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Hu Chen, Hong Li, Fei Lin, Yi-Jiao Zhao, Yu-Jiao Guo, Xin-yue Zhang, Yong Wang, Peijun Lyu,

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Hu Chen
Center of Digital Dentistry, Peking University School and Hospital of Stomatology and National Engineering Laboratory for Digital and Material Technology of Stomatology, Beijing, China
Hong Li
First Clinical Division, Peking University School and Hospital of Stomatology, Beijing, China
Fei Lin
Department of Cariology and Endodontology, Peking University School and Hospital of Stomatology, Beijing, China
Yi-Jiao Zhao
Center of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, China
Yu-Jiao Guo
Department of Stomatology, Beijing Children's Hospital, Capital Medical University, Beijing, China, and
Xin-yue Zhang, Yong Wang and Peijun Lyu
Center of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, China

Abstract
Purpose – This paper aims to use cone-beam computed tomography (CBCT) and computer-aided design/3D printing technology to design and fabricate a drill guide template for access cavity preparation of permanent molars, and conduct a preliminary evaluation of its effectiveness.
Design/methodology/approach – CBCT scans were performed on two permanent maxillary first molars extracted due to periodontitis. Based on the scans, guide templates of access cavities were designed. The angle of the guiding cylinders was determined based on the direction of the long axis of the tooth. A 3D resin printer with high resolution was used to print the guide templates. The printed guide templates were used by a dentist with specialized clinical experience to perform access cavity preparation in a dental simulator. Then the prepared access cavities were scanned again by CBCT, and scan data were compared to the design data.
Findings – The 3D printed drill guide template had a close fit with the extracted tooth fit. The access cavity prepared using the guide template enabled the removal of the pulp chamber roof, and formed a straight-line access. Points were selected for measurement at regularly spaced intervals of 0.5 mm along the side wall of the access cavity. The mean deviation between the actual access cavities of the two permanent maxillary first molars and the designed cavities was less than 0.1 mm, with a maximum deviation of about 0.5 mm, showing a good conformance between the actual cavity and the designed cavity.
Originality/value – A drill guide template was designed and fabricated by 3D printing technology, which easily guided burs to complete the access cavity preparation work forming an ideal cavity shape with satisfying accuracy, and thus may reduce the complications during pulp chamber entry.

Keywords Computer aided design, Cone-beam computed tomography, Drill template, Root canal therapy, Three-dimensional printing

Paper type Research paper

Introduction

In endodontic therapy, pulp chamber entry and crown preparation are the first steps of the complete treatment process. Good design of pulp chamber entry and proper preparation of the pulp chamber is of crucial significance for successful endodontic therapy (Johnson, 2009; Druttman, 2004). Pulp chamber entry, also known as endodontic access, refers to entry from the crown into the pulp chamber and requires direct access to the root canal orifice. Crown preparation refers to the initial preparation and shaping of the pulp chamber, to ensure that cleaning and shaping endodontic instruments are able to gain smooth entry into the root canal. Thus, an appropriate endodontic access cavity needs to facilitate the straight-line entry of instruments to the root canal, while also maximally preserving dental tissue, to ensure stability and resistance (Lang *et al.*, 2006). Improper endodontic access often increases the difficulty of subsequent steps in endodontic therapy (Carrotte, 2005) and leads to endodontic failure. As a result, appropriate endodontic access is one of the most essential steps of endodontic therapy

