Virtual reality simulation for learning minimally invasive endodontics: a randomized controlled trial

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Abstract

Background Learning minimally invasive endodontic techniques presents unique challenges, requiring precise tooth structure preservation and strong spatial awareness. This study evaluated a clinically realistic virtual reality (VR) simulator, featuring eye-tracking feedback and automated outcome scoring, as an innovative tool to support student learning in minimally invasive endodontics.

Methods A prospective randomized controlled trial was conducted with 30 fourth-year preclinical dental students assigned to either a VR group (n = 15) or a standard phantom head (PH) group (n = 15). The VR system featured high-fidelity dental arch modeling, dual haptic devices, a head-mounted display with eye-gaze and tool trajectory tracking (mirror and handpiece), and automated outcome scoring. All students completed three 1-hour training sessions and performed both Traditional Access Cavity (TradAC) and Conservative Access Cavity (ConsAC) techniques. The primary outcome was tooth volume loss assessed via micro-computed tomography (micro-CT). Secondary outcomes included procedural error scores (rated by blinded experts) and task completion time. Wilcoxon signed-rank tests evaluated pre–post differences. A split-plot ANOVA analyzed training method (between-subjects) and access technique (within-subjects).

Results Significant improvements were observed across all outcomes in both groups ($p < 0.05$). There was no significant main effect of training method or interaction. A significant main effect of access technique was found for tooth volume loss ($F(1,28) = 10.46$, $p = .003$) and task completion time ($F(1,28) = 6.86$, $p = .014$), favoring ConsAC.

Conclusion This study supports the feasibility of automated virtual reality (VR) simulation as a scalable and effective tool to support student learning in minimally invasive endodontic procedures within preclinical dental education.

Trial registration

This randomized controlled trial was registered on 29 April 2025, at the TCTR registry with the study registration number TCTR20250502004.

Keywords

Virtual reality, Minimally invasive endodontics, Dental education

Background

Minimally invasive dentistry (MID) has become increasingly important in oral health care, emphasizing the preservation of natural tooth structure while ensuring effective treatment outcomes [1]. One of the key aspects of MID in endodontics is minimally invasive access cavity preparation in root canal treatment, which aims to create an access route to the dental pulp with the least amount of enamel and dentin removal. This approach is critical for maintaining the integrity and strength of the tooth, reducing the risk of fractures, and promoting better long-term outcomes [2]. By limiting the amount of tissue removal, minimally invasive techniques enhance the tooth's ability to withstand future stresses and prevent weakening [3].

In traditional dental education, students are typically trained to perform access cavity preparation on phantom head models or simulators, which provide an introductory platform for developing psychomotor skills [4]. However, these methods present several limitations. Phantom heads offer minimal variability in tooth anatomy, failing to replicate the diverse clinical scenarios encountered in real patients. Additionally, traditional simulators lack tactile feedback, which is critical for teaching students how to distinguish between enamel, dentin, and pulp layers. In clinical practice, this tactile sensation guides dentists in applying appropriate pressure and depth when drilling [5, 6]. The absence of this feedback in simulators makes it challenging for students to develop the fine motor skills and precision required for minimally invasive techniques. Educators often struggle to ensure that students achieve consistent performance, particularly in balancing effective access to the pulp with minimal removal of tooth structure, a critical aspect of minimally invasive endodontics (MIE) [4].

With advancements in digital technologies, virtual reality (VR) has emerged as a transformative tool in dental education. VR offers an immersive and highly realistic learning environment, allowing students to practice procedures in a controlled, repeatable setting [7]. This technology enables trainees to simulate complex techniques, such as accessing the dental pulp, without the risk of harming actual patients. One of the most valuable features of VR systems is the incorporation of haptic feedback, which provides users with the physical sensations of drilling through various layers of the tooth [8]. This enhances the realism of the training experience, allowing students to refine their skills in a manner that closely mirrors real-life dental procedures. Combined with head-mounted displays (HMDs) that provide a fully immersive 3D visual experience, VR offers an interactive and engaging way to develop spatial awareness and procedural accuracy [9], both of which are crucial for performing minimally invasive dental techniques.

VR simulators have become increasingly integrated into undergraduate dental education for developing procedural skills across various domains, including restorative dentistry and anesthesia administration [10–12], and particularly in endodontic training such as access cavity preparation [13–16]. Evidence from recent studies suggests that VR platforms effectively support skill acquisition by providing haptic feedback, three-dimensional visualization, and a safe, repeatable practice environment. Comparative evaluations have shown that VR-based training can yield performance outcomes comparable to those achieved with traditional phantom head models [13]. When implemented alongside or prior to physical simulation, VR training has been associated with enhanced student confidence, spatial awareness, and procedural precision [14]. A multimodal approach incorporating 3D-printed teeth, plastic models, and virtual simulation emphasized the precision of digital tools, particularly when used early in the training sequence, and demonstrated strong student support for integrating simulation technologies into the curriculum [15]. Moreover, the use of VR haptic simulators before preclinical training on artificial teeth has been shown to improve manual dexterity, reduce student stress, and increase self-confidence in clinical skill development [16].

However, these studies primarily focused on conventional access techniques and instructor-driven assessments. The specific challenges of minimally invasive endodontic techniques, such as Conservative Access Cavity (ConsAC) preparation, which requires precise spatial awareness and conservation of dentin—remain underexplored in VR-based training models, especially using objective outcome measures. To address these challenges, emerging simulation systems have integrated features that closely replicate clinical conditions and support learner-centered feedback. These include immersive 3D visualization through head-mounted displays, dual haptic devices simulating dental instruments, real-time tracking of gaze and tool movement, and high-fidelity modeling of the maxillary arch [9]. Some systems also offer automated outcome scoring and video playback for reflective learning [17].

