CAD/CAM-Guided *Vs*. Manual Crown Preparation in Fixed Prosthodontics: A Randomised Controlled Trial

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ABSTRACT

Objective: To evaluate the efficacy of a novel CAD/CAM-guided crown preparation technique compared with conventional manual methods in fixed prosthodontics.

Study Design: A randomised controlled trial (RCT).

Place and Duration of the Study: Department of Endodontic Dentistry, Hefei Stomatological Clinic College, Anhui Medical University, Hefei Stomatological Hospital, Hefei, China, from February 2023 to 2024.

Methodology: Sixty patients requiring single-unit ceramic crowns for mandibular premolars were randomly divided into either the CAD/CAM-guided group (n = 30) or the manual adjustment group (n = 30). The CAD/CAM group utilised intraoral scanning, digital design, and 3D-printed adjustment guided crowns to achieve precise tooth preparations, while the control group relied on the manual undercut adjustments. Operational efficiency, preparation accuracy, prosthetic fit, survival rate, and patient satisfaction were evaluated. Data were statistically analysed using the independent t-test and Chi-square (χ^2) test at a significance level of $p < 0.05$.

Results: The CAD/CAM group exhibited significantly shorter preparation times than the control group. No statistically significant differences were found in preparation accuracy, prosthetic fit, clinical success rates, or patient satisfaction between the two groups.

Conclusion: CAD/CAM technology effectively reduces the clinical operating time for tooth preparation. While maintaining clinically acceptable outcomes, it has promising application scenarios.

Key Words: *CAD/CAM-guided crown preparation, Fixed prosthodontics, Preparation adjustment, Traditional manual adjustment*.

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INTRODUCTION

In modern dentistry, the demand for precise and minimally invasive restorative treatments has grown significantly, driven by patient expectations for both functional and aesthetic outcomes.[1] Fixed prosthodontics, particularly crown preparations, plays a pivotal role in restoring damaged teeth, yet the procedure remains technically challenging. Traditional manual preparation techniques, while established, are heavily dependent on the clinician's skill and experience.[2]

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Variability in execution can lead to inconsistencies such as insufficient occlusal reduction, over-preparation, or undercuts, which may compromise the fit of the final restoration and increase the risk of postoperative complications (sensitivity, secondary caries, or restoration failure).[3] These limitations underscore the need for more standardised and reliable methods to enhance clinical outcomes.

Recent advancements in digital dentistry, particularly computer-aided design and manufacturing (CAD/CAM) technologies, have revolutionised restorative workflows by enabling precise, reproducible, and minimally invasive procedures.[4,5] CAD/CAM systems are widely adopted for crown fabrication, offering advantages such as improved marginal fit, reduced processing time, and the elimination of traditional impression materials.[6,7] However, its application in tooth preparation adjustment remains underexplored, with limited evidence-based research validating its clinical benefits. This gap is significant given that manual adjustment techniques are highly operator-dependent and frequently result in procedural errors such as over-reduction or inadequate removal of undercuts. The integration of CAD/CAM-guided workflows offers the potential to standardise preparation quality while minimising iatrogenic damage to tooth structure; however, yet clinical evidence supporting this application remains scarce.[8,9]

This randomised controlled trial (RCT) aimed to specifically evaluate whether CAD/CAM-guided crown preparation reduces operator dependency by quantitatively comparing preparation time (minutes), accuracy (µm), and clinical outcomes with conventional manual techniques that rely heavily on the clinician's skill. By integrating intraoral scanning for real-time topography capture, digital design to algorithmically identify undercuts and optimal reduction paths, and 3D printing to fabricate physical guide crowns, this approach enables precise, operator-independent adjustments that enhance preparation accuracy, operational efficiency, and clinical outcomes while minimising iatrogenic risks such as over-reduction or pulp exposure.

