

Review article

Impact of Digital Manufacturing Techniques on the Accuracy of Single Unit Fixed Prostheses: A Clinical and Laboratory Study

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ABSTRACT

Keywords:

CAD/CAM, Single unit fixed prostheses, Marginal accuracy, Proximal contact, Digital workflow, Lost wax technique

This clinical and laboratory study evaluated the impact of computer aided design and computer aided manufacturing (CAD/CAM) technologies on the accuracy of single unit fixed prostheses, specifically full crowns, in terms of marginal fit, proximal contact integrity, and occlusal accuracy, compared with the conventional lost wax casting technique. A randomized controlled trial was conducted involving 80 patients requiring single unit crowns. Participants were allocated equally into CAD/CAM (n=40) and conventional (n=40) groups. Marginal gap measurements were obtained from 1,280 measurement points using digital microscopy at 50× magnification. The CAD/CAM system demonstrated statistically significant superiority across multiple parameters. Marginal gaps were substantially reduced in the CAD/CAM group ($54.3 \pm 5.8 \mu\text{m}$) compared with conventional techniques ($78.6 \pm 9.2 \mu\text{m}$; $p < 0.001$). Digitally fabricated restorations exhibited higher consistency and predictability, with a 68% reduction in the need for clinical adjustments compared with conventional methods. Overall fit was rated as excellent in 60% of CAD/CAM crowns versus 40% of conventional crowns. Marginal adaptation was judged superior in 70% of CAD/CAM restorations, and occlusal accuracy was rated ideal in 80% of CAD/CAM crowns compared with 50% in the conventional group. CAD/CAM technology significantly enhances marginal adaptation and occlusal accuracy while reducing chairside time and clinical adjustments. However, conventional methods demonstrated superior proximal contact accuracy, suggesting that hybrid approaches or further technological refinement may optimize outcomes across all parameters.

Introduction

The integration of digital manufacturing technologies in dentistry has fundamentally transformed prosthodontic practice. Computer aided design and computer aided manufacturing (CAD/CAM) systems have become indispensable components of contemporary dental workflows, offering unprecedented precision throughout the prosthetic fabrication process from digital impression acquisition and virtual design to subtractive milling or additive three dimensional printing (1,3,6). Despite widespread clinical adoption, the dental literature demonstrates a persistent need for rigorous comparative studies examining the actual accuracy of digitally fabricated restorations against conventionally produced counterparts (4,7). This need is particularly pronounced for single unit restorations, which demand exceptional precision in marginal adaptation and occlusal accuracy to ensure long term clinical success, periodontal health, and patient satisfaction (5,8). The conventional lost wax casting technique, while well established and extensively validated, is inherently susceptible to operator dependent variables and laboratory induced errors, including expansion contraction discrepancies, investment material variability, and casting imperfections (3,6). Conversely, digital workflows offer theoretical advantages in consistency, reproducibility, and accuracy, yet the extent to which these theoretical benefits translate to clinical superiority requires systematic investigation (2,7).

The evolution of intraoral scanning technology has significantly enhanced the accuracy of digital impressions, reducing the potential for dimensional errors associated with conventional elastomeric impression materials and gypsum cast fabrication (6,8). Furthermore, advancements in milling technology and the development of high strength ceramic materials have expanded the indications for CAD/CAM restorations, making them a viable alternative to conventional casting techniques across a wide range of clinical scenarios (1,4).

This study aimed to critically evaluate and compare the accuracy of single unit fixed prostheses fabricated using CAD/CAM technology versus conventional lost wax casting techniques, with specific emphasis on marginal fit, proximal contact integrity, and occlusal accuracy.

Methodology

A randomized controlled clinical and experimental investigation was conducted at the Department of Fixed Prosthodontics, Faculty of Dental Technology, Tripoli, Libya and private dental clinics in Tripoli, between February 2023 and March 2025. The study protocol received institutional ethical approval EA 17-025, and all participants provided written informed consent prior to enrollment.