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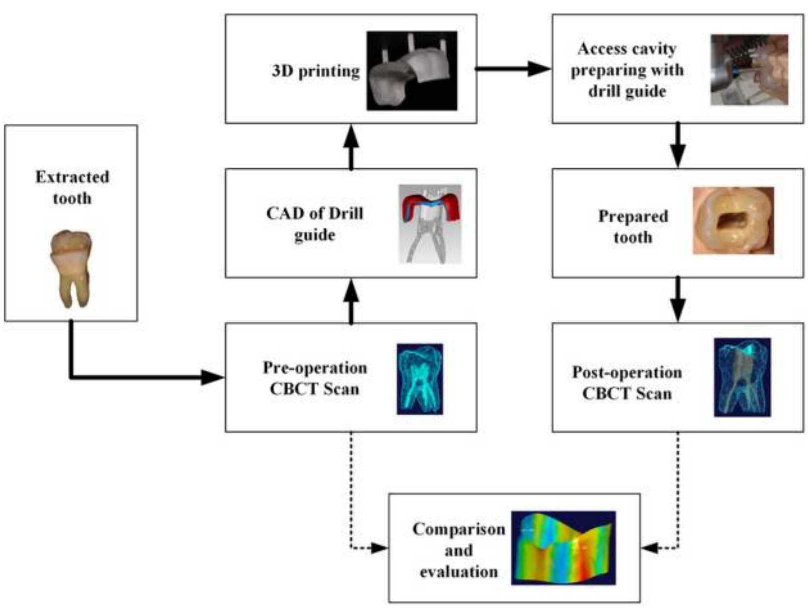
(Fouad *et al.*, 2008). Pre-operative periapical radiograph is helpful to determine the position, size, depth and shape of the pulp chamber, position of the pulp horns, number of roots and the degree of curvature (Patel and Rhodes, 2007). Endodontic performance is enhanced when clinicians thoughtfully view pre-operative radiographic images, visualize minimally invasive, yet complete, treatment and then use this mental picture to guide each procedural step (Ruddle, 2007). Dentists currently visualize and design access cavity shape and axis primarily based on 2D dental X-rays, combined with their own knowledge of dental anatomy (Vertucci, 2005; Deutsch and Musikant, 2006; Mickel *et al.*, 2007; Chogle *et al.*, 2007) and clinical experience. Tooth morphology and its relationship to endodontic procedures were well described and illustrated in a previous study (Vertucci, 2005). It was found that anatomic morphological measurements concerning the pulp chamber tended to be consistent in every tooth (Deutsch and Musikant, 2006), and the correlation of occlusal and pulp chamber anatomy was studied to provide landmarks for access cavity entry (Mickel *et al.*, 2007; Chogle *et al.*, 2007). Constant adjustments based on visual and tactile feedback during actual operations are needed to produce the required crown cavity shape. If the clinician is not familiar with dental anatomy or makes an incorrect judgment during an operation (if the roof and base of the pulp chamber or the axis of the tooth were incorrectly determined), it is easy for an improper access cavity to be created, which could be manifested as an incomplete or excessive access cavity, or even as more serious complications such as pulpal floor or lateral perforation (Motamedi, 2006). Individual differences in dental morphology (Cleghorn *et al.*, 2007) also increase the difficulty of endodontic therapy. Furthermore, anatomical variations (Lu *et al.*, 2006) and pulp chamber calcification often affect the ability of clinicians to locate root canal orifices, thus making it easy to miss the root canal or create an excessively large access cavity. Evidently, depending on experience alone to create an endodontic access cavity that matches the morphology of the pulp chamber and root canal is extremely difficult. This difficulty is particularly pronounced in endodontic therapy of the molars (de Pablo *et al.*, 2012), which are the most posterior teeth in the dentition, provide limited room for operation and are difficult to view directly. Furthermore, molars have many root canals with high degrees of curvature, necessitating care and caution during operations from even the most experienced dentists.

