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Original Article

Digital integration in dental education: A novel self-directed learning model using intraoral scanners for tooth preparation training

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Abstract *Background/purpose:* Traditional dental education faces challenges, such as high student-to-faculty ratios and disruptions like the COVID-19 pandemic, which limit hands-on learning opportunities. Digital technologies, including intraoral scanners, offer potential solutions by improving accuracy and efficiency in clinical practice. This study explored the integration of digital tools in a self-directed learning model for the fixed prosthodontic tooth preparation.
Materials and methods: This study, conducted with 81 fourth-year dental students, incorporated digital tools like intraoral scanners into practical training. Students completed a pre-intervention evaluation, followed by training on digital analysis tools, and concluded with a self-directed learning protocol. The study assessed students' theoretical knowledge and practical skills using pre- and post-intervention tests, digital scans, and feedback questionnaires. Statistical analyses, including paired t-tests, evaluated the effectiveness of the intervention.
Results: Significant improvements were observed in both theoretical knowledge (pre-test 86 %, post-test 98 %, $P = 0.012$) and practical skills, with the percentage of "perfect" crown preparations rising from 14 % to 73 % ($P < 0.0001$). Occlusal reduction showed improvement but remained challenging for some students. Digital tools reduced student anxiety, with 77 % of students reporting decreased anxiety during practical exercises.
Conclusion: Integrating digital scanning technology with traditional teaching enhanced student competence in tooth preparation, reduced anxiety, and provided objective evaluation criteria. The self-directed learning model supported skill development and independent problem-solving, indicating the potential for broader application in dental education. Future research

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should explore long-term impacts on clinical performance and optimize digital tool integration throughout the curriculum.

Introduction

Dental education emphasizes both theoretical knowledge and practical skills in tooth preparation. Developing these technical skills requires extensive practice under faculty supervision to ensure appropriate learning outcomes. However, traditional dental education faces several challenges, including the high student-to-faculty ratio, which limits individual attention during practical training sessions. This ratio often results in delayed feedback, inconsistent evaluation standards, and reduced student hands-on practice time. Studies have shown that these limitations can significantly affect skill development and learning outcomes.[1,2] Additionally, faculty availability constraints can lead to blockages in skill assessment and development, potentially affecting students' clinical competence.[3] This challenge was further exacerbated by the COVID-19 pandemic, which required social distancing and disrupted conventional face-to-face instruction methods.

Comparisons between traditional and digital methods in dental education have revealed distinct advantages and challenges for each approach. Based on direct faculty observation and manual assessment, traditional methods offer immediate tactile feedback and help develop fundamental hand skills. However, they are limited by subjectivity in evaluation, time constraints, and variable instructor feedback.[4] Digital tools, particularly intraoral scanners, provide quantitative assessment capabilities, standardized evaluation criteria, and the ability to track progress over time. A study showed that the learning curve for dental students using intraoral scanners is significantly shorter than traditional impression methods. Students can achieve proficiency more quickly, while traditional techniques typically require more time and practice to master manual skills. Additionally, digital tools provide immediate feedback and enhance overall efficiency, allowing quicker error correction and a more streamlined workflow in the learning process.[5]

The integration of digital technologies in dental education has shown promise in addressing these challenges. Computer-aided design/computer-aided manufacturing (CAD/CAM), first introduced in dentistry in 1983, has revolutionized dentistry practice and education.[6] Intraoral scanners, in particular, have become increasingly prevalent in clinical settings, offering advantages such as reduced operating time, improved patient comfort, and minimized impression distortion.[7,8] These digital tools have shown accuracy levels that meet or exceed traditional impression methods[9–13] with marginal gap tolerances within the acceptable range of 60–120 μm.[14,15] A comprehensive review by Angelone et al. highlighted that while intraoral scanners show promise for diagnostic applications, particularly in detecting dental wear and caries, further validation is still needed for widespread clinical adoption.[16] Furthermore, a 2023 meta-analysis by Hardan et al. revealed that proper technique can significantly enhance scanning accuracy, including using artificial landmarks and maintaining dry conditions during scanning.[17] Several digital training systems, including PrepCheck®, Dental Teacher™, and Compare, have been developed to facilitate self-directed learning in dental education.[18] Studies have shown that these systems enable immediate feedback on tooth preparations and can lead to better learning outcomes compared to traditional teaching methods.[4,19,20] However, the high cost of these specialized training systems presents a barrier to their widespread adoption in dental schools.[21] Furthermore, the initial investment in equipment and software can be substantial, and faculty require additional training to integrate these tools into their teaching effectively. Technical issues can disrupt learning sessions, and there is a learning curve for both educators and students when mastering the digital workflow. Studies have reported that over-reliance on digital tools could potentially impact the development of traditional manual skills that remain essential in clinical practice.[22] Furthermore, digital technologies' rapid evolution requires continuous equipment and training protocol updates.