Sample Selection and Participant Demographics

Eighty patients (40 males and 40 females) with a mean age of 34 ± 8 years were included in the study. Inclusion criteria required a single full coverage crown indication for maxillary or mandibular premolars or molars. Patients with active periodontal disease, severe bruxism, or insufficient tooth structure for crown preparation were excluded from the study. Patients were randomly allocated into two equal groups:

CAD/CAM Group (n = 40): Crowns were fabricated using a complete digital workflow, including digital impression acquisition with the CEREC Primescan intraoral scanner (Dentsply Sirona), computer aided design, and milling using the MC X5 milling unit (Dentsply Sirona).

Conventional Group (n = 40): Crowns were fabricated using a conventional workflow comprising polyvinyl siloxane (PVS) impressions, gypsum cast fabrication, and the lost wax technique with nickel–chromium alloy casting.

Standardized Tooth Preparation

All tooth preparations were performed by a single calibrated operator according to standardized criteria based on established prosthodontic principles (3,6):

- Occlusal reduction: 1.5–2.0 mm
- Convergence angle: 6–10°
- Finish line: 1.0 mm shoulder
- Fabrication Protocols

Digital Group: Digital impressions were obtained using the CEREC Primescan intraoral scanner. Crown designs were completed using CEREC Software version 5.2, followed by milling from high purity zirconia blocks (Zenostar MT) as recommended by previous studies (1,6).

Conventional Group: Impressions were made using polyvinyl siloxane (PVS) elastomeric material, followed by gypsum cast fabrication. Crowns were manufactured using the lost wax technique with subsequent nickel–chromium alloy casting according to conventional laboratory protocols (3,6).

Measurement Methodology

Marginal Gap Assessment: Marginal gap measurements were performed using a digital microscope at 50× magnification. Sixteen standardized measurement points were recorded for each crown, yielding a total of 1,280 individual measurements across both groups, consistent with methodologies described in previous studies (4,7).

Evaluation of Clinical Parameters: Three calibrated independent evaluators, blinded to the fabrication method, assessed overall fit, marginal adaptation, occlusal accuracy, and proximal contact integrity using standardized criteria based on established prosthodontic evaluation protocols (5,8).

Statistical Analysis

Data were analyzed using SPSS software (IBM Corp., Version 26.0). Descriptive statistics, including means and standard deviations, were calculated for marginal gap values in both study groups. One way analysis of variance (One Way ANOVA) was employed for intergroup comparisons, with statistical significance established at $p < 0.05$.

Results

A total of 80 monolithic lithium disilicate crowns were evaluated, comprising 40 crowns fabricated using CAD/CAM technology and 40 crowns produced via conventional lost wax casting techniques. Clinical assessment was performed across four key parameters: overall fit, marginal adaptation, occlusal accuracy, and proximal contact integrity. The results demonstrated distinct patterns of performance for each fabrication method across the evaluated parameters, with CAD/CAM technology showing clear advantages in certain domains while conventional techniques excelled in others.

Marginal Gap Assessment

A total of 1,280 marginal gap measurements were analyzed (640 measurements per group). The CAD/CAM group exhibited significantly smaller marginal gaps compared with the conventional group, confirming superior marginal adaptation for digitally fabricated crowns as shown in table 1

Table 1: Descriptive Statistics for Marginal Gap Assessment

Group	N	Mean (μm)	Std. Deviation	Std. Error Mean
CAD/CAM	640	54.3	5.8	0.229
Conventional	640	78.6	9.2	0.364
Total	1,280	66.45	14.12	0.395

One Way ANOVA for Marginal Gap Measurements

The one way analysis of variance revealed a statistically significant difference between groups ($F = 3,456.78$; $p < 0.001$). The CAD/CAM group demonstrated a mean marginal gap of $54.3 \pm 5.8 \mu\text{m}$, while the conventional group showed a significantly larger mean of $78.6 \pm 9.2 \mu\text{m}$, representing a mean difference of $24.3 \mu\text{m}$ in favor of digital fabrication as demonstrated in table 2.

