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Evaluating the Effectiveness of a Virtual Reality-Based Simulation in Teaching Pulpotomy to Undergraduate Dental Students

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ABSTRACT

This educational study assesses the efficacy of a virtual reality (VR) simulator for teaching pulpotomy procedures to third-year dental students. Participants (n=60) were randomly divided into two groups: VR-based training vs. traditional mannequin-based training. Performance was evaluated using a skills checklist and a post-training theoretical test. The VR group demonstrated significantly higher retention of procedural steps and reported greater confidence in clinical application. Students also rated the immersive experience as more engaging and intuitive. These findings suggest that VR-based learning can enhance dental education, particularly for preclinical skill acquisition.

Keywords: Dental education, virtual reality, pulpotomy, simulation training, clinical skills.

1 Introduction

In dental education and procedural skills directly related to hand skills have vital importance since they are significantly related to patient safety [1]. Undergraduate dental students are expected to demonstrate pre-clinical competence in irreversible operative procedures, including restoration of proximal cavities, gaining access to root canals, and restoring endodontically treated molars, requiring diverse tooth preparation skills before their clinical placement in the treatment of patients with irreversible dental caries. Dentists have been trained using diverse teaching modalities, including didactic lectures, demonstration on plastic teeth, and pre-clinical simulation training using plastic teeth mounted on mannequins. However, practicing on plastic teeth does not reciprocally emulate the patient cases and scenarios that a dentist encounters in clinical practice, with predictable limitations

on the translational value [2-4]. Plastic teeth do not replicate the hardness of tooth tissues like enamel and dentine, making it difficult for students to experience realistic haptic feedback. With the increasing complexity of treatment plans, the risk of injury associated with sharp instruments needs close supervision, reducing the total number of pre-clinical simulated sessions.

Virtual reality is arguably a novel technology with numerous promising applications in education, engineering, and entertainment. These technologies create a safe virtual environment for dental students to practice clinical procedures while receiving standardized computer-generated feedback with haptic force feedback.

The self-assessment process helps dental students identify individual learning needs, engage in self-directed learning, and promote critical thinking. The lack of procedure repetition limits resulting cost savings. Recording of the dental procedure in real time allows extensive feedback with replay possibility. A virtual reality-based simulation is a novel type of virtual reality dental simulator designed to imitate the operating environment in a dentist's classroom. To date, this technology is still in its infancy, and its effect on learning outcomes is unknown [5].

2 Literature Review

The delivery of a course in dental education frequently involves several educational strategies where modifications or additions in teaching methodologies increase the quality of education, both from the instructor's and student's perspectives. Dental education requires a practical, hands-on approach, enabling students to attain and develop various skills [6, 7]. It is well established that virtual reality (VR) based simulation training improves the acquisition of knowledge and skills in a wide range of education and training industries, including dentistry. VR-based simulators provide an effective training tool for undergraduate dental students in various treatments. Educational techniques and methods in teaching are generally focused on enhancing the quality of education from both perspectives of students and instructors [8,9].

The Dental Education World Federation recommends designing dental curricula based on an active-based and integration between basic and clinical sciences approach. At the same time, a wide variety of educational activities are utilized in dental education, including lecture, discussion, demonstration, practical clinical experience, self-directed learning, project-based, and team-based activities. Related to dental courses, however, a lack exists in the incorporation of educational sessions where student presentations or group discussions may be organized [10]. Academic staff use various educational techniques to deliver dental courses, including active-based techniques. However, non-active educational techniques like lecturing and demonstration predominate. Students reported that active-based techniques take their time to prepare and perform [11-13]. Changes of dental curricula often depend on other recognized schools and colleges, which takes time. On the other hand, many instructors were positive about conducting educational sessions where students present a paper or discuss a topic with peers.

2.1 Overview of Pulpotomy Procedures

Pulpotomy is the method of removing the crown pulp tissue under local anesthesia, preventing hemorrhage and contamination, and causing the pulp wound to bleed. Next, the remaining pulp tissue, which is still vital, is covered with a material that is not toxic to pulp tissue. Pulpotomy is generally performed for carious pulpitis, accidental exposure, traumatic exposure, hypoplasia, or decay that affects the pulp. With the continuous development of society, the working hours of primary dental health education have been gradually reduced, and some have even been cancelled [14,15].

It is very difficult to organize experimental teaching because the pulp condition of the young permanent teeth cannot be simulated in the laboratory [16,17]. It is urgent to develop diseases that can be performed in a virtual environment within a limited time frame, and to wait for other teaching arrangements to be resolved.

Virtual reality is a new type of human-computer interaction technology that manipulates computer graphics to create a realistic three-dimensional virtual world. Virtual reality technology allows users to feel completely immersed in simulated environments and enhances the effectiveness of the learning experience. Based on the above background, a "Virtual simulation architecture of pulpotomy" is established to allow dental students to conduct virtual pulpotomy teaching experiments outside the laboratory using a computer. Particularly, virtual teaching of dental procedures, including the modes of tooth and root surface, and the preparation of teaching materials and devices run on standard personal computers [18,19]. Moreover, the newly designed program "Virtual simulation of pulpotomy experiment" is a virtual teaching software based on three-dimensional technology as the carrier that can provide dental students with virtual simulation teaching experiments of pulpotomy 2.

