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Endodontic applications of 3D printing

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ABSTRACT

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies can leverage cone beam computed tomography (CBCT) data for production of objects used in surgical and nonsurgical endodontics and in educational settings. The aim of this article is to review all current applications of 3D printing in endodontics and to speculate upon future directions for research and clinical use within the specialty. A literature search of PubMed, Ovid and Scopus was conducted using the following terms: stereolithography, 3D printing, computer aided rapid prototyping, surgical guide, guided endodontic surgery, guided endodontic access, additive manufacturing, rapid prototyping, autotransplantation rapid prototyping, computer aided design (CAD), computer aided manufacturing (CAM). Inclusion criteria were articles in the English language documenting endodontic applications of 3D printing. Fifty-one articles met inclusion criteria and were utilized. The endodontic literature on 3D printing is generally limited to case reports and pre-clinical studies. Documented solutions to endodontic challenges include: guided access with pulp canal obliteration, applications in autotransplantation, pre-surgical planning and educational modeling and accurate location of osteotomy perforation sites. Acquisition of technical expertise and equipment within endodontic practices present formidable obstacles to widespread deployment within the endodontic specialty. As knowledge advances, endodontic postgraduate programmes should consider implementing 3D printing into their curriculums. Future research directions should include clinical outcomes assessments of treatments employing 3D printed objects.

INTRODUCTION

Computer-aided design and manufacturing (CAD/CAM) applications emerged in the 1960s and 1970s, first employed by large aerospace and automotive companies (Cohn 2010). Cost-savings initiatives in the automotive industry increased growth and development of additive manufacturing

(AM) using incremental deposition of material, which is an innovation over subtractive manufacturing (SM) where an object is cut from a block of material (van Noort 2012, Abduo *et al*. 2014). The term AM is used by the International Standards Organization and the American Society for Testing and Material (https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en). However, in medical and dental applications, the term 3D printing is commonly used. AM allows for greater intricacy, reduced waste, and a wider selection of materials over SM (van Noort 2012, Abduo *et al*. 2014, Torabi *et al*. 2015, Kim *et al*. 2016).

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). 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.

Dental applications of 3D printing adopt one or more of the following common technical type classifications: stereolithography apparatus (SLA), fused deposition modeling (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). SLA systems direct the exposure path of a UV laser onto the surface of a vat of photosensitive resin. During a sequential curing process layers bind together to form a solid mass, beginning from the bottom of the object and building upward (van Noort 2012, Kim *et al*. 2016). 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 steriolithography CAD/CAM file format (van Noort 2012, Torabi *et al*. 2015). In addition to being utilized to describe SLA systems, the term stereolithography has been used to describe 3D printing in general.

With FDM printing, layers of molten material are deposited from a filamentous nozzle and then solidify within 0.1 second (van Noort 2012, Torabi *et al*. 2015, Kim *et al*. 2016). FDM is generally less accurate and less expensive than other 3D printing methods (Kim *et al*. 2016). MJP and PolyJet printing are characterized by the jetting of photopolymer material in ultra-thin layers, curing each layer after deposition onto a build tray (van Noort 2012); they differ only in their support structures and post-processing requirements (Kim *et al*. 2016). In CJP, a print head selectively disperses binder onto layers of powder and like PolyJet printing, the build platform lowers with each subsequent layer (Kim *et al*. 2016). There is extensive documentation of dental applications of CJP, PolyJet and MJP.

DLP printers have a projector that exposes a vat of photosensitive resin to a two-dimensional image; printing occurs sequentially in layers as the supporting platform is manipulated to incrementally produce the object. The resin is cured from the bottom and as a platform moves up, more resin is exposed (van Noort 2012, Kim *et al*. 2016). SLS and SLM printers use a computer-directed laser and roller to distribute layers of powdered material on top of a preceding layer; a solid object takes shape as each new layer is sintered (SLS) or melted (SLM) (van Noort 2012, Torabi *et al*. 2015, Atta 2016, Kim *et al*. 2016, Buican *et al*. 2018). SLS printing is used to fabricate metal objects through direct metal laser sintering (DMLS) (Kim *et al*. 2016).