Although there have been many guidelines established to give instructions of the access cavity preparation in previous studies, no actual guide tool was developed. The thoughtfully considered pre-operative plan could only exist in mind and each step was guided by the "imagination". What's more, a great proportion of the root canal 3D morphology information, which is very important in complex cases, was missing in the 2D dental X-ray. With the rapid development of oral 3D digitization technology, it is hoped that these problems surrounding endodontic therapy can be solved using the application of 3D data acquisition technology on oral hard tissues and computer-aided design/3D printing (CAD/3DP) technology. Cone-beam computed tomography (CBCT) has many advantages including rapid scan speed, high spatial resolution, low radiation dose and fewer image artifacts. The oral 3D data acquired using CBCT has been widely applied in the diagnosis of oral diseases, planning of dental implants and fabrication of surgical guides (Ball *et al.*, 2013; Ikram *et al.*, 2009). This study used CBCT to accurately obtain 3D morphological data of the molar crown and pulp chamber. Then, based on the endodontic principles of crown preparation, CAD was used to design the access cavity, followed by 3DP of corresponding access cavity guides, to facilitate endodontic therapy. In addition, preliminary evaluation of the results of using these guides was carried out via *in vitro* experiments. The work flow of this article was illustrated in Figure 1.

Materials and methods

This study was approved by the bioethics committee of Peking University School and Hospital of Stomatology (PKUSSIRB-

Figure 1 Flowchart of the methodology in this research



201627043). The procedures and risks involved with participation in this study were discussed with the volunteers, and written informed consent was obtained from each included participant. The methods were carried out in accordance with the approved guidelines.

3D data acquisition

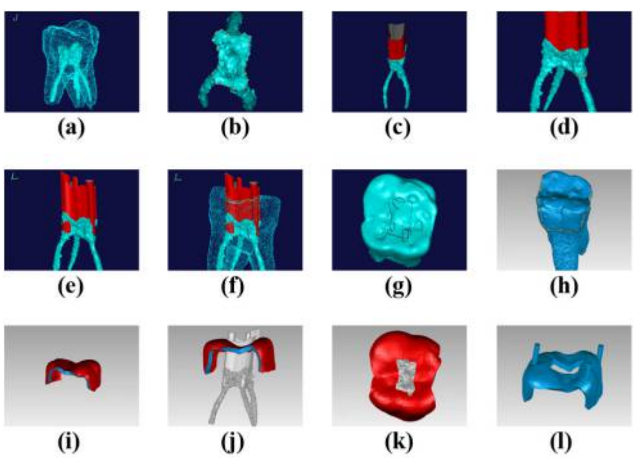
Intact maxillary first molars extracted due to advanced periodontitis were collected from the Department of Oral and Maxillofacial Surgery, Peking University School of Stomatology. After removing tartar from the dental surface, the teeth were disinfected by immersing in formalin for 24 h, followed by rinsing in normal saline. After drying, the tooth was scanned using CBCT (NewTom VGi, NewTom, Italy) to obtain 3D data at a reconstruction precision of 50 μm. Thresholding was performed using the medical imaging software, Mimics 17.0 (Materialise, Belgium). Segmented 3D data of the whole tooth and pulp chamber were obtained and exported as STL file format.

Design and fabrication of access cavity guides

The work flow of drill guide CAD was shown in Figure 2. Data were imported into the reverse engineering software, Geomagic Studio 2012 (Raindrop Geomagic, USA). The long axis of the tooth was confirmed. Then, the crown surface data was cropped, with the distal and mesial boundaries were defined by the distal and mesial edges of the coronal/occlusal surface and the buccolingual surface. The buccolingual boundary was defined as 1 mm below the height of contour line of the buccolingual crown surface. Data outside these four boundary lines were cropped. To account for errors in the 3D dental data obtained from CBCT scanning and 3D printing of the guides, and to ensure smooth placement of the guide on the dental surface, an overall outward offset of 0.1 mm was performed on the cropped crown surface along the normal to form the tissue surface of the base plate, and the base plate was hollowed outward along the normal by 1 mm to form base plate entity data. Using a different reverse engineering software (Imageware 13.0, EDS, USA), 3D data of the pulp chamber and root canal orifice were extracted. The access cavity boundary was formed by projecting along the long axis toward the occlusal surface. Then, the boundary was stretched beyond the thickness of the base plate along the long axis to form the curved surface of the cavity. Boolean operations were performed on the 3D data of the base plate to remove the curved surface of the cavity, thereby forming an endodontic guiding cavity in the center of the base plate. Immediately after the guide structure was designed, three cylinders with a diameter of 1 mm and parallel to the long axis of the tooth were created at the edge of the access cavity at the base plate surface; the three guiding cylinders with heights of 3-6 mm were placed at equal heights.