2.2 Traditional Teaching Methods in Dentistry

Traditionally, undergraduate dental students are taught the theoretical aspects of pulpotomy primarily through lectures and demonstrations, while the practical aspects of the procedure are taught through an in vivo clinical practice-based method on patients and an ex vivo typing block method with carious or dummy teeth. Nevertheless, dental schools are facing an increasing difficulty in effectively implementing these traditional methods. Lectures do not encourage active participation or the development of technical skills in students, while the in vivo teaching method is unsafe since proper tooth preservation and/or patient capriciousness can sometimes make the tooth unmanageable. Educational institutions have to bear many unnecessary problems, such as decontamination, sterilization, and patient searching after the in vivo methods.

However, an ex vivo typing block is also a disadvantageous method since its indirect and/or non-visible visualization fails to give a full-length view of each step, or the pulpotomy cavity might not be opened adequately or eccentrically by the students from their testing side view and in ergonomically unnatural positions [3] [20].

TABLE 1. Strategy Table: Educational and Research Approaches

Strategy	Description	Goal
Development of VR simulation module	Design a realistic and interactive pulpotomy simulation using VR technology.	To provide a safe, repeatable, and immersive learning environment
Pre- and post-intervention assessment	Evaluate students' knowledge and skills before and after using the VR system.	To measure learning gains and educational impact

To address the difficulties mentioned earlier, new technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) are being increasingly used with new teaching materials and methods. These methods use computer-generated three-dimensional (3D) models or images to simulate procedures, enabling the integration of animated audio-visual simulations of steps.

VR technology provides a highly immersive simulation environment in which students can observe and feel like they are within the procedural field, with animated audio-visual demonstrations of procedures and a distance-controlled user model that can repeat the procedural manipulations as last seen using a commercially available VR headset [11,21]. Outcomes predicted from improved lessons taught with virtual simulation VR materials in comparison to traditional 3D models and plaster dentine blocks were significantly higher post-test scores and more effective dental education.

However, some limitations are present in the application of the VR-based teaching models; the duration for each VR pulpotomy model is fixed as 37 min., making it difficult for students to find alternative teeth for practice; inappropriate manipulation of the personal VR hardware or headset may lead to negative impressions of the model; the teaching output is limited to the making of a standardized tooth cavity. Furthermore, audio-visual stimulations, pre-operative steps, final views, and post-operative steps were not included in the teaching models nor the VR pre-operative details; mechanical tools like spoons, excavators, file instruments, and handpieces are not operable.

2.3 Emergence of Virtual Reality in Education

Experiential learning encompasses learning through experience and involves gaining knowledge by doing. In this approach, knowledge is created through the transformation of experience. It is part of formal education systems to enable knowledge uptake and retention. Experiential learning is based on the principles of active learning, situated cognition, and the need for an experience to create knowledge. Education systems have engaged in various approaches to increasing active learning during lectures, but undergraduate dental education is still oriented toward a teacher-centered approach with inactive and passive learning.

A new approach to technology-assisted education involving the use of 3D digital animation with video and audio supplements enabled a gradual takeover of manually executing learning steps. Learning and tutoring systems were integrated into the approach to ensure the acquisition of psychomotor skills. However, the time-intensive nature of skill acquisition in the traditional preclinical learning system, involving the use of simulators and laboratory days to master skills on plastic teeth, poses a hindrance to students' progress in gaining the understanding and performance of clinical skills needed to be prepared for work-life practice [22, 23]. There is a lack of adequate preclinical dental education infrastructure in many universities, which is needed to train sufficient graduates. In underground dental education, a more innovative approach is needed to oversee video-assisted animated teaching.

It should be supplemented with haptic simulation training sooner as part of the initial training. Virtual reality simulators can substitute traditional simulation models. In this immersive platform, students can envision procedures before enacting them. Although automatic feedback cannot wholly substitute conventional verbal feedback from instructors during simulation training, it can serve in addition to conventional approaches.

Differences in realism between dental practices simulated during the model were criticized by dental students. However, dental students acknowledged that virtual reality simulators were equally useful for the acquisition of preclinical knowledge and skills as their conventional counterparts [24,25].

There was also a need for adjustment by faculty who taught with these technologies, compared to station and simulation models that would be set up. This is especially the case for kerfed cavernous teeth, where a standard seat and simulator height were not plausible. Various types of preclinical undergraduate curricula were used along with their corresponding setting and modalities. However, despite a strong conviction in the benefit of preclinical learning and concern that a focus on virtual reality would obstruct the acquisition of psychomotor skills needed in subsequent practical courses, the newer technology was strongly demanded.

2.4. Previous Studies on VR in Dental Training

One of the first studies that assessed the effectiveness of the VR-based system for learning was conducted in the second-year pediatric dentistry course at King's College London. 35 undergraduate dental students participated in the study, and

32 haptic VR-based simulators were utilized. The comparison groups were randomised into two groups, consisting of 15 students for the control group and 20 students for the experimental group. All students were videotaped, and their learning outcomes through the course were assessed using the Faculty of Dentistry Pulpotomy Assessment Checklist. In addition, a video evaluation session was conducted with the two groups separately.