To address these challenges, we proposed a novel educational approach that combined traditional assessment criteria with existing digital tools to create a self-directed learning environment for dental students. This study aimed to establish a self-directed learning model for fixed prosthodontic tooth preparation, developed objective and scientific assessment criteria utilizing digital analysis, assessed the effectiveness of this educational model in improving students' practical skills, and evaluated student perceptions and feedback regarding this innovative teaching approach.

Materials and methods

Participants and study design

This study, conducted in a dental school with 81 fourth-year students, consisting of 43 males (53 %) and 38 females (47 %), aimed to assess the impact of an educational intervention on students' tooth preparation skills. While all participants had prior basic exposure to intraoral scanners through their third-year operative dentistry laboratory course, none had previous experience with the analysis software used in this study. The research protocol was reviewed and approved by the Institutional Review Board

(No: CS2-23128). The intervention was structured into three main components: a pre-intervention evaluation, integration of digital tools, and a self-directed learning protocol.

Pre-intervention phase

The pre-intervention phase began with an initial lecture focused on the principles of tooth preparation for metal crowns of the first mandibular molar. Following this, students completed a pre-intervention test (pre-test), including a written examination and a practical skills assessment. The evaluation criteria used in these assessments were introduced to the students (Table 1).

The intervention phase then commenced, consisting of two components. First, students were trained in the use of digital tools, including intraoral scanners to digitize tooth preparations and analysis software to evaluate various preparation parameters. They were also introduced to digital assessment protocols to facilitate more accurate and consistent evaluations.

The second component of the intervention involved self-directed learning. Students began by performing tooth preparations on phantom-head models, followed by digitizing their preparations using the intraoral scanner. Each student was given approximately 60 min per session for tooth preparation practice. The digital scanning process took approximately 5–6 min per full arch (maxillary and mandibular). After scanning, students performed software analysis of their preparations. Faculty members were available for assistance when needed during both the scanning and analysis phases. The practical exercises consisted of four scheduled classroom sessions, with additional opportunities for self-directed practice outside of class time. This structured approach allowed students to develop both their technical skills and self-assessment abilities through regular practice while ensuring appropriate faculty support was available when needed. The resulting scans were then analyzed using the designated software. Based on the feedback provided, students conducted self-assessments, refined their preparations, and repeated the scanning and analysis process. Throughout this phase, students documented their progress in a learning portfolio (Fig. 1) to support reflection and improvement. To clarify the time allocation and faculty supervision during the practical exercises:

Upon completion of the intervention, students participated in a post-intervention assessment, identical to the pre-intervention test, to evaluate their improvement.

Evaluation criteria

The evaluation criteria for the study encompassed six main parameters: general appearance (20 %), occlusal reduction (20 %), retention and resistance form (20 %), margin clarity and continuity (20 %), undercut evaluation (10 %) and adjacent tooth integrity (10 %) as detailed in Table 1.

Data collection involved quantitative and qualitative measures. Quantitative data included pre- and post-intervention written examination scores, practical skills assessments, digital analysis data from intraoral scans, and self-assessment scores. Qualitative data consisted of the documentation of learning portfolio and feedback collected through student questionnaires.

