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ENDODONTIC APPLICATIONS OF 3D PRINTING

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ABSTRACT

Current research suggests an emerging value of 3D printed guides use in the endodontic field. Computer-aided design and manufacturing technologies can be used to create 3D printed guides with endodontic clinical applications. Computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies can leverage cone beam computed tomography data for production of objects used in surgical and nonsurgical endodontics and in educational settings. The aim of this article was to review all current applications of 3D printing in endodontics and to speculate upon future directions for research and clinical use within the specialty. Documented solutions to endodontic challenges include: guided access with pulp canal obliteration, applications in auto transplantation, pre-surgical planning and educational modelling and accurate location of osteotomy perforation sites. Future research directions should include clinical outcomes assessments of treatments employing 3D printed objects.

INTRODUCTION

Digital imaging and 3D printing are rapidly revolutionizing dental practice. Fabrication of dental appliances such as veneers, crowns, and bridges using dental CAD-CAM technology is not new, however, new and improved systems are becoming available in the market very quickly . An emerging application for this technology is in the field of endodontics; specifically, the fabrication of 3D printed guides. A well-made guide can significantly improve the quality and safety of endodontic procedures. Duret & Preston (1991) demonstrated the first dental application of CAD/CAM introducing a numerically controlled SM miller for the fabrication of fixed restorations (Duret & Preston 1991, Miyazaki et al. 2009)[1]. Although modernized SM is still the preferred method for fixed CAD/CAM restorations, limited material options and confining orientation requirements have precluded its use for other dental applications (van Noort 2012, Abduo et al. 2014, Torabi et al. 2015). All CAD/CAM applications involve three steps: digital data acquisition using an intraoral scanner and/or a cone beam computed tomography (CBCT), data processing and design within a software application, and manufacturing by milling or printing (van Noort 2012, Kim et al. 2016). 3D printing provides utility in several scenarios where SM is incapable or impractical[2].

Dental applications of 3D printing adopt one or more of the following common technical type classifications: stereolithography apparatus (SLA), fused deposition

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modelling (FDM), MultiJet printing (MJP), PolyJet printing, ColorJet printing (CJP), digital light processing (DLP) and selective laser sintering (SLS) also known as selective laser melting (SLM) (Torabi et al. 2015, Kim et al. 2016).[3] SLA was the earliest and is the most commonly used technology employed in dentistry (Kim et al. 2016). Its inventor (3D Systems, Rock Hill, SC, USA) also developed the STL or stereolithography CAD/CAM file format (van Noort 2012, Torabi et al. 2015).

Guided endodontic access

Pulp canal obliteration, calcific metamorphosis, and pulp canal calcification are all terms that describe increased apposition of tertiary dentin in the root canal system. Increased apposition of dentin decreases the translucency of the tooth and causes discoloration; this is the most common clinical sign of pulp canal obliteration. Orthodontic treatment, aging, dental caries, and dental trauma can increase pulp canal calcification; 15-40% of patients who undergo dental trauma will develop pulp canal obliteration[4] . Approximately 60-80% of teeth will remain asymptomatic and require no endodontic treatment. However, the remaining 20-40% of teeth will develop pulp necrosis with radiographic signs of periapical disease . This obliteration makes it more challenging to negotiate canals, complicates root canal treatment, and increases the risk of iatrogenic events. In addition, 20% of perforations occur when trying to locate canals of severely calcified incisors .In an article and case series, van der Meer et al. (2016a) acquired digital impressions and CBCT scans; CAD software merged digital impression files with CBCT DICOM data to form a STL file containing boney architecture for teeth in pulp canal obliteration-affected maxillary incisors (Fig. 1) [5]. Access guides were printed and utilized to target burs to otherwise elusive canal spaces without perforation. Similarly, case reports describing the use of 3D printed guides to access an obliterated maxillary incisor (Krastl et al. 2016), a mandibular molar (Shi et al. 2017), type V dens evaginatus (Mena-Álvarez et al. 2017) and obliterated mandibular incisors (Connert et al. 2018) support the clinical utility of the technique. In ex vivo investigations of accuracy, Buchgreitz et al. (2016), Zehnder et al. (2016) and Connert et al. (2017) assessed stent guided access preparations by superimposing a post-access CBCT upon a pre-operative designed access[6]. Buchgreitz et al. (2016) found the mean deviation of the access cavities to be lower than the 0.7-mm threshold defined by the radius of the bur plus the radius of the root canal. Zehnder et al. (2016) and Connert et al. (2017) also found small deviations from the intended access (0.12–0.34 mm at the tip of the bur) and a mean angular deviation of less than 2°[7]. These investigations suggest that 3D printed access guides represent an efficient and safe means of addressing challenging endodontic scenarios, enabling both chemo-mechanical debridement and conservation of tooth structure. Treatment of teeth with pulp canal obliteration, malposition or extensive restoration may be more effective with designed targeted access guides. Further clinical investigation in this area is warranted.

