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Interactive E-Learning Module: Enhancing Panoramic Radiograph Interpretation Skills of Dental Students

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ABSTRACT

Objectives: Two interactive e-learning modules were developed, focusing on dental panoramic radiograph (DPR) interpretation and a virtual dental clinic (VDC) for communication skills. The aim of the study was twofold: to quantitatively evaluate the effectiveness of the modules in enhancing students' skills in interpreting DPRs and complying with reporting standards in clinical practice, and to qualitatively assess students' perceptions of the module's effectiveness.

Methods: A mixed-methods cohort study was conducted over four weeks and included forty-five dental students in their final year. Students were assessed using objective structured radiographic interpretation and objective structured clinical examination assessments before (baseline) and after the e-learning modules. Student perceptions of the modules were evaluated quantitatively using an online questionnaire and qualitatively in focus group discussions. Quantitative data were analyzed using a Wilcoxon signed rank test. Qualitative data from focus group discussions were analyzed using thematic analysis.

Results: After the modules, students' DPR interpretation skills improved for reporting radiographic findings (all $p < 0.01$), anatomical landmark identification (all $p < 0.05$), and pathology detection (all $p < 0.05$). Communication skills improved for reduced jargon usage ($p < 0.01$). Compliance with DPR reporting increased from 63.3% before to 81.3% after the module ($p = 0.03$). Students indicated positive perceptions of the modules, highlighted their flexibility, and provided reinforcement.

Conclusion: The e-learning modules with DPR and VDC significantly enhanced student skills in DPR interpretation and clinical communication. These findings support the integration of e-learning modules in dental curricula to improve diagnostic accuracy, knowledge retention, and communication skills.

1 | Introduction

As educational methods evolve, there has been an emphasis on innovative, technology-driven teaching strategies, particularly in higher education [1]. For example, e-learning uses digital tools to promote learner-centered instruction. In dental education, these technologies are essential for upholding modern teaching standards [1, 2]. Although the adoption of e-learning has recently surged, maintaining student engagement and development of practical skills remains challenging, especially in dental fields like oral radiology which require clinical exposure to develop diagnostic skills [3]. Despite attempts to replicate traditional face-to-face experiences, e-learning tools can only partially replace hands-on aspects of clinical training [3–5]. However, as virtual simulations, augmented reality, computer-aided design, computer-aided manufacturing, and teledentistry education tools advance, they

are likely to improve the skill acquisition, engagement, and clinical readiness of dental students [6]. Since digital proficiency is increasingly necessary for effective practice, the American Dental Education Association recommends the use of technology to align dental training with contemporary standards [1].

Oral radiology interpretation skills are a cornerstone of the dental diagnostic process and require the integration of anatomical knowledge, pathology, and thorough clinical examination for effective clinical problem-solving [7]. Among the radiographic modalities routinely used in dental practice, dental panoramic radiograph (DPR) provides the most comprehensive view of the maxillomandibular complex, making it an essential diagnostic tool [8, 9]. However, the interpretation of DPR images can be limited by technical errors during image acquisition. Therefore, dental students should be taught to develop proficiency in radiographic acquisition, interpretation, and imaging quality assessment by combining theoretical knowledge and practical experience [10].

Although research suggests e-learning effectively supports theoretical aspects of dental training [11, 12], the continuing development and use of e-learning tools also enhances students' ability to communicate imaging findings to their patients in clinical settings. This training is also necessary to adequately prepare dental students for hands-on and clinical practice. To our knowledge, no previous research has investigated the impact of interactive, case-based e-learning on DPR interpretation and compliance with DPR reporting guidelines in clinical practice. Unlike prior studies that focus on radiographic interpretation alone, this study uniquely integrates a Virtual Dental Clinic (VDC) to simulate real-world patient interactions, bridging the gap between radiographic interpretation and patient-centered communication. Although e-learning has been evaluated for radiographic interpretation, its role in improving adherence to DPR reporting standards remains unexplored. By incorporating structured reporting guidelines alongside case-based virtual simulations, this study aims to provide a more comprehensive approach to radiographic education. In this study, compliance referred to students' adherence to established guidelines for accurately documenting radiographic findings in patient charts, as mandated by the Private Medical Practice Control Section [13]. Thus, we developed two interactive e-learning modules that focused on DPR interpretation for identifying anatomical landmarks and pathologies and on a virtual dental clinic for communication skills. The purpose of the current study is to quantitatively evaluate the effectiveness of the modules in enhancing students' skills in interpreting DPRs and complying with reporting standards in clinical practice and to qualitatively assess students' perceptions of the module's effectiveness.

2 | Materials and Methods

2.1 | Study Design

For the current study, we used a mixed-methods cohort design, which allowed for longitudinal observation of changes in skills and perceptions. The study was conducted in 2020 at the International Medical University (IMU), Kuala Lumpur, Malaysia with approval from the University Joint Committee on Research and Ethics (IMU-JC 478/2020). Only students in their final year of the dental undergraduate program were eligible to participate. Quantitative measures assessed knowledge acquisition and DPR reporting skills; qualitative feedback of students' perceptions was included to evaluate e-learning effectiveness. The study workflow is illustrated as a flowchart in Appendix S1.

2.2 | Study Participants

Participants were recruited using universal sampling to ensure the inclusion of the entire year cohort. While participation was strongly encouraged as part of the study's integration into the educational curriculum, it remained voluntary and written informed consent was obtained from all students, using Google forms, before study participation. A briefing session was conducted to explain the study design, procedures, and interventions. Participants were told their module results would not be used in summative assessments and the confidentiality of their information was guaranteed.

