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Digital applications in endodontics: An update and review

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Abstract

The aim of this review was to provide an overview of the applications of digital dentistry technologies in endodontics, such as digital two-dimensional (2-D) and three-dimensional (3-D) imaging techniques, computer aided diagnosis (CAD) and improvement of artificial intelligence (AI) models, computer-controlled access cavity designs and 3-D printing applications. Advantages and disadvantages of these newly introduced technologies were discussed briefly with their indications. Apart from therapeutical or rehabilitative procedures, the use of digital technologies adapted for student training and research simulations were also presented.

Keywords: computer aided applications, computerized dentistry, cone-beam computed tomography, endodontology

1. Introduction

The discipline of endodontics focuses on the etiology, diagnosis, prevention and treatment of diseases of the human dental pulp and periradicular tissues in relation with their morphology, physiology and pathology (American Association of Endodontists, 2016). Endodontic treatments might aim to maintain the vitality of the pulp, to preserve and restore the pulpless tooth by the proper shaping, cleaning and filling of root canals or to replace damaged tooth structures by biologically-based procedures (American Association of Endodontists, 2016a; 2016b). Endodontics has benefited from the developments in digital dentistry due to the requirement of a proper visualization technique to reveal root canal anatomy and periradicular structures by means of digital 2-dimensional (2-D) radiography and cone-beam computed tomography (CBCT). Recently, the developments in the digital applications also enabled the developments of clinical techniques that include artificial intelligence aided diagnosis and guided access cavity preparations to directly access to root canals even in obliterated roots. The applications of digital technology in endodontics from diagnosis to clinical applications along with their advantages and disadvantages are covered in this review article.

2. Digital radiography

The use of periapical radiographs has become an indispensable part of endodontic practice since Kells calculated working length of a root canal using a lead wire in 1899 (Jacobsohn and Fedran, 1995). Imaging techniques have been widely used in endodontics to evaluate dental and alveolar hard tissue morphology and pathological changes preoperatively, to determine working length of root canals and locate intracanal objects intraoperatively and to evaluate the root canal filling and periapical healings postoperatively.

Digital radiography systems have replaced the conventional systems with the latest developments with the upcoming advantages of image processing. In conventional systems, X-ray film is the place where the image is occurred and stored; whereas in digital systems, X-ray beam falling on the detector is converted into electrical energy and digitized. The resulting image is stored in a different digital medium and can be processed further. Most important feature of digital systems is the lower radiation dose compared to conventional radiography (Petrikowski, 2005). Digital radiographic systems can be classified as direct and indirect systems according to the transformation technique that converts X-ray beam to electrical signals (Wakoh and Kuroyanagi, 2001). In direct digital techniques, a photoconductor is used that can convert X-ray directly into electrical current, thereby enabling an instant image formation on the computer screen immediately after exposure (Parks and Williamson, 2002; Kurt and Nalçacı, 2016). Radio visiography (RVG) is the most known direct digital radiography system and composed of X-ray unit, electronic timer, intraoral sensor and processing unit (Mouyen et al., 1989).

Indirect digital systems are referred as photostimulable phosphor (PSP) plates and require an extra processing step compared to direct technique (Parks and Williamson, 2002). The latent image occurs within energetic phosphor electrons, which will be stimulated by red laser beam during processing in order to be digitally manipulated to be exposed on computer's display. In terms of handling, PSP is similar to

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conventional intraoral radiography, it is practical and user-friendly (Yorkston, 2007).

In digital radiography, image contrast and brightness can be changed on the screen regardless of the kilovoltage peak and milliampere-seconds used during exposure due to the wide dynamic range (Yaffe and Rowlands, 1997; Berkhout et al., 2004). This feature largely eliminated radiographic repetitions due to insufficient exposure parameters. Digital techniques require less radiation dose than conventional techniques however, wide dynamic range also brings the risk of unnecessary radiation, which violates “As low as reasonably achievable” (ALARA) principle (International Commission on Radiological Protection, 1973; Berkhout et al., 2004). There are recommended measures to be taken to eliminate the risk of overexposure (Seibert and Morin, 2011). The optimal exposure factors determined according to the patient size should be recorded on the device for operator to select appropriate parameters. The exposure index should be displayed on the radiography device screen and the values shown should be checked. The use of devices with high detective quantum efficiency value indicating the X-ray sensitivity of the detector and the use of noise reduction algorithms in preprocessing enables to obtain low noise radiographs at standard doses (Schuncke and Neitzel, 2005; Seibert and Morin, 2011).

