Title page

Title: 3D imaging, 3D printing and 3D virtual planning in endodontics

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Abstract

The adoption and adaptation of recent advances in digital technology, such as three-dimensional (3D) printed objects and haptic simulators, in dentistry have influenced teaching and/or management of cases involving implant, craniofacial, maxillofacial, orthognathic, and periodontal treatments. 3D printed models and guides may help operators plan and tackle complicated non-surgical and surgical endodontic treatment, and may aid skill acquisition. Haptic simulators may assist in the development of competency in endodontic procedures through the acquisition of psycho-motor skills. This review explores and discusses the potential applications of 3D printed models and guides, and haptic simulators in the teaching and management of endodontic procedures. An understanding of the pertinent technology related to the production of 3D printed objects and the operation of haptic simulators are also presented.

1. Introduction

Recent advances in digital technology and their application to dentistry, particularly in the disciplines of orthodontics, prosthodontics, oral and maxillofacial surgery have resulted in the emergence of devices or tools that may be used to improve teaching and management of various treatment procedures [1-4]. These aids include cone beam computed tomography (CBCT), three-dimensional (3D) printed objects and haptic simulators.

CBCT enables the assessment of teeth in relation to neighbouring hard and soft tissues through the creation of 3D images [3,5]. In endodontics, compared with conventional two-dimensional (2D) images, CBCT has improved the understanding and interpretation of complex anatomical structures; thus, benefiting teaching and case management, including treatment planning and follow-up [2,3,6-8]. Globally, the use of CBCT in endodontics is increasing rapidly [3] and various guidelines have been published to assist clinicians in case selection and to promote their safe use. These include the joint position statements by the American Association of Endodontists (AAE) and American Academy of Oral and Maxillofacial Radiology (AAOMR) [9,10] the European Commission Radiation Protection No. 172 guidelines [11], the Faculty of General Dental Practice (UK) CBCT selection criteria [12], and the European Society of Endodontology (ESE) position statement [13].

3D printed objects are models and guides that are produced through automated processes and based on virtual (computer-generated) renderings of the dentition and associated skeletal tissues. The automated processes involve devices (3D printers), which utilise various 3D printing techniques to fabricate objects [14]. Haptic simulators are computer systems that create interactive 3D virtual simulations of teeth and skeletal tissues by mimicking likely challenges of various treatment procedures and providing real-time multi-sensory peri-operative feedback [15]. The design and production of 3D printed objects and operation of haptic simulators rely on the exchange of digital information (data) between 3D imaging, 3D virtual planning and/or 3D printing technologies.

The advantages of CBCT scans over 2D radiography and its application within endodontics has been reviewed and discussed extensively in the literature [2,3,7,8,16-18]. However, owing to the relatively recent introduction of 3D printed objects and haptic simulators, there is paucity of published literature with respect to endodontics. Only a few case reports detailing the application of 3D printed guides, studies experimenting with 3D printed objects and reports on the validity of haptic simulators have been published. Therefore, this review will:

- present the pertinent literature explaining the technologies used to design and produce 3D printed objects and operate haptic simulators; and
- discuss the applications of 3D printed objects and haptic simulators systems in endodontics.

Given the scope is wide, this review will primarily focus on access cavity preparation and periradicular surgery in endodontics.

2. Review

Design and production of 3D printed objects

Advances in information technology, including the availability of inexpensive/open-source software, have permitted inter-operability between 3D imaging devices, 3D virtual planning systems and 3D printers to efficiently create, manipulate and process data for the design and production of 3D printed [14,19]. 3D imaging data from CBCT scans exist as a Digital Imaging and Communications in Medicine (DICOM) or proprietary formats [14,20,21]. The DICOM format facilitates the transfer of medical images and related data between computer devices built by various manufacturers and operating on different platforms [14,20].