2.3 | E-Learning Module Development

In collaboration with our institution's e-Learning Unit, two e-learning modules were developed using the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model [14]. This structured approach involved analyzing our students' learning needs, designing the module framework, and creating interactive content using Articulate Storyline 360 (New York, NY, USA) and Adobe Illustrator (San Jose, CA, USA). These modules enabled the development of dynamic features, including interactive quizzes, realistic simulations, and visually detailed graphics designed to effectively illustrate dentist-patient interactions, enhancing both engagement and comprehension for students. The finalized modules were accessible on our institution's e-learning platform through hyperlinks, and their effectiveness was evaluated through performance assessments and student feedback. Students accessed the modules via Moodle (Perth, WA, Australia), an open-source learning management system, using their personal devices, including laptops, desktops, and smartphones. Engagement was self-directed and asynchronous, allowing students to complete the modules at their convenience, typically at home or in study spaces. Although students worked individually, they had the option to discuss concepts with peers outside the module sessions. The modules were available for four weeks, and students had the flexibility to revisit content multiple times during this period.

The first module focused on DPR interpretation and featured interactive content designed to enhance student's ability to identify normal anatomical landmarks and diagnose five patient-based cases: generalized periodontitis, periapical pathology, odontogenic cysts, dental trauma, and fibro-osseous lesions (Figure 1). Each case was carefully selected to represent common diagnostic challenges in clinical practice, ensuring that students engaged with realistic and diverse radiographic scenarios. The module provided high-resolution annotated images to facilitate recognition of key radiographic features, with structured explanations outlining the learning outcome for each interpretation. This module was a core component of the e-learning intervention,

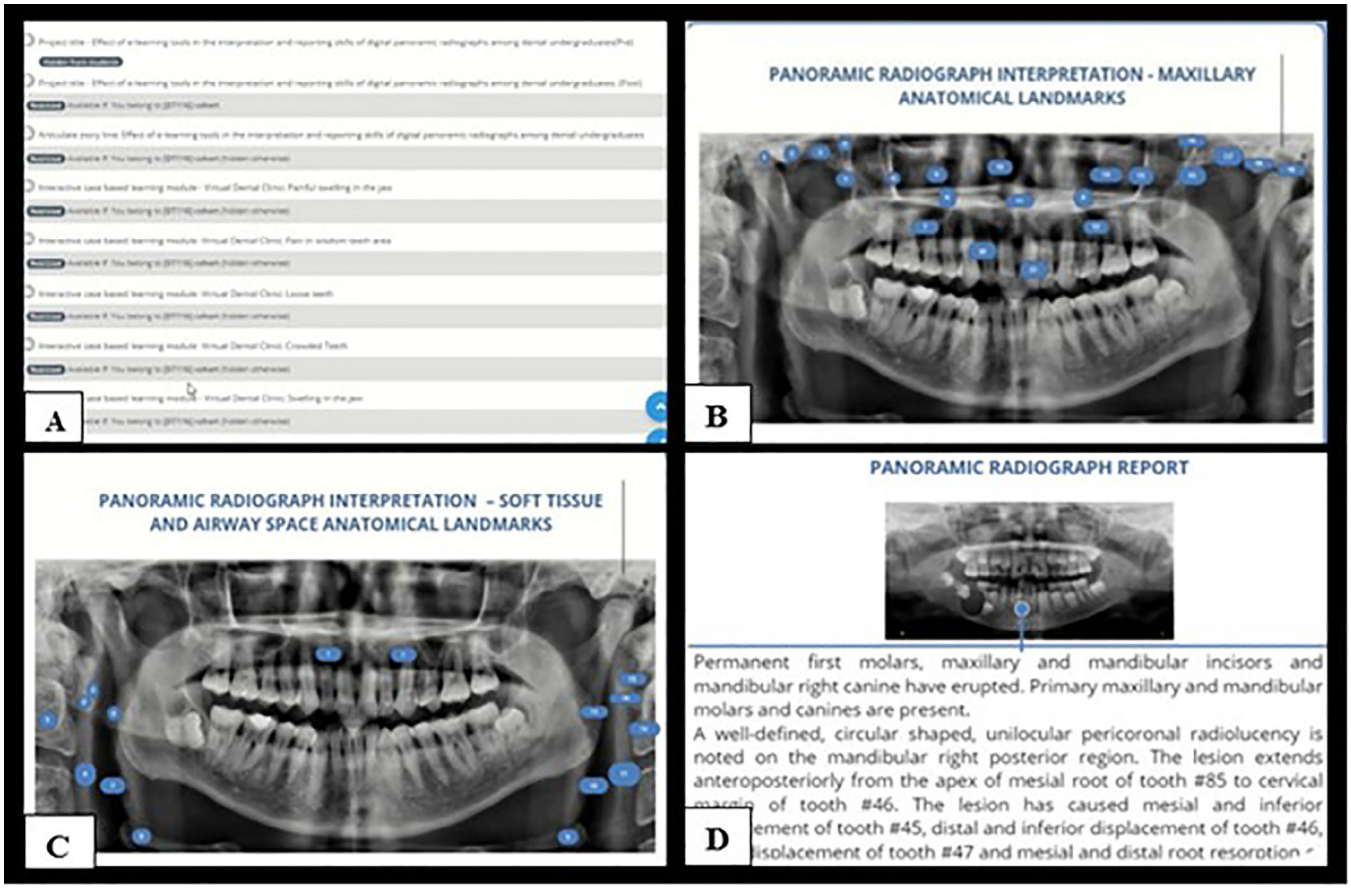

FIGURE 1 | Articulate Storyline-Based E-Learning Module Interface (A), trigger points for anatomical landmarks (B and C), and radiographic report (D).

providing a structured framework for systematic radiographic analysis and interpretation. These topics aligned with our institution's final-year dental curriculum. Students interacted with the module to receive detailed descriptions of anatomical landmarks, radiographic findings, diagnostic errors, diagnoses, and systematic approaches to reporting DPR findings.