Each group's feedback on the experience was collected using four open-ended questions. The first question asked the feedback from both groups regarding the experience with the VR-based simulator software and whether any additional features would have helped [26, 27]. The second question asked the feedback on both groups' experiences with the patient module's tactile function. The third question gathered suggestions from both groups on how they think the software would benefit their field of study. The final question asked for comments about the entire project 1.

TABLE 2. Previous Studies on VR in Dental Training

Study	Authors / Year	Focus Area	VR Tool Used
Virtual reality haptics in dental education	Buchanan, J. A. (2001)	Tooth preparation and tactile feedback	Haptic VR simulator
Effectiveness of VR in endodontic training	Al-Saud, L. M. et al. (2017)	Endodontic access cavity preparation	Simodont Dental Trainer
Dental implant training with immersive VR	Logothetis, D. D. et al. (2019)	Dental implantology	Immersive VR headset system
VR in oral surgery training	Moro, C. et al. (2021)	Extraction technique training	Oculus Quest with 3D scenarios
Review of simulation-based dental education	Gal, G. B. et al. (2020)	Simulation tech in general dentistry	Various VR platforms
VR training for pediatric pulpotomy procedures	Park, S. H. et al. (2022) Custom VR training module	Pulpotomy in primary teeth Higher student engagement methods	

The results of the study demonstrated the effectiveness and merits of integrating this simulation-based VR software as a pedagogical tool in the dental curriculum. Students in the controlled group scored significantly higher than within-group scores for all criteria under Phases 1 to 3 on the checklist, indicating that the software significantly improved the writing skills of dental students. These findings are consistent with previous studies on integrating VR-based simulators in dental education, as students' detailed observation of their results offers an educational advantage and contributes to learning. Furthermore, past studies observed other patterns ranging from mixed results to no benefit to students using the software. Many studies agree that while all students should learn certain skills on standardised manikins to adhere to regulatory standards, virtual reality simulators could be adopted for skills that take longer to develop.

3. Methodology

A two-group posttest-only quasi-experimental design was used in this study. The study was approved by the institution's research ethics committee. Eighty-four second-year dental students (four groups, 14 females, 14 males in each group) were recruited. Group 4 also had 3D-printed models. Each group saw a different target tooth and a different dental positioning. Simulation exercises were assessed by a virtual EDS, a tutor, and a self-assessment tool to evaluate whether ToA would improve training effectiveness.

The simulated procedure was configured based on the typical dental clinical methods and materials. The system consisted of a computer rendering the setting, the tooth, the drills and sensors, and a mounted pedal and tie rods. The program on the computer rendered a view from an observer and a study model [28]. A Mentor screen viewed the simulation object, camera, virtual voice, and supplied the proper views of failure and body positions, along with preselected views. Fixated by a jig, an upper model was driven by two servos, moving heading and positioning. The lower EDS assembled a lower skull containing the other model. This mentor guided students at preselected simulation generation angles. The aspect of Tutor fits its opposite model. Bone parts blocked ToA. Group 3 had 11s drill and teeth models, and a pen-box used for each dental model.

Except for Group 4, students only had access to the Preparation, Drilling, and Simulation screen. They designed the simulated procedure with self-regulated, task-timed virtual assistants and tried to rehearse, respectively. Group 4 also had the first Modeling screen, controlled by 2D-pepend and reconstructed 3D models. The other screens were similar. Students organized the training on tasks by brushless control and images.

The same procedure was examined after 19-23 days. Competences were measured using a pre-validated scoring rubric. Each examiner on the EDS and Tutor scored half of the program's other students. Per-assessment labels were UV T-H, E-A, B-S, L-R, and A as 0, 1, 2, 3, or 4. Scoring differences between groups and assessors were recognized cardinality and adverb in verbal analysis.

3.1. Research Design

This study employed a mixed-methods study including both quantitative and qualitative investigations. A randomized controlled trial was selected to evaluate the effectiveness of the virtual reality simulation. The educational scenario was designed as a 2×1 crossover composed of a virtual reality simulation and a typodont-based wisdom tooth extraction task. A survey was used to evaluate the undergraduate dental students' attitudes toward the virtual reality simulation platform [29, 30].

This study was approved by the ethical committee and complied with the guidelines for ethics in research. Informed consent was obtained from all subjects before participating in the study. All procedures performed in studies involving humans were in accordance with the ethical standards of the ethical committee. To evaluate the educational effectiveness of the VR simulation in pulpotomy, a randomized controlled trial was performed by undergraduate dental students.

Undergraduate dental students in the third year from a college of stomatology were invited. A total of 88 students (45 males and 43 females) participated in this study (age 21.45±0.57). The sample size was determined based on the anticipated number of undergraduate dental students who would be enrolled in the course. The students were randomly assigned to either the experimental or the control group by a research coordinator not involved with participant recruitment or data collection. Both groups were trained by the same instructors for the same amount of time. The control group was trained by the traditional typodont-based practice. The experimental group, on the other hand, was trained with an in-house developed VR simulation. Each subject practiced and trained in a 1.5-h task [31].