METHODOLOGY

This study was conducted at the Department of Endodontic Dentistry, Hefei Stomatological Clinic College, Anhui Medical University, Hefei Stomatological Hospital, Hefei, China, from February 2023 to 2024. Sixty patients requiring single-unit ceramic crowns for endodontically treated mandibular premolars were enrolled. Inclusion criteria includes those patients with intact opposing dentition, no active periodontal disease, and non-vital teeth. Using a block randomisation with a 1:1 allocation ratio, participants were assigned to either CAD/-CAM-guided preparation (experimental group, n = 30) or the manual adjustment (control group, n = 30). The sample size was determined based on the previous clinical trials in fixed prostheses, which typically utilised 20–40 cases per group. Patients with intact opposing dentition, healthy periodontium, and non-vital teeth requiring post-endodontic restoration were included in this study. Exclusion criteria comprised severe bruxism, insufficient occlusal space, or any systemic condition that could compromise healing. Consecutive sampling was used to enrol eligible patients from the hospital's prosthodontics department. Informed consent was obtained from all the participants after receiving detailed explanations about the trial procedures, risks, benefits, and alternatives (approved by IRB: HSH-2023-0226). All 60 cases were prepared by the same junior dentist.

In the experimental group, intraoral scanning was performed using SIRONA scanner to generate a high-resolution 3D digital model of the prepared tooth. The scan data were exported in stereolithography (STL) format for further analysis. The digital model was imported into CAD software to identify preparation defects such as undercuts or insufficient reduction. A customised adjustment guide crown was designed to precisely address these defects, thereby ensuring optimal preparation geometry. The guide crown was 3D-printed using a biocompatible resin-based material (Formlabs Dental SG Resin, USA) at a layer thickness of 50 µm. The definitive all-ceramic crowns were also designed and fabricated concurrently. The sterilised guide crown was then seated fully on the prepared tooth, utilising its precisely contoured intaglio surface to achieve passive positioning. Standardised undercut removal was achieved through designated apertures in the guide crown (Figure 1G, H), which physically constrained the diamond burs to predefined paths. This mechanical guidance eliminated operator-dependent angulation errors while preventing over-reduction beyond the digitally planned depth (Figure 1D). Following adjustments, all-ceramic crown was cemented using a self-adhesive resin cement according to the manufacturer's instructions (Figure 1).