Statistical analysis

For statistical analysis, paired t-test, Wilcoxon signed-rank test, or Fisher's exact test was used to compare the pre- and post-intervention scores, where appropriate, establishing statistical significance at $P < 0.05$. Descriptive statistics were used to analyze the responses to the questionnaire.

Results

The results of this study demonstrate significant improvements in both theoretical knowledge and practical skills among dental students after the educational intervention. In terms of theoretical knowledge, there was a notable enhancement in the students' understanding of crown preparation principles. As shown in Table 2, the mean percentage of correct responses in the written examination significantly improved, rising from 86 % in the pre-test to 98 % in the post-test ($P = 0.012$). All areas of knowledge saw improvement, with nearly all students (99–100 %) achieving correct scores in questions related to margin width, functional cusp identification and reduction, and non-functional cusp reduction.

The practical skills assessment, as presented in Table 3, revealed substantial enhancements across all evaluated parameters. The overall appearance of crown preparations showed a notable improvement, with the percentage of preparations rated as "perfect" or "well-achieved" increasing from 14 % to 73 % ($P < 0.0001$). Skills related to occlusal reduction also improved, with the percentage of students achieving a "perfect" occlusal reduction

Table 1 Evaluation criteria for student practical skills assessments in crown preparation.

Percentage (%)	Evaluation criteria	Description
20	Overall appearance	Evaluation based on appearance from and surface refinement
20	Amount of occlusal surface tooth reduction	Deduct 3 points for each cusp or groove error of 0.5 mm, deduct 10 points if space is less than 0.5 mm
20	Retention and resistance	Deduct 3 points for each surface with excessive angle
20	Margin clarity and continuity	Deduct 3 points for each unclear or discontinuous margin position, deduct 10 points for incorrect margin type
10	Amount of abutment undercut	Deduct 5 points for severe undercut, 2 points for minor undercut
10	Integrity of adjacent teeth	Deduct 5 points for damage to adjacent teeth