Despite increasing interest in VR-based training, most existing studies have focused on conventional endodontic access techniques and relied on subjective evaluations. The application of immersive VR simulation to teaching minimally invasive approaches—particularly the ConsAC technique—remains underexplored. These procedures demand greater precision, spatial control, and dentin conservation, which may not be optimally taught or assessed through traditional methods. Moreover, the integration of automated scoring, gaze tracking, and haptic feedback in a clinically realistic VR environment has not been thoroughly evaluated in terms of learning effectiveness.

This study aimed to evaluate the effectiveness of a virtual reality-based simulation platform with automated feedback in teaching minimally invasive access cavity—particularly the ConsAC technique—to preclinical dental students. The primary objective was to determine whether VR training could enhance student performance in ConsAC by improving tooth structure preservation, as measured by micro-computed tomography (micro-CT). Secondary objectives included evaluating procedural accuracy through expert-rated error scores and assessing efficiency via task completion time. We hypothesized that students trained using the VR simulation system would demonstrate superior performance in minimally invasive endodontic access compared to those trained using conventional phantom head models.

Methods

Study design

A prospective, randomized, controlled, and blinded trial was conducted to evaluate whether VR training provides comparable performance outcomes to traditional PH training. The study was approved by the university ethics committee (Approval No.: COA 060/2567) and registered with the national clinical trial registry (Approval No.: TCTR20250502004, https://www.thaiclinicaltrials.org/show/TCTR20250502004). All procedures were conducted in accordance with the Declaration of Helsinki. The study adheres to CONSORT guidelines.

Two types of endodontic access cavity preparations were used in this study: Traditional Access Cavity (TradAC) and Conservative Access Cavity (ConsAC). The TradAC technique involves complete removal of the pulp chamber roof, followed by direct access to the canal orifices, with slightly diverging axial walls, so that all orifices are visible within the outline form. In contrast, the ConsAC preparation begins at the central fossa of the occlusal surface and continues with slightly converging axial walls, preserving part of the pulp chamber roof and extending only to the limit necessary to detect the canal orifices [18].

Before the training sessions began, all participants completed a pre-training assessment to establish baseline performance in both the TradAC and ConsAC techniques. This assessment was performed using a Nissin B22X-26 Endo Typodont tooth model embedded in a phantom head. Each student prepared one access cavity per technique (i.e., one TradAC and one ConsAC) using a 1-mm-diameter, 6-mm-long tapered bur with a high-speed handpiece and water coolant. No performance feedback was provided during or after this initial session.

Participants then underwent three consecutive days (Day 1 to Day 3) of training, with each session lasting one hour, using either the VR system or the phantom head (PH) model, according to their assigned group. The training protocol was identical in structure and objectives across both groups.

After completing the training sessions, a post-training assessment was conducted following the same procedures as the pre-training session but using a different set of plastic tooth models. As before, participants completed one TradAC and one ConsAC preparation without receiving any feedback. These pre- and post-training assessments were used for quantitative comparison of learning outcomes.

Participants

The participants in this study were fourth-year preclinical dental students. In the Thammasat University curriculum, fourth-year students are categorized as preclinical, as they have completed laboratory training but have not yet begun clinical treatment of patients. All participants had previously received instruction and limited practice in both TradAC and ConsAC techniques on one lower and one upper extracted human molar as part of their fourth-year curriculum. However, they had not yet performed these procedures in clinical settings. A continuous response variable from independent control and experimental groups, with one control per experimental participant, was analyzed. The sample size was calculated using G*Power 3.1.9.2 software based on an assumed medium effect size (Cohen's f = 0.25), which is commonly applied in educational and simulation-based research. With a power of 0.80 and an alpha level of 0.05, this required a minimum of 15 participants per group (30 total). A medium effect size was chosen conservatively to accommodate variability in learner performance and instructional settings.

Fourth-year dental students were invited and recruited for the study. Inclusion criteria required students to have achieved over 70% on a knowledge assessment of minimal endodontic access cavity preparation, based on their scores in the Endodontics course. Exclusion criteria included prior experience with VR simulation, and withdrawal criteria applied to any student unable to complete the entire experiment. Randomization was conducted by an independent statistician who was not involved in the implementation or analysis of the study. Allocation concealment was maintained using sequentially numbered, sealed, opaque envelopes, which were opened only after participant enrollment to ensure group assignment remained blinded to both participants and researchers responsible for recruitment. Informed consent to participate was obtained from all of the participants in the study. All participants were exclusively assigned to either the VR or PH training group, with no crossover between groups during the study period.

Virtual reality training

The VR simulator utilized in this study used Unreal Engine (UE) 4.27.2. An HTC Vive Pro Eye headset, with a combined resolution of 2880 × 1600 and integrated eye-tracking sensors, was employed to render stereo images through the UE SteamVR plugin. Eye-tracking functionality was facilitated via the SRanipal Unreal plugin [17]. The virtual dental handpiece and mirror were operated using two Geo-Magic Touch haptic devices (Phantom), providing 6 degrees of freedom. These devices delivered haptic feedback, simulating the tactile interaction between the handpiece and the virtual tooth, while realistic drill sound effects were also incorporated (Figure 1).