The second module was an interactive case-based VDC resource that simulated dentist-patient interactions (Figure 2). It presented detailed information on radiographic findings, diagnoses, errors, reports, and self-assessment tools through five case scenarios: loose teeth, malocclusion, painful jaw swelling, pain in the wisdom teeth area, and jaw swelling. The VDC primarily employed role-play scenarios and interactive patient simulations, enabling students to develop their communication skills by articulating radiographic findings in clear, patient-friendly language while avoiding jargon and maintaining professional rapport. A structured patient satisfaction rating system was integrated into the module, allowing students to receive immediate feedback on their communication effectiveness based on simulated patient responses. Although MCQs were incorporated as a supplementary evaluative tool, they were not the primary focus of the module. Students actively participated in simulated conversations using role-play scripts, selecting structured responses to patient inquiries, reinforcing their ability to explain radiographic findings and treatment recommendations effectively. The MCQs assessed students' ability to communicate clearly and empathetically. Their responses directly influenced the patient satisfaction rating, displayed using a three-star system, providing immediate feedback on communication effectiveness (Figure 2). To support learning, students received evidence-based explanations, structured feedback, and relevant references for further study, promoting reflection and improved patient communication skills.

2.4 | Module Assessment

The study was conducted over a four-week e-learning period during which students were given time to complete both modules. Student learning was assessed using a standardized set of DPRs which remained the same before the intervention and immediately after completing both modules to ensure consistency in pre- (considered the baseline assessment) and post-intervention evaluations. These assessments were conducted through the objective structured radiographic interpretation (OSRI) and the objective structured clinical examination (OSCE). A pretest was conducted before students engaged with the interactive e-learning modules to establish a baseline for their knowledge and skills, allowing for a comparative evaluation of learning outcomes after their exposure to the e-learning module. In contrast, the DPRs assessed for compliance with DPR reporting in clinical practice varied (30 pre-test vs. 32 post-test) due to routine patient case fluctuations rather than study design constraints. This difference did not impact the intervention itself or the study outcomes.

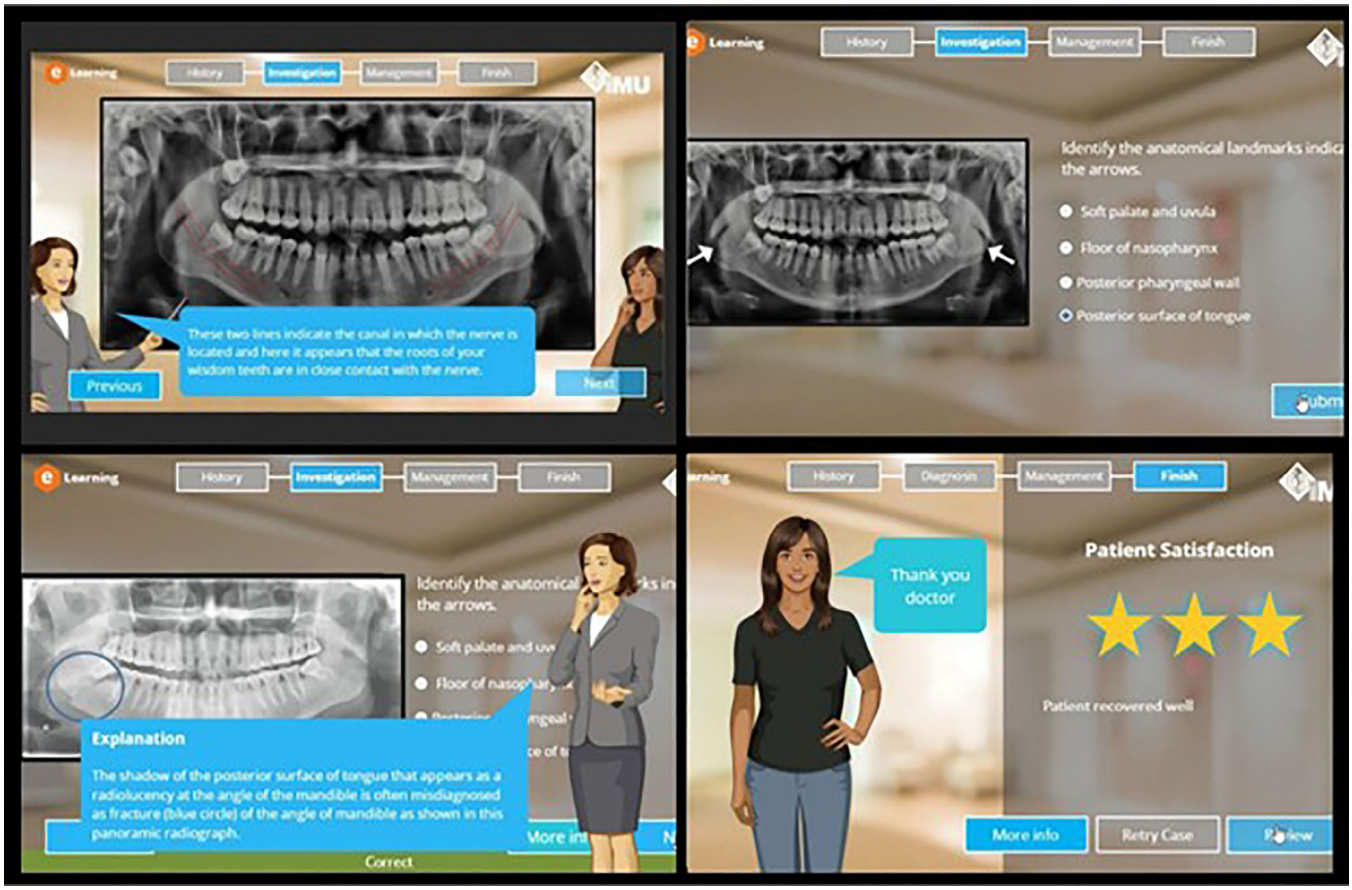

FIGURE 2 | E-Learning tool of a virtual dental clinic for a dentist-patient interaction.