The volumetric data (DICOM format) from CBCT scans is acquired by 3D virtual planning systems that use specialised software to convert the data to the Standard Tessellation Language (STL) file format representing the virtual 3D surface shape [14,19,22]. 3D imaging data from optical intra-oral/plaster model scans, existing as STL formats, are also acquired by 3D virtual planning systems. Using specialised software, the CBCT and corresponding intra-oral/plaster model STL data sets are matched to eliminate streak and void artefacts caused by metallic restorations through the precise alignment of anatomical landmarks such as crowns [22,23]. The resultant computer-generating 3D image is then edited with computer-aided design (CAD) or implant planning software to create a blueprint of the 3D printed object [14,24,25]. The finalised design is then digitally sliced and exported to a 3D printer for fabrication. Figure 1 summaries the key steps in the design and production of 3D printed objects.

3D printed objects (models and guides) are fabricated using additive manufacturing techniques, which involve the selective curing or binding of material in successive vertical layers that fuse together on an ascending/descending platform [4,14,19]. Accurate objects with geometrically complex shapes and variations in cross-sectional form, density, colour, and/or mechanical properties can be created [4,14]. Post-processing is usually required for final refinement of the 3D printed object, and may involve further curing, strengthening, and/or removal of supports [4,14,25,26]. 3D printing processes suitable for creating 3D printed objects for dental applications include:

- Stereolithography (SLG), which uses motorised mirrors for moving a beam of ultraviolet (UV) light to selectively cure and fuse successive surface layers of a reservoir containing a photoreactive liquid resin (Figure 2) [14,19,27]. A wiper recoats the cured surface layer before curing and fusion of the subsequent layer [4,19,25,26] and support structures are required for overhangs [4,14,19]. Complex and highly accurate objects can be created, and may be stained or infiltrated with dye to highlight specific areas [4,14,19].

- Digital light processing (DLP), which is similar to SLG except that it uses a Digital Micromirror Device™ (Texas Instruments, Dallas, TX, USA) to project a cross-sectional UV image instead of a moving beam [14,25,28].

- Multi-jet modelling (MJM), which involves jetting droplets of photoreactive resin, which are precisely positioned using charge deflection plates and then cured with UV light (Figure 3). Support material is simultaneously ejected through an accessory nozzle [4,14,19,25]. Complex multi-material and multi-coloured 3D printed objects can be created [4,14].

- Plaster-based 3D printing (PBP), which utilises a print head to selectively disperse liquid binder to the surface layer of a material powder bed [14,19,26]. A roller or blade then spreads a coating of powdered material for the binding of the next layer [4,14]. Coloured 3DP objects with overhangs and elastomeric properties can be created [4,14]; however, the accuracy, finish and strength are poor. Thus, strengthening with wax, sealing with cyanoacrylate, infiltrating with an epoxy resin, or sintering is required after fabrication [4,26].

- Selective laser sintering (SLS), which fuses together small particles of thermoplastic polymer, metal, ceramic or glass in successive surface layers using high-power pulsed laser systems [4,14,19,25]. Each sintered surface layer is refreshed with powdered material by a roller or blade.

Applications of 3D printed objects in endodontics

3D printed objects, based on 3D imaging scans, designed by 3D virtual planning software and produced using 3D printing processes have been successfully used in prosthodontic, orthodontic, orthognathic, craniofacial, and oral and maxillofacial procedures [29-34]. The benefits of 3D printed objects for teaching and management of treatment procedures in these disciplines have been widely reported. Hence, similar benefits can be expected with endodontic procedures, including simplification, being minimally invasive, of greater accuracy, a reduction in operating times, improvement in patient comfort and to facilitate operator skill development.

The treatment of complicated endodontic cases, for example, in non-surgical endodontics, teeth with calcified canals, dilacerated roots or developmental abnormalities, or in surgical endodontics, teeth with apices close to critical anatomical structures or covered under thick cortical bone, expose patients to increased risks of procedural errors that may compromise treatment outcomes. These cases are more routinely encountered in specialist practices, can be challenging for most operators and are less frequently performed in public health service systems such as the UK's National Health Service [35]. Furthermore, a reduction in the frequency of certain surgical endodontic procedures, such as periradicular surgery, due to successful management by the non-surgical retreatment approaches, increased tooth replacement with implants and a rise in dento-legal litigation [36-38] may contribute to operator skill erosion and insufficient training opportunities [39]. Therefore, the use of 3D printed models and guides as learning and treatment aids may promote optimal treatment outcomes and support operator skill development. The applications of 3D printed models and guides in endodontics are discussed below.