The virtual patient model was created using the Metahuman framework and integrated into the UE environment. High-fidelity visuals were used, including subtle animations like eye blinking and tongue movements. To avoid altering tooth positioning, care was taken in limiting these animations. A transparency texture was applied to conceal tooth number 26 of the Metahuman model (left maxillary first molar), so that it could be replaced with a custom-modeled tooth based on micro-CT scans of human teeth. This model was approved by an expert dentist and rendered using UE's Procedural Mesh Component (PMC). The tooth volume was approximated by sphere packings and its surface was tessellated using a metaballs method at runtime through a parallel marching cubes implementation with a resolution of 90×135×90. All modifications of the tooth during runtime were performed on a second GPU using custom CUDA code. Haptic feedback was computed outside the UE main loop to maintain independence from the rendering frame rate. Force calculations were based on sphere packing representation, with the enamel modeled by 100,000 spheres, dentin by 170,000 spheres, and pulp by 10,000 spheres. Parameters for force, drilling, and friction were fine-tuned with guidance from an expert dentist.

An automated outcome scoring system was developed and validated in the previous work [9]. This system aligned each student's virtual cavity outcome against an ideal drill pattern defined by experts, encompassing the pulp chamber walls and floor. The F1-score, was used to measure similarity across the full outcome range. The virtual outcomes were then mapped to a standardized clinical error scale (0–12) using a supervised model. Validation with expert raters showed excellent agreement (Cohen's $\kappa = 0.87$, ICC = 0.98), and automated scores exhibited high concordance with expert judgments across a range of drilling outcomes.

During training, participants were able to view the tooth from multiple planes and manipulate both the virtual handpiece and mouth mirror using haptic devices. The training task involved performing endodontic access cavity preparation on tooth number 26 using both TradAC technique and the minimally invasive ConsAC technique. The simulator recorded performance data, including tooth tissue volume loss and task completion time. After each session, participants received video playback of their performance, which included their access cavity preparation and mirror usage, as tracked by the eye-tracking system. Feedback on the outcome and tooth volume loss was provided by the VR simulator, at the end of each training trial. The training was conducted over three consecutive days, with each session lasting one hour.

Fig. 1 Virtual Reality (VR) training setup for minimally invasive endodontic access cavity preparation. The VR system includes an HTC Vive Pro Eye headset, dual haptic devices for simulating the dental handpiece and mirror, and high-fidelity visual rendering of the dental environment.

Phantom head training

The access cavity preparation was performed using a 1-mm-diameter, 6-mm-long tapered bur in a high-speed handpiece with water coolant. The procedures were carried out on an endodontic plastic tooth model (Nissin B22X-26 Endo Typodont, Nissin Dental Products, Inc., Japan) embedded in a phantom head. Participants were tasked with performing endodontic access cavity preparation on tooth number 26 using both TradAC and ConsAC techniques. Feedback on the outcome was provided by a qualified endodontic instructor at the end of each trial. The training sessions spanned three days, with each session lasting 1 hour.

Outcome measures

The study was a pre-training/post-training control group design. The main outcome measure was the tooth volume loss using micro-CT analysis. The endodontic plastic teeth (Nissin B22X-26 Endo Typodont, Nissin Dental Products, Inc., Japan) were scanned before and after the access cavity preparations using a high-resolution micro-CT scanner (Skyscan-1275, Bruker-microCT, Kontich, Belgium). The scanning parameters included 20 μm at 40 kV, 50 μA, and 0.4-degree rotation angles to capture detailed structural data. The pre- and post-preparation scans were aligned using automatic rigid registration to ensure that both datasets were in the same spatial orientation. The difference in volume between the pre- and post-training scans represented the tooth tissue volume loss, which was computed using 3D image analysis software (CTAn, Bruker microCT, Belgium). A thresholding technique was applied to differentiate between the tooth material and the air, allowing accurate segmentation of the tooth structure.

The percentage of access cavity volume change was analyzed using CTAn software (Bruker microCT, Belgium). The volume change was computed as the difference between the pre- and post-access cavity volumes, divided by the preoperative volume, using the formula: Access cavity volume change (%) = [(postoperative access cavity volume – preoperative access cavity volume) / preoperative access cavity volume] × 100.

To ensure measurement accuracy, pre- and post-training scans were aligned using automatic rigid registration, and threshold segmentation was consistently applied for all scans. This micro-CT analysis method has been validated in previous studies for its precision in evaluating internal tooth structure changes and has been widely used for quantifying hard tissue removal in endodontic research.

All micro-CT scans were anonymized and assigned randomized identification codes prior to analysis. The operator conducting the image processing and volume quantification using CTAn software was blinded to participant group assignment (VR vs. PH) and training status (pre- or post-training). This blinding procedure ensured that outcome assessments were conducted independently and without bias.

The secondary outcome measure was procedural errors assessed by two experts who are board certified in endodontics blinded to trainee and training status. Procedural errors were assessed by two board-certified endodontic experts, blinded to both the trainee and training status. A three-point scoring system was used to evaluate procedural errors across six regions: the four axial walls (buccal, lingual, mesial, and distal), the roof of the pulp chamber, and the pulpal floor. The criteria were defined as follows: Score 0 – Minimally extended cavity that permits effective debridement of the canal system; Score 1 – Slightly under- or overextended cavity that still allows for effective debridement without compromising the subsequent restoration; Score 2 – Severely under- or overextended cavity resulting in inadequate retention form for maintaining a proper restoration, or presence of a perforation. All six regions were equally weighted, resulting in a maximum total score of 12. The third outcome measure was task completion time. The total time taken to complete the task was recorded to the nearest 0.01 minutes.