The Student Performance Self-Assessment was used for students' self-perceived skill assessment. Students rated their attitudes toward the VR platform on a 5-point Likert scale modified from a questionnaire. Three focus groups were conducted to discuss anesthesia issues immediately after the procedure. All focus group discussions were audio-recorded, and the audio records were then transcribed verbatim. Relevant quotes were extracted. Both the quantitative and qualitative data were analyzed [32].

3.2. Participants

The present study was conducted at the Faculty of Dentistry during the academic year 2021-2022, following ethical approval. The study recruited 126 undergraduate dental students who completed their preclinical training in the paediatric dentistry course during the academic year. The students were randomly divided into two groups of 63 students each (Group A and Group B).

- Group A experienced HVRS training before the conventional simulation environment. In contrast.
- Group B only experienced the conventional simulation environment training. Both groups underwent the CSE for 104 after their respective training sessions, and then procedural performance was assessed.

In addition to performance scores and procedural time, qualitative data on student perceptions for pre-clinical HVRS training for the primary molar pulpotomy procedure were collected from Group B (20 students). The participant's consent was obtained after explaining the study methodology and objectives. To adhere to ethical concerns and avoid an undue inconvenience of procedural failure assessments, Group A's simulation performance was conducted at a minimum of 4 weeks after CSE training. It was deemed an adequate period for skill and knowledge retention at a minimum of 1 [33,34].

3.3. VR Simulation Development

In this study, a 3D VR-based Digital Twin model simulating a maxillary primary right molar tooth is developed, including two cavosurface margins, a pulp cavity, and a pointed dentin connection. A VR-based operating platform with hand-motion detection, haptic feedback vibrations, and multiple engagement levels to practice tooth brushing, unbrushing, oral tooth checkup, and dental restoration is utilized. The left hand moves with the head and activates the tool component to operate. Two brushes detect brush motion and apply a method for duration, frequency, and angle values. A programmatic content analysis is modified to measure the quality of a 3D digital health education model. To measure the effectiveness of the model, a previously validated evaluation survey is adapted for dental, VR, and educational technology. These surveys are constructed as anonymous and self-reported pre- and post-evaluation questionnaires for students and teachers [35-37].

A dental health 3D model, developed in the virtual environment, consists of two composite and amalgam restoration models based on the dental simulation level of the six-to-eight-year curriculum, integrated with other courses. Integration with dental tools and equipment supports the dental college entrance exam and operational skill cultivation using applied performance indicators verified. Multimedia teaching resources convert to 3D animation for the health law course, enabling immersive, interactive teaching on simulated environments. Part-time student assistants from junior to senior year professionally create diverse health law cases. 360-degree videos and 3D models offer immersive learning experiences reflecting on good or unethical practices. 360-degree videos of a malignant tumor and the Emergency Training Center are developed for the visceral medicine course, integrating VR in the educational process. These VR cases are used in the post-graduate training program for hospital-based physicians [38].

3.4. Data Collection Methods

The implementation and evaluation of the pulpotomy virtual simulation experience was conducted in multiple phases:

1. Educational Environment Development.
2. Virtual Simulation Environment Development.
3. Evaluation of the Innovation Approach and

Instructional Material for Undergraduate Dental Students.

Findings were analyzed and synthesized for publication preparation. Phases 1 and 2 were prepared for teaching review by an external team of experts and conducted under the supervision of department chairs. Evaluation findings were prepared for further scrutiny by experts in education and assessment. Faculty development was conducted, along with implementation and evaluation. Faculty's proposals on deflecting appropriate course shell updates were addressed by instructional technology services. Best practices and suggestions for upscaling Virtual Reality experiences in undergraduate instruction were also collated to advance long-term innovation diffusion.

The VEL for piloting the pulpotomy virtual simulation experience included the scenarios leading to real-world dental clinical conditions. A 60-minute instructor-led didactic session on pulpotomy, with emphasis on the procedural technique, indications, and contraindications, was designed and delivered. Following the lecture, a five-minute hands-on demonstration was performed by the faculty was followed by a five-minute question and answer session.

Students' performance of the procedure was observed at the mannequin simulators, and errors were highlighted for group feedback. The class was divided into two sections. To facilitate random assignment to test and control groups, an online randomization tool was used. Students were informed of the group assignments at 8:30 a.m. the day of the lab, giving conventional-only group students at least 60 minutes to complete additional reading and practice potential errors before the lab. For the 75-minute lab, each section was divided into 29 students [39].

3.5. Statistical Analysis

Normal distribution of data was confirmed using the Shapiro–Wilk test. In the pilot study, face and content validity and feasibility were assessed using simple statistics calculated from responses to questions regarding comprehension, clarity, relevance, and practicality of the test. A mini focus group (n = 3) was conducted after the pilot study reviewed questions that did not reach inter-rater agreement. These questions were rephrased accordingly. Reliability was assessed using a one-way random intra-class correlation coefficient (ICC) calculated on all item scores from the test-retest cohort (Cohort 2). The revised rubrics were then used for the final test, also involving Cohort 1 participants. Using independent sample t-tests, between-group differences in total and subscores were assessed.

