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ORIGINAL ARTICLE

Evaluation of Cone Beam Computed Tomography Resolution, 3D Printing Resolution and Drilling Depth on Drilling Accuracy in Guided Endodontics: An *In-Vitro* Study

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ABSTRACT

Objective: The aim of this study was to evaluate the influence of cone-beam computed tomography (CBCT) resolution, 3D printing resolution, and drilling depth on drilling accuracy in guided endodontic access.

Methods: Fifty-six printed canines were designed, fabricated, and mounted in maxillary arch models. Preoperative CBCT and 3D surface scan were matched and used to design a surgical guide with different planning parameters: 1) reference (high-resolution CBCT (80 µm) and 3D printing (50 µm), shallow drilling (14 mm), 2) low-resolution CBCT (120 µm), 3) low-resolution 3D printing (100 µm) and 4) deep drilling (high-resolution CBCT (80 µm) and 3D printing (50 µm), deep drilling (21 mm). Guided access into the printed canines was performed in a simulated clinical setting. A postoperative CBCT was matched with the planning data in order to determine the angular and linear (total, mesiodistal, buccolingual and depth) deviation between the planned and performed cavities. Mann-Whitney test was used to analyse differences between the reference group and each test group.

Results: Angular, total linear and buccolingual deviations were significantly higher in the low-resolution CBCT group than in the reference group (median: 3.10° and 2.0° ($p<0.01$), 1.41 mm and 1.06 mm ($p<0.05$) and 0.77 mm and 0.41 mm ($p<0.05$), respectively). Depth deviation was significantly higher in the low-resolution 3D printing group than in the reference group (median: 0.90 mm and 0.45 mm ($p<0.01$), respectively). No other significant differences between the groups were noted ($p>0.05$).

Conclusion: Higher CBCT resolution resulted in lower angular and total linear deviation during guided endodontic access. Higher 3D printing resolution yielded lower vertical linear deviation.

Keywords: Access cavity preparation, accuracy, printed guide, pulp canal obliteration, static navigation

HIGHLIGHTS

- This study provides evidence-based data on the influence of cone-beam computed tomography (CBCT) resolution, 3D printing resolution, and drilling depth on drilling accuracy in guided endodontic access.
- The higher the CBCT resolution, the lower the angular and total linear drilling deviations.
- The higher the 3D printing resolution, the lower the vertical linear deviation.

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INTRODUCTION

As a consequence of lifelong dentine apposition, the pulpal space is progressively filled with secondary dentine with increasing age, resulting in a significant decrease in pulp chamber volume, and a more apical position of the pulp chamber roof within the tooth (1). In younger patients, teeth that underwent dental trauma may undergo pulp canal obliteration (PCO), a condition characterized by the progressive obliteration of the pulp, resulting in partially or fully obliterated pulp canals (2). Besides those, carious lesions (3), coronal restorations (4), vital pulp therapy (5) and orthodontic forces (6) can also lead to pulpal calcifications. Gaining access to the calcified root canal space to be treated can be a challenging task, as required drilling depth is greater, and canal space is not easily identified, increasing the risk of drilling deviation (7, 8). As a consequence, iatrogenic errors such as root perforations (9) and significant tooth substance loss (10) are more likely to occur, leading to decreased tooth rigidity (11).

A "guided endodontics" concept has been introduced for the treatment of teeth with a calcified pulp space, which involves gaining access to the root canal space using computer-designed guides (12). Briefly, a software program is used to match cone-beam computed tomography (CBCT) and surface scan data of the jaw containing the calcified tooth for the virtual planning of an optimal access cavity, which is then used to generate a drilling template through computer aided manufacturing (CAM). This drilling guide is then used to access the root canal space in a minimally invasive way (13).