Statistical analyses

The Wilcoxon signed-rank test was used to examine the differences between pre-training and post-training tooth volume loss, error scores, and task completion time within the same participants, for each combination of training method and access cavity preparation technique. To evaluate the effects of the training method (VR vs. PH, a between-subjects factor) and the access cavity preparation technique (TradAC vs. ConsAC, a within-subjects factor) on student performance, a Split-Plot ANOVA (Mixed ANOVA) was conducted using the difference scores (Δ) between pre-training and post-training for each outcome measure. The following outcome measures were analyzed: Tooth volume loss (measured via micro-CT), Procedural error scores, and Task completion time. For each measure, the difference score (Δ = post-test value – pre-test value) was calculated for both techniques (TradAC and ConsAC) and used as the dependent variable. The Split-Plot ANOVA assessed: the main effect of training method (VR vs. PH), the main effect of cavity preparation technique (TradAC vs. ConsAC), and the interaction effect between training method and preparation technique. Inter-rater reliability for procedural error scores, assessed by two blinded board-certified endodontic experts, was evaluated using Cohen's kappa coefficient. All results are reported as mean ± standard deviation. A p-value < 0.05 was considered statistically significant. Analyses were conducted using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).

Results

Figure 2 illustrates the study design and flowchart, providing an overview of the participant selection process, randomization and the sequential phases undertaken by each group. A total of

30 fourth-year dental students participated in the study, with 15 students in each of the PH and VR training groups. The majority of participants in both groups were right-handed, with 93% (14/15) in the PH group and 80% (12/15) in the VR group. Left-handed participants accounted for 7% (1/15) in the PH group and 20% (3/15) in the VR group. Regarding eyesight, most participants reported having myopia, with 73% (11/15) in the PH group and 67% (10/15) in the VR group. Normal vision was reported by 20% (3/15) of PH participants and 33% (5/15) of VR participants. Only one participant in the PH group reported hyperopia (7%), while none in the VR group did. No participants in either the VR or PH group withdrew from the study before completing the post-training assessment. No unintended effects were observed in either group.

Table 1 shows the baseline outcome data of the selected students. Accordingly, there were no statistically significant differences between groups or genders regarding age and pre-evaluation test values ($p > .05$), indicating a well-balanced distribution. Comparisons of pre- and post-training tooth volume loss, procedural error scores, and task completion time for the TradAC and ConsAC techniques in the PH and VR training groups are presented in Table 2. Post-training performance (mean ± SD) improved across all outcomes in each training and technique combination. Exact p-values for these comparisons are provided in Table 2.

Descriptive statistics (mean ± SD) for each outcome measure are summarized by training method and access cavity preparation technique in Table 3. Table 4 presents the split-plot ANOVA analysis of the effects of training method (between-subjects) and access technique (within-subjects).