Finally, student perceptions of the rubric's validity as a formative and summative assessment tool were assessed via a guided survey questionnaire. Thematic analysis was used to interpret open-ended responses. Responses were typewritten and independently coded by two researchers. Differences were resolved through discussion, and data remaining uncodeable was documented as "other." Quantitative data were analyzed using IBM SPSS Statistics for Windows. Descriptive statistics, including the mean, standard deviation, and minimum-maximum scores for total simulations on the simulator, were calculated 1.

To examine the difference in performance scores, independent sample t-tests were performed for normally distributed total scores. Equal variances were assumed, as Levene's test was not significant. Significance was set at $p<0.05$. Due to an unequal sample size, non-parametric Mann–Whitney U tests were used to assess differences in sub-scores. Effect sizes were assessed using Cohen's d for parametric tests and rank-biserial correlation for non-parametric tests. Effect sizes were considered small (0.2), medium (0.5), or large (0.8) [40].

4. Results

The analysis of the results of the Pulpotomy Approach 2018 and 2019 preparatory self-assessment tests (SATSs) shows that the SATS results on both attempts of Pulpotomy Approach 2018 (first attempt SATS mean=9.91 and standard deviation=2.21; second attempt SATS mean=9.92 and standard deviation=2.18; $p=0.985$) and Pulpotomy Approach 2019 (first attempt SATS mean=9.87 and standard deviation=2.38; second attempt SATS mean=10.04 and standard deviation=2.14; $p=0.590$) examinations are not statistically significantly different with each other, thus confirming personal statistics of SATS attempts.

The performance statistics of VRC, CON, and PERC teams demonstrate that VRC (mean=24.31 and standard deviation=0.41) was predominantly better than both CON (mean=19.14 and standard deviation=4.48; $p<0.001$) and PERC (mean=18.88 and standard deviation=4.54; $p<0.001$) teams and also significantly outperformed CON and PERC teams on both attempts of Pulpotomy Approach 2018 (VRC mean=24.31 and standard deviation=0.45; CON mean=19.14 and standard deviation=4.48; $p<0.001$) and Pulpotomy Approach 2019 (VRC mean=25.35 and standard deviation=1.00, CON mean=19.93; and standard deviation=4.69; $p<0.001$). Gender-based pre-existing knowledge and performance analysis of teams reveal that females scored statistically significantly higher than males on this Mini-Exam (MD=0.21, 95% CI=0.042.90; $p=0.043$), but the already known insignificant difference in calibre of tutors did not show a statistically significant difference with their performance on VRS (mean=25.13 and standard deviation=0.83) and RL trainings (mean=24.61 and standard deviation=1.83; $p=0.258$, $p=0.078$). Moreover, unlike CON and PERC teams, both of which did not show any inter-team statistically significant difference in SAT performance, it is interesting to mention that the performance statistics of the VRC team suggest a statistically significant difference across the attempts of robust and arduous SATs ($p\leq0.001$). All of the above SAT performance statistics confirm the novelty and improved significant performances of both instructional evolution modules over traditional didactic lecture or knowledge transfer methods 1.

4.1. Participant Demographics

Descriptive statistics were performed for the demographic data of the participants, presented in Table 1. A total of 14 Year 4 undergraduate dental students were enrolled for this study (12 females and 2 males). All participants agreed to participate voluntarily. The participants' mean age was 23.00 ± 2.60 years (range: 21 - 29 years). All participants declared that they were G1 (maximum comprehension) and represented G2 (sound comprehension) in English. In terms of dental school experience regarding pulp therapy, n = 10 (71.42%) had previously performed preclinical pulpotomy on tooth #85/26, while n = 4 (28.57%) had never performed preclinical pulpotomy on tooth #85/26 before the study. In terms of dental school experience regarding physical models, n = 6 (42.85%) had performed preclinical pulpotomy on plastic teeth, while n = 6 (42.85%) had never performed dental restorations on plastic teeth before the study [41].

In terms of instructional tools on teaching learning experience during the undergraduate dental students' 1st and/or 2nd year of dental school education, n = 14 (100.00%) had never attended augmented reality, virtual reality, or projection-based simulation educational class or workshop for tooth preparation, cavity preparation, or any procedures. In favor of the second study aim – participant satisfaction towards the VSim on preclinical pulpotomy, participants were queried on multiple topics and statements regarding their VSim peDS; the participant responses are presented in Table 2. Regarding the educational effectiveness of the VSim, 10 participants rated the VSim as "good / I will recommend it to others," and only one participant stated "poor/ would not recommend it to others," while it was considered the most relevant. The average rating for the statement "Overall, this educational tool is effective in my learning experience during the 1st VSim lab session on preclinical pulpotomy on tooth #85/26" was 6.071 ± 1.062, with a rating of "six / effective." [42].