CEREC products are an example of a closed system in which acquisition, design, and manufacturing phases require proprietary Sirona technology (Dentsply Sirona, York, PA, USA) (van Noort 2012). A key innovation in the rise of 3D printing in dentistry occurred with the advent of "open sourcing systems" that allow for a variety of acquisition sources to be used with several design and manufacturing technologies on a personal computer (van Noort 2012, Alghazzawi 2016, Cohn 2017). The capability to use Digital Imaging and Communication in Medicine (DICOM) files with a variety of CAD/CAM systems is a major advantage of open sourcing. In these open systems, data is converted to a STL file prior to CAD and CAM. STL files can be used in local fabrication or for printing at distant laboratories. (Alghazzawi 2016).

Throughout the 1990s oral and maxillofacial surgery increasingly used Computed Tomography (CT) files to 3D print surgical planning models for identification of anatomic structures, decreasing surgical risk and shortening treatment time (Mankovich *et al*. 1990, Bill *et al*. 1995, Erickson *et al*. 1999). The US Food and Drug Administration (FDA) approved the first CBCT for dental use in the United States in 2000 (Danforth 2003). In contrast to the medical CT voxel, where axial height is determined by slice thickness, the CBCT voxel is cubic, allowing for higher resolution and more accurate measurements in multiple planes (Scarfe *et al*. 2006, Cotton *et al*. 2007). CBCT is a more accurate source of data for 3D printing applications and has the added benefits of reducing radiation exposure, scan time and cost (Scarfe *et al*. 2006, Cotton *et al*. 2007). As a result, today CBCT is widely used throughout the dental specialties (Arnheiter *et al*. 2006, Setzer *et al*. 2017).

Since the introduction of CBCT, documentation of 3D printing applications in Periodontics, Prosthodontics, Orthodontics and Oral Surgery have steadily accumulated (Nikzad & Azari 2008, D'haese *et al*. 2012, Kumar & Ghafoor 2016, Alharbi *et al*. 2017). CAD/CAM fabrication of surgical implant guides has been used extensively for targeting implant osteotomy drills (Ersoy *et al*. 2008, Schneider *et al*. 2009, D'haese *et al*. 2012). Oral surgery applications generate printed anatomic reproductions for surgical planning and treatment during post-traumatic reconstruction, removal of pathological tissue, autotransplantation, and obturator prosthesis fabrication (Nayar *et al*. 2015, Bartellas *et al*. 2017, Verweij *et al*. 2017a). Orthodontic applications of 3D printing include diagnostic models, trays for indirect bonding, and tooth movement appliances (Nayar *et al*. 2015, Kumar & Ghafoor 2016, https://smiledirectclub.com/, https://www.digitalortho.com.au/). Recent applications of 3D printing in the endodontic literature point to a possible paradigm shift in the way challenging surgical and non-surgical endodontic treatments are accomplished. The aim of this article is to review all current English language literature documenting applications of 3D printing in endodontics, and to speculate upon future directions for research and clinical use within the specialty.

REVIEW OF ENDODONTIC APPLICATIONS

A literature search of PubMed, Ovid and Scopus was conducted using the following terms: stereolithography, 3D printing, rapid prototyping, autotransplantation rapid prototyping, surgical guide, guided endodontic surgery, guided endodontic access, additive manufacturing, computer aided design (CAD), computer aided manufacturing (CAM). Results were filtered using the terms: endodontics or endodontic. Inclusion criteria were: 1) article addressed an application of 3D printing in endodontics, 2) article was published in English. Articles describing use of 3D printing in other dental specialties were excluded, with the exception of relevant autotransplantation articles from oral surgery and orthodontic sources. Fifty-one articles met the inclusion criteria. One systematic review (Verweij *et al.* 2017b) and two prospective studies (Lee *et al.* 2001, Lee & Kim 2012) regarding applications in autotransplantation exist. Otherwise, articles are limited to case reports and pre-clinical studies of the following applications: surgical guides, guided endodontic access, autotransplantation, educational models and clinical simulation (Table 1).