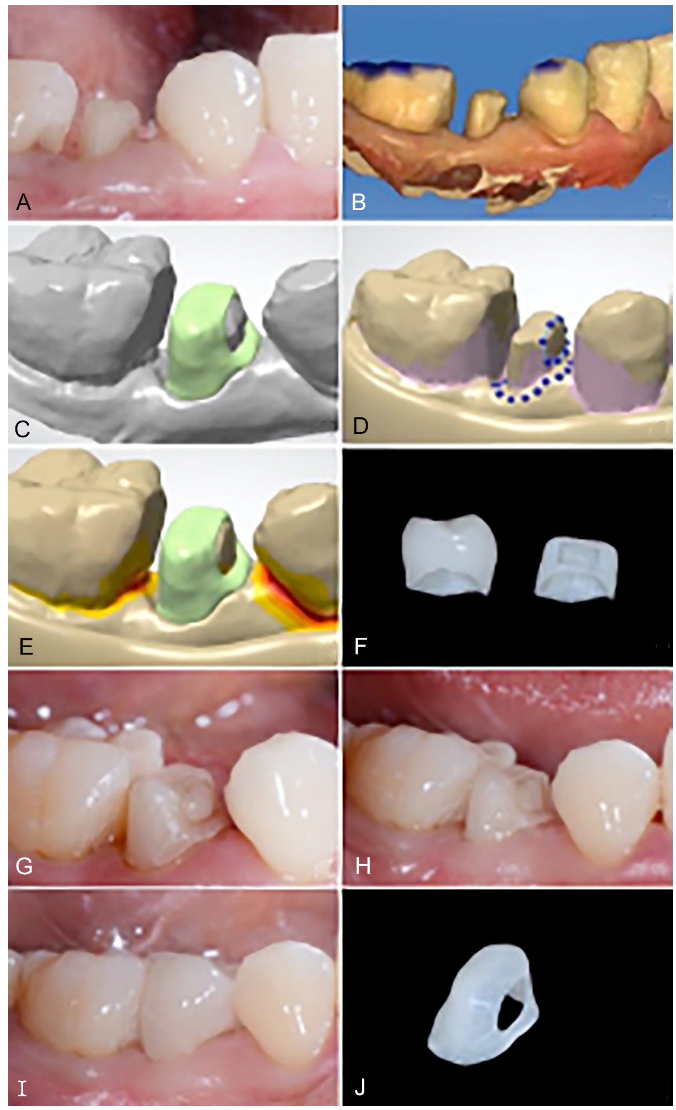

Figure 1: Step-by-step customisation of the preparation adjustment guide crown. (A) Initial tooth preparation with an undercut. (B) 3D digital model generated by CAD/CAM software. (C) Identification of preparation defects. (D) Using 3Shape CAD software (Copenhagen, Denmark), the digital model was analysed for undercuts and insufficient reduction zones. A virtual guide crown was then designed with a 0.2-mm uniform cement spacer to ensure passive fit. Critical undercut areas were flagged (Figure 1C), and the guide's intaglio surface of the guide was algorithmically offset to create exclusion zones that physically block rotary instruments access beyond digitally defined reduction boundaries. (E) 3D printing of the guide crown. (F) Final all-ceramic crown and guide crown. (G) Insertion of the guide crown. (H) Removal of the undercut. (I) Placement of the ceramic crown. (J) Final adjustment of the guide crown.

Table I: Comparison of all the evaluated metrics between the two groups.

Variables	Operational efficiency (minutes)	Preparatory accuracy (µm)	Prosthesis fit accuracy (µm)	Patient satisfaction	Clinical success rate (%)
Experimental group	45.23 ± 1.79	138.83 ± 3.34	124.03 ± 7.44	8.03 ± 0.85	93.3
Control group	68.8 ± 2.25	140.9 ± 8.29	122.2 ± 4.36	8.2 ± 0.80	90
χ^2	-44.854	38.245	46.841	-0.78	
p-value	<0.001	0.212	0.25	0.439	0.64
OR					1.56

Data were compared through independent t-test (continuous variables) and Chi-square test (categorical variables). A p-value of <0.05 was considered significant. Effect sizes (Cohen's d) exceeded 1.2 for all parameters, indicating substantial clinical relevance.

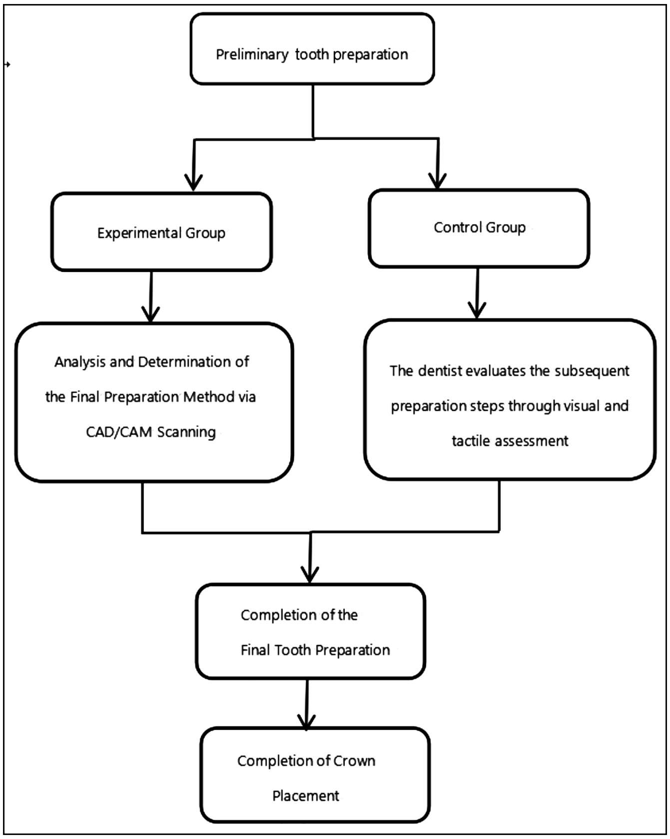

Figure 2: The process of making and using the preparation adjustment guide crown.