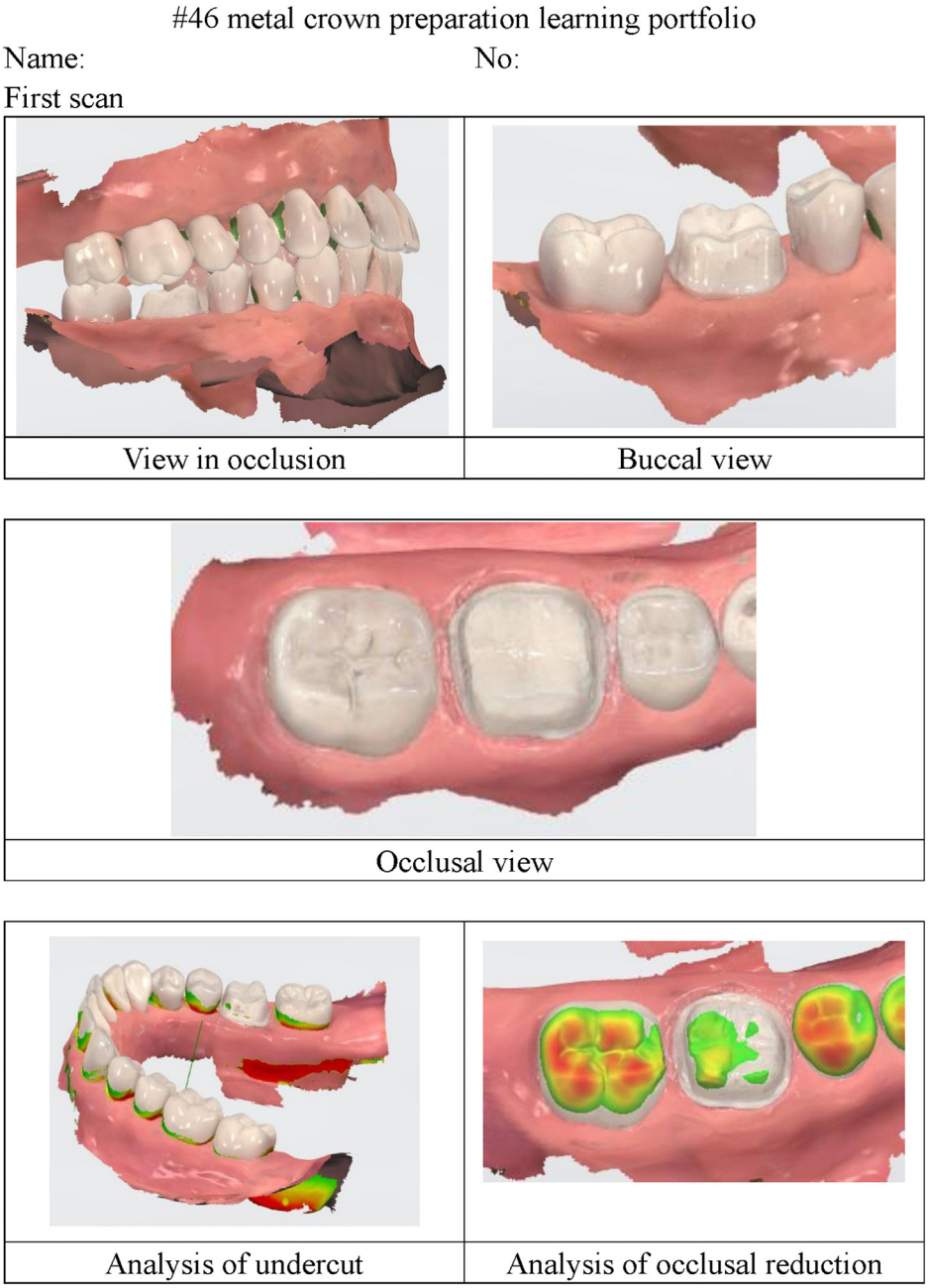

Figure 1 Buccal and occlusal views of a mandibular molar preparation for a metal crown. The figure presents the learning portfolio for the first scan, showcasing various perspectives of the tooth preparation: occlusal view, buccal view, analysis of undercut, and analysis of occlusal reduction. These images highlight the students' work in terms of preparation accuracy, including occlusal reduction and evaluation of undercuts, as analyzed using digital scanning technology. The digital feedback from these scans facilitated self-directed learning by allowing students to reflect on and improve their tooth preparation techniques.

increasing from 16 % to 45 % ($P = 0.0003$). However, occlusal reduction remained a significant challenge, with 46 % of the students not meeting acceptable standards after the intervention. Detailed analysis revealed that the most common errors included insufficient reduction depth (32 % of cases), uneven reduction patterns (28 % of cases), and improper anatomical form (18 % of cases). Digital analysis showed a mean occlusal reduction of 1.3 ± 0.4 mm against a target of 1.5–2.0 mm, with particular challenges in functional cusp reduction (58 % accuracy rate) and central fossa depth (64 % accuracy rate). Student feedback indicated that 75 % experienced difficulty visualizing adequate reduction depth, 68 % were uncertain about maintaining proper anatomical contours, and 82 % found the real-time digital feedback helpful in understanding their errors.

Edge clarity and continuity saw dramatic improvement, with "perfect" or "well-achieved" ratings increasing from 5 % to 66 % ($P < 0.0001$). Additionally, undercut removal, which was already proficient before the intervention (96 % "perfect" or "well-achieved"), further improved to 100 % ($p = 0.0095$). Retention status also saw a significant

Table 2 Comparison of students' theoretical knowledge before and after the intervention, showing the percentage of students with the correct answers for specific questions related to crown preparation.

	Question	Pre-test score (%)	Post-test score (%)
1	What bur is used for the #46 crown margin?	84	98
2	What's the required margin width for #46?	88	100
3	Where is the margin placed for #46?	66	96
4	Which is the functional cusp for #46?	93	100
5	How much reduction for the functional cusp on #46?	88	99
6	Which is the non-functional cusp for #46?	91	98
7	How much reduction for the non-functional cusp on #46?	96	99
	Mean	86	98[a]

[a] Paired t-test, *P*-value 0.012, compared to pre-test.