Guided Endodontic Access

Pulp canal obliteration produces a clinical scenario in which canals must be located in more apical portions of progressively narrowing roots as a result of age-based apposition of dentin, caries, orthodontics, systemic disease or trauma (Delivanis & Sauer 1982, Şener *et al*. 2009, McCabe & Dummer 2012). Intervention for pulp canal obliteration is indicated when pulpitis or apical periodontitis is detected during clinical or radiographic examination (Holcomb & Gregory 1967, Lundberg & Cvek 1980, Cvek *et al*. 1982, Schindler & Gullickson 1988). Pulp canal obliteration is implicated in up to 75% of perforations during attempted location and negotiation of calcified canals (Kvinnsland *et al*. 1989). Risk of perforation is mitigated by measures that produce a true path of canal access and instrumentation.

In an article and case series, van der Meer *et al*. (2016) 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 (Figure 1). 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 J *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. 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 degrees. These investigations suggest that 3D printed access guides represent an efficient and safe means of addressing challenging endodontic scenarios, enabling both chemomechanical 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.

Autotransplantation

Successful autotransplantation requires preservation of periodontal ligament (PDL) cells and adequate adaptation of the transplanted tooth to the recipient site (Tsukiboshi 2002, Verweij *et al*. 2017b). Extra-oral time and trauma to the PDL during the procedure profoundly influence outcomes (Tsukiboshi 2002, Verweij *et al*. 2017b). Conventional methods use the transplant tooth as a template for preparation of the recipient site, often requiring multiple "fitting" attempts with adjustments to the alveolar bone that increase extra-oral time and risk damage to the PDL (Kim *et al*. 2005, Tsukiboshi 2002, Strbac *et al*. 2016, Verweij *et al*. 2017b). Tsukiboshi (2002) described the unpredictability of autotransplantation in his classic 2002 paper: "Words associated with transplantation of teeth are 'pessimism and tragedy' for some dentists but 'hope and pleasure' for others." Measures that improve outcomes of autotransplantation may increase the utility and acceptance of this tooth-saving 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). 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 (Keightley *et al*. 2010, Honda *et* *al*. 2010, Pang *et al*. 2010, Shahbazian *et al*. 2010, 2012, Park *et al*. 2012, 2013, Cross *et al*. 2013, Jang *et al.* 2013, Lee *et al.* 2014, Park *et al.* 2014, Vandekar *et al.* 2015, van der Meer *et al*. 2016b, Khalil *et al*. 2016, Anssari Moin *et al*. 2016; 2017, Cousley *et al*. 2017, Kim *et al*. 2017, Verweij *et al.* 2017a). In a case report, Strbac *et al*. (2016) described the autotransplantation of immature premolars in a maxillary incisor avulsion scenario using a completely digital workflow. 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. 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 1mm 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 one minute. In a multi-disciplinary case, successful autotransplantation of tooth 21 to the site of tooth 9 was made possible by CARP (Figure 2). Future studies may further clarify the outcomes impact of CARP prior to autotransplantation.

Educational models and clinical simulation

Dental education has historically relied upon extracted teeth, human cadavers, resin blocks, or commercially available resin teeth for preclinical exercises (Spenst & Kahn 1979, Nassri *et al*. 2008). Extracted teeth provide semi-realistic clinical simulation, but teeth with desirable properties are not always available and disinfection, storage and preservation can compromise properties. For regenerative endodontic simulations, teeth with open apices must often be created by root end manipulation. Human cadavers have been used for both root canal therapy and EMS simulation exercises, but availability, cost and storage present obstacles to their use. Commercially available resin teeth provide a predictable and simple alternative to the natural dentition but can be expensive.

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 dentin, to print ceramic models for endodontic lab exercises. Custom designed regenerative endodontic educational models have enhanced preclinical residency exercises (Figure 3).