The most important disadvantage of periapical radiographs, whether obtained in conventional or digital techniques, is that it provides a compressed 2-D image of a 3-dimensional (3-D) object. Diagnostic ability of periapical radiographs is limited to show spatial relationship between roots and their periapical structures, actual dimension and location of a periapical lesions and root resorptions (Gröndahl and Huumonen, 2004). Multiple radiographs with varying angulations are suggested to obtain more data for assessment however, this does not guarantee the correct diagnosis of all relevant anatomy or pathology (Cotti and Campisi, 2004; Gümrü and Tarçın, 2013). Geometric distortion of the radiographic image is another important limitation, that damages the diagnostic ability of periapical radiographs (Gümrü and Tarçın, 2013).

3. Cone-beam computed tomography (CBCT)

The introduction of CBCT specifically for the imaging of dental and maxillofacial structures in 1998 caused a paradigm shift from 2-D to 3-D approach for wide range of applications from diagnostic to intraoperative guidance of surgical procedures (Mozzo et al., 1998). CBCT differs from conventional CTs by the rotation of the detector and X-ray source around a stabilized patient. CBCT has also advantages of lower radiation dose, less expensive equipment, less room space, less time for scanning compared to CT. X-ray beam is cone-shaped and captures a cylindrical data volume, identified as the field of view (FOV), which can be determined according to the region of interest. CBCT has been reported to provide images with higher quality for the assessment of dental structures than medical CT.

CBCT overcomes the disadvantages of 2-D radiography, such as elimination of superimposition of anatomical structures by assessing structures in slices with three orthogonal planes individually. Actual spatial relations and dimensions of periapical lesions can be visualized accurately, although spatial resolution is lower than conventional film based or digital periapical radiographs (Farman and Farman, 2005). Image quality is also affected by noise and artifacts such as scatter and beam hardening, which are partially prevented by artifact reducing algorithms during image reconstruction (Scarfe et al., 2009; Schulze et al., 2011).

CBCT has been reported to show higher sensitivity and specificity for the diagnosis of apical periodontitis than periapical radiographs (Patel and Horner, 2009; Davies et al., 2015). A novel classification as an update of periapical index has also been suggested using CBCT scans (Estrela et al., 2008). CBCT can also provide valuable information regarding the relationship of root tip or periapical pathology with adjacent anatomical structures when planning surgical intervention (Patel et al., 2019) (Fig. 1). It might be useful to improve the diagnosis and management of root resorptions (Patel et al., 2019). Moreover, diagnosis of dental anomalies of shape such as dens invaginatus or presence of extra roots can be improved by the use of CBCT (Patel, 2010; Keskin and Özdemir, 2018). *In vivo* CBCT studies have proposed a correlation between posttreatment apical periodontitis and undetected untreated root canals (Karabucak et al., 2016; Costa et al., 2019; Baruwa et al., 2020). CBCT was also used to assess root canal treatment quality in relation with periapical pathosis and prevalence of extra canals in larger populations in cross sectional studies (Wu et al., 2017; Martins et al., 2020; Meirinhos et al., 2020). Although CBCT is the only 3-D imaging technique suitable for clinical use, the accuracy of CBCT in revealing root canal anatomy in vitro studies falls behind micro-computed tomography (micro-CT). CBCT provided limited efficiency to distinguish different canal configurations according to the Vertucci classification (Vertucci, 2005; Ordinola-Zapata et al., 2017). CBCT detected main canals but failed to visualize fine anatomical structures connecting canals and changing their configurations and led to inaccurate diagnosis regarding canal configuration (Ordinola-Zapata et al. 2017; Tolentino et al., 2018; 2020). It has been reported that despite high resolution parameters CBCT has limited ability to visualize isthmuses in apical third, where isthmus diameter would be smaller than voxel size. Authors emphasized that CBCT image of the root canals might not reflect the actual complexity of apical anatomy (Tolentino et al., 2020).