3D printed models

Plaster models can serve as educational tools for students [40] and patients. They can also be used for record keeping, assessing potential management difficulties and to fabricate custom guides or splints. However, plaster models cannot be representative of internal anatomical structures; they cannot be accurately duplicated, fabricated with differentiating colours, textures and grades of transparency, reliably utilised to simulate dental procedures and sterilised. Additionally, they require dedicated storage space and their disposal is regulated due to their gypsum content [31,41].

3D printed models and their digital counterparts can fulfil the same functions of plaster models and overcome the above limitations [31]. The digital file can be easily reproduced, stored, and exchanged electronically [31]. Depending on the 3D printing process used, models can be fabricated in multiple colours, textures, transparencies, and/or mechanical properties suitable for simulation or sterilisation.

3D printed models fabricated using SLG, DLP, MJM and PBP have a comparable accuracy with plaster models [42,43]. Additionally, these models can be stained at the post-processing stage or have varying colours and/or textures incorporated during fabrication to assist in differentiating tissue types (Figure 4) [14]. Therefore, 3D printed models can be used in endodontics as a teaching aid for students to improve understanding of tooth, root and canal morphologies, and to simulate access cavity and root canal preparation. Duplicate 3D printed models can be used to assess skill progression for individual students or cohorts and for standardised unbiased skill assessments.

They can be also used to improve management of endodontic procedures by enabling duplication and maintenance of accurate records, educating patient, aiding treatment planning through improved visualisation and determination of important anatomical landmarks or pathosis such as internal/external root resorption and allowing the fabrication of laboratory-manufactured directional or surgical guides [44-48]. 3D printed models produced from thermoplastic material using SLS are autoclavable due to the high melting point of the constituent material [4]. Thus, during endodontic treatment, they can be safely handled when intended for guidance or navigation purposes.

3D printed models manufactured using PBP and infiltrated with epoxy resin have a bone-like quality and may be ideal for practising osteotomies [19]. Therefore, as an educational aid for students or management tool for treatment planning, these models can be used for simulation of surgical procedures [47]. This can improve student/operator coordination and familiarity when challenges arise during treatment such as difficult osteotomy sites, unusual root anatomy and curvature, and proximity to delicate anatomical structures.

Due to the likely exposure to chemicals and dust, health risks associated with the use of 3D printed models for simulated procedures must be investigated. Therefore, in addition to the accuracy of 3D printed models, research is required to investigate their safety for use in teaching and management of endodontic procedures.

3D printed guides

Non-surgical endodontics can be relatively easily performed for teeth where the pulp space is not significantly reduced or altered enabling easier location of canal orifices and negotiation of the canal entrance/s. Similarly, surgical endodontics is less challenging to perform on anterior teeth, where lesions may have perforated the cortical plate, enabling easier location of osteotomy sites. However, difficulties may be experienced in locating canal entrance/s or negotiating the apical canal due to pulp canal obliteration (PCO), developmental abnormalities and where procedural errors had occurred. It can also be difficult to accurately determine the osteotomy site and the correct level of root resection due to the proximity of critical anatomical structures, thickness of cortical plates, tooth position and orientation of root apices. The operator’s skill and experience and the patient's co-operation may also vary and these will impact on treatment challenges. To overcome these difficulties and optimise outcomes for challenging endodontic cases, 3D printed directional or surgical guides, based on principles similar to guided implant surgery, may be useful.