After the design was completed, 3D data was exported in STL file format to a resin 3D printer (Envisiontec Perfactory DDP, ENVISIONTEC, Germany). A kind of acrylate 3D printer material (E-Shell® 300 Series, Envisiontec, Germany) was used, and the printing resolution was 0.1 mm. After removing the supports, the printed drill guide template could be placed on extracted dental crowns with relatively good retention.

Figure 2 CAD process of drill guide template



Notes: (a) 3D data extracted after CBCT scan, including dental surface, pulp chamber and root canal; (b) boundaries of pulp chamber and root canal extracted from pulp chamber 3D data; (c-g) access cavity boundary determined by combining the boundaries of the pulp chamber and root canal orifices; projection toward the occlusal surface along the long axis of the tooth to form the side walls of the access cavity; (h-i) boundary lines of the access cavity base plate were drawn on the dental surface; dental surface was cropped and hollowed outward along the normal by 1 mm to form the base plate; (j-k) Boolean operations were performed between the base plate and the previously produced access cavity side walls; an access cavity was formed in the center of the base plate; (l) three guiding cylinders with the same direction as the long axis of the tooth were connected to the base plate; column diameter was 1 mm

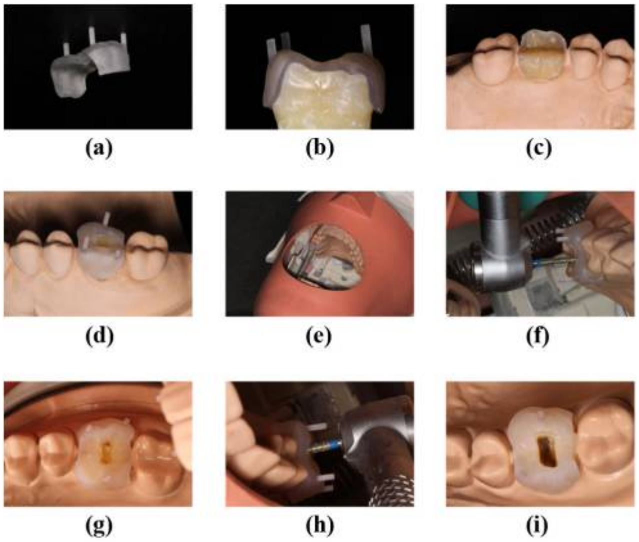
Drill guide template-assisted access cavity preparation

As shown in Figure 3, to simulate the process of access cavity preparation in clinical practice, plaster models of extracted teeth were made and placed in a dental simulator (NISSIM Dental Chair Fix Type, NISSIM, Japan). Drill guide templates were fitted on the teeth, their adaptation to the dental surface was confirmed and a diamond bur was selected for access cavity preparation. The direction of the bur was maintained parallel to the direction of the guiding cylinders on the guide template. A 2-3-mm diameter hole was first created at the central fossa. After penetrating the pulp chamber, the cavity was progressively expanded until it matched the shape of the access cavity as specified by the guide template. In this study, access cavity preparation of two molars (tooth 1: right maxillary first molar, tooth 2: left maxillary first molar, both teeth with slight calcification) was completed with the help of the 3D printed drill guide. The drilling work was carried out by a dentist who had three years of experience in endodontics treatment.