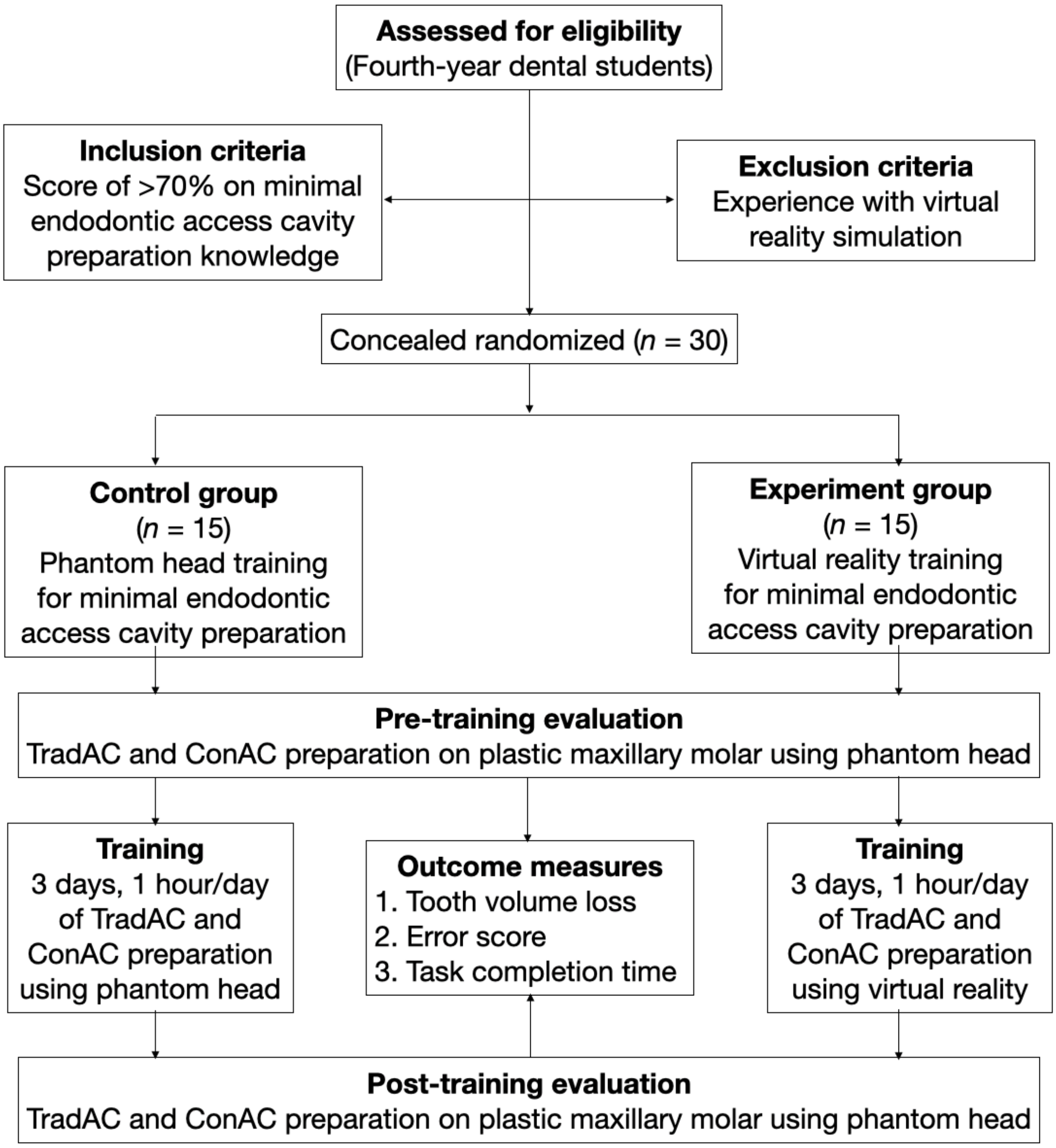

Fig. 2 Overview of the study design and participant flow diagram for the randomized controlled trial. The diagram illustrates the randomization process, participant allocation to either Virtual Reality (VR) or Phantom Head (PH) training groups, and the subsequent evaluations pre- and post-training for both Traditional Access Cavity (TradAC) and Conservative Access Cavity (ConsAC) techniques. Participant recruitment, training, and data collection milestones are shown.

Table 1 Baseline outcome data of students (mean ± SD) based on gender and training group.

		Traditional Access Cavity			Conservative Access Cavity		
	Age	Tooth volume loss	Error score	Task completion time	Tooth volume loss	Error score	Task completion time
Gender							
Female (n= 19)	26 ± 0.77	40.47 ± 1.16	4.84 ± 0.49	19.85 ± 1.41	32.90 ± 1.16	5.34 ± 0.71	10.01 ± 1.13
Male (n=11)	25.73 ± 1.33	40.04 ± 1.90	4.50 ± 0.59	20.43 ± 3.88	31.99 ± 0.85	4.18 ± 0.81	9.38 ± 3.12
p-value	0.83	0.39	1.00	0.70	0.56	0.48	0.32
Group							
PH (n=15)	26.27 ± 1.04	41.71 ± 1.72	4.66 ± 0.59	20.65 ± 2.71	32.89 ± 0.84	4.96 ± 0.67	9.04 ± 2.15
VR (n=15)	25.53 ± 0.89	38.92 ± 0.92	4.76 ± 0.48	19.48 ± 1.93	32.77 ± 1.46	4.86 ± 0.88	10.52 ± 1.57
p-value	0.96	0.25	0.48	0.83	0.44	0.69	0.35

Table 2 Comparison of pre- and post-training means (± SD) for tooth volume loss, procedural error scores, and task completion time in Phantom Head (PH) and Virtual Reality (VR) training groups.

		Tooth volume loss	Error scores	Task completion time
Training method	Access cavity preparation technique			
PH	TradAC			

	Pre-training	41.71 ± 1.72	4.66 ± 0.59	20.65 ± 2.71
	Post-training	29.78 ± 0.44	2.73 ± 0.33	7.92 ± 1.19
	p-value	0.001**	0.001**	0.02*
	ConsAC			
	Pre-training	32.89 ± 0.84	4.96 ± 0.67	9.04 ± 2.15
	Post-training	25.85 ± 0.28	1.96 ± 0.54	3.674 ± 0.57
	p-value	0.001**	0.001**	0.001**
VR	TradAC			
	Pre-training	38.92 ± 0.92	4.76 ± 0.48	19.48 ± 1.93
	Post-training	30.44 ± 0.62	2.96 ± 0.39	14.42 ± 1.71
	p-value	0.001**	0.007**	0.031*
	ConsAC			
	Pre-training	32.77 ± 1.46	4.86 ± 0.88	10.52 ± 1.57
	Post-training	25.98 ± 0.52	2.83 ± 0.74	6.40 ± 0.78
	p-value	0.001**	0.017*	0.04*

*p-value<.05., **p-value<.01.

Table 3 Descriptive statistics (mean ± SD) of differences between pre- and post-training values for tooth volume loss, procedural error scores, and task completion time by training method and access cavity preparation technique.

	Δ Tooth volume loss	Δ Error scores	Δ Time
Training method			
PH	9.48 ± 0.97	2.46 ± 0.40	9.05 ± 1.55
VR	7.63 ± 0.72	19.17 ± 0.41	4.58 ± 1.43
Access cavity preparation technique			
TradAC	10.19 ± 0.88	1.86 ± 0.33	8.89 ± 1.74

ConsAC	6.91 ± 0.75	2.51 ± 0.46	4.74 ± 1.20

Table 4 The split-plot ANOVA analysis of the main effects and interaction effects of training method and access cavity preparation technique.