Checklists for the OSRI [15] and OSCE [16] (Appendix S2) were designed and validated by experts for content validity, and calibration sessions for supervisors were conducted to maintain consistency of evaluations. To ensure the elimination of bias between assessments, each student underwent evaluation by the same calibrated supervisor using identical checklists. Although interrater reliability was not analyzed in the study, our four research supervisors (one oral and maxillofacial radiologist, two endodontists, and one orthodontist) were trained and calibrated for consistency.

Students accessed the OSRI, which was used to evaluate radiographic interpretation skills, using Moodle, and activity was monitored through Microsoft Teams. The assessment involved four DPRs, with each designated to evaluate a specific domain: interpretation of radiographic findings, identification of radiographic anatomy, recognition of positioning errors, and detection of pathology or anomalies. In the pathology detection domain, students were assessed on their ability to identify three distinct pathologies, each represented by one case of a complex odontoma, an ameloblastoma, and a cementoblastoma. Students were required to write their responses for landmarks, errors, and diagnosis. Rather than selecting from a predefined MCQ option, students were required to construct written responses. This approach encouraged deeper analytical thinking, requiring students to justify their interpretations and engage in a structured diagnostic reasoning process. Partial credit was awarded for near-correct responses, meaning students could receive a range of scores rather than a strict correct/incorrect binary score. Responses were assessed using a structured 10-point checklist (Appendix S2), and each radiograph was assigned a maximum score of ten points, reflecting complete fulfillment of the evaluation criteria. The mean scores for DPR 1–4 were calculated by averaging individual student scores for each respective DPR assessment. Each student was allowed five minutes per radiograph to complete the assessment.

For the OSCE, which was used to assess communication skills, students were divided into four groups, and four trained examiners oversaw the process. The OSCE included four stations with each station presenting an identical set of three clinical cases, ensuring consistency in assessment across all students. These cases provided patient history, clinical information, and DPR. Students were allowed five minutes per station, totaling twenty minutes per student. Students presented radiographic findings, impressions, differential diagnoses, incidental findings, and management plans to the examiner, who acted as a simulated patient. Student competencies in professionalism and patient safety, communication skills, diagnostic skills, and decision-making in clinical management were assessed using a structured rubric with a 5-point scale: unacceptable (1), poor (2), unsatisfactory (3), satisfactory (4), and good (5). Each domain was evaluated independently, ensuring a consistent and objective assessment of specific competencies without aggregating the scores. To enhance scoring reliability, all OSCE examiners underwent calibration training before the assessment. This

standardized approach provided a detailed understanding of individual strengths and areas requiring improvement.

2.5 | Compliance of DPR Reporting Skills in Clinical Practice

The evaluation focused on the systematic documentation of critical observations necessary for diagnosis, treatment planning, and patient management. This was done by assessing sixty-two DPRs before ($N = 30$) and after ($N = 32$) the intervention. The difference in the number of DPRs assessed before and after the intervention reflects natural variations in clinical practice, as the number of patient cases requiring radiographic evaluation varied over time. This difference was unrelated to the intervention and did not influence the study design or its outcomes. Not all patient cases required follow-up radiographs, and the number of DPRs taken depended on clinical needs rather than a predetermined study design. Since the assessment of DPR reporting compliance was based on real patient cases, fluctuations in the number of available radiographs were expected, aligning with routine clinical workflows. These DPRs were evaluated for compliance with Private Medical Practice Control Section requirements [13]. An oral and maxillofacial radiologist evaluated DPR compliance using a customized 10-point checklist. Key components included findings critical to patient management or prognosis (4 points), dentition (1 point), periodontal status/alveolar bone level (1 point), jaw bones (1 point), temporomandibular joint (1 point), maxillary sinus (1 point), and diagnosis (1 point). Compliance rates and category-specific scores were compared before and after the intervention to assess the impact of the e-learning module on DPR reporting skills. To ensure reliability, all DPR reports were double-checked by two independent reviewers, and discrepancies were resolved through consensus, enhancing the accuracy and consistency of reporting compliance assessments. This scoring system provided a comprehensive evaluation of reporting accuracy and adherence to clinical standards.

2.6 | Student Feedback

Student perceptions of the e-learning module were collected using an online questionnaire and focus group discussions. The questionnaire, adapted from Vuchkova et al. [17], included ten specific statements addressing the perceived effectiveness of the module in areas such as content, learning impact, and ease of use. Responses were measured on a 5-point Likert scale ranging from strongly disagree to strongly agree. The questionnaire was designed to take approximately five to seven minutes to complete, ensuring a manageable and focused evaluation process.

Focus group discussions collected insights about e-learning for DPR interpretation [18]. All 45 students were invited to participate, and data saturation was achieved with ten volunteers, who participated in a thirty-minute online discussion conducted through Microsoft Teams. This approach ensured a manageable, diverse sample while capturing a range of perspectives representative of our institution's student population. Thematic analysis was conducted, and saturation was confirmed when recurring themes emerged, indicating that additional discussions would not yield new insights, aligning with qualitative research principles [18, 19]. One supervisor moderated, another took notes and two transcribed discussions. Student feedback was collected anonymously to encourage honest responses and minimize potential social desirability bias.