Evaluation of access cavity preparation results

After the plaster models were recovered from the dental simulator, it was found that the access cavities created were consistent with the boundaries of the guide template, and the three root canal orifices of the first molars were clearly visible. After the extracted teeth were removed from the plaster

Figure 3 Drill guide template-assisted access cavity preparation



Notes: (a) 3D-printed drill guide template; (b) successful placement of drill guide template on extracted tooth; (c-e) extracted tooth was used to create a plaster model and placed in a dental simulator along with the drill guide template; the dental simulator was fixed on a dental chair to simulate the clinical operating environment; (f-i) a high-speed bur was used for access cavity preparation assisted by the guide template; (f) a small hole with diameter of about 2-3-mm was drilled in the center of access cavity boundary delineated by the guide template; (g) after penetration into the pulp chamber, the access cavity was expanded until it matched the boundary of the guide template; (i) attention was paid to ensure the direction of the bur was consistent with that of the guiding cylinders during the entire process

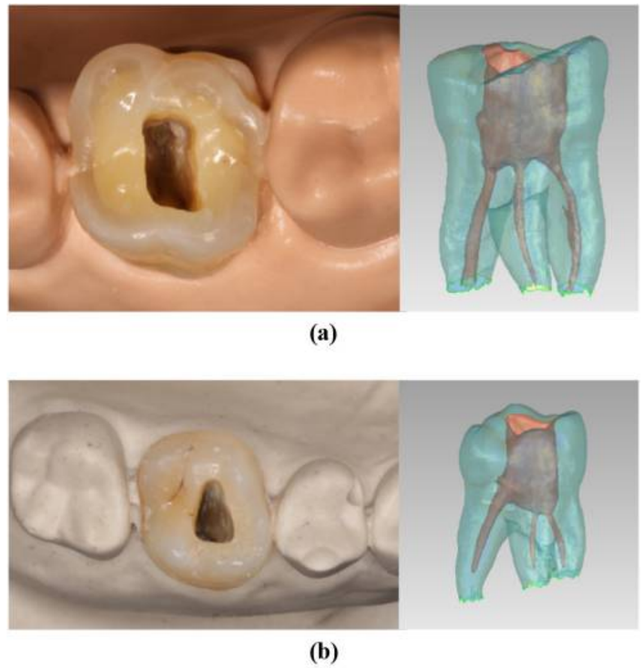
models, they were cleaned and scanned with the NewTom CBCT. The dental morphology after cavity preparation was exported in STL file format.

CBCT scan data of the extracted teeth before and after access cavity preparation were imported into Geomagic Qualify 12.0 (Raindrop Geomagic, USA). After image registration, the deviation between the access cavity side walls of the design and the actual preparation were compared. Points were selected uniformly at 0.5 mm intervals along the side wall of the extracted teeth after access cavity preparation (tooth 1: 297 points, tooth 2: 347 points). Imageware 13.0 was used to measure the distances between these points and the corresponding points in the designed cavity. Data were imported into SPSS 17.0 (IBM, USA) for statistical description.

Results

As shown in Figure 3, the 3D-printed drill guide template closely fitted the extracted teeth and had sufficient retention. During the operation process, the drill guide template was an excellent indicator. The operator was able to easily create the access cavity in the direction indicated by the boundaries of the guide template without having to guess the shape of the cavity or the long axis direction of the tooth. Results of the access cavity were satisfactory. Figure 4 shows that the completed access

Figure 4 Access cavity shape attained under the guidance of the drill guide template