Outcome		Independent variable	F	p-value
Δ Tooth volume loss	Main effect	Training method	2.19	0.15
		Access cavity preparation technique	10.46	0.003^{**}
	Interaction effect	Training method * Access cavity preparation technique	2.47	0.12
Δ Error scores	Main effect	Training method	1.20	0.28
		Access cavity preparation technique	1.02	0.31
	Interaction effect	Training method * Access cavity preparation technique	0.42	0.52
Δ Time	Main effect	Training method	3.47	0.07
		Access cavity preparation technique	6.86	0.01^{*}
	Interaction effect	Training method * Access cavity preparation technique	4.10	0.05

*p-value<.05., **p-value<.01.

Tooth Volume Loss

A split-plot ANOVA was conducted to examine the effects of training method (VR vs. PH) as a between-subjects factor and access cavity preparation technique (TradAC vs. ConsAC) as a within-subjects factor on the change in tooth volume loss (Δ volume loss) from pre- to post-training (Table 4). F-values refer to the F-ratio from split-plot ANOVA, which represents the ratio of variance between groups to the variance within groups. There was no significant main effect of training method, F(1, 28) = 2.19, $p = 0.15$, indicating that the extent of tooth volume loss did not differ significantly between the VR and PH groups. A significant main effect of access cavity preparation technique was observed, F(1, 28) = 10.46, $p = 0.003$, suggesting that the type of access cavity preparation significantly influenced the amount of tooth structure removed. The interaction effect between training method and access technique was not significant, F(1, 28) = 2.47, $p = 0.12$.

Representative micro-CT images of the endodontic plastic teeth before and after training are shown in Figure 3, providing visual comparisons of the extent of access cavity preparation. The images highlight differences in structural preservation across training methods (VR vs. PH) and access techniques (TradAC vs. ConsAC) and demonstrate the overall impact of training on tooth morphology.

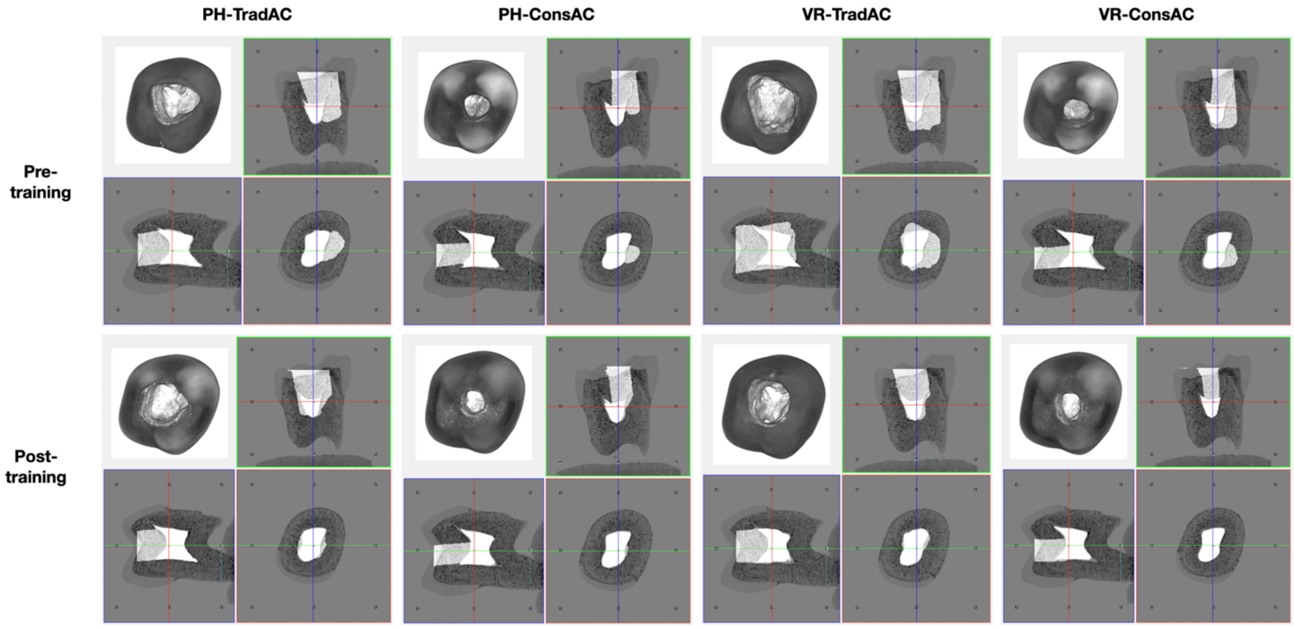

Fig. 3 Representative micro-CT images (occlusal view; and sagittal, transverse, cross-sectional planes) of the endodontic plastic tooth model showing access cavity preparations before and after training in Virtual Reality (VR) and Phantom Head (PH) groups, across Traditional Access Cavity (TradAC) and Conservative Access Cavity (ConsAC) techniques. Each row displays paired pre-

training and post-training 3D micro-CT reconstructions of the endodontic plastic teeth for one experimental condition. Columns represent training method (VR or PH), and subpanels compare the TradAC and ConsAC techniques. Post-training images show variations in the amount of dentin removal, with ConsAC preparations exhibiting smaller and more conservative cavity outlines.

Procedural Error Scores

To evaluate changes in procedural accuracy, a split-plot ANOVA was performed on the difference in error scores (Δ error) before and after training (Table 4). The analysis revealed no significant main effect of training method, $F(1, 28) = 1.20$, $p = 0.28$, and no significant main effect of access cavity preparation technique, $F(1, 28) = 1.02$, $p = 0.31$. Furthermore, the interaction effect between training method and access technique was not significant, $F(1, 28) = 0.42$, $p = 0.52$, indicating that the changes in procedural error scores were comparable across all groups. Inter-rater reliability for the procedural error assessments, performed by two blinded board-certified endodontic experts, demonstrated excellent agreement, with a Cohen's kappa coefficient of 0.924.