The availability of CBCT information and implant planning software supported the development and application of 3D printed surgical guides in guided implant surgery [32,49-51]. Using the implant planning software, for example coDiagnostiX™ (Dental Wings Inc., Montreal, Canada) and Simplant® dental planning software (Dentsply Sirona Implants, Weybridge, Surrey, UK), matched data from CBCT and digitised plaster model scans are used to virtually plan the implant surgery and design the 3D printed surgical guide [22,52].

The main objective of the 3D printed surgical guide was to precisely guide implant surgery and fixture placement as prescribed using virtual treatment planning. Therefore, the design of a 3D printed surgical guide should incorporate adequate support from bone, teeth, or mucosa with guidance for the implant preparation and fixture placement procedures provided by specifically orientated guide sleeves [32,33,51]. The guide sleeves contain a prefabricated cylindrical, or a customized, metal tube manufactured using CAD-CAM devices [51]. Depth calibrated drills are used for the preparation of osteotomies through the guide sleeves with drill keys to direct the drilling procedure [33,53]; they are selected using virtual counterparts on implant planning software. Figure 5 illustrates these components as found on Dentsply Sirona Simplant® guides.

Tooth-supported 3D printed surgical guides have been shown to have smaller accuracy deviations for implant placement than mucosal- or bone-supported guides [54]. Stability, material stiffness, length of guide sleeves or drill keys, fabrication errors, operator, and patient, factors can also affect their accuracy [33,49,53-56]. Therefore, to account for any deviation from the pre-operative treatment plan a 2 mm safety distance is recommended to avoid damaging critical anatomical structures [33,50,51,57].

3D printed guides, based on the design and fabrication principles for guided implant surgery, have been adapted for use in guided non-surgical and surgical endodontic procedures [58-61].

Guided non-surgical endodontics

3D printed directional guides can be useful for canal location during non-surgical endodontic treatment where there are significant risks of procedural errors, including root perforation, which can severely compromise treatment outcome [62,63]. Recently, case reports have been published describing the successful use of tooth-supported 3D printed directional guides for canal location during non-surgical endodontic treatment of anterior teeth with PCO or *dens invaginatus* [58-60]. In these reports, CBCT scans, optical scans of intra-oral anatomy or plaster models were matched and implant planning/CAD software were used to virtually design the directional guides and select the depth calibrated implant drills/dental burs. The guides were tooth-supported and included multiple units mesially and distally for stability. The 3D printed directional guides were fabricated using SLG or MJM and prefabricated, or CAD-CAM, cylindrical metallic tubes were inserted into the guide sleeves. Teeth with multiple orifices or root canal systems, as found in a *dens invaginatus* case [58], required the fabrication of individual directional guides for every canal orifice.

Favourable treatment results were obtained after the 3D printed directional guides were used for the creation of precise and minimally invasive access cavities to gain entry to the root canals using depth calibrated implant drills/dental burs. Additionally, it was claimed that chair-side operating times and excessive loss of tooth structure were reduced, and the risk of perforation avoided. Furthermore, the use of a single access drill/bur [58,59] or two burs [60] ensured the accuracy of the drilling procedure. An *ex vivo* study by Zehnder *et al.* [23] demonstrated that the accuracy of the drilling procedure using 3D printed directional guides was greater than that of implants, as only one access drill/bur was used. Although the design and fabrication procedures lengthen total treatment time and increase costs [58-60], and dentinal cracks may occur from the use of depth calibrated implant drills/dental burs in teeth with PCO [59], the preparation of conservative access cavities and avoidance of procedural errors outweighs these disadvantages.

3D printed directional guides can, therefore, aid in safe, cost-effective, and efficient management of teeth with PCO and developmental abnormalities affecting root canal systems. They may also be used as educational tools for training, especially postgraduate students to develop skills in negotiating these treatment obstacles in the laboratory and clinics. However, further research is warranted to determine their accuracy and the incidence of dentinal cracks associated with the use of depth calibrated implant drills/dental burs. Research is also required to assess clinical feasibility for other treatment scenarios where access to the apical canal is required, such as creation of staging platforms for the removal of separated instruments and negotiation of blockages/ledges, in both anterior and posterior teeth. Table 1 summaries these case reports and Figure 6 illustrates the general principles of guided non-surgical endodontics.

