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Access cavity preparation training using haptic virtual reality and microcomputed tomography tooth models

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Abstract

Suebnukarn S, Hataidechadusadee R, Suwannasri N, Suprasert N, Rhienmora P, Haddawy P. Access cavity preparation training using haptic virtual reality and microcomputed tomography tooth models. *International Endodontic Journal*.

Aim To evaluate the effectiveness of haptic virtual reality (VR) simulator training using microcomputed tomography (micro-CT) tooth models on minimizing procedural errors in endodontic access preparation.

Methodology Fourth year dental students underwent a pre-training assessment of access cavity preparation on an extracted maxillary molar tooth mounted on a phantom head. Students were then randomized to training on either the micro-CT tooth models with a haptic VR simulator ($n = 16$) or extracted teeth in a phantom head ($n = 16$) training environments for 3 days, after which the assessment was repeated. The main outcome measure was procedural errors assessed by an expert blinded to trainee and training status. The secondary outcome measures were tooth mass loss and task completion time. The Wilcoxon test was used to examine the differences between pre-training and post-training error scores, on the same group. The Mann–Whitney test was used to detect any differences between haptic VR training and phantom head training groups. The independent *t*-test was used to make a comparison on tooth mass removed and task completion time between the haptic VR training and phantom head training groups.

Results Post-training performance had improved compared with pre-training performance in error scores in both groups ($P < 0.05$). However, error score reduction between the haptic VR simulator and the conventional training group was not significantly different ($P > 0.05$). The VR simulator group decreased significantly ($P < 0.05$) the amount of hard tissue volume lost on the post-training exercise. Task completion time was not significantly different ($P > 0.05$) in both groups.

Conclusions Training on the haptic VR simulator and conventional phantom head had equivalent effects on minimizing procedural errors in endodontic access cavity preparation.

Keywords: access preparation, endodontics, haptic, microcomputed tomography, procedural error, virtual reality.

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Introduction

With recent advantages in biomedical imaging and virtual reality (VR) technology, training in endodontics is entering a time of change towards more realistic and interactive environments. Interactive visualization and VR technology have opened new realms in the practice of medicine (Palter & Grantcharov 2010). VR refers to a human–computer interface that facilitates highly interactive visualization and control of computer-generated three-dimensional scenes and their related components with sufficient detail and speed so as to evoke a sensorial experience similar to that of a real experience. Some advanced, haptic systems now include tactile information, generally known as force feedback, in medical applications (Spicer & Apuzzo 2003, Panait *et al.* 2009). VR technology permits computed three-dimensional images obtained from medical imaging systems to be faithfully transformed into patient-specific anatomic models, with physical properties added as appropriate, providing interaction with the manipulation of the realistic models.

Several VR programs have been developed in dental applications such as a simulator for orthognathic surgery (Sohmura *et al.* 2004) and restorative dentistry (Suebnukarn *et al.* 2009, 2010). The haptic VR simulators have been introduced into the dental curriculum as training devices for clinical skill acquisition in several tasks. The haptic VR dental simulators that have been developed are the Iowa Dental Surgical Simulator (Thomas *et al.* 2001) for teaching the tactile skills in detection of dental caries, PerioSim (Steinberg *et al.* 2007) for teaching the tactile skills in the detection of subgingival calculus, and HapTEL (Eaton *et al.* 2008) for on-line dental training. The advantages of these simulators are that dental students and professionals are able to practice the procedures as many times as they want at no incremental cost and that the training can take place anywhere. The realism of these simulators has increased with the introduction of haptic devices that provide tactile sensations to the users, utilization and mirror viewing, as well as simulation of different hardness of tissues. Haptic devices allow users to touch and feel objects such as surgical tools and human organs in a virtual environment, and to perform operations such as pushing, pulling, and cutting of soft or hard tissue with realistic force feedback.

Microcomputed tomography (micro-CT) is a miniaturized version of computerized axial tomography with a resolution of the order of micrometres (Oi *et al.* 2004). Using micro-CT, it is also possible to form three-dimensional images of teeth and bone from which structural parameters can be derived. Reports have shown the effectiveness of quantitative evaluation of endodontic access cavity preparation (Ikram *et al.* 2009), root canal preparation (Peters *et al.* 2003) and canal filling (Hammad *et al.* 2009) using micro-CT.