Table 2: One Way ANOVA for Marginal Gap Measurements

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	189,225.60	1	189,225.60	3,456.78	< 0.001
Within Groups	69,912.45	1,278	54.70		
Total	259,138.05	1,279			

Clinical Evaluation Parameters

Clinical evaluation of 80 crowns (40 CAD/CAM, 40 conventional) revealed that CAD/CAM restorations demonstrated superior overall fit (60% excellent vs. 40%), marginal adaptation (70% superior vs. 30%), and occlusal accuracy (80% ideal vs. 50%), with no CAD/CAM crowns requiring adjustment compared with 20% of conventional crowns. However, conventional crowns achieved better proximal contact accuracy (60% optimal vs. 40%) as showed in table 3.

Table 3: Clinical Evaluation Parameters for CAD/CAM versus Conventional Crowns

Parameter	Rating	CAD/CAM (%)	Conventional (%)
Overall Fit	Excellent	60	40
	Acceptable	40	40
	Requiring Adjustment	0	20
Marginal Adaptation	Superior	70	30
	Not Superior	30	70
Occlusal Accuracy	Ideal	80	50
	Not Ideal	20	50
Proximal Contact	Optimal	40	60
	Suboptimal	60	40

Discussion

The findings of this study demonstrate a clear preference among evaluators for CAD/CAM restorations in terms of marginal fit and occlusal accuracy parameters critically associated with long term periodontal health, resistance to recurrent caries, and functional performance. This superiority is likely attributable to the high precision afforded by digital scanning and controlled subtractive milling processes, which substantially minimize operator dependent variability and laboratory errors induced in traditional workflows (1,2,7). These findings align with research conducted in the Libyan context, where Eljabali et al. [9] assessed die spacing materials for metal crowns and emphasized the importance of precise marginal fit in fixed prosthodontics. Furthermore, a Libyan multi-center study by Hwisa et al. [10] reported that 63.9% of final year dental students were aware of CAD/CAM clinical applications, with crown and bridge fabrication being the most recognized use (66.4%), reflecting growing adoption of digital technologies in Libyan dental education and practice.

The statistically significant reduction in marginal gaps observed in the CAD/CAM group ($54.3 \mu\text{m}$ versus $78.6 \mu\text{m}$) is clinically meaningful, as marginal discrepancies exceeding $100 \mu\text{m}$ are generally considered unacceptable and associated with increased cement dissolution, bacterial colonization, and periodontal inflammation (3,6). The CAD/CAM group consistently achieved marginal gaps well within clinically acceptable thresholds, whereas the conventional group exhibited greater variability and approached the upper limits of clinical acceptability. These findings corroborate the systematic review by Tsirogiannis et al. (1), which reported superior marginal fit for CAD/CAM restorations across multiple ceramic systems, and are consistent with the meta-analysis by Al Hamad et al. (4) demonstrating a significant reduction in marginal discrepancies with digital workflows. However, it is important to note that a recent systematic review and meta-analysis comparing CAD/CAM and conventional techniques found a pooled mean difference of only $2.3 \mu\text{m}$ (95% CI, 10.6 to $+5.9 \mu\text{m}$; $P = .582$), suggesting that when studies are pooled, the difference may not be statistically significant, though substantial heterogeneity ($I^2 = 95.2\%$) was noted [9]. This highlights that conventional techniques performed by experienced technicians can achieve similarly successful outcomes within clinically acceptable limits ($< 120 \mu\text{m}$) [9]. Notably, a study from the

University of Tripoli by Zeglam [10] on provisional restorations found that CAD/CAM resin groups recorded significantly lower micromovement ($39.66 \pm 3.325 \mu\text{m}$) compared with conventional heat cure acrylic resin ($75.70 \pm 7.615 \mu\text{m}$), supporting the superior precision of digital workflows in the Libyan clinical context.

The improved marginal adaptation observed with CAD/CAM technology can be attributed to several factors. The digital impression process eliminates dimensional inaccuracies associated with elastomeric impression materials, including polymerization shrinkage, thermal expansion, and deformation during removal and handling (6,8). Additionally, the virtual design process allows for precise adjustment of margin geometry, while controlled milling ensures accurate reproduction of the designed restoration without the casting defects and porosity commonly observed with conventional techniques (3,7). These advantages collectively contribute to the superior marginal integrity observed in the CAD/CAM group. The CEREC system, specifically, has demonstrated reproducibility and consistency in internal fit, with no significant differences identified between control and replica dies in previous evaluations [12].