Guided surgical endodontics

3D printed surgical guides can be adapted for use in surgical endodontics where there is difficulty in determining the osteotomy site and level of root resection in complex cases, or for skill development in an educational setting [45]. Guided surgical endodontics, like other guided procedures, is reliant on meticulous treatment planning that includes finalising the design of the 3D printed surgical guide, using implant planning software loaded with the matched CBCT and optical scan data sets [22,48,52,59]. During treatment, the position of the guide sleeve over the cortical plate helps to identify the osteotomy site. Depth calibrated drills or piezoelectric instruments used to perform the osteotomy maintain parallelism with the guide sleeve, thereby limiting its size to 4 mm [64]. If necessary, a drill key can be used to direct root-end resection at the predetermined level and angle. Figure 7 below summaries these general concepts for guided surgical endodontics.

A recent case report by Strbac *et al.* [61] described the treatment planning and application of 3D printed surgical guides to perform predefined osteotomies and root-end resections for root-filled posterior maxillary teeth (first molar and second premolar) with periapical lesions. Following flap elevation and retraction, osteotomies and root-end resections were performed using piezoelectric instruments directed by the teeth- and bone-supported 3D printed surgical guides. The surgical guides were also used to locate extruded root filling material for precise removal, without perforating the sinus membrane. Healing of the periapical lesions was demonstrated radiographically at the one-year follow-up. The potential benefits of guided surgical endodontics claimed include shortened operation time, improved accuracy and reduced post-operative discomfort [61].

No other case reports have been published demonstrating the use of 3D printed guides in surgical endodontics. Furthermore, as surgical endodontics is less commonly indicated and performed [35,65], there is a need for 3D printed surgical guides to encourage skill acquisition, and facilitate management of complicated cases. Therefore, further research is required to investigate the techniques used for guided surgical endodontics and its potential benefits in dental education.

Operation of haptic simulators

Virtual reality simulation systems have been used in medicine to train surgeons and medical students [66-68]. Virtual reality simulation systems electronically generate visual and auditory simulations of environments and allow dynamic interactions through specialised peripheral devices, such as haptic devices.

Haptics is a science pertaining to the sense of touch and its interaction with the virtual environment. Haptic devices linked with virtual reality simulation systems, haptic simulators, stimulate a sensory tactile experience through real-time robotic feedback systems capable of generating vibrations and counter-forces [15,69]. Most haptic devices provide 6 degrees of freedom (DOF) for spatial location but 3 DOF for force feedback, which limits realism. Examples of haptic devices include (Figure 8): Geomagic® Touch™ and Touch™ X (3D Systems Inc., Rock Hill, SC, USA) previously known as PHANToM® Omni and PHANToM® Desktop respectively; and Virtuose™ 6D Desktop (Haption S.A., Soulgé-sur-Ouette, France).

The convergence of haptic and virtual reality technology and integration with 3D imaging data in dentistry had resulted in the emergence of dental haptic simulators that can create virtual oral anatomy, and facilitate simulation (3D virtual planning) of dental procedures with real-time visual, tactile, and auditory feedback [15,70]. Thus, these devices are primarily used in dental education for 3D virtual planning [71].

Haptic simulators depend on specialised software for generation of a 3D virtual simulation with haptic interactions. The software relies on the concurrent operation and interaction between two processes - graphics and haptics renderings. Graphics rendering process is responsible for the stereo visualisation of the 3D virtual environment [72]. Haptics rendering process monitors the spatial location of the haptic stylus, detects collisions with the virtual environment, and calculates the reaction forces to be applied by the robotic mechanism [72]. Complex algorithms are used within these processes to replicate operative procedures.