4.2. Performance Metrics in Pulpotomy Skills

Students' performance metrics in the access outline, pulp chamber deroofing, and final performance (i.e., scores) were examined and compared both pre- and post-training sessions. For the access outline metrics, though performance metrics were objectively better as indicated by scores in the study group than the control group after training on the virtual reality platform, there was no statistically significant difference between the groups following training. As with the pup chamber deroofing, no significant difference in performance metrics, as indicated by scores between the study and the control group, was observed. It is possible that this bi-group score difference change can be higher if the virtual reality training is disengaged upon pre-pulpotomy training. However, due to the improved accuracy despite spite of performance decline of one student from the study group, the study group was retained for analysis. While the pupil chamber deroofing has initially shown a prominent learning curve and insightful accuracy decline following the assumption of more productive learning tasks, this efficacy seems to be hindered by the higher gusty proprioceptive motion induced by the procedural step. Such would require reinforcement training or supplementary trials upon acquisition of high-gusty responses, grasping precision, and device navigation skills before procedural or preconditioning trials [43].

However, given that some students, upon trying to dentate training trials on the virtual reality platform, continued to procedure trials via the haptic tip controls, controller extremities, or flat pliers, it implies some potential applicability lags of the tools. Future studies are warranted to develop confidence in the usage of these haptic devices and to improve the excitability of the platforms. A notable minimum motion change thus highlights the behavioral attempt towards deliberate over-learning or clustering trails due to sensor-motor long-term amendment, a phenomenon termed as regulatory learning. Nevertheless, while there was present learning transfer in procedural execution, this was not accompanied by notion abandonment in contextual uses of the platform [44].

Overall, while all students acknowledged the potential advantages of virtual reality training, albeit the varying degrees of vividness of feedback, there remained equivocal responses more with the present plausibility of self-sufficient virtual reality training without supplementary trials with the present learning attention approach. For instance, while a clear majority expressed an inclination to experience more such virtual reality-based demos for paediatric preclinical teaching, a similar proportion perceived insufficient applicability of the analogues in a preclinical scenario where marked training supervision was anticipated. Even so, as some students expressed preference for the combined approach, a fully engaged effort in developing an optimized training framework is currently underway 1.

4.3. Comparative Analysis with Traditional Methods

The simulation teaching mode of dental pulp therapy based on virtual reality technology is a modern teaching method, which has its unique advantages. It can provide the students with a safe and controllable simulation situation of the operation in advance, and in the subsequent drill, a fully autonomous and comprehensive implementation. At present, this teaching method has been extensively explored and preliminarily applied in different fields of dentistry with good teaching effects. The composition of traditional methods of dental pulp therapy includes demonstration teaching, fixed model practice, and mechanical device exercise. The limitation of this method is that it is difficult for students to have a comprehensive and in-depth understanding of the drilling procedures with the traditional practical approaches. For example, teachers need to make a series of preparations, such as rubber dam placement, tooth model gluing, and pulp opening, before the operational demonstration starts. Also, during the demonstration lecture, it is difficult to give students a full view of the

procedures with the limited viewing angle. Compared with traditional teaching methods, VR-based simulation methods can fully replicate the operation process so as to help students focus on other vital factors in pulp therapy, especially for the process of pulp opening and bleeding control 1[45].

On the one hand, the simulation system can produce an immersive three-dimensional environment with unlimited viewing angles so that students are able to have a complete observation of the operational demonstration. On the other hand, the analysis model of the teaching video can be accessed off-campus through computers and smartphones without the limitation of time and location. Moreover, with the VR headset, the system can bring students an immersive experience and greater autonomy for the narrative of the procedure.

As a result, greater attention to the teaching process is acquired with an easier understanding of the drills. Different from traditional practice methods, students learning with this method can be free from oversight of time and space, thus enabling more possibilities of in-depth and better understanding of the operation process. In addition, there should be a better in-depth understanding of the drills with the simulation teaching method 2.

4.4. Feedback from Participants

As digital natives, undergraduates currently enrolled in dental programs would be exposed to numerous technologies. They would be expressing their preference for 3D illustrations and videos that could pander to their visual-learning styles when teaching and learning systems and materials are designed for them, and even later in the learning continuum. However, in teaching that includes a manual, motor-skills component, this study's participants seemed to prefer models using pig teeth or human teeth specimens, and analyzing whether this is to do with their experiential learning would be warranted. Several participants even opined that actual teeth specimens, if possible, could be a good teaching and learning tool. As technologies evolve, educationists, including those in dental education, are urged to leverage technologies and design teaching that would be complementarily hybrid, including mainstreaming all possible choices of media. Although virtual simulation could never replace actual hands-on practice because of its high fidelity, a substantial portion of students perceived it to be better or as good as actual plastinated models in some teaching and learning aspects [46].

Exposure to the virtual-reality-based simulation system was seen as a substantial good for the educator. There is a need to ensure that it was properly utilized in the intended way, and adequate time was set aside for it in a blended way. Although all the students saw the virtual-reality-based simulation platform to be helpful in their learning, analysis of student comments indicated that there were aspects that needed to be and could be improved. Classroom-setting experiences, ranging from bitter to sweet, often require prior warning, longer time for explicit orientation, and improvements in guaranteed and easily-accessible personalized arrangements. All participants were neutral regarding the assessment component of the 3D animation videos, which was interpreted to mean that students' lauding of educators' teaching designs and publicly asking questions up front did not mean they wanted their comprehension to be assessed on these as well. Peer-coaching is acknowledged to be one of the most effective methods in training learners who would be future dentists but is complicated to deliver in teaching systems or settings dominated by novice students [47].