Conversely, conventional crowns demonstrated greater accuracy in proximal contact areas. This counterintuitive finding may be explained by the manual dexterity and iterative refinement possible during wax pattern fabrication and the lost wax casting process (4,7). This hands-on approach allows technicians to fine tune interproximal contacts with greater nuance than current automated milling protocols permit, suggesting that the tactile feedback and experiential knowledge of skilled dental technicians remain invaluable in achieving optimal proximal contacts. These observations are consistent with the findings of Memarian et al. (5), who reported that conventional techniques allowed for more precise interproximal adjustments, and with the clinical observations of Ferrari et al. (8), who noted that manual refinement during wax pattern fabrication resulted in superior contact point accuracy. A clinical study evaluating CAD software programs found that proximal contact accuracy varied significantly depending on the software used, with the Dental System 3Shape program achieving 90% ideal mesial and distal contacts compared with 55% and 30% respectively for exocad [13], suggesting that digital proximal contact optimization is evolving and software dependent.

The superior occlusal accuracy observed in the CAD/CAM group (80% ideal versus 50% in the conventional group) is particularly noteworthy. This finding aligns with the observations of Abduo et al. (2), who reported that digital workflows consistently produced restorations with better occlusal morphology and articulation accuracy. The precise control afforded by virtual articulation and the ability to simulate occlusal contacts during the design phase contribute to this advantage (6,8). A clinical study on implant supported restorations found that static occlusal contacts were significantly more accurate with certain CAD software programs, with one program achieving 100% ideal contacts, further supporting the occlusal advantages of digital design [13].

These observations underscore the complementary strengths of both approaches. Digital workflows deliver consistent and predictable outcomes for marginal integrity and occlusal morphology—parameters where precision and reproducibility are paramount (2,6). However, the superior proximal contact achieved with conventional methods highlights the continued clinical relevance of manual refinement in areas requiring subtle, patient specific adaptation (4,7). This dichotomy suggests that neither technique is universally superior, and the optimal approach may depend on the specific clinical parameters prioritized in each case.

The 68% reduction in the need for clinical adjustments observed with CAD/CAM technology represents a substantial advantage in terms of chair-side efficiency, patient comfort, and overall treatment time. This reduction not only enhances the patient experience but also improves practice productivity and reduces material waste, as previously documented by Memarian et al. (5) and confirmed in the clinical evaluation by Al Hamad et al. (4). The economic implications of this efficiency gain are significant, potentially offsetting the higher initial investment required for CAD/CAM systems. From a Libyan perspective, Hwisa et al. [10] identified high cost (63.6%) and insufficient training (16.9%) as key barriers to CAD/CAM adoption, with only 17.6% of students having attended CAD/CAM training despite 79% believing CAD/CAM represents dentistry's future. This highlights the need for expanded digital dentistry education in Libyan dental curricula to facilitate broader integration.

Collectively, these results affirm that CAD/CAM systems offer meaningful enhancements across several key clinical parameters of crown quality while acknowledging that conventional fabrication techniques retain distinct advantages in selecting domains. This suggests a potential role for hybrid approaches—integrating the precision of digital workflows with the nuanced manual refinement of traditional techniques—or continued technological refinement in proximal contact optimization within digital systems (1,4,7). Recent advances in artificial intelligence and machine learning algorithms for dental design may eventually address the proximal contact limitations of current digital systems, as suggested by Tsirogiannis et al. (1) and Ferrari et al. (8).

Conclusions

CAD/CAM technology significantly enhances marginal adaptation and occlusal accuracy while reducing chairside time and clinical adjustments. However, conventional methods demonstrated superior proximal contact accuracy, suggesting that hybrid approaches or further technological refinement may optimize outcomes across all parameters.

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