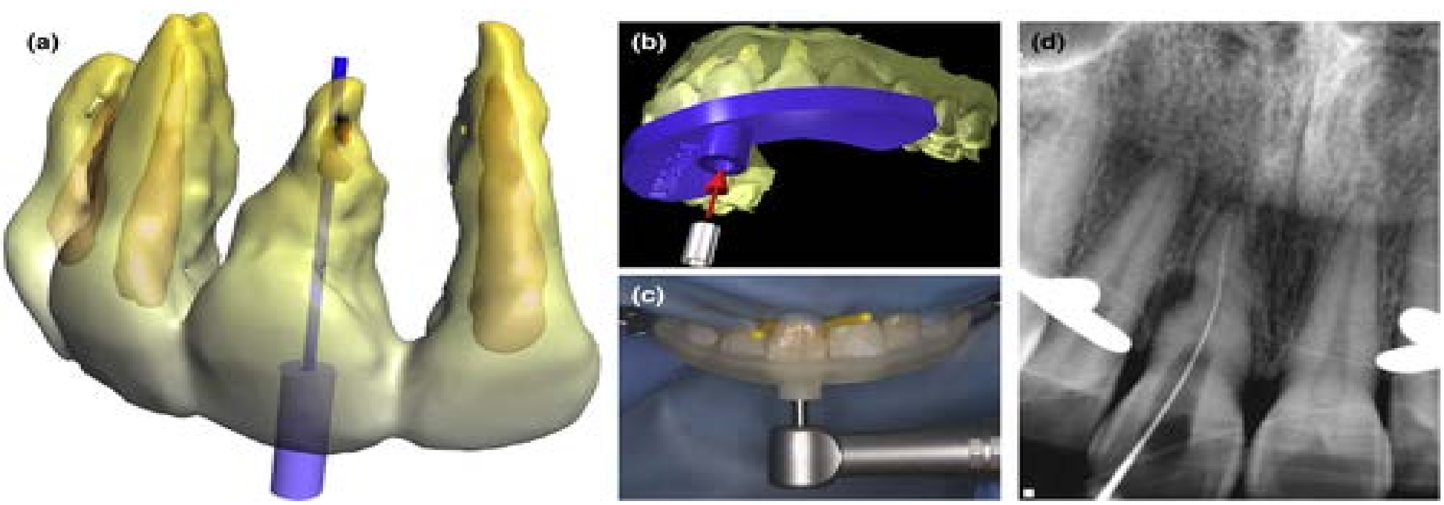

Figure 1: van der Meer et al. Guided Endodontic Access: (a) Planning of a directional guide. A cylinder is used to depict the direction of the drill necessary to locate the root canal system. Other cylinders are automatically aligned with the directional cylinder. Those cylinders are used for the design of the directional guide. (b) The final directional guide design. After the rapid prototyping of the guide a metal tube is placed in the corresponding hole. The metal tube has an inner diameter that is slightly larger than the bur used during the location of the root canal system. (c) The directional guide in place, whilst a bur is used to gain access to the canal system. As can be seen, the direction of the bur is not exactly parallel to the long axis of the tooth during preparation. This coincides with the 3D planning. (d) Working length radiograph after the root canal system had been located with the aid of a directional guide.