2.7 | Statistical Analysis

Data was tabulated and analyzed using SPSS statistical software (version 26.0; IBM Corp., Armonk, NY, USA). Data were summarized using frequency, percentage, mean, standard deviation, or median for study variables. The Shapiro-Wilk test was performed to assess the normality of the data. Because data were not normally distributed, the Wilcoxon signed-rank test was used for comparisons between module outcomes before and after the intervention. To control possible confounders, we used consistent evaluation criteria and the same supervisors for both assessments. A $p < 0.05$ was considered statistically significant. Given the number of statistical comparisons performed, we acknowledge the potential for increased Type I errors. However, no formal multiple comparison correction was applied due to the exploratory nature of the study and the risk of inflating Type II errors. Future studies may consider employing statistical corrections to account for multiple comparisons while maintaining statistical power. To quantify the magnitude of observed differences, effect sizes (Cohen's d) were calculated for key outcomes. According to Cohen's guidelines, values of 0.2 indicate a small effect, 0.5 a medium effect, and 0.8 or greater a large effect. In our study, effect sizes ranged from 1.58 to 3.22, indicating large to very large effects, reinforcing the substantial impact of the e-learning intervention on diagnostic and radiographic interpretation skills. Frequency and percentage were used to analyze the distribution of student feedback responses collected after the intervention. Qualitative data from focus groups were thematically analyzed to evaluate students' perceptions of the intervention [18, 19]. The transcriptions were categorized into four themes: comparison of face-to-face teaching and e-learning modules, attitudes toward communication and learning through VDC, usefulness in clinical practice, and overall satisfaction with e-learning modules.

3 | Results

A total of 180 pre-post assessments were conducted across forty-five students, with each student completing two key assessments, OSRI and OSCE before and after the intervention. These represent 98% of the year cohort (13 men, 33 women, mean age: 24 [±1] years), who participated in the study. One student (2%) declined to participate for personal reasons and did not provide consent.

The outcomes of the OSRI and OSCE assessments indicated improvements in the four evaluated domains after the intervention. Baseline assessment results, as detailed in Tables 1 and 2, provided a reference point for before-intervention performance, highlighting the extent of improvement across all evaluated criteria. For the OSRI, the mean overall scores improved across all four DPRs after the intervention (all $p < 0.001$) (Table 1). Substantial improvements were also found in identifying radiographic anatomical landmarks (all $p < 0.003$) and radiographic errors (all $p < 0.03$). Radiographic diagnosis outcomes also

TABLE 1 | Student outcomes for the objective structured radiographic interpretation (ORSI) before and after the e-learning intervention ($N = 45$).

Student outcomes	Mean (SD) or No. (%)		*p*-Value
	Before	After	
OSRI scores			
DPR 1	4.8 (1.2)	7.1 (0.9)	<0.001
DPR 2	5.2 (1.3)	7.7 (1.0)	<0.001
DPR 3	4.3 (1.1)	7.4 (0.8)	<0.001
DPR 4	4.5 (1.1)	7.5 (0.9)	<0.001
Radiographic anatomical landmarks			
Oropharyngeal airway	19 (42.2%)	38 (84.4%)	<0.001
Lower surface of the soft palate	18 (40.0%)	36 (80.0%)	<0.001
Zygomaticotemporal suture	6 (13.3%)	23 (51.1%)	<0.001
Superior margin of the tongue	10 (22.2%)	20 (44.4%)	0.003
Base of the middle cranial fossa	17 (37.8%)	37 (82.2%)	<0.001
Radiographic errors			
Inappropriate tongue position	18 (40.0%)	32 (71.0%)	<0.001
Chin down	17 (37.8%)	27 (60.0%)	0.02
Earring	24 (53.3%)	38 (84.4%)	<0.001
Neck position	10 (22.2%)	21 (46.6%)	0.03
Radiographic diagnosis			
Complex odontoma	24 (53.3%)	29 (64.4%)	0.04
Ameloblastoma	28 (62.2%)	35 (77.7%)	0.04
Cementoblastoma	29 (64.4%)	38 (84.4%)	0.03

Outcomes were compared before and after the intervention using a Wilcoxon signed rank test.
Abbreviation: DPR, dental panoramic radiograph.

improved, particularly for complex odontomas ($p = 0.04$) and ameloblastoma ($p = 0.04$).

For the OSCE assessments, communication skills improved overall. Specifically, the use of complex medical jargon decreased, and straightforward communication increased (both $p < 0.001$) (Table 2). Improvements were also found for incidental findings, particularly in the identification of maxillary sinus cyst ($p = 0.03$) and dentigerous cyst ($p < 0.001$).

3.1 | Compliance of DPR Reporting in Clinical Practice

Overall compliance with DPR reporting in clinical practice increased from 63.3% before to 81.3% after the module ($p = 0.03$) (Table 3). Findings critical to patient management or prognosis had 100% compliance before (30/30) and after (32/32) the intervention. The remaining key components for compliance also improved after the intervention (all $p < 0.05$).

TABLE 2 | Student outcomes for the objective structured clinical examination (OSCE) interpretation before and after the e-learning intervention ($N = 45$).

Student outcomes	Mean (SD) or No. (%)		*p*-Value
	Before	After	
OSCE scores			
DPR 1			
PPS	3.6 (0.7)	3.7 (0.5)	0.10
CS	3.5 (0.6)	3.7 (0.6)	<0.01
DS	3.0 (0.8)	4.5 (0.7)	<0.001
CM	2.5 (1.0)	3.1 (0.7)	<0.001
DPR 2			
PPS	3.5 (0.8)	3.9 (0.6)	<0.001
CS	3.6 (0.6)	4.4 (0.5)	<0.001
DS	2.9 (0.6)	4.2 (0.6)	<0.001
CM	2.2 (0.9)	3.0 (0.5)	<0.001
DPR 3			
PPS	3.4 (0.8)	3.9 (0.5)	<0.001
CS	3.6 (0.7)	4.4 (0.6)	<0.001
DS	3.6 (0.9)	4.7 (0.4)	<0.001
CM	2.8 (1.1)	3.4 (0.7)	<0.001
Communication skills			
Use of complex medical jargon	26 (57.8%)	7 (15.5%)	<0.001
Use of straightforward language	19 (42.2%)	38 (84.4%)	<0.001
Incidental findings			
Maxillary sinus cyst	5 (11.1%)	10 (22.2%)	0.03
Chronic periodontitis	41 (91.1%)	45 (100%)	0.03
TMJ arthritis	10 (22.2%)	15 (33.3%)	0.046
Impacted teeth	38 (84.4%)	42 (93.3%)	0.046
Dentigerous cyst	25 (55.6%)	36 (80.0%)	<0.001

Outcomes were compared before and after the intervention using a Wilcoxon signed rank test.
Abbreviations: CM, clinical management (decision-making); CS, communication skills; DPR, dental panoramic radiograph; DS, diagnostic skills; PPS, professionalism and patient safety; TMJ, temporomandibular joint.