The ability of 3D printing to create a large number of identical prototypes has recently been employed in pre-clinical research. Factors such as the shaping ability (Ordinola-Zapata *et al*. 2014) and stress values (Eken *et al*. 2016) of different rotary file systems, centering ability of access preparations (Yahata *et al*. 2017) and different obturation techniques for C-shaped canals (Gok *et al*. 2017) have been investigated with uniformly controlled canal configurations. Mohmmed *et al*. (2017a) demonstrated growth of *E. faecalis* biofilms on SLA materials comparable to dentin and subsequently applied this novel *in vitro* model to evaluate irrigation techniques (Mohmmed *et al*. 2017b, 2017c). Developments in CAD/CAM materials continue to make more realistic alternatives to extracted teeth possible.

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). 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. 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) (Figure 4) 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. These articles suggest exciting possibilities for future creative applications of 3D printing within the modern EMS concept.

DISCUSSION

All fifty-one articles documenting applications of 3D printing in endodontics were included. Applications for autotransplantation were sufficient to yield a systematic review (Verweij *et al.* 2017). As further evidence accumulates, systematic reviews of patient centered outcomes in other applications may be possible. Like other emerging technologies within the specialty, 3D printing will evolve over several years, with increased impact on endodontic practice and education. Several obstacles to wide-spread deployment of 3D printing in endodontics exist including prohibitive cost, diverse product availability with little clinical testing, and a substantial learning curve with lack of expertise within the specialty.

Out of thiry-one articles in which the technical type classification of the printer was disclosed, over half (17/31, 55%) used either MJP, PolyJet or CJP. These are patented technologies with preferable properties such as the ability to accurately print in thin layers and minimal surface finishing requirements. In 2014 the majority of professional 3D printers sold for medical use were patented PolyJet models costing in excess of $160,000 (Stansbury & Idacavage 2016). Economic realities restrict use of these technologies to large institutions or commercial dental laboratories. Due to expiration of patents for early additive manufacturing technologies such as FDM and SLA, with subsequent emergence of startup companies, dramatic growth in the accessibility of 3D printers for industrial and public use has occurred (Stansbury & Idacavage 2016, Schoffer 2016). Overall 3D printer sales rose 32% in 2016; however, the number of high-end printers shipped that year decreased by 10% (Schoffer 2016). Personal and desktop printer sales increased by 34% in 2016, largely due to over 300 companies selling devices for less than $5000, with some models costing as little as $100 (Allen *et al*. 2016, Schoffer 2016, Stansbury & Idacavage 2016). Khalil *et al*. (2016) demonstrated high volumetric accuracy of teeth printed from low cost SLA and FDM printers when using a PolyJet device as the gold standard. Beyond this, the search strategy failed to identify literature investigating the accuracy of less expensive devices for endodontic applications. Future studies may provide evidence for affordable printing within individual practices where clinicians could utilize CBCT, digital scanners, CAD software and a bench-top printer to create surgical stents, tooth prototypes or other clinical adjuncts.

Accuracy of 3D printers is defined by 2 specifications: XY resolution and layer thickness (Bryant 2017, https://pinshape.com/blog/4-things-you-need-to-know-about-3d-printing-resolution/). XY resolution is the most common specification used in describing the quality or detail of a print and is analogous to pixel size; it is the smallest movement that a printer laser can make within a horizontal layer. However, XY resolution fails to account for a number of variables that impact part quality. In fact, professional 3D printers have over 100 different settings that impact XY resolution (Bryant 2017). Layer thickness or Z height typically describes the surface finish of a part, the implication being that lower layer heights improve surface finish. Layer thickness is impacted by the type of resin and the printer's settings (Favero *et al*. 2017, Bryant 2017, https://pinshape.com/blog/4-things-you-need-to-know-about-3d-printing-resolution/). More layers may introduce increased error (Favero *et al*. 2017). Considering that product size, orientation and geometry also impact variables such as part quality and printing speed, it is virtually impossible to perform a side-by-side comparison of devices using their advertised specifications (Olszewski *et al*. 2014, Bryant 2017). In a review of the literature, D'haese *et al*. (2012) found substantial deviations between the planned and actual position of implants placed using printed guides, with a wide range of 0.95 to 4.5mm. The orthodontic literature describes the accuracy of 3D printed objects by scanning and comparing model or appliance products with a source scan for dimensional conformity (Lee *et al*. 2015, Favero *et al*. 2017, Camardella *et al*. 2017, Bryant 2017). There is no gold standard for evaluating 3D printers (Cristache & Gurbanescu 2017). Extrapolating the results of existing orthodontic and implant accuracy studies for endodontic applications is not advisable because clinical tolerances and objectives differ (Favero *et al*. 2017); endodontic clinical applications should be evaluated.