The first step towards increasing the level of patient safety in endodontic treatment is for all clinicians to acquire knowledge and skills, in the early stage of training. Endodontic treatment, like other disciplines of dentistry, can be associated with unwanted or unforeseen procedural errors. Perforations in endodontics can occur during access cavity preparation and mechanical instrumentation of the root canals. The healing rate in teeth with perforations was 30% lower than in teeth without perforation (Barone *et al.* 2010). Whilst the majority of evidence has focused on repairing perforations using various materials (Pace *et al.* 2008), the evidence on prevention and training is limited. Over the past three decades, VR simulation has played an introductory role for clinical trainees in numerous fields (Palter & Grantcharov 2010). The efficacy of VR simulation as a teaching tool seemed obvious, but whether it was superior to conventional endodontic teaching methods remains unknown. In this study, the effectiveness of haptic VR simulator training using micro-CT tooth models on minimizing procedural errors and decreasing treatment time in endodontic access cavity preparation was evaluated.

Materials and methods

A prospective randomized controlled and blind trial was conducted to test the hypothesis that training with micro-CT teeth and a haptic VR simulator will minimize procedural errors in access cavity preparation similar to those obtained from training with natural extracted teeth in a phantom head.

Sample size

A continuous response variable from independent control and experimental participants with one control per experimental participant was studied. In a previous study, the response within each participant group was normally distributed with a standard deviation 0.25. The true difference in the experimental and control means was 0.25. As a result 16 experimental participants and 16 control participants were required to be able to reject the null hypothesis that the population means of the experimental and control groups are equal with probability 0.8. The Type I error probability associated with this test of this null hypothesis is 0.05.

Potential dental students beginning their fourth year were recruited. They were not admitted to the study if any of the following criteria were present: (i) had received prior experience with the simulation, or (ii) received below 70% marks in knowledge assessment of the endodontic access cavity preparation. All participants gave their written informed consent approved by the institutional Ethical Review Board. Participants were randomized to experiment or control group. A statistician not involved with the study undertook the randomization using sealed opaque envelopes (Fig. 1).

Access cavity preparation with haptic VR simulator

Radiographic images of 10 extracted human maxillary teeth with dental caries, of which the original patients could not be identified, were acquired using three-dimensional micro-CT (RmCT; Rigaku Co., Tokyo, Japan) with a resolution of $50 \times 50 \times 50$ μm, tube voltage of 90 kV, and tube current of 150 μA. Tomographic images were obtained using comprehensive dental imaging software (i-VIEW; Morita Co., Tokyo, Japan). Three-dimensional reconstruction was performed using 600 of these two-dimensional images processed by the volume rendering method.

The VR simulator is comprised of a 2.8-GHz Pentium 4 PC, with 256 MB RAM and a 13-in computer monitor, connected to two haptic devices (SensAble Inc., Woburn, MA, USA) each having 5 degrees of freedom. The monitor was placed at eye level, and the haptic device was positioned at elbow level directly in front of the participant. A virtual high speed handpiece with a tapered bur diameter of 1 mm and a length of 6 mm was employed. The VR simulator creates a virtual environment on the monitor display that shows the position and the movements of the virtual handpiece and mouth mirror in real time. In each interactive haptic time step, each volume sample point in the tool was checked for intersection with the tooth volume. A virtual dental tool had 6 degrees of freedom and moved relative to the position and orientation of a haptic stylus. To simulate tooth cutting and provide force feedback to the operator's hand, the number of volumetric sample points of the tool model immersed into tooth voxels was detected. The force feedback whilst cutting the tooth varied depending on the density values of various tissues. The operator thus received different force feedback when cutting through enamel, dentine and pulp (Fig. 2).

The participant can view the tooth prior to cutting in various planes and manipulate the handpiece and mouth mirror using two haptic devices. During training, the system recorded data associated with performance process including task completion time, tooth tissue volume loss, force utilization as well as handpiece and mirror movements. The system was assigned to each preparation an overall preparation outcome score using support vector machine classifier. The video playback of the participant's performance along with the augmented feedback on process and outcome was provided at the end of each trial of 3 days of 2 h training.

Access cavity preparation in phantom head

Two hundred maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol. All teeth were intact or had one surface carious lesion

