arch implant-supported zirconia prostheses, where accurate data acquisition, virtual design, and manufacturing precision are essential.

Pan et al. (2022) [14] investigated the cumulative influence of errors occurring throughout the digital workflow for complete-arch implant-supported frameworks. Their in vitro findings emphasized that inaccuracies may accumulate at different stages, particularly during data acquisition and computer-aided manufacturing. Importantly, although some aspects of the complete digital workflow demonstrated clinically acceptable accuracy, certain angular discrepancies remained a concern. These observations highlight that digital dentistry does not completely eliminate technical errors; rather, accuracy depends on careful control of each individual stage of the workflow. The present study therefore underscores the importance of standardized scanning, precise virtual alignment, appropriate CAD procedures, and controlled manufacturing to minimize cumulative discrepancies in full-arch zirconia prostheses.

Cai et al. (2024) [15] conducted a systematic review and meta-analysis comparing intraoral scanning with conventional implant impressions in completely edentulous patients. Their analysis included 49 studies and demonstrated that the accuracy of digital impressions was generally clinically acceptable, although the results varied according to measurement method and implant configuration. The authors also emphasized the influence of scanning conditions and the need for additional clinical evidence. These findings reinforce the importance of accurate digital data acquisition as a fundamental component of full-arch implant rehabilitation and support further evaluation of standardized digital workflows for zirconia prosthesis fabrication.

Collectively, the findings reported by above mentioned studies demonstrate the progressive development of digital workflows in full-arch implant prosthodontics. The literature indicates that digital approaches can improve treatment efficiency, facilitate prosthetic design, support prototype verification, and reduce dependence on conventional laboratory procedures. At the same time, the potential accumulation of errors throughout scanning, virtual planning, and manufacturing remains an important consideration. These findings provide a strong rationale for evaluating the overall clinical and in vitro performance of a standardized digital workflow for full-arch implant-supported zirconia prostheses

LIMITATIONS

The present study has certain limitations that should be considered when interpreting the findings. First, the study included a relatively limited sample of 60 participants, with 30 participants in each workflow group, which may restrict the statistical power and generalizability of the findings to larger and more diverse patient populations. Second, the clinical evaluation was conducted within a defined study setting and under controlled conditions; therefore, the results may not fully reflect variations encountered in routine clinical practice across different operators, institutions, and patient populations. Another limitation is that the assessment involved both clinical and in vitro outcomes, and the in vitro measurements of 3D accuracy and implant positional deviation may not completely represent the biological and functional conditions encountered intraorally. Although the digital workflow demonstrated lower deviations and improved prosthetic fit, factors such as patient-related movement, soft-tissue conditions, occlusal dynamics, and long-term functional loading may influence clinical outcomes. The study also evaluated prosthetic complications during the clinical evaluation period, and the relatively low frequency of complications limits the ability to draw definitive conclusions regarding differences in complication rates

between the two workflows. Furthermore, although a significant correlation was identified between 3D deviation and clinical prosthesis fit, the observational nature of this association does not establish a direct causal relationship.

Finally, the findings were based on the specific conventional and digital workflow protocols used in the present investigation. Differences in scanning systems, software, milling or fabrication protocols, implant systems, materials, and operator experience may influence workflow efficiency and prosthetic accuracy. Long-term, multicenter studies involving larger samples, standardized protocols, multiple operators, and extended clinical follow-up are therefore recommended to validate the present findings and determine their broader clinical applicability.

CONCLUSION

Within the limitations of the present study, the digital workflow demonstrated more favorable outcomes than the conventional workflow for full-arch implant-supported zirconia prostheses. It significantly reduced total workflow, chairside, and occlusal adjustment times while achieving better clinical fit and patient satisfaction. A greater proportion of digital prostheses required no occlusal adjustment, and more patients reported satisfaction scores. The digital workflow also showed significantly lower 3D and implant positional deviations, marginal gaps, and internal gaps. Implant positional deviation was consistently lower across anterior, premolar, and molar regions, although it increased toward the posterior region in both workflows. The moderate negative correlation between 3D deviation and clinical fit indicated that lower deviation was associated with better prosthetic fit. Overall, the digital workflow appears to offer greater accuracy, efficiency, prosthetic adaptation, and patient satisfaction. Larger, long-term clinical studies are recommended to validate these findings.

Conflicts of Interest: Nil

Financial Support: None

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