In addition to the accuracy of the 3D printer, the quality of the CBCT image and the capabilities of the designer and CAD software conspire to determine the accuracy of the printed object (Block & Chandler 2009, Kim *et al*. 2016). The average CBCT slice thickness used in endodontic applications can be as small as 0.076 to 0.6 mm, much thinner than the recommended maximum limit of 1mm for 3D printing (Kim *et al*. 2016). Stents often require larger scans in order to fabricate stable full-arch surgical guides or to facilitate accurate digital merger of a CBCT and digital impression within CAD software. A small field of view (FOV) may not capture enough crown morphology to recreate the patient's occlusion during guide fabrication, especially if metallic restorations are present. The advantages gained by the use of the surgical guide must be weighed against the radiation exposure to the patient. Many endodontic applications of 3D printing to date were adapted from implant planning software. A wide array of CAD software options with varying degrees of cost and accessibility are available. In trouble-shooting the entire process of fabricating implant stents, Block & Chandler (2009) identified key areas where inaccuracies can be introduced. Among these, lack of technical expertise in file creation and merge, limited expertise with CAD software, and inadequate knowledge of printing device operation represent considerable obstacles to wide-spread deployment of bench-top 3D printing in endodontic practices. Alternatively, data can be provided to commercial laboratories where initial design occurs followed by pre-print digital approval by the clinician.

After nearly two decades of 3D printing in dentistry, the first certified biocompatible resin, NextDent SG (3D Systems, Soesterberg, Netherlands) was introduced in 2016. 3D printed bioscaffolds containing Mineral Trioxide Aggregate (Chiu *et al*. 2017) and Biodentine (Ho *et al*. 2017) enhanced the differentiation of human dental pulp cells in favor of osteogenesis in *in vitro* models. Additional studies evaluating new materials may expand the utility of 3D printing to regenerative endodontics, guided tissue regeneration, and wound healing. Future investigations of printer accuracy, software utility, printing materials, stent design features, novel clinical applications, preoperative time expenditure, clinical time savings, enhanced safety, clinical outcomes assessment and tooth prototyping and educational modeling will likely emerge in the literature in coming years.

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, autotransplantation and educational modeling 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. Research clarifying the possible utility of more affordable bench-top printers for use in individual clinics is warranted. Acquisition of technical expertise within endodontic practices is a formidable obstacle to widespread deployment. As knowledge advances, endodontic postgraduate programmes should consider implementing 3D printing as part of their curriculum. 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.

Conflict of Interest statement

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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Figure Legend

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, while 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.

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Figure 2 CARP Autotransplantation: 19 years after trauma and RCT tooth #9 was deemed non-restorable 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 non-restorable #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.

Figure 3 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 hemorrhage.

Figure 4 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 color 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.