Treatment of dental morphology anomalies

Dental malformations like dens invaginatus and dens evaginatus are rare malformations that create anatomical disturbances that affect the ability to prepare conservative access and, presents with an added complication during root canal treatment. In addition, dental morphology anomalies can present with an increase rate of appositional dentin disposition, leading to pulp canal calcification, making it even more challenging to isolate canals[8].Mena-Alvarez et al. reported a clinical case showing a root canal treatment of a type V Dens evaginatus using CBCT and a 3D printed guided for a conservative access[9]. Tooth #9 presented with a fistulous lesion and had a tubercle at the medial gingival third and on the medial buccal surface. At the 12-month follow-up the buccal defected was repaired, and there was resolution of the periapical radiolucency (Figures 2-3). Another case report of a Type 2 dens invaginatus noted the successful treatment of tooth #10 using guided access[10]. At an 18-month follow-up the authors reported radiographic reduction of the periapical lesion and an absence of clinical signs . Using guided access, treating teeth with these complex root canal anatomies resulted in a successful and simplified endodontic treatment process that might not have succeeded using hands-free methods[11]. Ali et al. presented a case series that used a guided endodontic approach for the conservative management of Type II dens invaginatus by prophylactic sealing of dens with mineral trioxide aggregate (MTA) to prevent any pulpal damage to the tooth due to deep palatal pits which are commonly vulnerable to carious lesion[12]. They concluded that this technique can be a valuable tool for negotiating the dens part, thereby reducing chairside time and more significantly decreasing the risk of iatrogenic damage to the remaining tooth structure .

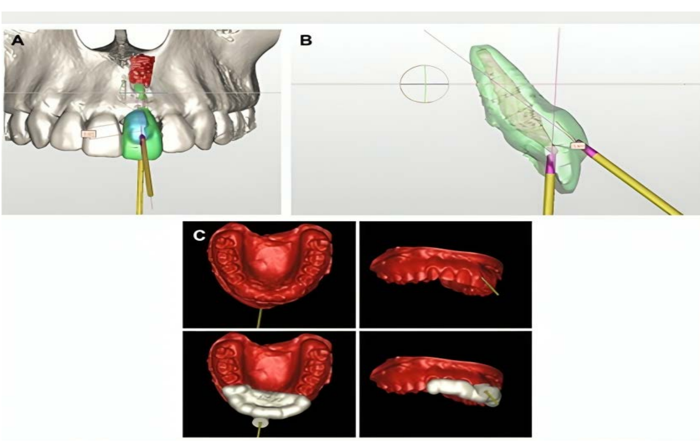

Figure 2: (A) Tridimensional reconstruction of vector direction that represents the cavity access path of dens evaginatus and tooth2.1. Coronal view. (B) Tridimensional reconstruction of vector direction that represents the cavity access path of Dens Evaginatus and tooth 2.1. Sagittal view. (C) Tridimensional reconstruction of the design of the splints for guided endodontic treatment.

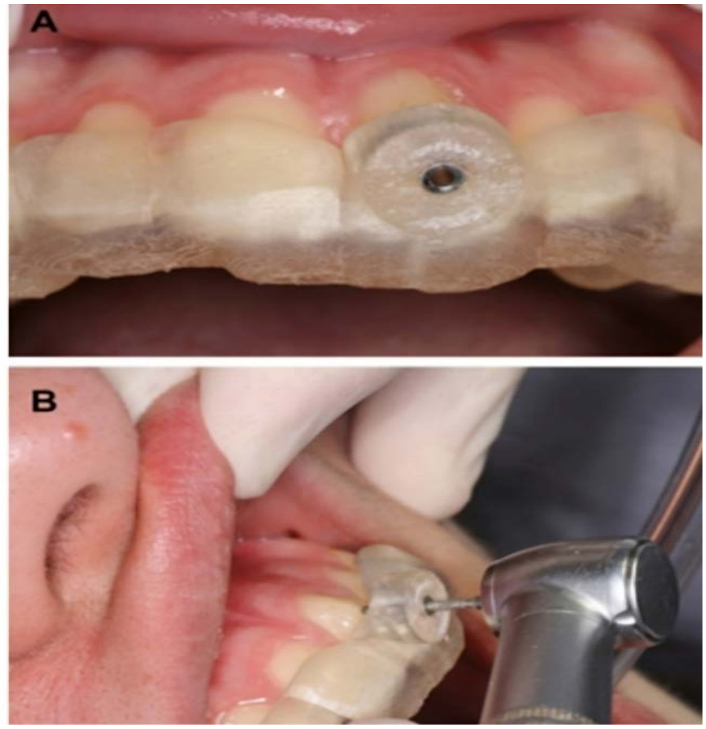

Figure 3: (A) Stereo-lithographied splint for performing guided endodontic treatment. (B) Positioning of the cavity access drill on stereo-lithographed splint.