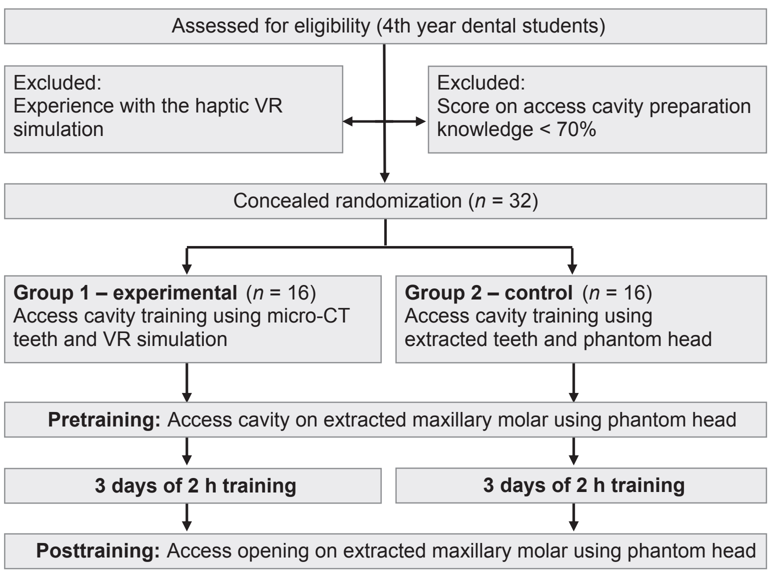

Figure 1 Flow chart of participants through the trial.

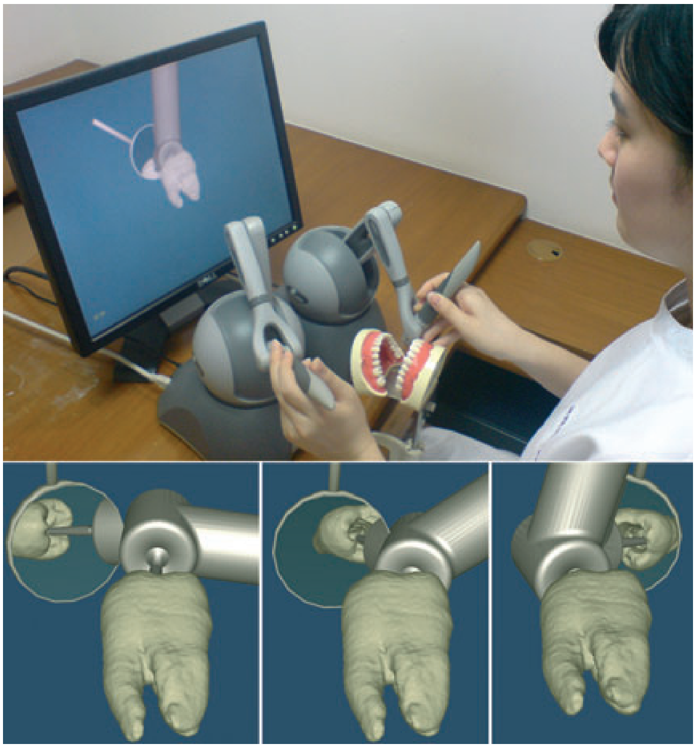

Figure 2 Three-dimensional models of extracted human teeth were reconstructed from microcomputed tomography images. The virtual reality (VR) simulator was comprised of a 2.8-GHz Pentium 4 PC, with 256 MB RAM and a 13-in computer monitor, connected to two haptic devices.

penetrating to the pulp chamber. Teeth with pulp chambers compromised by calcification or when mesiodistal or occlusogingival dimensions were below 2 mm (determined radiographically) were excluded. Initial preparation of the teeth involved the removal of any surface debris and calculus by an ultrasonic scaler (Piezon Master 400; EMS SA, Nyon, Switzerland). The carious lesion was excavated with a slow speed handpiece and steel round bur (size 7 REF 100-3223; Henry Schein, Gillingham, UK), and restored by glass ionomer cement (Fuji IX; GC, Tokyo, Japan). The mass for each tooth was measured and recorded before and after performing access preparations. All teeth were blotted for 10 min on absorbent paper towels prior to weighting on a digital analytical balance (Analytical balance, Model SI 124; BDH, London, UK), accurate to 0.0001 g. Prior to preparation, each tooth was held with vinyl polysiloxane putty (Lab-Putty; Coltene/Whaledent Inc., Langenau, Germany) and attached to the model connected to the phantom head. The access preparation was performed using a 1-mm-diameter and 6-mm-long tapered bur in a high speed handpiece with water coolant. The feedback on outcome was provided by a qualified endodontic laboratory instructor at the end of each trial of 3 days of 2 h training.