Task Completion Time

A split-plot ANOVA was also performed to assess the change in task completion time (Δ time) from pre- to post-training (Table 4). The analysis revealed no statistically significant main effect of training method, $F(1, 28) = 3.47$, $p = 0.07$. A significant main effect of access cavity preparation technique was identified, $F(1, 28) = 6.86$, $p = 0.01$, suggesting that the type of access cavity preparation significantly influenced the change in task completion time. The interaction effect between training method and access technique was also not statistically significant but approached significance, $F(1, 28) = 4.10$, $p = 0.05$.

Discussion

This study evaluated the effectiveness of VR training compared to traditional Phantom Head training in the context of minimally invasive endodontic access cavity preparation. Using micro-CT analysis of tooth volume loss as the primary outcome measure, along with procedural error scores and task completion time, we assessed student performance across both TradAC and ConsAC techniques. The results demonstrated a significant main effect of access cavity technique on both tooth volume loss and task completion time, with ConsAC consistently associated with reduced volume loss and shorter preparation time, regardless of training method. This confirmed the hypothesis of this study that VR-based training would preserve tooth structure to a similar extent as traditional training while improving procedural accuracy and task completion time. However, the trend toward reduced task completion time and volume loss in the VR group, along with an interaction effect that approached significance, suggests a potential advantage of immersive simulation that may become more apparent with larger sample sizes or extended training. These findings support the value of conservative access techniques in minimizing tissue removal and highlight the need for continued refinement and investigation of VR-based education in endodontics.

Access cavity preparation is a critical step in root canal therapy, as it significantly influences subsequent procedural steps and ultimately affects treatment outcomes. For decades, the traditional access cavity approach has been the standard, emphasizing straight-line access to the apex by removing coronal interferences [19, 20]. In this technique, the entire pulp chamber roof is removed in posterior teeth to allow unobstructed visualization of all canal orifices within a smoothly divergent axial outline. In contrast, the conservative access cavity design has been introduced to enhance the fracture resistance of endodontically treated teeth by minimizing structural loss. Conservative access cavity typically begins at the central fossa of the occlusal surface and extends with convergent axial walls only as far as necessary to locate the canal orifices, intentionally preserving portions of the pulp chamber roof [21]. This design reflects a shift toward minimally invasive endodontic approaches that prioritize long-term structural integrity without compromising access to the canal system.

Given the small scale of the tooth and the subtle differences between training methods, a highly detailed analytical approach was essential to detect meaningful variations in outcomes. To address this, micro-computed tomography (micro-CT) analysis [22] was employed to provide precise, three-dimensional assessments of tooth mass removal and the accuracy of access cavity preparations across training groups. Micro-CT enabled the measurement of fine structural changes that are often undetectable with traditional evaluation methods, allowing for a detailed assessment of the primary outcome—tooth volume loss. This study found that dentine and enamel removal (DER) was 10.19% in the TradAC group and 6.91% in the ConsAC group. According to the classification by Isufi et al. [23], cavities with DER >15% are categorized as Traditional Endodontic Cavities (TEC), those with DER ≤15% as Conservative Endodontic Cavities (CEC), and those with DER ≤6% as Ultraconservative Endodontic Cavities (UEC). The DER value in the TradAC group falls within the CEC range but approaches the upper threshold. In contrast, the DER in the ConsAC group is closer to the UEC classification, reflecting improved preservation of dentin and enamel. These findings support the conservative design of CEC and underscore its potential to minimize unnecessary removal of dental tissue during access cavity preparation.

A previous study using a haptic VR simulator combined with micro-CT tooth models demonstrated that training on the simulator and conventional phantom head models had equivalent effects on minimizing procedural errors in endodontic access cavity preparation [13]. More recently, Slaczka et al. [14] compared the Simodont® haptic VR system with artificial teeth in phantom heads and found no statistically significant differences in post-training performance, supporting the feasibility of using VR as a complementary training tool. Similarly, Duan et al. [15] reported high precision in access cavity preparation using virtual simulation and emphasized its value in combination with 3D printed and plastic models, especially at early stages of skill development.

The VR simulation used in the present study differs from prior systems by incorporating a simulated patient within a clinical setting, realistic maxillary arch positioning, and automated performance scoring—features intended to better replicate real-world conditions and support independent learning. Using a split-plot design, we compared VR and phantom head training across both traditional and conservative access cavity techniques. Consistent with previous findings, no significant differences were observed in error scores or task completion time between training groups. However, a trend toward more conservative tooth structure removal in the VR group—particularly when paired with the ConsAC technique—was observed. The significant main effect of access cavity technique reinforces prior studies showing that conservative designs reduce dentin removal and may improve fracture resistance without compromising access [24, 25]. Together, these findings contribute to the growing body of evidence supporting immersive VR simulation as a viable tool for developing minimally invasive skills in endodontic education.

The findings from this study have important implications for both dental education and clinical practice. In dental education, the significant improvement in tooth preservation and procedural accuracy achieved through VR-based training highlights the potential of immersive technologies to enhance skill development, particularly in minimally invasive techniques like access cavity preparation. Unlike traditional training methods using phantom heads, VR training provides a highly controlled, repeatable, and realistic environment that allows students to practice complex procedures with visual and tactile feedback [5, 6]. The ability to simulate real patient scenarios without the risk of harm offers educators an efficient and scalable solution for improving student competence and confidence.