Guided post removals

Fiber-reinforced composite resin posts are used when restoring endodontically treated teeth to provide retention of the core and for root reinforcement, sometimes the removal of these post is necessary to perform a retreatment of a root canal[18]. The conventional method for post removal includes using drill kits specific to the type of post, drills combined with ultrasound, and long-shank endodontic burs with an operating microscope[13].However, even with these tools, the task remains difficult; root perforation, axis deviation, and roots' weakening remain serious risks . 3D printed surgical guides enable the clinician to maintain the axis of the drill at precisely the angle at which the post should be removed. In a case report, Perez et al. demonstrated using a surgical guide to clinically remove a fiberglass post fromthe palatal canal of a maxillary first molar[14].Later in an in vitro study, Perez et al. showed the reliability of guided endodontic technique to remove bonded fiber-posts. Apical gutta-percha was accessed successfully in 87.5% of the teeth[16]. The mean deviation between the planned and actual drill paths was 0.39 mm coronally and 0.40 mm apically; notably, no root perforations were reported . Cho et al. in case series used the 3D guided to safety remove fiber posts in 4 teeth; it took less than 5 min. to remove the complete each fiber post removal and there were no perforations. However, they do mention that using the operating microscope is still advisable even with the use of a guide as they observed a slight discrepancy between the planned and actual drilling path [16]. Maia et al. reported the successful removal of the fiber reinforced composite post while preserving the crown [17]; and Goncalves et al. reported the post removal in a molar . They all agreed that removing the fiber post with virtual planning and a 3D guide resulted in a safe and faster procedure.

Tooth auto transplantation

Auto transplantation of a tooth is indicated to replace a lost tooth in cases with complex tooth fracture, deep dental caries, endodontic treatment failure, and congenitally missing teeth. The evolution of 3D printing and cone beam computed tomography (CBCT) scanning has opened the door for modifications to the conventional auto transplantation approach. Planning the guided osteotomy utilizing CBCT imaging and specialized software to [19]create an osteotomy guide can minimize bone loss and limit damage to soft tissue and neurovascular structures . This guided approach to auto transplantation is helping to reduce iatrogenic damages that can occur during the procedure.

In two early prospective studies at the Yonsei University College of Dentistry (Seoul, Korea), computer aided rapid prototyping (CARP) was used to print replicas of teeth such that manipulation of the recipient bone sites could be completed prior to extraction of the transplanted teeth without PDL damage from repeated insertion and removal (Lee et al. 2001, Lee & Kim 2012) [20]. Numerous additional case reports, clinical studies and in vitro models provide evidence that preoperative CARP of transplant teeth decreases extra-oral time and improves outcomes (Honda et al. 2010, Keightley et al. 2010, Shahbazian et al. 2010, 2012, Pang et al. 2011, Park et al. 2012, 2013, 2014, Cross et al. 2013, Jang et al. 2013, Lee et al. 2014, Vandekar et al. 2015, Anssari Moin et al. 2016, 2017, Khalil et al. 2016, van der Meer et al. 2016b, Cousley et al. 2017, Kim et al. 2017, Verweij et al. 2017a). In a case report, Strbac et al. (2016) described the auto transplantation of immature premolars in a maxillary incisor avulsion scenario using a completely digital workflow[21]. The authors used CAD to select the appropriate donor teeth based on dimensions and stage of root development. Prototype teeth were modified to accommodate the dimensions of Hertwig's epithelial root sheath and to minimize damage to the apical papilla. The CAD modified prototype teeth were virtually auto-transplanted into the donor sites to create successively larger osteotomy guides that allowed for a more precise and efficient surgical phase[22]. In a proof of concept, Anssari Moin et al. (2016) used CAD to print custom surgical instruments accommodating the transplanted tooth, achieving an apical deviation of less than 1 mm from the planned final tooth position in a human mandible. A systematic review by Verweij et al. (2017b) found an overall success rate of 80–91% when rapid prototyping was applied attributing success to preparation of the recipient site prior to extraction of the transplanted tooth, in some cases enabling an extra-oral time of less than 1 min[23]. In a multi-disciplinary case, successful auto transplantation of tooth 21 to the site of tooth 9 was made possible by CARP (Fig. 4). Future studies may further clarify the outcomes impact of CARP prior to auto transplantation.