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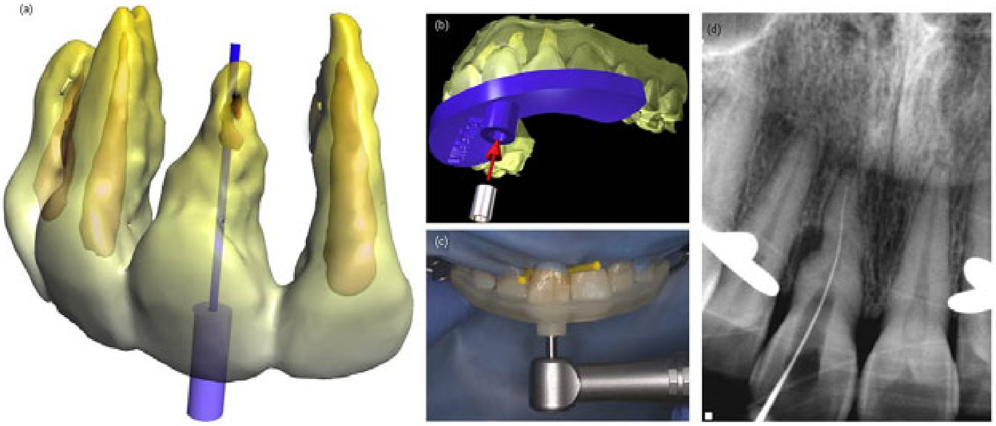
Table 1 Endodontic applications of 3D printing. CJP, ColorJet Printing; MJP, MultiJet Printing; SLA, stereolithography apparatus; FDM, fused deposition modeling; DLP, digital light processing; SLS, selective laser sintering; DMLS, direct metal laser sintering.

Authors	Type of Study	Endodontic Application	Printer	Technical Type Classification
Lee *et al.* 2001	prospective	autotransplantation	undisclosed	undisclosed
Kim *et al.* 2003	case report	diagnosis	undisclosed	undisclosed
Lee *et al.* 2006	case report	diagnosis	undisclosed	undisclosed
Pinsky *et al.* 2007	pre-clinical	guided EMS	undisclosed	undisclosed
Keightley *et al.* 2010	case report	autotransplantation	ZPrinter 310 Plus (Z Corporation, Burlington, MA, USA)	CJP[a]
Honda *et al.* 2010	case report	autotransplantation	SCR8000 HD (Denken Ltd. Co., Kyoto, Japan)	undisclosed
Pang *et al.* 2010	case report	autotransplantation	undisclosed	undisclosed
Shahbazian *et al.* 2010	pre-clinical	autotransplantation	undisclosed	SLA
Park *et al.* 2012	case report	autotransplantation	undisclosed	undisclosed
Lee & Kim 2012	prospective	autotransplantation	undisclosed	undisclosed
Shahbazian *et al.* 2012	case report	autotransplantation	SLA 3500 (3D Systems, Valencia, CA, USA)	SLA
Park *et al.* 2013	case report	autotransplantation	undisclosed	undisclosed
Kfir *et al.* 2013	case report	diagnosis	Objet Eden 260 V (Objet Inc. Billerica, MA, USA)	PolyJet[b]
Jang *et al.* 2013	case series	autotransplantation	undisclosed	undisclosed
Liu *et al.* 2014	case report	guided apicoectomy	Connex 500 (Objet, Israel)	PolyJet
Ordinola-Zapata *et al.* 2014	pre-clinical	research simulation	Pro-Jet HD 3500 (3D system, Rock Hill, SC, USA)	MJP[a]
Lee *et al.* 2014	case report	autotransplantation	undisclosed	undisclosed
Bahcall 2014	technique	pre-treatment simulation	undisclosed	undisclosed
Park *et al.* 2014	case report	autotransplantation	Connex 350 (Stratasys Ltd, Minneapolis, MN)	PolyJet
Kato & Kamio 2015	case report	pre-treatment simulation	Value3D MagiX MF-2000 (MUTOH Industries LTD., Tokyo, Japan)	FDM
Byun *et al.* 2015	case report	pre-treatment simulation	Objet500 Connex (Stratasys Ltd, Eden Prairie, MN, USA)	PolyJet
Vandekar *et al.* 2015	case report	autotransplantation	EnvisionTEC Prefactory (EnvisionTEC, Gladbeck, Germany)	DLP
van der Meer *et al.* 2016a	case series	guided endodontic access	commercial laboratory	undisclosed
Krastl *et al.* 2016	case report	guided endodontic access	Objet Eden 260 V (Stratasys Ltd.Minneapolis, MN, USA)	PolyJet
			Objet Eden 250 (Stratasys, Eden Prairie, MN)	SLA
Khalil *et al.* 2016	*in vitro*	autotransplantation	Objet Connex 350 (Stratasys)	PolyJet
			UP Plus 2 (Dynamism, Beijing, China)	FDM
van der Meer *et al.* 2016b	case report	autotransplantation	commercial laboratory	undisclosed