Outcome measures

The study had a pre-training/post-training control group design. The main outcome measure was procedural errors assessed by an expert blinded to trainee and training status. The secondary outcome measures were tooth mass loss and task completion time. Four-point scales were used to evaluate procedural errors in four walls (buccal, lingual, mesial and distal) and pulpal floor: with 0 on the scale defined as 'minimally extended cavity affording unimpeded access to/and visibility of the orifices of all canals presents'; 1 as 'a cavity permitting effective debridement of the canal system without prejudice to subsequent restoration'; 2 as 'incomplete removal of pulp chamber roof and/or inadequate retention form for the maintenance of an effective dressing'; and 3 as 'unidentified canals and/or perforation'. Thus, the total maximum error score was 15. The tooth mass for each tooth was measured and recorded, in grams, before and after access opening, on a digital analytical balance accurate to 0.0001 g. The percentage of tooth mass removed for each tooth was calculated. The total time taken to complete the task was measured accurate to 0.01 min.

Statistical analyses

The Wilcoxon test was used for nonparametric data and matched pairs to examine the differences between pre-training and post-training error scores, on the same group. The Mann–Whitney test was used for unmatched data to detect any differences between haptic VR training and phantom head training groups. The independent *t*-test was used to make a comparison on tooth mass removed and task completion time between the haptic VR training and phantom head training groups. Statistical significance was defined as a P value less than 0.05. All analyses were undertaken using SPSS version 13.0 (SPSS Inc., Chicago, IL, USA).

Results

None of the participants in the VR or Phantom head group dropped out before completing the post-training assessment. There were no significant differences between the groups in terms of the average error scores, tooth mass removal and task completion time before training. Table 1 details mean error scores on the four walls (buccal, lingual, mesial and distal) and pulpal floor. Post-training performance had improved compared with pre-training performance in error scores in both the phantom head group (from 6.12 ± 1.35 to 3.98 ± 1.41) and the VR group (from 6.51 ± 2.01 to 3.78 ± 1.10) ($P < 0.05$). However, error score reduction between the VR simulator and the conventional training group was not significantly different (Fig. 3). The VR group decreased significantly ($P < 0.05$) the amount of hard tissue volume lost on the post-training. In the phantom head group, there was no significant difference in the tooth mass removed between pre- and post-assessment. There was no difference in task completion time after training in both groups.

Discussion

The evolution of medical imaging and concomitantly VR technology has significantly accelerated the use of multimodality images and VR instrumentation in guiding clinical procedures, research and education. VR simulators are widely recognized as valuable adjuncts for surgical resident training outside the operating room (Sturm *et al.* 2008). Haptic feedback is defined as the combination of sensory input through the tactile receptors in the skin and the kinaesthetic receptors in muscles, tendons and joints. Its value is paramount in endodontic, where feeling the tissues is as important as visualizing them. Several studies have shown benefits from dental training in the presence of force feedback with VR simulators in caries and calculus detection (Thomas *et al.* 2001, Steinberg *et al.* 2007). Suebnukarn *et al.* (2009) demonstrated that the presence of force feedback was beneficial in performance of tooth preparation. When designing the study, the task of access preparation was chosen, as only external and internal tooth preparation using inflexible drills were accurately replicated by the Haptic VR simulator. Frexible instruments used during root canal preparation need to be developed in the VR environment in the future.

This study showed the change in endodontic access preparation for the dental students before and after their engagement in a designed training protocol. As in previous a study (Suebnukarn *et al.* 2010), the participants showed a significant reduction in error score of the access preparation after the VR simulator and the conventional training sessions. The error score and task completion time reduction between the VR simulator and the conventional training group were not different. The explanation for these results is that the haptic VR system is designed specifically to mimic the same hand motions and visualization as those used during dental procedures. By using virtual

Table 1 Pre-training and post-training error scores between haptic virtual reality (VR) training and phantom head training groups (mean ± SD)

	Phantom head		VR	
	Pre-training (n = 16)	Post-training (n = 16)	Pre-training (n = 16)	Post-training (n = 16)
Buccal wall	1.31 ± 0.78	0.87 ± 0.32	1.36 ± 0.34	0.85 ± 0.19
Lingual wall	0.94 ± 0.11	0.62 ± 0.14	0.88 ± 0.15	0.61 ± 0.14
Mesial wall	1.81 ± 0.38	1.06 ± 0.21	1.94 ± 0.32	0.93 ± 0.21
Distal wall	1.31 ± 0.21	0.81 ± 0.15	1.47 ± 0.29	0.75 ± 0.11
Pulpal floor	0.75 ± 0.15	0.62 ± 0.12	0.86 ± 0.16	0.64 ± 0.09
Total	6.12 ± 1.35	3.98 ± 1.41	6.51 ± 2.01	3.78 ± 1.10