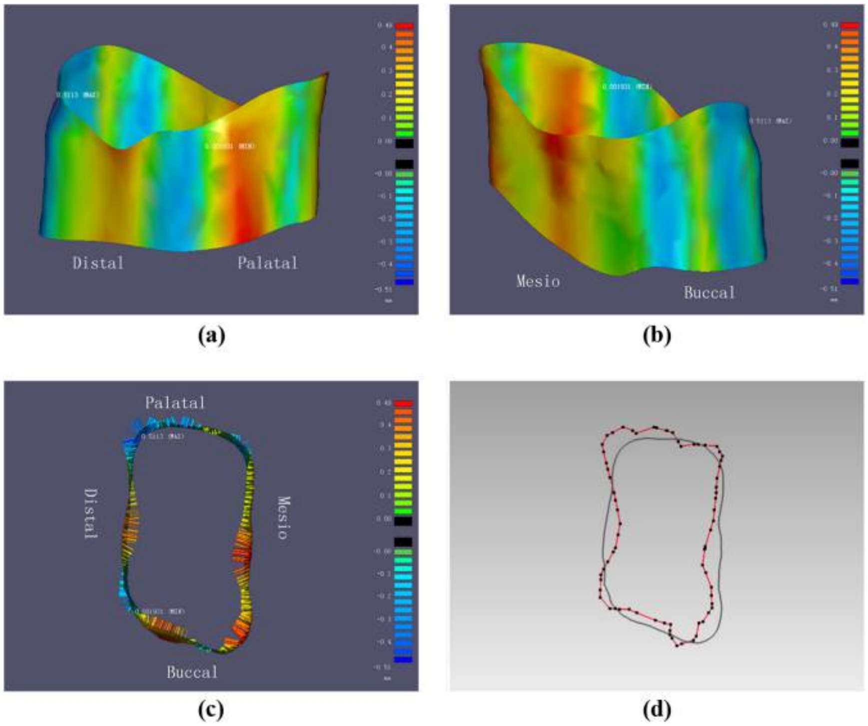
Notes: Images on the left are photographs of the actual objects, and images on the right are the 3D reconstruction after CBCT scanning (red areas indicate pulp chamber and root canal morphology after access cavity preparation); (a) right maxillary 6 and (b) left maxillary 6

cavity had removed the roof of the pulp chamber, forming a straight-line path to the root canal while preserving dental tissues by avoiding excessive preparation. The 3D deviation of selected test points showed that the mean distance between the actual access cavity and the designed access cavity was 0.05 ± 0.22 mm (maximum: 0.49 mm, minimum: −0.51 mm) for Tooth 1 and −0.08 ± 0.12 mm (maximum: 0.27 mm, minimum: −0.41 mm) for Tooth 2, as shown in Figure 5 and Table I. Positive values indicate that the position of the access cavity side wall extended beyond that of the designed cavity, implying that an excessive amount of dental tissue had been removed. Conversely, negative values indicate that less dental tissue had been removed when the access cavity position was compared to the designed cavity. The mean distance between the actual cavity and the designed cavity was nearly 0 for both teeth, indicating that on the whole, the actual cavity conformed very well with the designed cavity. The maximum deviation between the actual and designed cavities was limited to about 0.5 mm, suggesting that the guide template could assist dentists in planning access cavity preparation with acceptable accuracy.

Discussion

Preserving dental tissue as much as possible in every aspect of endodontic therapy is essential for the resistance and long-term prognosis of diseased teeth. Thus, many researchers believe that creating a straight-line access to the root canal is sufficient to avoid complete exposure of the pulp chamber roof, thereby

Figure 5 Deviation analysis of actual and designed access cavity (Tooth 1, right maxillary 6)



Notes: (a) Distal and palatal surfaces; (b) mesial and buccal surfaces; (c) occlusal view; (d) schematic diagram of actual access cavity boundary (red) and designed access cavity boundary (grey) from an occlusal view

Table I Deviation between the prepared sidewalls and the designed ones

Tooth	*N*	Minimum/ mm	Maximum/ mm	Mean/ mm	Std/mm	95% CI LB/mm	95% CI UB/mm
1	297	−0.51	0.49	0.05	0.22	0.03	0.08
2	347	−0.41	0.27	−0.08	0.12	−0.07	−0.09

Notes: N: number of tested points; LB: lower bound of 95% CI; UB: upper bound of 95% CI

preserving more dental tissue (Clark and Khademi, 2010; Clark and Khademi, 2010). In practice, digitized design and fabrication of drill guide templates can achieve this goal with greater precision. If removal of the pulp chamber roof is not considered, it is possible to design the access cavity as a projection from the occlusal surface to the root canal orifice along a straight line. In which case, only a few small holes matching the number of root canals are needed to be drilled onto the occlusal surface, to achieve smooth access into the root canals. Evidently, more research must be conducted to develop effective methods to remove infected tissue in the pulp chamber as a large area of pulp chamber roof is retained using this approach, as well as thorough cleaning and disinfection.