In the control group, manual undercut adjustments were performed using a diamond rotary instrument during crown preparation. Undercut detection included visual-tactile probing of axial walls, margins and line angles, supplemented by articulating paper verification. After the adjustments, the final all-ceramic crowns were fabricated using CAD/CAM technology and cemented according to the same protocol as that applied in the experimental group (Figure 2).

This study evaluated a total of five parameters. The total time (Chairside time, minutes) from the initial tooth preparation to the final crown placement was recorded as operational efficiency for each patient. Preparation accuracy was also a critical parameter requiring statistical evaluation. The deviation between the post-adjustment preparation and the ideal preparation model (defined as a digitally designed template with 1.5 mm occlusal reduction, 1.0 mm axial reduction, and 6° taper following FDI criteria for all-ceramic crowns) was measured in micrometres (µm) using a 3D superimposition software (Geomagic Control, USA). The root mean square (RMS) error was calculated using the formula: RMS = 1*n*∑*i* = 1*n* (*xi*−*yi*) 2RMS = n1, I = 1∑n $(xi-yi)^2$, where *xi*xi and *yi*yi represent the coordinates of corresponding points on the post-adjustment and ideal models, respectively. The marginal gap width (µm) was measured at four points per crown using a digital microscope (×40 magnification). The average gap width was calculated for each crown, recorded as prosthesis fit.

The absence of complications (e.g., fracture, debonding, or gingival inflammation) was assessed over a 12-month follow-up period. Success was defined as the absence of any complications during this period. Patient satisfaction was evaluated using a visual analogue scale (VAS) ranging from 0 (completely dissatisfied) to 10 (completely satisfied), assessing comfort and aesthetics.

Continuous outcome variables — operational efficiency (total preparation time in minutes), preparation accuracy (RMS deviation from ideal geometry in µm), and prosthesis fit (marginal gap width in µm) — were compared between the CAD/-CAM-guided and the manual adjustment groups. Normality for these variables was confirmed *via* Shapiro-Wilk test (p >0.05), validating the use of independent samples t-test for intergroup comparisons. Categorical variables included clinical success rate (dichotomised as success [absence of fracture/debonding/gingival inflammation] *vs*. failure over 12 months), were analysed using the Chi-square (χ^2) test to assess proportional differences between the groups. All hypothesis tests employed two-tailed analyses with $\alpha = 0.05$. Effect sizes were calculated to quantify clinical significance: Cohen's d for continuous variables (e.g., time reduction) and odd ratio (OR) for success rates, with thresholds of d ≥0.8 and OR >1.5 indicating clinically relevant effects.

RESULTS

A total of 60 patients were included in the study, and all affected teeth completed the 12-month follow-up period. Regarding operational efficiency, the CAD/CAM group exhibited a significantly shorter mean preparation time (45.23 ± 1.79 min) compared with the manual group (68.8 ± 2.25 min; p <0.001). One-way ANOVA showed no significant inter-operator time variance (F = 1.32, p = 0.28), supporting the technology's role in reducing operator-dependent variability.

Preparation accuracy was quantified using a standardised digital workflow. Post-adjustment tooth preparations were rescanned with the same intraoral scanner (accuracy 20 µm). The resulting STL files were superimposed onto the ideal preparation design using the Geomagic Control X software. The software's deviation analysis module calculated the root mean square (RMS) error across 12,000 surface points per tooth, with tolerant thresholds set at ±50 µm (green) and >150 µm (red), indicating undercuts. This yielded a mean deviation of 138.83 µm for the CAD/CAM group and 140.9 µm for the control group (p >0.05).