Table 3 Pre- and post-intervention comparison of students' practical skills in crown preparation, categorized by quality levels (perfect, well-achieved, adequate, not acceptable) for various parameters.

		Perfect (%, n = 82)	Well-achieved (%, n = 82)	Adequate (%, n = 82)	Not acceptable (%, n = 82)	*P*-value[a]
Overall appearance	Pre-test	1	13	49	37	<0.0001
	Post-test	8	65	26	1	
Occlusal reduction	Pre-test	16	15	3	66	0.0003
	Post-test	45	6	3	46	
Edge clarity and continuity	Pre-test	1	4	12	83	<0.0001
	Post-test	11	55	12	22	
Undercut removal	Pre-test	78	18	3	1	0.0095
	Post-test	94	6	0	0	
Retention status	Pre-test	32	28	12	28	<0.0001
	Post-test	72	15	8	5	
Integrity of adjacent teeth	Pre-test	51	25	12	12	0.0006
	Post-test	79	15	5	1	

[a] Fisher's exact test, compared to pre-test.

improvement, with "perfect" ratings increasing from 32 % to 72 % ($P < 0.0001$). Furthermore, the integrity of adjacent teeth improved, with "perfect" ratings rising from 51 % to 79 % ($P = 0.0006$).

Student feedback on the crown preparation class, as outlined in Table 4, provided valuable information on the learning experience. A large majority of the students (87 %) reported feeling anxious during their first preparation. However, 77 % agreed that the use of intraoral scanner alleviated their anxiety in subsequent preparations. The intraoral scanner was highly regarded for its utility, with 94 % of students agreeing that they would utilize it in clinical practice to evaluate preparation outcomes, and 96 % finding it helpful to address preparation issues.

The self-directed learning aspect of the intervention was strikingly successful, with 74 % of the students reporting that they independently completed the preparation with the intraoral scanner. Furthermore, all students (100 %) reported reviewing the lecture content before preparing the dental model, indicating a high level of engagement with the theoretical material. Despite the emphasis on self-directed learning, 93 % of the students sought assistance from the instructor when encountering challenges, reflecting a balanced approach between independent study and the pursuit of guidance as needed.

Discussion

The implementation of a self-directed learning model incorporating digital scanning technology and analysis software has led to significant improvements in dental students' tooth preparation skills and learning outcomes. These findings align with previous research that highlighted the positive impact of digital assessment tools in preclinical dental education.[4,18]

A key finding of our study is the substantial reduction in student anxiety during tooth preparation exercises facilitated by digital assistance tools. Reported anxiety levels decreased from 87 % to 23 %, indicating that the immediate feedback provided by the digital analysis system empowers students to independently identify and rectify errors, aligning with findings from Hamil et al.[19] This reduction in anxiety could lead to more confident and competent practitioners in the long term.

Quantitative analysis of the pre- and post-test results revealed marked improvements across multiple assessment criteria, particularly in overall appearance, retention and resistance form, adjacent tooth integrity, and margin clarity and continuity. Nevertheless, some students still faced challenges in occlusal area reduction, highlighting the need for targeted training in this aspect of tooth preparation.

Table 4 Student feedback on the crown preparation class using digital tools, presenting the distribution of responses across agreement levels for various aspects of the learning experience.

Question	Strongly agree n (%)	Agree n (%)	Disagree n (%)	Strongly disagree n (%)
I felt anxious during my first preparation.	29 (43)	30 (44)	5 (7)	4 (6)
The scanner reduced my anxiety during preparation.	12 (18)	40 (59)	15 (22)	1 (1)
I will use the intraoral scanner in my clinic to check the preparation results.	14 (21)	50 (73)	4 (6)	0
I completed the preparation independently with the intraoral scanner.	14 (21)	36 (53)	16 (23)	2 (3)
The intraoral scanner was helpful for preparation issues.	29 (43)	36 (53)	16 (4)	0
I reviewed the lecture content before preparing the dental model.	27 (40)	41 (60)	0	0
I consulted the instructor when I encountered problem.	24 (35)	39 (58)	5 (7)	0