3.2 | Student Feedback

Forty-two students, representing 93.3% of the total participants, completed the feedback questionnaire and indicated high satisfaction with the e-learning module (Table 4). A majority agreed or strongly agreed that the module improved their ability to interpret pathological structures on DPR (85.7%, 36/42) and facilitated the identification of radiographic anatomy (92.9%,

TABLE 3 | Comparison of compliance with dental panoramic radiograph reporting in clinical practice before and after the e-learning intervention.

Compliance outcomes	No. (%)		*p*-Value
	Before ($n = 30$)	After ($n = 32$)	
Overall compliance	19 (63.3%)	26 (81.3%)	0.03
Key compliance components			
Findings critical to patient management or prognosis	30 (100%)	32 (100%)	NA
Dentition	16 (53.3%)	32 (100%)	0.02
Alveolar bone level	5 (16.7%)	12 (37.5%)	0.03
Jaw bones	3 (10.0%)	9 (28.1%)	0.03
TMJ	7 (23.3%)	11 (34.4%)	0.04
Maxillary sinus	3 (10.0%)	5 (15.6%)	0.049
Diagnosis	21 (70.0%)	30 (93.8%)	0.02

The following scoring system was used for key components of compliance: findings critical to patient management or prognosis (4 points), dentition (1 point), periodontal status/alveolar bone level (1 point), jaw bones (1 point), TMJ (1 point), maxillary sinus (1 point), and diagnosis (1 point).
Abbreviations: NA, not applicable; TMJ, temporomandibular joint.

39/42). Most students also agreed or strongly agreed that the module increased their confidence in independently interpreting DPRs (76.2%, 32/42), and they supported integrating the module into the curriculum (92.9%, 39/42).

3.3 | Qualitative Analysis

All 45 students were invited to participate in the focus group discussions, with ten volunteering. The final sample size ($n = 10$) was determined based on data saturation, ensuring a diverse representation of student experiences. Thematic analysis identified recurring themes, confirming that additional participants were unlikely to provide new insights. For the theme of comparison of face-to-face teaching and e-learning modules, many students preferred the flexibility provided by the e-learning format, particularly the ability to revisit materials as needed. Two students stated that the e-learning modules allowed them to understand more clearly and conveniently access materials at any time, highlighting the flexibility and ease of reviewing content. For the theme of attitudes toward communication and learning through the VDC, students reported that the case-based VDC learning module enhanced their understanding of anatomical concepts and emphasized the practical applications of their learning. One student noted that it helped in applying anatomical knowledge in clinical scenarios and another emphasized the convenience of accessing materials at any time for practical use. Such comments highlighted the role of the modules in enhancing readiness and confidence in a clinical context. However, some students felt that the VDC did not fully replicate real-world patient interactions, particularly in areas such as non-verbal communication and empathetic engagement. For the theme of overall satisfaction with e-learning modules, students indicated high satisfaction. In particular, they appreciated that the modules allowed them to access and review materials as needed, which supported their learning and application in clinical practice. However, a few students found the self-directed nature of e-learning overwhelming, particularly in terms of time management, preferring face-to-face instruction due to its structured guidance. Additionally, some students reported technical challenges and engagement difficulties, suggesting the need for improved module usability and interactive design.

4 | Discussion

Two interactive e-learning modules including DPR interpretation and a VDC for communication skills were shown to be efficient in an educational environment. By including these two tailored e-learning modules in the dental curriculum, the diagnostic accuracy and communication abilities of participating students were enhanced. Our investigation of how e-learning modules can complement traditional teaching methods suggested manageable options for filling educational gaps and supporting the cognitive and practical skill development of students. Our findings also supported the modernization of the dental curricula by showing that blended learning approaches can strengthen core competencies and optimize the transition to more integrated, technology-based training in dental education. Our e-learning modules were demonstrated to be engaging and motivating, aligning with previous research indicating that virtual learning often outperforms [20–22] or matches [23, 24] traditional methods in improving students' cognitive outcomes. It is important to note that students in our study had consistent baseline knowledge, likely derived from prior didactic lectures, faculty-led demonstrations, practical training in a simulation lab, and supervised clinical training during their second year, which may have influenced the observed improvements. Traditional teaching methods at our institution included structured lectures on the radiographic principles of DPR, case discussion sessions with faculty, hands-on simulation exercises for radiographic interpretation using DPR images, and supervised patient-based learning in clinical settings. These experiences provided a strong foundation for acquiring the new skills introduced through the developed modules. However, the study's findings should be interpreted with caution due to the absence of a control group. Instead, this study used a pre- and post-intervention design. A control group receiving traditional teaching methods would provide stronger comparative evidence. Given ethical considerations and the need for equitable access to innovative learning, a pre-post design was implemented. Future studies should consider a randomized controlled or quasi-experimental design with a traditional instruction comparison group to enhance validity and minimize potential confounding variables.

After completing our e-learning module, students had a 71% increase in the accuracy of identification of anatomical landmarks. This finding is consistent with previous studies that reported significant gains through engaging educational formats [25, 26]. Research has also shown that blended learning enhances diagnostic capabilities [1, 2], which supports our findings that structured e-learning promotes knowledge acquisition and retention. Familiarity with anatomical features and the ability to recognize superimpositions and distortions significantly enhance

TABLE 4 | Student responses to the feedback questionnaire about the e-learning intervention.