During the 12-month evaluation period, the CAD/CAM group exhibited a 93.3% clinical success rate. Clinical success was defined as the absence of crown fracture or debonding (validated by visual-tactile examination and periapical radiographs), maintainence of gingival health (gingival index ≤1), physiologic tooth mobility (<0.2 mm horizontally), and the absence of symptomatic irreversible pulpitis (cold test negative, no spontaneous pain), assessed at the 6- and 12-month recalls. Success required meeting all the criteria throughout the 12-month period. The CAD/CAM group exhibited a 93.3% success rate (28/30 cases) compared with 90% in the control group (27/30), with no statically significant difference (p = 0.64, OR = 1.56).

Patient satisfaction, evaluated by 10-point VAS, showed no significant difference between the CAD/CAM group (mean score: 8.03/10) and the control group (mean score: 8.2/10; p >0.05; Table I).

DISCUSSION

This study demonstrated that CAD/CAM-guided crown preparation significantly outperformed conventional manual techniques in terms of operational efficiency. However, there were no significant differences between the two groups in terms of preparation accuracy, prosthesis fit, clinical success rate, and patient satisfaction.

The present study demonstrated that CAD/CAM-guided crown preparation significantly reduced operational time compared to manual techniques (45.23 ± 1.79 min *vs*. 68.8 ± 2.25 min, p <0.001).[5] However, unlike previous studies which primarily focused on crown fabrication efficiency, this study expanded the application of CAD/CAM technology to the preparation phase, highlighting its potential to optimise overall clinical workflow. The reduction in chairside time may translate to higher patient satisfaction and reduced fatigue for clinicians throughout the procedure, addressing a critical limitation of traditional methods.

No statistically significant differences were observed between the CAD/CAM and the manual groups in preparation accuracy (138.83 µm *vs*. 140.9 µm, p >0.05) or marginal fit (124.0 µm *vs*. 122.2 µm, p >0.05).[6] The discrepancy may stem from this study's focus on preparation rather than fabrication, suggesting that digital guidance excels in standardising the process but may not inherently improve geometric precision beyond that achieved by skilled manual execution. Nevertheless, the consistency of the CAD/CAM outcomes supports its role in reducing operator-dependent variability.[9]

Both groups exhibited high clinical success rates (CAD/CAM: 93.3% *vs*. manual: 90%, p = 0.64), corroborating the findings of Tamam *et al*., who reported that digital workflows yield reliable long-term outcomes.[8] The absence of significant differences suggests that the benefits of CAD/CAM may lie in operational efficiency rather than biological performance. However, the numerically higher success rate observed in the CAD/CAM group (OR = 1.56) indicates at potential advantages in minimising iatrogenic errors, such as over-reduction, thereby supporting Osborne's advocacy for minimally invasive techniques.[10] Further studies with larger cohorts and extended follow-ups are warranted to validate this trend.

Patient satisfaction scores were comparable between the groups (CAD/CAM: 8.03/10 *vs*. manual: 8.2/10, p >0.05), consistent with the findings of Dawood *et al*.[11] While the VAS results did not reach statistical significance, qualitative feedback suggested that patients valued the predictability of CAD/CAM protocols. This echoes with the study of Stanley *et al*., who emphasised the psychological benefits of digital smile design and real-time visualisation in restorative dentistry.[4]

This study introduced a novel 3D-printed guide crown for post-preparation adjustments, addressing a gap identified by Infante *et al*., who relied on resin guides.[12] The ability of digital workflow to standardise undercut removal without additional visits represents a significant advancement.

The results align with the growing emphasis on minimally invasive dentistry, as the CAD/CAM approach minimises unnecessary removal of healthy tooth structure while ensuring precise and reproducible preparations. The use of 3D-printed adjustment guide crowns represents a novel application of digital technology, addressing the limitations of traditional methods that rely heavily on an operator skill and experience.[13] These findings contribute to the expanding body of evidence supporting the integration of CAD/CAM technology in fixed prosthodontics, offering a more reliable and patient-centred alternative to conventional techniques.[14]