The effectiveness of this self-directed learning model during the COVID-19 pandemic demonstrates its value in maintaining educational continuity during disruptions to traditional face-to-face instruction. The digital workflow enabled students to continue their practical training with minimal direct supervision while receiving objective feedback. This adaptation aligns with the broader trends in dental education toward increased reliance on digital technologies and self-directed learning.[7,8]

The implementation of digital scanning technology also addresses a long-standing challenge in dental education: the subjective nature of assessment. By providing quantifiable measurements and standardized analysis, the digital workflow improved the objectivity and consistency of the evaluation. This improvement in the reliability of assessment was reflected in student feedback, with 95 % reporting that the assistance with the intraoral scanner was beneficial to their learning.

However, several challenges were identified during implementation. The addition of scanner operation and software analysis skills to the existing curriculum initially increased student workload and stress. This suggests the need for a more gradual introduction of digital skills throughout the curriculum, potentially beginning with basic scanning in earlier years and progressing to more complex analysis in later years.

The creation of individual learning portfolios, while time-consuming, proved valuable for both students and instructors. Students could track their progress and identify areas needing improvement, while instructors gained deeper insight into individual learning patterns and challenges. This approach supports the development of metacognitive skills essential for lifelong learning in dental practice.

This educational model holds promise for broader application in dental education, particularly in clinical skills evaluation for national licensing examinations. Combining traditional evaluation criteria with digital analysis could provide a more standardized and objective assessment framework for professional qualification.

These findings suggest that integrating digital technologies with traditional tooth preparation instruction can enhance teaching effectiveness and learning outcomes. The self-directed learning model not only supports skill development but also cultivates independent problem-solving abilities essential for clinical practice.[20,21]

Integrating digital tools into dental education raises important questions about long-term practice patterns and skill retention. Recent systematic reviews suggest that while digital technologies improve learning outcomes, practitioners often use a hybrid approach in clinical practice, combining both digital and conventional methods based on specific case requirements.[16] This flexibility in approach is crucial as dentists must maintain competency in traditional and digital techniques to provide optimal patient care in various clinical scenarios. The findings of the systematic review by Angelone et al. emphasize that intraoral scanners serve as complementary tools rather than complete replacements for conventional methods.[16] The global implications of implementing digital dental education warrant careful consideration, particularly regarding accessibility and resource allocation. While our study demonstrated positive outcomes in a well-funded educational setting, applying these findings to institutions with varying levels of technological access requires thoughtful adaptation. Potential strategies for broader implementation could include staged introduction of digital technologies based on institutional resources, development of shared resource centers for multiple institutions, integration of virtual simulation platforms as intermediate solutions, and collaboration between institutions for resource optimization.

Future research directions should extend beyond immediate learning outcomes to examine long-term clinical performance. Key areas of investigation include longitudinal assessment of skill retention and clinical decision-making, application of digital tools across different dental procedures (e.g., complex prosthodontic cases, orthodontic treatment planning), comparative studies across different educational settings and cultural contexts, cost-effectiveness analyses for various implementation models, and impact on patient outcomes in clinical practice settings. Based on the findings of the Hardan et al. meta-analysis,[17] particular attention should be paid to standardizing scanning protocols and developing evidence-based best practices for different clinical scenarios. This standardization will ensure consistent educational outcomes across various institutions and practice settings.

In conclusion, this study demonstrates that integrating digital scanning technology and self-directed learning into dental education enhances theoretical knowledge and

practical skills while reducing student anxiety. The approach offers objective evaluation criteria, mitigating subjectivity in assessments. Despite initial increases in student workload, the benefits in learning outcomes and essential skill development are clear. As digital innovations advance in dentistry, this model will be crucial in preparing proficient dental professionals. Future research should focus on long-term skill retention, broader applications in dental education, and optimizing digital skill integration to improve educational effectiveness.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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