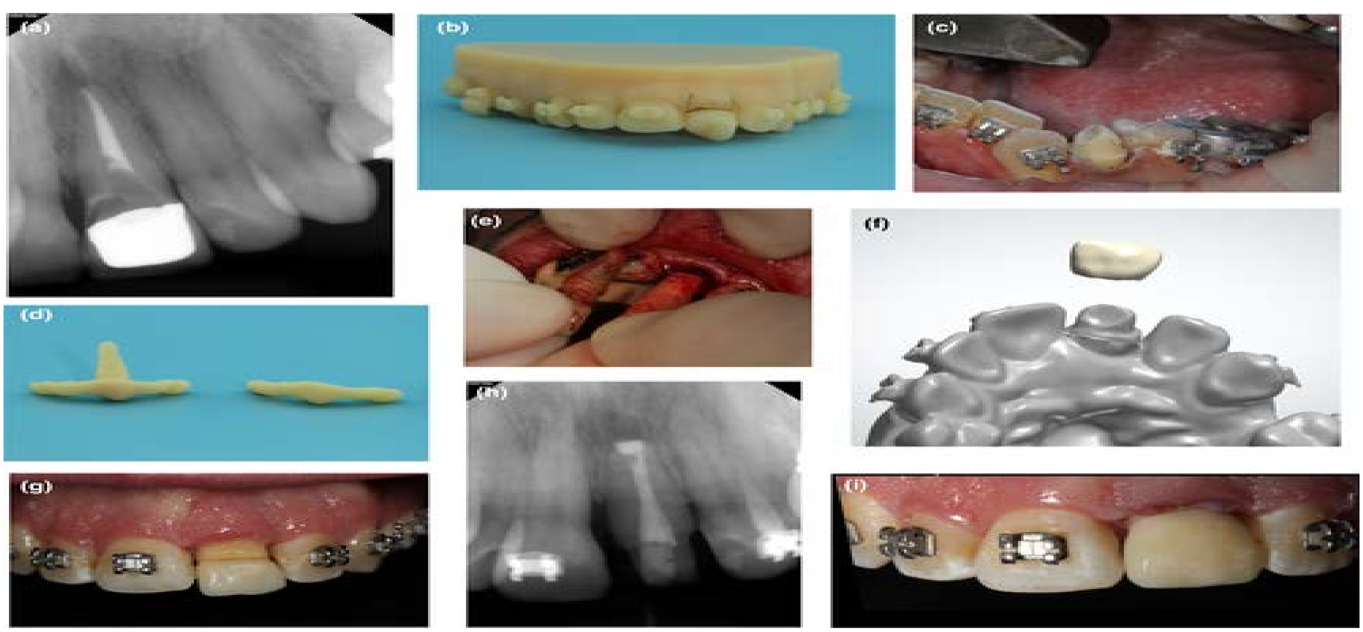

Figure 4 :CARP Autotransplantation: 19 years after trauma and RCT tooth #9 was deemed nonrestorable due to cervical resorption. (a) Preoperative presentation. (b) 3D printed model used to assess orientation and dimension requirements for transplantation of #21 to #9. (c) #21 was prepared for crown and scanned for immediate CAD/CAM provisional restoration prior to extraction. (d) 3D printed prototype of #21 root and surgical guide used during preparation of #9 alveolus. (e) Replacing nonrestorable #9 with root canal treated #21 which also received extraoral root end resection and fill. (f) Virtual planning of immediate provisional. (g) Immediate provisional placed following autotransplantation. (h) Tooth #21 in recipient site. (i) Interim restoration #9.