Feedback question	No. (%)					Mean (SD)
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	
I found it easier to interpret pathological structures on DPR after the intervention	0 (0%)	0 (0%)	8 (19.0%)	26 (61.9%)	8 (19.0%)	4.0 (0.6)
The use of an Articulate Storyline facilitated easier identification of radiographic anatomy on DPR	0 (0%)	0 (0%)	3 (7.1%)	25 (59.4%)	14 (33.3%)	4.3 (0.6)
After utilizing the e-learning modules, I felt more confident in interpreting DPRs without external assistance	0 (0%)	1 (2.4%)	9 (21.4%)	22 (52.3%)	10 (23.8%)	4.0 (0.7)
The e-learning modules significantly enhanced my learning experience regarding DPR interpretation	0 (0%)	0 (0%)	4 (9.5%)	28 (66.6%)	10 (23.8%)	4.1 (0.6)
The structure and design of the course content were effective in facilitating my understanding of DPR interpretation	0 (0%)	0 (0%)	4 (9.5%)	29 (69.0%)	9 (21.4%)	4.1 (0.6)
Using Articulate Storyline made it easier to identify incidental findings on DPRs compared to focusing solely on specific regions of interest	0 (0%)	0 (0%)	7 (16.6%)	25 (59.5%)	10 (23.8%)	4.1 (0.6)
The application of Articulate Storyline improved my ability to identify radiographic errors in DPRs	1 (2.4%)	1 (2.4%)	6 (14.3%)	21 (50.0%)	13 (30.9%)	4.0 (0.8)
Navigating the images within Articulate Storyline was more effective for learning oral radiographic anatomy and the systematic approach to DPR	0 (0%)	0 (0%)	6 (14.3%)	26 (61.9%)	10 (23.8%)	4.1 (0.6)
Utilizing the Interactive Case-based Learning module was more beneficial for developing my reporting skills for DPR findings to patients	0 (0%)	0 (0%)	7 (16.7%)	26 (61.9%)	9 (21.4%)	4.1 (0.6)
Incorporating e-learning modules into the Bachelor of Dental Surgery curriculum for teaching DPR interpretation is essential	0 (0%)	0 (0%)	3 (7.1%)	22 (52.3%)	17 (40.5%)	4.3 (0.6)

Abbreviation: DPR, dental panoramic radiograph.

diagnostic effectiveness [10]. Interestingly, our scores for radiographic anatomy identification were about 43.% lower than those of Razmus et al. [27], who reported an 87% correct response rate. This discrepancy likely stems from differences in assessment style. Our study did not use a multiple-choice format for assessment. Instead, students were required to write their responses by labeling anatomical structures rather than selecting from predetermined options to foster deeper cognitive engagement and understanding. Further, our inclusion of hard and soft tissue structures may have increased identification difficulty because of their complexity and subtlety on DPR images. Previous studies have also reported challenges in accurately identifying a wide range of anatomical features, especially when features overlap or are less distinct [8, 10].

Our results showed a marked improvement of almost 49% in the students' ability to identify radiographic errors after the e-learning intervention. Their limited understanding of these errors before the intervention may have been caused by a lack of practical training specifically focused on patient positioning for DPR, which contributed to their difficulties in accurately identifying errors in extra-oral radiographs. Additionally, students may have perceived positional errors as less clinically important than identifying positive radiographic findings, which could potentially lead to an undervaluation of the impact of these errors on patient care [28]. Our findings were supported by a previous study that emphasized the importance of combining practical exposure with theoretical knowledge to effectively teach panoramic imaging techniques [12]. However, the absence of long-term follow-up remains a limitation of this study. Future research should implement extended follow-up assessments to evaluate whether the observed improvements are retained over time and translate into clinical proficiency.

Students in the current study had significant improvements in their ability to identify pathologies. There was a 20% increase in accuracy for diagnosing bony lesions. Studies have shown that virtual education can substantially advance theoretical knowledge and practical skills in radiographic interpretation, which supports the notion that interactive modules can be instrumental in strengthening the diagnostic capabilities of dental students [20, 25]. For instance, some complex conditions assessed in our study, such as complex odontoma, were still challenging for a small number of students. This finding highlighted the ongoing need

for more focused instruction in dental abnormalities [8]. However, dental educators should also consider that the effectiveness of e-learning may vary based on individual learning styles and that the importance of adaptable, student-centered approaches should be emphasized to maximize the benefits of these modules [12].

Effective communication is crucial for establishing a strong dentist-patient relationship because it alleviates patients' concerns, enhances their satisfaction, and leads to a more positive dental experience [29]. Despite its importance, the assessment of communication skills among dental students is rarely investigated [30]. For this reason, we included OSCEs in our study to assess this important skill. After our intervention, there was a 42% reduction in the use of complex medical jargon, which suggested an improvement in our students' ability to convey information clearly and effectively to patients. However, 16% of students still struggled to avoid complex medical jargon after the intervention, indicating that further reinforcement through real-world simulations or patient interactions may be necessary. Our findings were supported by previous research that indicated similar improvements in students' communication skills after educational interventions [31]. The shift toward using lay language when communicating with patients has been shown to improve patient comprehension and satisfaction [32]. In this current study, the structured scenarios provided in the e-learning module likely contributed to the observed gains and are consistent with previous findings that indicated e-learning could complement traditional clinical training by enhancing communication and diagnostic skills [33]. However, while these improvements were evident immediately after the intervention, long-term retention of communication skills remains uncertain and warrants additional study. Although the VDC module facilitated dentist-patient interactions and incorporated role-play, it may not have fully addressed all aspects of real-world communication, such as nonverbal cues and empathetic engagement. Future studies could explore enhancements like advanced video-based simulations, AI-driven virtual patient interactions, or additional structured role-play scenarios to further refine communication training.