Recent literature supports the growing role of VR simulation in endodontic training. Studies have shown that VR platforms such as Simodont® can produce learning outcomes comparable to traditional methods and are well accepted by students [14]. Moreover, integrating virtual simulation alongside 3D-printed and plastic models has been shown to improve accuracy in cavity preparation and student engagement in preclinical endodontics [15]. Another study demonstrated that haptic VR training introduced early in the curriculum could reduce student stress while improving manual dexterity and procedural accuracy [16]. These findings align with the results of this study and reinforce the value of simulation-based learning in fostering both technical proficiency and learner confidence. Additionally, the real-time feedback and performance analytics provided by VR systems, such as video playback and automated outcome scoring, can accelerate the learning curve by enabling students to identify and correct their mistakes more effectively [5]. Simulation-based training, such as the VR platform evaluated in this study, may be most beneficial when introduced during the preclinical phase of dental education—before students perform procedures on patients. This early integration supports the development of foundational psychomotor and cognitive skills in a low-risk, controlled environment. However, the optimal timing, frequency, and curricular integration of VR simulation remain areas for further investigation.

In clinical practice, the tooth preservation observed in the VR training group underscores the importance of integrating minimally invasive techniques into routine endodontic procedures. With growing emphasis on tooth conservation to improve long-term outcomes [1], the adoption of training tools like VR can help future clinicians develop the precision and judgment needed to minimize tissue removal while achieving optimal access to the treatment. The observed differences in tooth volume loss—particularly with the ConsAC approach—are clinically relevant, as excessive dentin removal is strongly associated with increased risk of tooth fracture and reduced long-term prognosis of endodontically treated teeth. Even modest reductions in structural loss can significantly enhance post-treatment restorability and resistance to functional stress. As the dental field continues to advance, the integration of VR training into curricula could bridge the gap between education and clinical practice, ensuring that practitioners are better equipped to meet the demands of modern minimally invasive dentistry.

Although the present study did not find statistically significant differences between the VR and PH groups in terms of performance outcomes, the pedagogical advantages of VR training merit consideration. VR offers a standardized, immersive, and repeatable learning environment that reduces instructor burden and provides immediate, objective feedback. These features are particularly beneficial in large cohort settings or institutions with limited faculty resources. Additionally, the real-time performance analytics and automated scoring in VR platforms can help students reflect on and self-regulate their learning, which is aligned with modern competencybased education models. As such, the adoption of VR may enhance educational efficiency and learner autonomy, even when traditional models produce similar outcome measures.

Despite the promising findings, several limitations of this study should be acknowledged. Limitations of this study include the relatively small sample size, limited duration of training, and possible learning curve effects associated with VR technology. These factors may have influenced the extent of performance improvement observed across groups. While we used course grades from the endodontics curriculum as an inclusion criterion to ensure foundational knowledge, we recognize that these scores may be influenced by factors beyond knowledge and technical proficiency. A standardized pre-study knowledge or skills assessment might have offered a more direct measure of baseline competence. This limitation should be considered when interpreting the generalizability of the findings of this study. The use of endodontic plastic and simulated teeth in phantom head models and the VR simulation may not fully replicate the complexity of real human anatomy, including variations in tooth structure, pulp chamber size, and canal morphology. This could limit the generalizability of the results to real clinical scenarios. Moreover, the training duration was limited to three one-hour sessions, which may not fully capture the long-term benefits of VR training on skill retention and clinical performance. Extended training periods or follow-up assessments to evaluate the retention of skills acquired through VR training would provide more comprehensive insights into its effectiveness. Finally, while the study compared VR training to traditional phantom head models, other training methods, such as mixed-reality simulations or augmented reality, were not included and could offer additional benefits that should be explored in future research.

Future research could address these limitations by incorporating real patient data or digital model of variety of extracted human teeth into the VR simulation to create a more realistic training environment. Additionally, expanding the study to include a longitudinal design, with follow-up assessments to evaluate skill retention and clinical performance in real-world settings, would offer valuable insights into the long-term impact of VR training. Moreover, comparing VR training with other advanced technologies, such as augmented reality (AR) or mixed reality (MR), would provide a broader understanding of how different digital tools can complement traditional methods in dental education. Finally, future studies should explore the cost-effectiveness and scalability of implementing VR training on a larger scale within dental curricula, especially as the technology evolves and becomes more accessible. This would provide valuable information for educational institutions considering the adoption of VR as a standard training tool.

Conclusions

This study supports the use of automated VR simulation as an effective tool for student learning in minimally invasive endodontics. Performance outcomes were comparable to traditional methods, particularly in conservative access cavity training. These findings highlight the potential of VR as a valuable and scalable tool in preclinical dental education, particularly for teaching minimally invasive endodontic techniques.

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Author contributions

CS, SS, PH and GZ contributed to conceptualization, methodology, supervision, and writing the original draft. KB contributed to the statistical analysis. CS, MK, RW, MSY, PA, PP and KP contributed to data collection and project administration. All authors wrote, revised and edited the manuscript prior to submission.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the Human Research Ethics Committee of Thammasat University (Approval no.: COA 060/2567) and the Thai Clinical Trials Registry Committee (Approval no.: TCTR20250502004, https://www.thaiclinicaltrials.org/show/TCTR20250502004). The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.