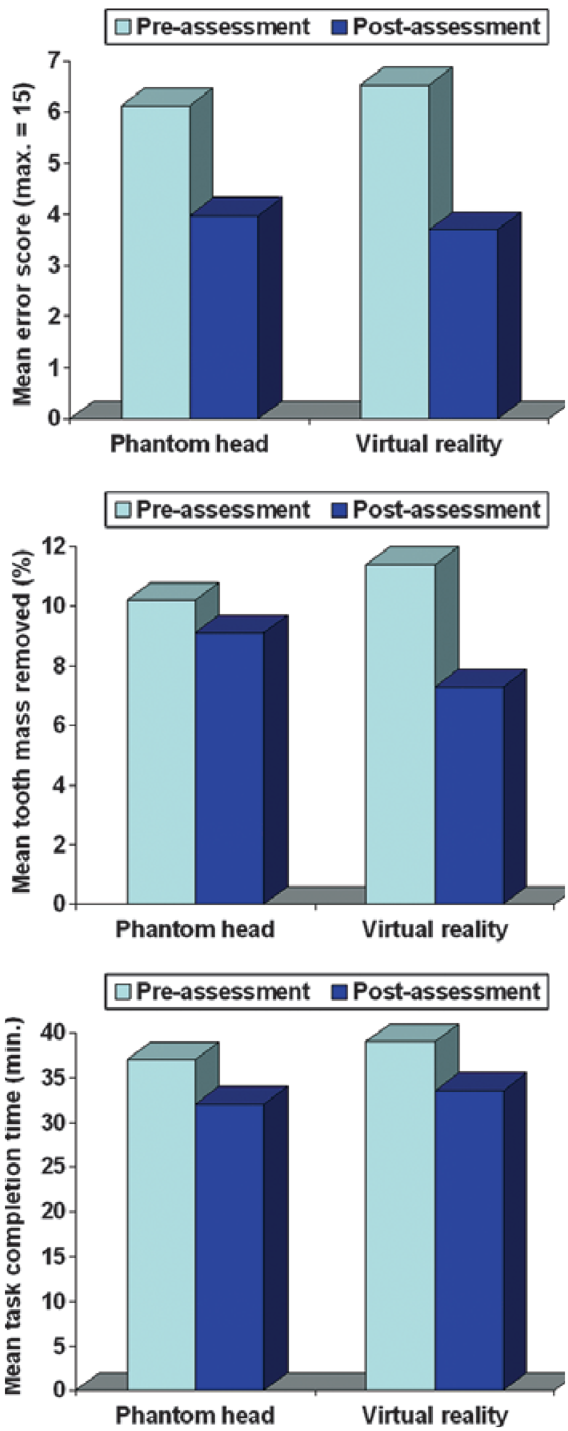

Figure 3 Mean error scores, tooth mass removed and task completion time of pre- and post-assessment comparing training on phantom head and virtual reality.

tooth models similar to Yoshida *et al.* (2011) that have multiple layers with different mechanical hardness in each layer (enamel, dentine and pulp), the participants feel tooth cutting in the same way as in a real tooth.

Interesting results were obtained regarding the percentage of tooth mass removed. The control group had almost no change in the tooth mass removed regardless of the training. Participants trained with the VR simulator tended to remove less tooth structure. Hence, it is thought that the VR simulator may contribute to training for minimal removal of tooth tissue. The participants could not only view the micro-CT tooth prior to and during cutting in 3D as well as receive different force feedback when cutting through enamel, dentine and pulp, they could also receive the augmented feedback on tooth mass loss and movements of the handpiece at the end of each trial. Moreover, changing from high to slow speed cutting was not possible in the current VR simulation. So, the technique used to prepare an access cavity using high speed burs only was selected. This may explain why the students after practicing removed less tissue as they may have been able to control the handpiece better whilst practicing with haptics and to work more carefully resulting in a more conservative approach on real teeth. A potential pitfall of simulation is that learners become expert at using simulators but not in the clinical contexts that the simulators are intended to mirror (Kneebone *et al.* 2007). It is essential therefore to investigate whether the skills acquired on a simulator actually result in improved skills in patients in the real-time clinical setting.

In summary, the data suggest that the incorporation of micro-CT tooth models and haptic VR simulators may be justified for skill development in dental students when practicing endodontics, particularly as technology continues to improve and more advanced procedural simulations become available. Efforts should continue to attempt to achieve and maintain proficiency utilizing these innovative devices as valuable adjuncts to conservative endodontic training.

Conclusion

Training on the haptic VR simulator and conventional phantom head had equivalent effects on minimizing procedural errors in endodontic access cavity preparation. The VR group decreased the amount of hard tissue volume lost on the post-training. The results suggested great promise of haptic VR and micro-CT tooth models as a tool for endodontic access cavity preparation training.

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