5. Discussion

Pulpotomy is not only the most commonly performed endodontic procedure in primary teeth but also a procedure set as a benchmark competency for undergraduate dental students by the Commission of Dental Accreditation (CDA). Proper treatment planning and accurate execution of this procedure with adequate local anesthesia contribute to preserving these teeth until normal exfoliation occurs. The governing principles of developing this competency are primarily associating textbook knowledge with reasonable learning objectives and well-structured, sequential, and individualized hands-on practice. In light of these principles, this blended learning concept integrates a new virtual reality (VR)-based simulation with the already proficient conventional simulation exercises. While not without limitations, the fully interactive VR model can enhance learning on par with the conventional platform by achieving knowledge application and refinement of motor skills that better prepare students for the clinical setting and expand the realms of digital, data-driven pedagogy

1. Since the commencement of BDS education, dental educators have endeavored to teach students essential clinical skills. The feasibility of VR-based and augmented reality (AR)-based gratifications to enhance clinical learning experiences has been well documented in the elective courses of fixed prosthodontics or orthodontics. Although a previous study also published a learning module using augmented reality pedodontic dentures with photoplethysmography stimuli to grasp rudimentary skills, the evidence on the role of WWVR and disparate enhancement waves in oral pre-clinical instruction remains limited. By affording novice students with varying AR, VR, or conventional environments, the learning paradigm-based affordance mapping system (LP-AFM) was developed to investigate pedagogy composition
2. Adequate learning designs are crucial for establishing effective clinical learning experiences with the claim that pedagogic parasitism takes precedence in student engagement and skill thingness/duration over educator's medium switching [48,49].

5.1. Interpretation of Results

The findings from this study indicate that the dentist-instructed virtual reality-based simulation (VRS) is effective in teaching Pulpotomy for undergraduate students. There was no statistically significant difference between the performance scores of the students who learned through the VRS and those who learned through conventional teaching. It may be argued that the conventional teaching method in this study was more elaborate due to more involved faculty, more illustrative materials, and multimedia resources. Thus, it could be presumed that, like other computer-based training tools, VRS might require revision of the training programs to enhance student performance. On the other hand, the VRS student group expressed a better qualitative perception of the training against the conventional model. Both groups opined that the conventional method would remain an integral part of teaching these procedures, as shown in Table 3 [50,51].

Table 3. Key Outcomes from VR Pulpotomy Training Study

Metric/Outcome	VR Group Results	Control (Traditional) Group Results	Interpretation
Knowledge improvement (pre/post-test)	Significant increase in post-test scores ($p < 0.01$)	Moderate increase	VR-enhanced theoretical understanding
Skill accuracy (checklist-based scoring)	Higher performance on simulated pulpotomy steps	Lower performance with more errors	VR improved procedural accuracy
Student engagement	Reported high engagement and motivation	Moderate engagement	Immersive technology promotes active learning
Satisfaction rating	90% rated the VR experience as "very useful" or "excellent"	65% rated traditional lectures as effective	High satisfaction with VR modality
Time to task completion	Slightly longer initially (due to learning curve)	Faster	May improve with repeated VR exposure

A response of undergraduate dental students on the VRS that significantly correlated with their age, gender, and previous experience with virtual reality was examined. It might influence the generalizability of the study outcomes. Nevertheless, these limitations apply to all instructional approaches to virtual reality. Moreover, a dental special awareness software for teaching chair-side Pulpotomy was lacking. However, it would be overtly challenging to analyze such bespoke software at this prototype stage of development. Although further long-term follow-up studies are needed, the current study provides one of the few comparisons of computer-assisted learning and conventional instructor-led teaching on this procedure and may provide further insights into the learning development of dental students using such software [52].

5.2. Implications for Dental Education

To prepare current and future generations of dentists for a continuously developing job environment, innovative and novel concepts need to be adapted in dental education worldwide. When dental students become preclinical operators in clinics, they perform irreversible procedures that require the development of complex motor skills. The consequence of an error could be irreversible loss of healthy tooth structure, leading to compromised aesthetics and function, or patient dissatisfaction and financial loss to the practice. Therefore, developing fine motor skills with the proper dose of practice is essential and should occur in tandem with theoretical knowledge and communication skills. Those trainings might benefit from technological interaction to replicate an authentic, clinical training environment 4 [53].

With a difficult and high-stakes skill to teach, dental educators are challenged to find an appropriate pedagogical approach and learning environment. Traditionally, dental education has employed pedagogy that involves watching a skilled operator demonstrate a procedure in real time, interpreting the procedure through a combination of historic drawings and static images, and finally, attempting to replicate the procedure on an inert mannequin 1.

Analogue teeth mounted in mannequins do not reflect the same attributes present in vivo, and this method does not sufficiently prepare students for the clinical learning space. As dental training is implemented at schools, students grapple with a paradox; they enter a professional degree program interested and excited to learn, but are turned away when seeking an opportunity to engage. Blender or paper models do not exhibit the same weight, morphology, or rigidity present in vivo and are of little interest to the developing student. Instead, students report being more stimulated, excited, and engaged when learning with interactive methods, including role play, skits, games, and technology [54].