Anssari Moin *et al.* 2016	*ex vivo*	autotransplantation	commercial laboratory LayerWise (3D Systems, Leuven, Belgium)	undisclosed SLS
Marending *et al.* 2016	pre-clinical	research simulation	commercial laboratory	undisclosed
Buchgreitz *et al.* 2016	*ex vivo*	guided endodontic access	commercial laboratory	undisclosed
Eken *et al.* 2016	pre-clinical	research simulation	Eden 500 (Stratasys, Rheinmünster, Germany)	PolyJet
Zehnder *et al.* 2016	*ex vivo*	guided endodontic access	Objet Eden 260 V (Stratasys Ltd., Minneapolis, MN, USA)	PolyJet
Strbac *et al.* 2016	case report	autotransplantation	Objet360 Connex3 (Stratasys, Minneapolis, MN, USA)	PolyJet
Cousley *et al.* 2017	case report	autotransplantation	Pro-Jet 660 Pro (3D Systems Inc. Rock Hill, SC, USA)	CJP
Mohmmed *et al.* 2017a	*in vitro*	research simulation	undisclosed	undisclosed
Mena-Álvarez *et al.* 2017	case report	guided endodontic access	Pro-Jet 6000 (3D Systems, Rock Hill, SC, USA)	SLA
Strbac *et al.* 2017	case report	guided EMS	Objet360 Connex3 (Stratasys, Minneapolis, MN, USA)	PolyJet
Robberecht *et al.* 2017	pre-clinical	research simulation	CryoCeram (CryoBeryl, Valenciennes, France)	SLA
Anssari Moin *et al.* 2017	*ex vivo*	autotransplantation	commercial laboratory LayerWise (3D Systems, Leuven, Belgium)	undisclosed SLS
Connert *et al.* 2017	*ex vivo*	guided endodontic access	Objet Eden 260 V (Stratasys Ltd., Minneapolis, MN, USA)	PolyJet
Kim *et al.* 2017	case report	autotransplantation	undisclosed	undisclosed
Chiu *et al.* 2017	*in vitro*	regenerative bioscaffold	BioScaffolder 3.1(GeSiM, Grosserkmannsdorf, Germany)	FDM
Shi *et al.* 2017	case report	guided endodontic access	Pro-Jet 3510 SD (3D Systems, Rock Hill, SC, USA)	MJP
Ho *et al.* 2017	*in vitro*	regenerative bioscaffold	BioScaffolder 3.1; GeSiM, Grosserkmannsdorf, Germany	FDM
Patel *et al.* 2017	case report	EMS soft tissue retraction	commercial laboratory	undisclosed
Gok *et al.* 2017	pre-clinical	research simulation	EnvisionTEC Ultra 3SP; Prefactory (EnvisionTEC, Gladbeck, Germany)	DLP
Verweij *et al.* 2017a	case report	autotransplantation	EOSINT M 280 DMLS machine (EOS GmbH, Krailling, Germany)	DMLS
Yahata *et al.* 2017	pre-clinical	research simulation	Pro-Jet 3500 HD Plus (3D Systems, Rock Hill, SC, USA)	MJP
Mohmmed *et al.* 2017b	*in vitro*	research simulation	Form2 (Formlabs Inc., Somerville, MA, USA)	SLA
Mohmmed *et al.* 2017c	*in vitro*	research simulation	Form2 (Formlabs Inc., Somerville, MA, USA)	SLA
Verweij *et al.* 2017b	systematic review	autotransplantation	undisclosed	undisclosed
Connert *et al.* 2018	case report	guided endodontic access	Objet Eden 260 V (Stratasys Ltd., Minneapolis, MN, USA)	PolyJet

[a]ColorJet (CJP) and MultiJet (MJP) technologies are exclusively licensed to 3D Systems, Rock Hill, SC.