Guided endodontics and 3D printing in education

Finally, the literature does shed some light on the use of 3D guides in dental education. The introduction of guided endodontic access in the pre-doctoral curriculum can help pre-doctoralstudents develop their manual dexterity, teach ideal access openingshape, and demonstrate how to preserve tooth structure. Studentswho perform guided access could also experience a reduction inoperating time . Guided exercises should complement thetraditional curriculum rather than replace it.It is typically challenging to find many extracted teeth in needof a specific endodontic treatment[24]. Also, proper disinfection,storage, and preservation of extracted teeth can be costly andtime-consuming . 3D printing can be used to create resin teethwith a simulated need for endodontic treatment, with numerousendodontic anatomic variations, which allows dental students topractice with a large number of endodontic procedures.

Tooth prototypes have been used for simulation exercises with advantages over extracted teeth (Kfir et al. 2013, Bahcall 2014, Kato & Kamio 2015, Marending et al. 2016, Robberecht et al. 2017). Some of the earliest demonstrations utilized CT slices and starch to reconstruct challenging clinical cases such as extracanal invasive resorption (Kim et al. 2003) and a molar with three distal roots (Lee et al. 2006). Kfir et al. (2013) used a clear tooth replica to simulate ideal access, instrumentation and obturation preoperatively in a complex type 3 dens invaginatus scenario, before treating the clinical case. In an evaluation of dental student file preferences, Marending et al. (2016) used commercially available 3D printed molar replicas (RepliDens, Zurich, Switzerland) to avoid variance in initial canal configuration. Robberecht et al. (2017) developed a porous, radiopaque hydroxyapatite-based matrix with hardness similar to dentine, to print ceramic models for endodontic lab exercises. Custom designed regenerative endodontic educational models have enhanced preclinical residency exercises (Fig.5).