The radiation dose might pose as a risk factor for CBCT in case of unnecessary referrals as a result of lack of proper education and awareness (Setzer et al., 2017; Krug et al., 2019). The American Association of Endodontists (AAE) and European Society of Endodontology published and updated position statements on the use of CBCT in endodontics (Fayad et al., 2015; Patel et al., 2019). The most important conclusion was that CBCT should not be used routinely and should only be considered when meticulous clinical and 2-D radiological examinations were inconclusive to clarify complex situations in accordance with ALARA principles. CBCT should not be regarded as an alternative to conventional radiographic examination techniques but rather as a complementary tool (Jung et al., 2012).

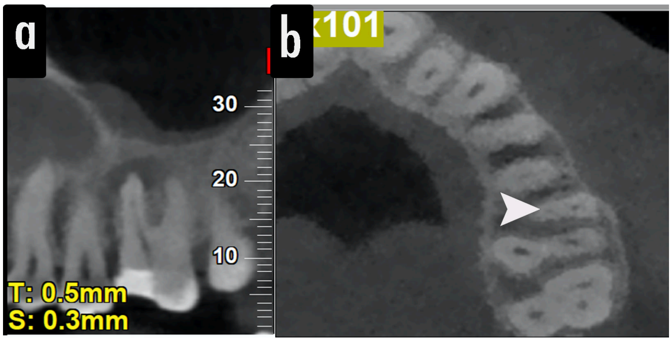

Fig. 1. Evaluation of different cross-sectional images obtained by CBCT allowed to evaluate the extent and location of periapical pathosis related to the mesiobuccal root of maxillary first molar (a), examination of axial cross section also revealed the presence of a second mesiobuccal root canal (depicted with white arrowhead) (b)

4. Computer aided diagnosis (CAD)

Despite advances in imaging technology, final diagnosis and treatment planning is based on the clinician's decision that may be prone to human error. The human error can cause the clinician to deviate from choosing the most optimal treatment option. CAD aims to perform a quantitative analysis and provide an objective report using computer algorithms.

CAD has been used widely in medical radiology and is relatively novel in dentistry. A caries detector program was developed in the late 90s that analyzed the radiography of the tooth and reported whether there was any caries, whether it was a simple decalcification or carious and whether it needed restoration or not (Gakenheimer, 2002). Neural network models for the diagnosis of interproximal carious lesions on periapical radiographs have been developed (Devito et al., 2008; Lee et al., 2018). CAD has also been developed to be used intraoperatively for real time detection of root canal orifices in combination with intraoral camera (Brüllmann et al., 2011). High sensitivity was reported for orifice detection software, which can assist students and practitioners without experience for detection of extra canal orifices (Brüllmann et al., 2011).

CAD has mainly focused on the development of artificial intelligence for the assessment of periapical lesions using digital periapical radiographs, panoramic radiographs and CBCT images (Katsumata and Fujita, 2014; Okada et al., 2015; Ekert et al., 2019; Orhan et al., 2020). These models provide objective data regarding the size of the periapical lesions and their classification, however in the lack of histological examination the true nature of the lesions is not decisive only based on their radiological appearance.

Overall, CAD should be considered as a tool that will assist the clinician for interpretation of clinical and radiological findings more objectively and combine them with the data obtained with the patient anamnesis and main complaint.