Digitized design of drill guide templates is significant because it allows pre-treatment 3D visualization of pulp chamber and root canal morphology (provided by CBCT scanning), design of access cavity shape (using CAD software) and high-resolution guidance of instrumentation. The final result is access cavity preparation that completely matches individualized root canal morphology and effectively avoids improper cavity formation. This is particularly valuable for root canals that are calcified or have atypical morphology. The guide template can accurately indicate the location of calcified root canal orifices (which can be indistinguishable to the naked eye), thereby avoiding blindly searching for the orifice, which could lead to an excessively large access cavity, or even pulpal floor or lateral perforations.

Considering the error of CBCT scanning and 3D printing, an appropriate tolerance should be set while design the tissue surface of the drill guide, to get a good fit between the guide and the crown. Therefore, in this study, the guide template tissue surface was given a 0.1-mm normal offset with respect to the tooth surface data, which accounts for any possible errors. Prior to this study, pilot studies were conducted using guides fabricated with no offset, a 0.1-mm offset, and a 0.2-mm offset, and observations with the naked-eye showed that the fit between guide and tooth was best with a 0.1-mm offset. The 0.1-mm offset corresponded to the CBCT resolution (50 μm) and the 3D resin printing resolution (100 μm) used in this study; if higher resolutions of CBCT and 3D printing were used, the offset needed should be decreased accordingly.

In this study, the possible reasons for the deviation between the actual access cavity and the designed cavity can be easily inferred. These include errors in CBCT scanning, errors in 3D printing of the guide template, incomplete placement of the guide template on the dental surface and errors in hand-eye coordination and distance determination. As the plate was only intended as a guide without rigid constraints, the outcome of access cavity preparation is highly dependent on the technical level of the operator. Therefore, the guide template is most appropriate for an experienced clinician. If further operational precision is needed, drill guide templates with rigid constraints can be designed and fabricated. However, the complexity and fabrication cost will be significantly increased. A cavity access resolution of 0.5 mm was considered sufficient for clinical application, allowing the clinician to drill into the tooth at the correct location. In addition, this type of open guide template does not affect the operator's monitoring or control over the process of access cavity preparation. The operator is still able to judge the location of the root canal orifice based on their own clinical experience, thereby avoiding dangerous events. It is hoped that these easy-to-use drill guide templates will have substantial value in clinical applications.

Owing to the well-developed CAD and 3D printing technology, the cost of drill guide manufacturing is controllable. However, the high radiation dose given to the patient by using CBCT is still an important factor to be considered. It is suggested that this technology is better used under complex circumstances, such as calcification or atypical morphology inspected in dental X-ray. While for simple cases, the access cavity preparation work can be easily accomplished without the help of drill guide. Subsequent research should focus on improving and perfecting the drill guide template, including markers for access cavity depth; automatic calculation of the optimal drilling direction; effective removal of dentin ferrules; establishing straight-line access given the conditions of the coronal root canal; improving the design of guiding cylinders, which will improve guide template accuracy from multiple perspectives; and the selection of more appropriate materials (not easily abraded) for the fabrication of the guide template.

Conclusion

In this primary study, the drill guide template for access cavity preparation of permanent molars designed and manufactured based on CBCT data, and CAD/3D printing technology achieved a good fit on the tooth surface and was useful to assistant the access cavity preparation work under an acceptable accuracy. However, due to insufficient sample size, the conclusion here cannot be generalized.

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Corresponding author

Peijun Lyu can be contacted at: kqlpj@bjmu.edu.cn