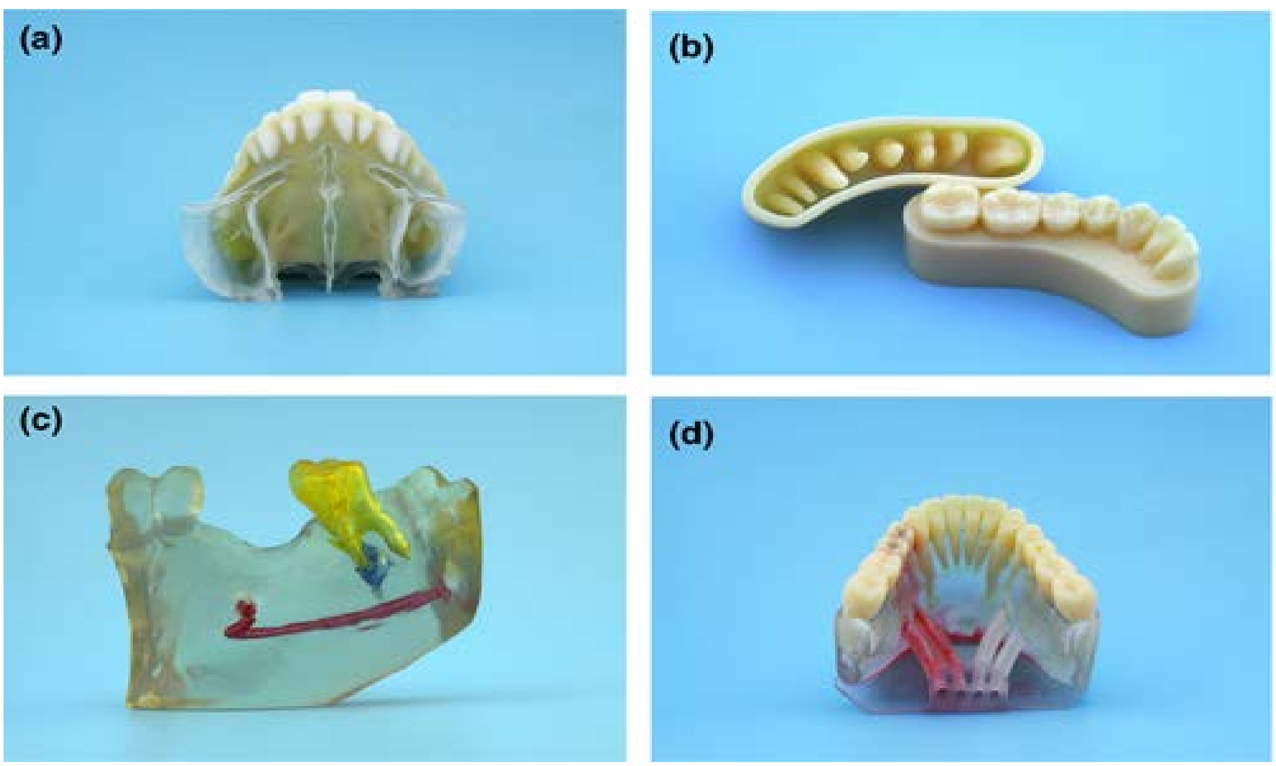

Figure 5:Endodontics Residency 3D printing applications: (a) Surgical model used for pre-surgical treatment planning and simulation. (b) Instructional models. (c) Large-scale model of periapical lesion adjacent to mandibular canal. (d) Regenerative endodontics model with open apices and ports for simulated apical haemorrhage.

Reymus et al. presented a workflow with feasible manufacturing of accurate 3D printed tooth replicas of extracted human teeth. Students in the third and fourth year of dental school who had trained on extracted molars, or who had performed root canal treatment in patients, were asked to complete root canal procedures in the replicas. Students felt they greatly benefited from using replicated teeth for endodontic training (Figure 6)[25].

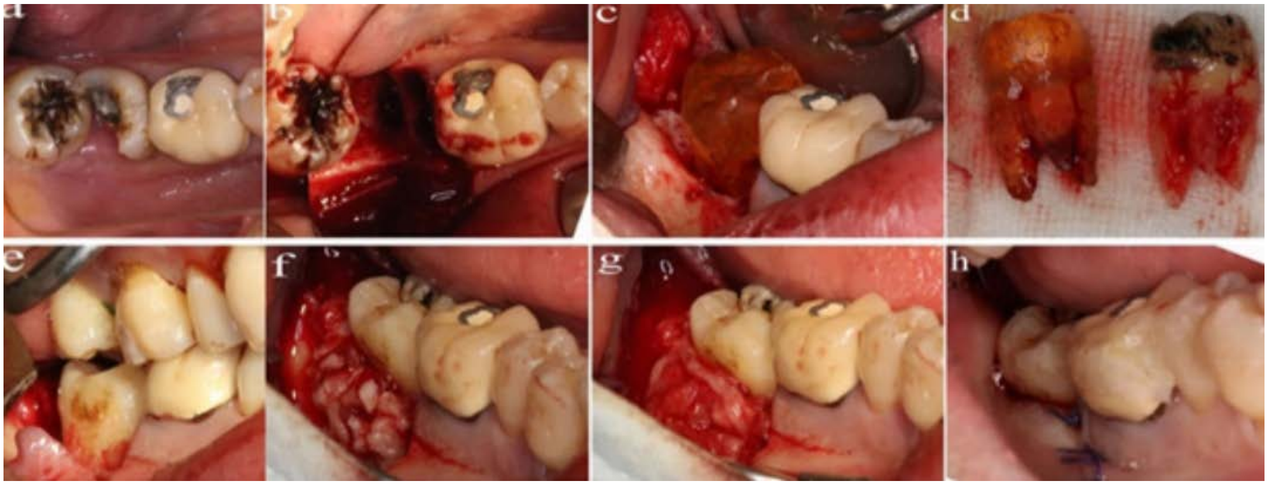

Figure 6: The surgical procedure of auto transplantation of a mature third molar tooth in a fresh socket of second molar tooth: A. compromised second molar tooth. B fresh socket of the second molar tooth after extraction. C try-in of the 3D replica of the donor tooth. D the 3D replica was almost the same of the donor maxillary third tooth. E try-in of the donor tooth. F grafting of the autogenous bone in the buccal and distal side of the donor tooth. G covering with CGF membrane. H suturing the flap and fixed the auto transplantation tooth.