[b]PolyJet is a registered trademark of Stratasys, Ltd. Minneapolis, MN.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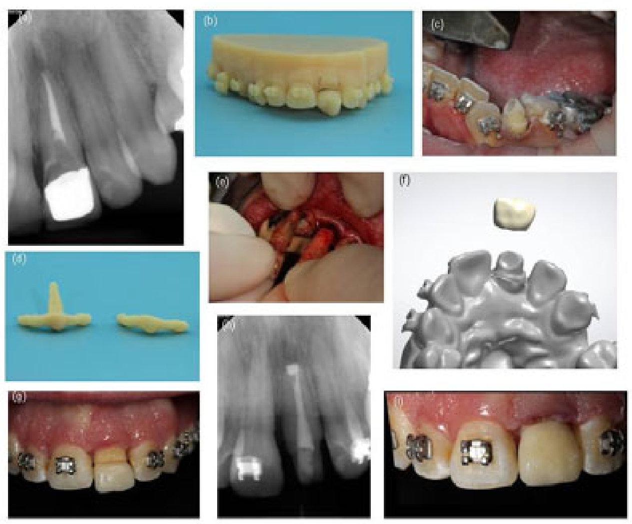
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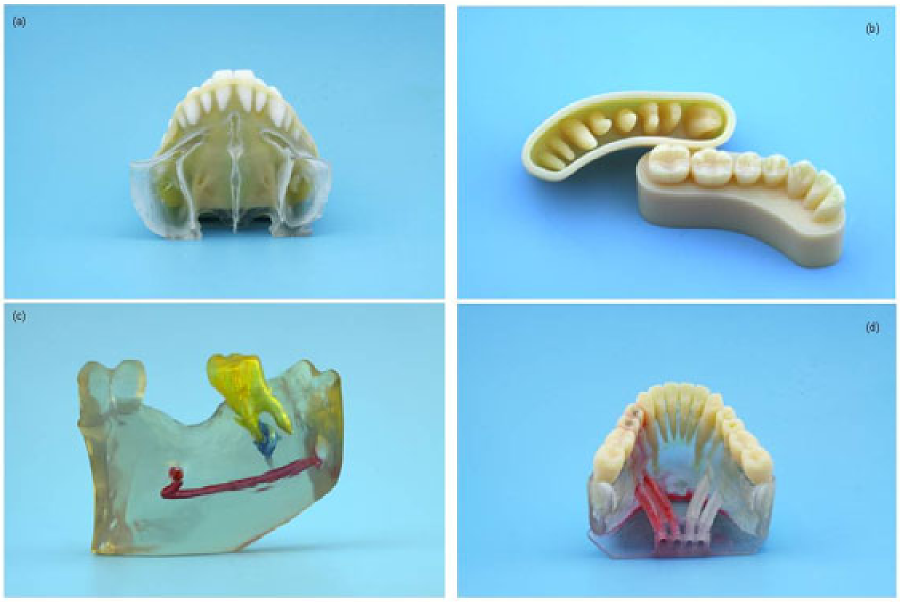
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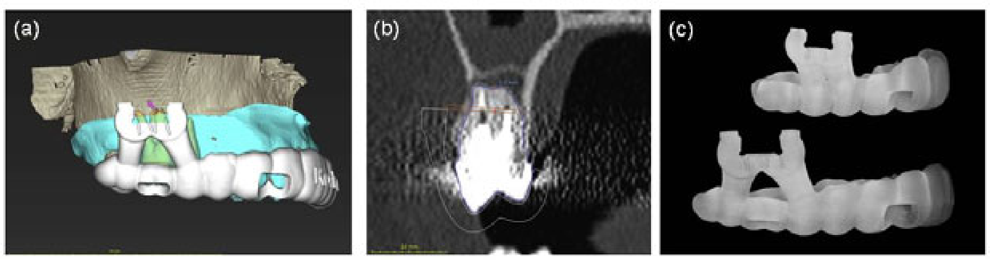
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