The device set-up of haptic simulators varies widely depending on development stage. To recreate realism, most commercially available devices project the interactive 3D virtual simulation on a semi-transparent mirror with a haptic device located underneath to replicate viewing angles, patient head position, and operator hand orientation [73]. Such devices can also have accessory monitors to display courseware, and/or additional haptic device representing a virtual dental mirror to encourage adaptation to indirect vision and bi-manual instrument manipulation. Two examples of haptic simulators, Simodont® Dental Trainer (Moog Inc., East Aurora, NY, USA) and Voxel-Man system (Voxel-man Group, Hamburg, Germany) (Figures 9 & 10).

The advantages of haptic simulators include reinforcement of academic teaching, acquisition of psychomotor skills, ergonomic chair-side positioning [73], unlimited opportunities to practise dental procedures [70], capacity to vary pathological conditions by alteration of data sets [73], self-evaluation, standardisation of assessments, reduced need for supervisors [71], and absence of waste generation. However, commercially available devices are expensive [71], utilise a limited range of virtual instruments, and do not simulate soft tissue accurately [74]. Furthermore, research on the realism provided by these devices for dental procedures is lacking.

Applications of haptic Simulators in endodontics

Endodontic procedures require an operator to have sound anatomical knowledge, correctly interpret radiographs and CBCT scans, be highly organised, exhibit manual competency, have good hand-eye co-ordination, correctly handle endodontic and surgical armamentarium, and be familiar with visual, acoustic, and tactile feedback sensations during treatment. Thus, for the teaching of endodontic treatments, haptic simulators should ideally provide realistic simulation of a wide variety of non-surgical and surgical treatment procedures, alongside relevant armamentarium, and consideration of anatomical complexities. However, only access cavity preparation, osteotomies and root-end resections are possible with commercially available haptic simulators. These include VirTeaSy Dental (HRV, Laval cedex, France) and Simodont® Dental Trainer.

Studies have been performed to test the suitability of two experimental haptic simulators, HVRS (Faculty of Dentistry, Thammasat University, and School of Engineering and Technology, Asian Institute of Technology, Thailand) and Voxel-Man, for non-surgical and surgical endodontic procedures respectively (Table 2). Collectively, these studies indicate that haptic simulators can be useful as a teaching tool for endodontic procedures involving access cavity preparations, osteotomies, and root-end resection. However, these studies were based on a small number of participants, subjective responses, and/or lack of randomisation or controls. Quantification of skill acquisition and/or proficiency [75], larger multi-centred cohorts, and well-designed studies can help to improve quality of research. In addition, further research should also focus on the transfer of psychomotor skills to clinical environment for commercially available devices.

3. Conclusions

With continuous improvements in 3D imaging, 3D printing, and 3D virtual planning, combined with the need for skill development, to optimise treatment outcomes and to improve patient comfort, there are potential benefits for teaching and management of non-surgical and surgical endodontic procedures using these technologies. Further research on the various applications of 3D printed models, 3D printed guides, and haptic simulators in endodontics is required.

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Compliance with Ethical Standards

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Table 1: summary of case reports for guided non-surgical endodontics.

Case report	Case summary	Conclusions	Comments
Zubizarreta Macho *et al.* [58]	• Maxillary lateral incisor with *dens invaginatus*. • CBCT used and matched with optical plaster model scan. • Three tooth-supported guides designed using implant planning software (Simplant®). • Guides printed using SLG, with prefabricated guide sleeve metal tube of internal diameter 1.3 mm and length 5 mm. • Single dental diamond bur used (diameter 1.2 mm and length 14 mm) to prepare three access cavities.	Supported the use of volumetric data from CBCT and use of implant planning software for design and production of 3D printed directional guides for conservative access cavity preparations.	Limitations of directional guide splints include expensive and time-consuming processes, risks of guide fracture or dislodgement of guide sleeve metal tube, and inaccuracies of guided procedures. However, there are significant benefits for teeth with developmental defects, specifically, conservative access preparation and facilitating endodontic treatment. Furthermore, the inaccuracy of guided implant surgery is more than that of guided non-surgical endodontics as only one drill was used to gain access to the root canal system.
Krastl *et al.* [59]	• Maxillary central incisor with PCO. • CBCT used and matched with optical intra-	Considered 3D printed directional guides to be safe and clinically feasible in locating root canals for	Cost of the design and fabrication of the 3D printed directional guide was justified as treatment time was significantly reduced and perforation risk