Surgical guides

Endodontic microsurgery (EMS) requires a targeted osteotomy and root end resection based upon anatomic landmarks and preoperative X-ray or CBCT measurements. Osteotomy can deviate from the ideal as a result of human error in clinical scenarios where proper orientation, angulation and depth of preparation are challenging. Improvements in magnification, armamentarium and materials have established EMS as a predictable procedure (Kim & Kratchman 2006, Tsesis et al. 2006, 2013)[26]. Under ideal conditions, osteotomy diameter can be as small as 3 mm, which has been correlated with shorter healing time, decreased postoperative pain and improved outcomes (Kim & Kratchman 2006, von Arx et al. 2007). Clinicians continue to encounter difficulty in posterior molar scenarios or in cases where anatomic structures approximate the root end, potentially leading to extraction of otherwise serviceable teeth. As in other specialties, 3D printed stents can mitigate risk through avoiding encroachment upon neurovascular structures and adjacent teeth, and through targeting of osteotomy perforation sites[27]. During the CAD phase, a 3D rendering of the surgical site is used to design a custom stent that reproduces the planned osteotomy access point. Once design is complete, the STL file is transferred to a 3D printer where a surgical guide reproducing the planned access pathway is fabricated. Surgical applications of 3D printing for EMS have been demonstrated when guides derived from CBCT produced more accurately localized osteotomies than a traditional free-hand technique in an in vitro model (Pinsky et al. 2007). A case report (Liu et al. 2014) described the use of a 3D printed guide for traditional root-end surgery. Strbac et al. (2016) (Fig. 7) designed a stent defining the upper and lower margins of the osteotomy, as well as the root resection site and angulation, resulting in increased clinical efficiency and precision, minimizing risk of sinus perforation. Patel et al. (2017) demonstrated the use of a 3D printed custom tissue retractor to enhance visualization and soft tissue handling during EMS on a maxillary incisor[28]. These articles suggest exciting possibilities for future creative applications of 3D printing within the modern EMS concept.

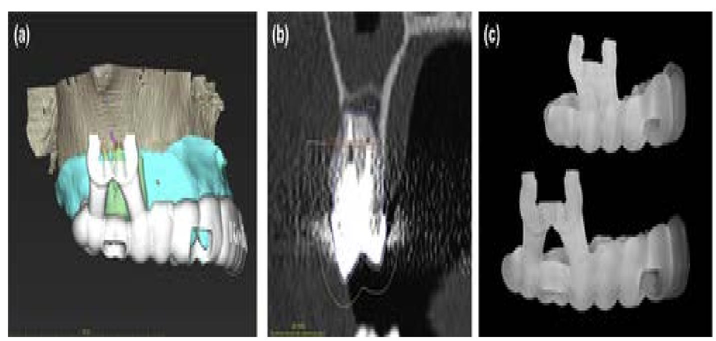

Figure 7: Strbac et al. Guided EMS: (a) Visualization of preoperative DICOM files with superimposed intraoral scan during pre-planning of osteotomy size for tooth #3 with the aid of virtually positioned surgical pins (1.5 mm in diameter); illustration showing surgical template of tooth #3 for guided surgical approach; vertical lines on 3D surgical template represent the root outline of each root for better visualization during resection of the roots with the piezoelectric instrument; object in pink colour presenting the segmented extruded gutta-percha material for detection and removal during surgical intervention. (b) Coronal slice of tooth #4, visualized in surgical planning software, presenting pre-planned 3-mm apical resection level and bevel angle within the limitations of the surgical template (c) 3D printed surgical templates of teeth #3 and #4 for guided surgical intervention.

Conclusions

The endodontic literature for 3D printing is limited to case reports and pre-clinical studies. Endodontic applications for stent-guided EMS, rapid prototyping of anomalous teeth, auto transplantation and educational modelling are documented within the literature. In the future, widespread use of 3D printing technology in endodontics will be possible as further research and development occur. Implementing 3D printing in endodontics opens the door to promising techniques with highly predictable outcomes and a low risk of iatrogenic damage. Results become less technique sensitive, and more teeth could be saved. Endodontic treatment time is reduced, and procedures become less invasive, resulting in greater patient comfort and satisfaction. Larger clinical studies with more participants, longer follow-up time, and standardized methodology are required to establish the validity of the proposed techniques in this review. Further research examining the accuracy of 3D surgical guides printed by affordable, benchtop 3D printers applied to endodontic procedures is also warranted. Increased expertise within the specialty will pave the way for a more robust body of evidence allowing endodontists to make informed decisions regarding employment in clinical practice.

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