5. Guided endodontics

Root canal treatment of a calcified root canal, which means the total or partial blockage of root canal space due to mineralization or calcification, is considered as a high-difficulty case according to the AAE (Langeland et al., 1971; American Association of Endodontists, 2006). Localization of a canal orifice and negotiation through apical are particularly challenging and access attempts might result in unnecessary loss of dentin or even root perforation (Cvek et al., 1982; Kvinnsland et al., 1989). Guided endodontics concept is suggested to prevent these complications, shorten the treatment time, and increase the success rate of root canal treated calcified teeth by bringing together the technology of CBCT, 3-D printing and digital intraoral impression or scanners (Krastl et al., 2016; van der Meer et al., 2016; Zehnder et al., 2016). Today, applications of guided endodontics are also used in the treatments of anomalous teeth such as dens invaginatus and dens evaginatus, during apical surgery and preparation of ultraconservative access cavities (Pinsky et al., 2007; Zubizarreta et al., 2015; Mena-Alvarez et al., 2017; Ahn et al., 2018). A high resolution CBCT and a digital impression of the teeth are acquired and co-registered using a special image processing software (Moreno-Rabie et al., 2020). Obtained data is used to design a template that will provide guidance for accurate treatment of root canals with correct pathway. The designed template is manufactured with 3-D printer or milling. Manufactured template is placed on the teeth and further treatment burs and files are guided by the template (Zehnder et al., 2016; Moreno-Rabie et al., 2020). Clinicians can adapt burs specific for the case or use commercially available access burs with long shafts and small head such as Munce Discovery burs (CJM Engineering, Santa Barbara, CA, USA) (Connert et al., 2017; Connert et al., 2018; Torres et al., 2019). The use of ultrasonic tips is also reported (Shi et al., 2018). The term "Microguided endodontics" emerged with the adaptation of minimally invasive techniques to the methodology in the treatment of smaller roots (Connert et al., 2017; Connert et al., 2018).

Recently, a new method using computer-aided dynamic navigation has been suggested for guided endodontics (Chong et al., 2019). A mobile unit including an overhead light, stereoscopic motion-tracking camera and computer with implant planning software is used for real time guidance of handpiece calibrated on a previously determined reference point. This technique also requires high resolution CBCT images to display the suggested pathway and motion of the drills within canals. The motion tracking camera guides the handpiece while providing visual feedbacks with color codes (Chong et al., 2019).

The guided access cavity preparation has been reported to be accurate irrespective of the operator experience with a higher success rate in locating canals compared to conventional technique (Zehnder et al., 2016; Connert et al., 2017). Preclinical studies and case reports suggest guided endodontics provides predictable outcome with lower risk of iatrogenic complications (van der Meer et al., 2016; Connert et al., 2017; Connert et al., 2018; Torres et al., 2019; Moreno-Rabie et al., 2020). Further controlled studies with larger sample size are required for the assessment of its efficiency.

6. 3-D Printing

The use of 3-D printing technology in endodontics is not only limited with the applications of guided access cavity preparations. 3-D printing was initially termed as additive manufacturing, which means creating an object by incremental deposition of the selected material. 3-D printing applications employ different technologies including fused deposition modelling, digital light processing, stereolithography apparatus (SLA), MultiJet printing, PolyJet printing, ColorJet printing, and selective laser melting (Abduo et al., 2014; Anderson et al., 2018). Stereolithography apparatus has been the first and most commonly used technology in dentistry.

Prior to the use of CBCT, CT files were used to produce planning models in surgical procedures, however CBCT data have been widely used today (Mankovich et al., 1990; Bill et al., 1995). In addition to being a more accurate source for 3D printing applications, CBCT has also expanded its use with previously mentioned advantages such as reduced radiation dose, shorter scanning time and reduced cost (Scarfe et al., 2006; Cotton et al., 2007).

3-D printing has been applied for guided endodontic access, autotransplantation, endodontic surgery applications, education and research simulations (Keightley et al., 2010; Shahbazian et al., 2010; Ordinola-Zapata et al., 2014; Krastl et al., 2016; Zehnder et al., 2016; Gok et al., 2017). Guided endodontics applications are covered previously in this article. In autotransplantation applications, 3-D printing manufactures teeth replicas to be fitted in the recipient bone prior to extraction. This pre-fitting prevents the trauma of periodontal ligament of the transplanted teeth and shortens the procedure time, thereby improve the treatment outcome (Honda et al., 2010; Keightley et al., 2010; Shahbazian et al., 2010). A systematic review reported an increased success rate up to 91% due to rapid application of teeth to the recipient site with extraoral time less than 1 minute and without periodontal ligament trauma (Verweij et al., 2017).