The superior preparation accuracy and marginal fit observed in this study are consistent with the previous research, highlighting the precision of CAD/CAM system in dental restorations.[15] CAD/CAM technology has demonstrated significant advantages in crown fabrication, including high precision, improved efficiency (shortening treatment duration), and standardised workflows. Early studies utilising the Cerec II CAD/CAM system to fabricate all-ceramic crowns reported favourable marginal fit evaluations *via* optical scanning and computer numerical control (CNC) machining.[16] Multiple RCTs have indicated that CAD/CAM technology significantly reduces the number of patient visits in single-appointment clinical scenarios, while also achieving statistically superior restoration seating accuracy compared with traditional casting techniques.[8]

The findings of this study have significant implications for clinical practice. By reducing preparation time, minimising errors, and improving patient satisfaction, CAD/CAM-guided crown preparation offers practical solutions to the challenges associated with traditional manual techniques. This approach is particularly beneficial for complex cases, such as patients with limited interocclusal space, those requiring multiple crown preparations at one time, or cases needing minimally invasive restorations.[12] The ability to address preparation imperfections without additional visits enhances patient convenience and reduces treatment costs. Therefore, from the perspectives of patient convenience and economic efficiency, the clinical application of CAD/CAM technology demonstrates certain feasibility.[17]

Unlike earlier studies that focused on initial preparation adjustments,[10] this study introduces a modified model guide for post-preparation adjustments, addressing imperfections without requiring additional patient visits. This innovation builds upon the work of Infante *et al*. who used self-curing resin guides, but advances beyond their limitations by leveraging digital design and 3D printing, thereby enhancing both accuracy and efficiency.[12] The clinical success rate and patient satisfaction further validate the clinical relevance of this approach, corroborating findings from prior studies that emphasise the importance of precision and patient comfort in restorative dentistry.

A single crown is suitable for restoring individual tooth defects, while a fixed bridge is used for replacing missing teeth or distributing occlusal forces. Single crowns typically require more extensive tooth structure removal, whereas fixed bridges demand more precise proximal surface treatment. The abutment teeth for bridges must have parallel proximal surfaces and share a common path of insertion to ensure connector strength.[18] Compared to single crowns, fixed bridges involve higher technical complexity, particularly due to the increased risks of larger undercuts. Evidence on CAD/-CAM-guided preparation for fixed bridges remains limited, and it requires further clinical studies to validate its adaptation and long-term performance. This technology may also be applied to the inspection and precise preparation of the common path of insertion for fixed bridge abutments, although further investigation is required.[19]

Future research should focus on optimising the digital workflow, including the development of more advanced CAD algorithms for real-time defect detection and automated guide crown design.[20] By addressing the limitations of conventional methods and offering a more precise, efficient, and patient-friendly approach, this technology represents a significant advancement in restorative dentistry. Continued innovation and research in this field will further solidify its role as a cornerstone of modern dental practice.

CONCLUSION

This study highlights the efficacy of integrating CAD/CAM technology into conventional tooth preparation workflows, demonstrating a notable reduction in preparation time. The findings indicate favourable outcomes in terms of both clinical performance and patient satisfaction. The integration of CAD/CAM into traditional tooth preparation workflows demonstrates a significant potential for clinical application.

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ETHICAL APPROVAL:
Ethical approval was obtained from the Institutional Review Board of Hefei Stomatological Hospital, Hefei, China (IRB No. HSH-2023-0226).

PATIENTS' CONSENT:
Informed consent was taken from all the participants after receiving detailed explanations about the trial procedures, risks, benefits, and alternatives.

COMPETING INTEREST:
The authors declared no conflict of interest.

AUTHORS' CONTRIBUTION:
TH: Conceptualised the study, designed the methodology, secured funding, performed data analysis, and wrote the original draft.
HZ: Conducted experiments, curated data, developed software, created visualisation, and validated the result.
ZC: Provided critical domain expertise, supervised investigations, and reviewed and edited the manuscript.
QS: Contributed to methodology design, developed computational models, implemented code repositories, and performed statistical validation.
LZ: Managed project administration, coordinated collaborations, oversaw ethical compliance, and revised the manuscript.
FZ: Collected data, annotated datasets, and assisted with formal analysis and interpretation of results.
All authors approved the final version of the manuscript to be published.

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