	oral scan. • Tooth-supported guide designed using implant planning software (coDiagnostiX™) • Guide printed using MJM, with a customised guide sleeve metal tube of internal diameter 1.5 mm and length 6 mm. • Single depth calibrated implant drill used (diameter 1.5 mm and length 37 mm) to prepare access cavity.	teeth with PCO and preventing perforation.	minimised. However, due to access problems with long implant drills, treatment is limited to anterior teeth. This may be partially overcome by creating side-entry slots on the guide sleeve to permit lateral insertion of depth calibrated implant drills.
Van der Mer *et al.* [60]	• Maxillary central incisor with PCO. • CBCT taken and matched with optical intra-oral scan. • Tooth-supported guide designed using CAD software (3ds Max; Autodesk, San Rafael,	Supported design and production technique of 3D printed directional guides for reliable and predictable access cavity preparations for teeth with PCO. Suggested the use of these guides by less experienced operators	No mention the length of the guide sleeve used. The length of the guide sleeve is critical in minimising deviations during the drilling procedure. The use of two depth calibrated burs to gain access may increase the deviation of the drilling procedure from

CA, USA). • Guide printed using MJM, with a prefabricated guide sleeve metal tube of internal diameter 2.4 mm. • Two burs (Munce bur no. 2; CJM engineering Inc., Santa Barbara, CA, USA), diameter 2.4 mm and length 31 and 34 mm respectively, used successively to prepare access cavity.	to successfully treat PCO cases.	the treatment plan.

Table 2: Studies on the effectiveness of haptic simulators in teaching of non-surgical and surgical endodontic procedures.

Study	Aim(s)	Method	Results	Conclusions
Non-surgical Endodontic treatment simulation				
Suebnukarn *et al.* [75]	Assessed skill acquisition in non-surgical endodontics using Haptic Virtual Reality Simulator (HVRS) by collecting kinematic data, and identify outcome variables for quantifying skill acquisition and proficiency.	Kinematic data (from the haptic device) collected on performance of access cavity preparation for 20 4th year undergraduate students with no experience in the procedure (novices) using HVRS seven times (one pre-training session at day 0, five training sessions at day 3, and one post-training session at day 7).	Data analysis showed shorter times, improved instrument handling, safer application of force, and better preparations, for post-training sessions, with consistent improvement from each training session.	Demonstrated consistent and significant improvement in time taken and quality of access cavity preparation by the novices using HVRS. Supported the collection of kinematic data for analysis of force utilisation and bimanual dexterity, rather than subjective responses from feedback.
Suebnukarn	Assessed effectiveness of HVRS	Randomised controlled and blind trial	In both groups, post-training access	Haptic simulator training with a

***et al.* [76]**	with microcomputed tomography models (micro-CT) at reducing procedural errors and reducing treatment times for access cavity preparations.	performed comparing access cavity preparation during training by 2 groups of 4th year undergraduate students with no experience in the procedure using micro-CT tooth model on HVRS (n=16), and extracted maxillary molar mounted on phantom head (n=16). Group specific pre-training, then training for 3 days, followed by a post-training phantom head test was performed.	cavity preparations had improved compared with pre-training. The HVRS group had significantly less tooth structure removed post-training than pre-training, whereas the control group had no difference. There was no significant difference in procedural error reduction and treatment times between both groups.	micro-CT tooth model was comparable to phantom head training with extracted tooth in reducing procedural errors related to access cavity preparation. Therefore, haptic simulators may be useful for skill development of dental students.
Surgical endodontic treatment simulation				
Heiland *et al.* [74]	Assessed realism of Voxel-Man system for dental applications.	Feedback from 40 final year undergraduate students classed as 'beginners' (no experience of surgical	Students found the haptic simulator easy to handle, perceived it as a valuable teaching aid, and	Further development to extend range of simulated surgical