After our interactive intervention, compliance in DPR reporting improved to 81%, which supported the effectiveness of e-learning modules for enhancing students' reporting capabilities. This finding was also consistent with previous studies [8, 25], showing the integration of practical experience with theoretical training is crucial, incorporating practical demonstrations into the dental curriculum could further enhance competencies [11, 12]. Our findings supported this need for curriculum adjustments that include practical demonstrations to fully prepare students for patient interactions and radiographic assessments [16, 34]. Interactive e-learning modules support cognitive skill acquisition and foster emotional engagement by making learning more interactive and student-centered [26]. Although repeated exposure may have contributed to skill improvements, our structured e-learning modules provided targeted learning experiences beyond simple practice, ensuring students engaged with cases in a meaningful and standardized manner.

The positive student feedback we received about our e-learning modules has also been observed in previous studies [35, 36]. The flexibility and accessibility of e-learning modules allow students to revisit complex material at their convenience, which is essential for effective learning and embodies the essence of blended learning. High satisfaction with e-learning modules has been reported to improve comprehension of challenging subjects like radiographic interpretation [36] and likely contributed to positive feedback from our students. Further, the students' positive feedback indicated increased confidence and clarity in diagnosing pathologies, highlighting how effective educational tools enhance knowledge acquisition and create a more engaging learning experience. However, some students found the self-directed nature of e-learning overwhelming and preferred face-to-face instruction for its structured guidance. These findings highlight areas for future improvement, including enhancing engagement strategies and integrating more structured instructor support into e-learning interventions. Moreover, self-reported satisfaction may be subject to social desirability bias, and additional qualitative research is needed to explore students' perspectives in more depth.

The limitations of the study included the small sample size ($N = 45$), which is limited to the size of the entire cohort of DDS students this year. While the findings demonstrate improvements in student performance, the small sample limits the generalizability of the results. Future studies should consider multi-institutional collaborations with larger sample sizes to enhance external validity. The lack of a control group should also be considered as the study findings are susceptible to confounding variables. A quasi-experimental design or adding a comparison group can help strengthen the validity of the educational studies electing to establish pre and post-testing. To further avoid this challenge, future studies could measure behavioral or clinical changes before and after exposure to a risk factor. The absence of long-term follow-up is another factor that limits the generalization and free extrapolation of our results. While this study assessed immediate post-intervention outcomes, the retention of knowledge and practical skills over time remains unknown. This study focused on short-term learning outcomes, and the long-term impact of the intervention on clinical proficiency has yet to be determined. Future research should implement follow-up assessments to evaluate long-term knowledge retention and clinical application. Additionally, some students found the self-directed nature of e-learning overwhelming and preferred face-to-face instruction for its structured guidance and immediate feedback. Enhancing instructor support and real-time engagement may help address this challenge. Furthermore, the VDC module demonstrated dentist-patient interactions and incorporated role-play elements, but it may still not fully capture key aspects of real-world communication, such as non-verbal cues and empathetic engagement. Future studies should explore video-based simulations or AI-driven virtual patients to further enhance communication training.

The use of the same DPR cases before and after the intervention may have contributed to student performance improvements, due to repeated exposure rather than actual skill acquisition. To avoid memory bias, this study team planned a washout period of 4 Articulate Storyline-Based E-Learning Module Interface weeks between both evaluations. Future studies should introduce varied test cases to minimize familiarity bias. Additionally, multiple comparisons were made in our analysis, which may have increased the risk of type I errors. Furthermore, although

efforts were made to calibrate examiners, interrater reliability was not analyzed, which may have introduced variability in the assessment process. Future research should include larger, multi-institutional cohorts, long-term follow-up, and control groups for broader validation.

Overall, our interactive teaching approach offered a detailed, engaging learning experience for the development of necessary skills in diagnostic accuracy and patient communication. The e-learning approach provided students with targeted training for identifying anatomical structures and pathologies on DPRs and for effectively bridging gaps in traditional learning methods. Although our findings suggested that interactive e-learning modules can enhance DPR interpretation, compliance, and communication skills, these results should be interpreted with caution because of the study's single-center design, small sample size, and lack of a control group. The improvements observed in student performance may be influenced by repeated exposure to DPR cases or other confounding factors not controlled within this study. Although our results highlighted the benefits of blended learning, practical demonstrations should be included with e-learning modules to better address complex areas and positional errors. Future research should explore the generalizability of these findings across diverse educational settings and larger cohorts.

5 | Conclusions

The tailored e-learning modules for DPR interpretation significantly enhanced the diagnostic accuracy, anatomical landmark identification, pathology detection, and communication skills of senior dental students. Although these results are promising, they should be interpreted with the study's limitations, which may limit the generalizability of findings. Compliance with DPR reporting standards increased by 20%, reinforcing the modules' role in enhancing adherence to clinical documentation protocols. Further, the integration of interactive modules, such as VDC, with traditional instruction enhanced radiographic training and patient interaction, resulting in better engagement and DPR interpretation skill retention. Qualitative feedback from students highlighted the modules' accessibility and flexibility, which supported their confidence and competence in interpreting DPRs independently. In general, our study supported the continuing integration of e-learning modules in the dental curricula and emphasized the need for targeted training to effectively prepare students for clinical practice.

Author Contributions

Swarna Yerebairapura Math: Substantial contributions to conception and design, acquisition of data or analysis and interpretation of data, drafting the article and revising the article critically for important intellectual content. **Omer Sheriff Sultan:** Acquisition of data and revising the article critically for important intellectual content. **Mohd Fadzil Bin Zainal Anuar:** Substantial contributions in designing the e-learning modules. **Camila Pacheco-Pereira:** Revising the article critically for important intellectual content and final approval of the version to be published.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed during this study are included in this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.