Preparation of surgical templates allowed for precise orientation, angulation and depth during osteotomy increasing clinical efficiency with minimizing risk of sinus perforation (Pinsky et al., 2007; Strbac et al., 2017). The precision of the procedure is especially important for the survival of teeth with problematic roots with difficult accessibility for resection (Pinsky et al., 2007).

3-D printing may be useful for dental education to demonstrate and simulate teeth with certain features. The use of artificial teeth for simulation exercises has been found superior than the use of extracted teeth (Kfir et al., 2013; Bahcall, 2014; Kato and Kamio, 2015). Apart from standardization of exercise materials, they might help to simulate anomalous teeth or root canals with a predetermined configuration, which could be rarely found in natural teeth. The printing material could be a problem to simulate dental hard tissues, however new materials are developed with similar hardness to dentine (Robberecht et al., 2017). A recent study developed a cost-effective modular 3-D print model manufactured from SLA, for the study with real or artificial teeth mounted on phantom heads to improve preclinical exercises with a better simulation of clinical scenarios (Hanafi et al., 2020).

Simulation of tooth models with certain morphologies also provided in vitro studies to evaluate the efficacy of different endodontic procedures (Ordinola-Zapata et al., 2014; Eken et al., 2016; Gok et al., 2017; Mohmmed et al., 2017; Yahata et al., 2017). Specimens with C-shaped canals were manufactured based on a single tooth with required anatomy and efficacy of different root canal filling techniques were compared (Gok et al., 2017). Use of 3-D printed specimens also eliminated the problems related with collection of extracted teeth.

7. Restoration of endodontically treated teeth with computer aided design-computer aided manufacturing (CAD-CAM)

The success of root canal treatment depends on the quality of the coronal restoration, which should support the remaining tissues in functional and aesthetical means (Faria et al., 2011). Design and selection of coronal restoration is mainly determined by the amount of remaining dental structures and ranges from conservative inlays to coronaradicular restorations. Indirect restorations have become popular due to the innovations in chairside CAD-CAM units with intraoral digital scanners for the manufacture of permanent restorations in a single visit in the cases with extensive tooth tissue loss. Indirect inlay, onlay, and overlay restorations are termed according to the remaining cavity shape and manufactured from gold, composite and ceramic (Felden et al., 1998; Schulz et al., 2003). The manufacturing stages of the restoration include scanning the cavity, designing the restoration, and producing the restoration in a central milling center or in laboratory or by chairside CAM units. Chairside CAD-CAM technology enabled design of a specific monoblock restoration that contains whole crown and a protruding apical core termed as “endocrown” (Bindl and Mormann, 1999; Otto, 2004) (Fig. 2). Today, endocrowns are advocated for the restoration of endodontically treated teeth with extensive tissue loss instead of post and core restorations for the advantage of reduced chair time and less preparation of remaining tooth structure (Sedrez-Porto et al., 2016).

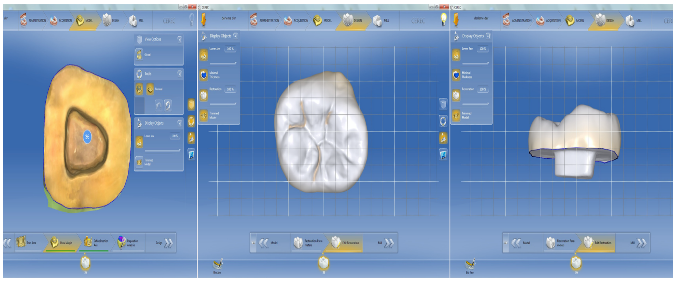

Fig. 2. Design and manufacturing of an endocrown restoration by a chairside CAD-CAM unit with an intraoral digital scanner can be completed in a single session.

8. Conclusion

The scope of digital applications in endodontics reaches far beyond digital radiographic techniques for improved 2-D and 3-D visualization. The improvements of the digital techniques and their introduction to endodontic procedures would certainly reduce treatment times as well as clinician's fatigue. The manufacturing of templates and models preoperatively would also decrease iatrogenic complications and improve treatment satisfaction irrespective of the clinician's experience. Combined use of digital techniques intraoperatively allows the survival of teeth that would otherwise be extracted or damaged due to increased complication rates.

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