		endodontics).	considered it suitable for simulation of osteotomies. However, the students found deficiency in soft tissue simulation.	procedures.
Pohlenz *et al.* [73]	Assessed realism of Voxel-Man system for dental applications.	Feedback from 53 undergraduate students with no experience of surgical endodontics.	The haptic simulator was considered suitable for training purposes in surgical endodontics by 51 students.	Further development to create new training modality.
Von Sternberg *et al.* [77]	Assessed the transfer of psychomotor skills using the Voxel-Man system and cadaveric pig jaws between two groups.	Group 1 (n=20) trained thrice on Voxel-Man system then both Group 1 and Group 2 (n=21) performed osteotomies and root-end resection on cadaveric pig jaws.	There was progressive improvement in performance of 3 virtual surgical endodontic procedures by Group 1. Group 1 students had significantly less damage to vital anatomical	Training with the device was effective and resulted in the acquisition of practical skills transferable from the virtual environment.

structures and created smaller osteotomies.

No significant differences between groups regarding accuracy of the level of root-resection and treatment time.

Figure legends.

Fig. 1: Stages involved in the design and production of a 3D printed object.

Fig. 2: Layered fabrication of a 3D printed object using SLG. The surface layer of the photoreactive liquid resin is cured by a moving UV light beam. After first layer is cured, the build platform descends and a wiper refreshes the photoreactive liquid resin over the cured layer to permit curing and fusion of the subsequent layer. Overhanging layers are supported with pre-assembled support structures.

Fig. 3: Fabrication of a 3D printed object using MJM. Photoreactive liquid resin, in droplet form, is ejected on to a build platform from a nozzle and rapidly cured by UV light. Simultaneously support material is ejected from a secondary nozzle and the platform descends as the 3D printed object is created.

Fig. 4: Mandibular 3D printed models with highlighted anatomical features produced using (a) SLG and (b) MJM. Reproduced with permission from Biomedical Modeling Inc., www.biomodel.com.

Fig. 5: Features of various 3D printed Dentsply Sirona Simplant® guides. Reproduced with permission from Dentsply Sirona Implants, SIMPLANT®, www.dentsply.com.

Fig. 6: Guided non-surgical endodontics: (a) anterior tooth with PCO; (b) tooth-supported 3D printed directional guide placed after isolation; (c) drilling procedure with a single depth calibrated drill/bur; (d) and completion of non-surgical endodontic treatment.

Fig. 7: Surgical endodontic treatment aided by a 3D printed surgical guide for accurate osteotomy and root-end resection procedures. (a) An endodontically treated tooth requiring surgical intervention. (b) Flap elevation and retraction, and a stably positioned teeth- and bone-supported 3D printed surgical guide to locate the osteotomy site. (c) Guided removal of cortical bone using depth calibrated drills fitting inside the cylindrical metallic tube of the guide sleeve and remaining parallel during drilling. (d) Removal of the inflamed/infected periradicular tissue and root tip exposure. (e) Insertion of a drill key into the guide sleeve to direct root-end resection with a depth calibrated drill (f) Flap closure and suturing after root-end cavity preparation and filling.

Fig. 8: Haptic user interface devices: (a) Geomagic® Touch™ X; (b) Geomagic® Touch™ Desktop (reproduced with permission from 3D Systems Inc., www.geomagic.com); and (c) The Virtuose™ 6D Desktop (reproduced with permission from Haption S.A., www.haption.com).

Fig. 9: The Simodont® Dental Trainer (reproduced with permission from Moog Inc., www.moog.com).

Fig. 10: The Voxel-Man system featuring two haptic devices for handpiece and dental mirror control in the interactive 3D virtual simulation displayed on a monitor and viewed with 3D glasses worn by the user. Reproduced with permission from Voxel-Man Group, University Medical Center Hamburg-Epperndorf, www.voxel-man.com/dental.