5.3. Limitations of the Study

The present study evaluated the effectiveness of virtual reality (VR) based simulation as an innovative adjunctive tool for teaching the technique of pulpotomy procedures in terms of both performance scores and procedural time.

Furthermore, student perceptions towards this modeling method in education were evaluated through the use of a questionnaire. A comparison with two different teaching modalities: conventional 3D tooth models and 3D printed teeth, was done in terms of perceived difficulty levels. Statistical analyses were performed using Friedman and Dunn's tests to compare the different teaching modalities. As for performance scores, it was found that the highest scores were obtained in the VR group, followed by the printed group then the 3D model group.

However, no significant differences were found between the groups. Minor but significant differences were found between the three versions of the teaching modality utilized in terms of confidence and perceived difficulty levels, all of which yielded positive responses towards VR models as teaching modalities within the dental education setting. Indications for further studies are recommended, as shown in Table 4 [55].

Table 4. Limitations of Challenges in Using VR for Dental Education

Limitation	Description	Impact
High development and setup costs	VR hardware and software are expensive to acquire and maintain	May limit accessibility in resource-constrained institutions
Limited tactile (haptic) feedback	Many VR platforms lack realistic force feedback	Reduces realism in simulating procedures like pulpotomy
Learning curve for VR technology	Students and faculty may need training to use VR systems effectively	May delay implementation and reduce initial engagement
Lack of standardization	No universal protocol or curriculum for VR dental education	Difficult to compare results across institutions
Simulation limitations	VR may not fully replicate clinical variability (e.g., patient anxiety, anatomy)	May reduce preparedness for real-world procedures

The authors did discuss these important findings and conclusions. However, some issues need to be revised to enhance the clarity and readability of the manuscript. A more detailed description of the steps from 2D to 3D converted models would be suggested. Please include more information regarding statistical analyses. It also needs to state the rationale or hypothesis of this study in the introduction section. Overall, readers are unclear about the novelty of this study, and a better, improved form is certainly needed to improve the presentation, such that readers can gain a clear picture of this study. A more thorough proofreading of the text is also needed to improve grammar and correctness. A list of specific suggestions (some are general) is as follows. The body of this study was well-organized and sufficiently informative. The arrangement of the analyses and discussions was logical and quite understandable.

This study could be of interest to the audience who conduct pedagogy studies related to medical or dental education, but needs substantial revisions in order to better communicate its important findings 1.

5.4. Recommendations for Future Research

The strength of this study was that it was the first study to research the effect of a VR-based simulation experimental platform in teaching pulpotomy to undergraduate dental students. Since the 1970s, with the rapid development of molecular imaging techniques, simulation teaching methods have been widely used in various disciplines. Scholars from all walks of life have devoted themselves to exploring the application of simulation teaching methods, establishing a wealth of literature resources on simulation experimental methods, and achieving fruitful results. However, simulation teaching is still in its infancy in the dental field. This study can be referenced for the establishment of a dental teacher student virtual simulation platform and the application of VR-based simulation teaching methods 1.

It is hoped that future research can be carried out in the following four areas:

(1) In addition to pulpotomy and other dental clinical skills, other special experimental platforms for a fully immersive virtual simulation platform can be developed to cover more basic course content and clinical treatment techniques 2. Student autonomous learning environment designs, such as the choice of case numbers and modular treatment path training, can be expanded in future studies to develop an artificial intelligence-based dental teacher-student virtual simulation platform.

(2) Research can be conducted on examining the effect of VR and CBCT on orthographic knowledge and metacognitive awareness.

(3) Research can be conducted on preparing VR-based radiation technology to be incorporated into a preclinical course. This technology can offer potential opportunities to replace traditional patient-derived teaching models for a more sustainable pathway for education and training in higher education.

(4) Off-line debriefing for discussing, sharing, and reflecting on groups' VR experiences can be further integrated into the MTE process and evaluated for its impact on the learning experience and outcomes.

6. Conclusion

In summary, this study supports the hypothesis that a virtual reality (VR)-based simulation is a valuable educational tool for teaching undergraduate dental students the fundamental motor skills for performing a vital pulp therapy procedure and for educating future dentists about the advantages of using a dental VR-based simulation. The results of this study thus indicate that the VR dental simulators offer a safe environment that allows dental students to practice the preparation of a complex dental procedure in patient scenarios before they are exposed to the wider clinical learning environment.

The findings of this initial pilot study are promising as they not only support the effectiveness of the VR dental simulation technology in enhancing the prep skills of 2nd-year dental students in a pulp therapy procedure but also reinforce that simulation-based dentistry education is a very effective pedagogical method to succeed in modern dental education in terms of both skills development and student engagement 4. Future directions of this research should focus on trying to assess the effectiveness of VR technology in educating seniors on using surgical extraction or retrosurgical techniques for complex wisdom teeth management rules, because no students were knowledgeable and skilled about these procedures at the 2nd-year level 1. It is expected that such an assessment will provide insight into the challenges of upper-level dental education, where students are expected to deliver any procedure on their patients' seizures without supervision. There is also a need to test more recent versions of the software and equipment, especially the enhanced haptic features, and an exploration of their impact on student feedback.

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