Accuracy of guided endodontics is critical to prevent iatrogenic errors, and has been previously investigated by measuring the drilling deviation between planned and performed cavities. Laboratory studies have shown that this technique is minimally invasive (12), accurate, fast, safe and not operator-dependent (14–18). Neither the operator's clinical experience (15) nor the type of the planning software (19) seem to affect the drilling deviation. However, the precision of drilling can vary based on prior studies, which is why a safety margin of 1 mm around the planned trajectory is suggested to minimize the risk of root perforation (20). Fitting of the guides to the dental arch is also a critical parameter that can be assessed by intra-oral scanning (21). In implantology, it has been demonstrated that drilling deviation increases with drilling depth (22). In the context of guided endodontics, Torres et al. (23) hypothesized that the drilling length can also impact drilling deviation. Although it has been suggested that the resolution of the CBCT and the 3D printing parameters may affect the drilling deviation (19, 21, 24–26), there is a lack of quantitative data regarding these factors on guided access accuracy. Therefore, this study aimed to investigate the impact of CBCT resolution, 3D printing resolution and drilling depth on the (angular and linear) deviation of drilling in guided endodontic access. The null hypothesis was that there is no influence of CBCT and 3D printing resolutions and drilling depth on drilling deviation.

MATERIALS AND METHODS

The sample size was determined using stat.ubc.ca software (University of British Columbia, Vancouver, Canada) with a power of 0.90 and α=0.05, showing a minimal sample size of 13 per group. Therefore, 14 samples per group were selected. The study protocol was conducted in accordance with the Declaration of Helsinki. A micro-CT scan of a calcified upper canine with a resolution of 20 µm served as the basis for development of the model. Data were loaded in CAD software (Meshmixer, Autodesk, Dublin, Ireland). The canine was mirrored along the longitudinal axis to obtain 28 teeth for the left and 28 teeth for the right upper jaw. Data were imported to the PreForm software (FormLabs, Somerville, MA, USA) and sent to a 3D printer (Form 2, Formlabs) for production by stereolithography (SLA) (resolution: 25 µm, resin: Dental model V2). The 3D-printed models were washed in isopropyl alcohol for 20 min to remove non-cured resin (Form Wash, FormLabs). Finally, the models were post-cured at 60°C for 30 min (Form Cure, FormLabs) and the supporting pillars were removed. A total of 56 printed canines were produced and fixated into upper jaw models to ensure stability during guided access procedures. The model was made of 2 materials: the upper part including the tooth crowns and the upper part of the alveolar ridge consisted of cold curing polymer (Unifast III, GC Europe, Leuven, Belgium), the lower part including the model base was made of putty silicone (Hydrorise, Zhermack, Badia Polesine, Italy). The base was removable ensuring that the root surface of the printed canines was not covered during computed tomography (CBCT) imaging, reducing noise (Fig. 1).

The study models underwent a preoperative CBCT scan (Green 2, Vatech, Puteaux, France) with the following exposure parameters: 95 kV, 8 mA, 9 s, and a field of view of 50×50 mm, and a resolution of either 80 or 120 µm. 3D surface scans were performed with a 3D-extraoral scanner (7Series, DentalWings, Montreal, Canada). CBCT and surface scan data were uploaded to CoDiagnostix software (version 10.4, DentalWings) and matched by aligning the contours of the teeth. Virtual cylindrical steel burs with a diameter of 1 mm (O.27.28.B044.052, Steco-system-technik GmbH, Hamburg, Germany) were superimposed to the data sets, and positioned in order to provide straight access to the root canals. Two drilling depths (14 and 21 mm from the tooth cusp point to the deepest drilling point) were selected to represent shallow and deep drilling. A surgical guide was then automatically designed by the CoDiagnostix (DentalWings) software. Virtual sleeves (M.27.28.D100. L5, Steco-system-technik GmbH) relevant to the bur were placed automatically in the space provided. Fourteen coronal tooth supports were added to guarantee the stability of the guide. Windows were added to the buccal side of the guides to allow visual control of the fit to the study models (27). The data were exported to 3D-printing software and equipment for stereolithographic additive manufacturing (PreForm; Form 2, FormLabs) using a biocompatible resin (DentalSG, FormLabs) in a standardized orientation. The surgical guides were printed in 2 resolutions: 50 and 100 µm. Metallic sleeves were fitted inside into the final guides (Fig. 2). Table 1 summarizes the four experimental groups created according to the virtual planning parameters (n=14/group): reference, low-resolution CBCT, low-resolution 3D printing and deep drilling.

The study models were mounted in a phantom head and rubber dams were placed to simulate clinical conditions. One blinded operator performed all access cavities following the protocol of Connert et al. (28). Briefly, the location of the access cavities was marked on the printed canines using the guide. A diamond bur (836KR, Komet, Gebrüder Brasseler, Lemgo, Germany) was used to make 2 mm deep cavities, in order to sim-

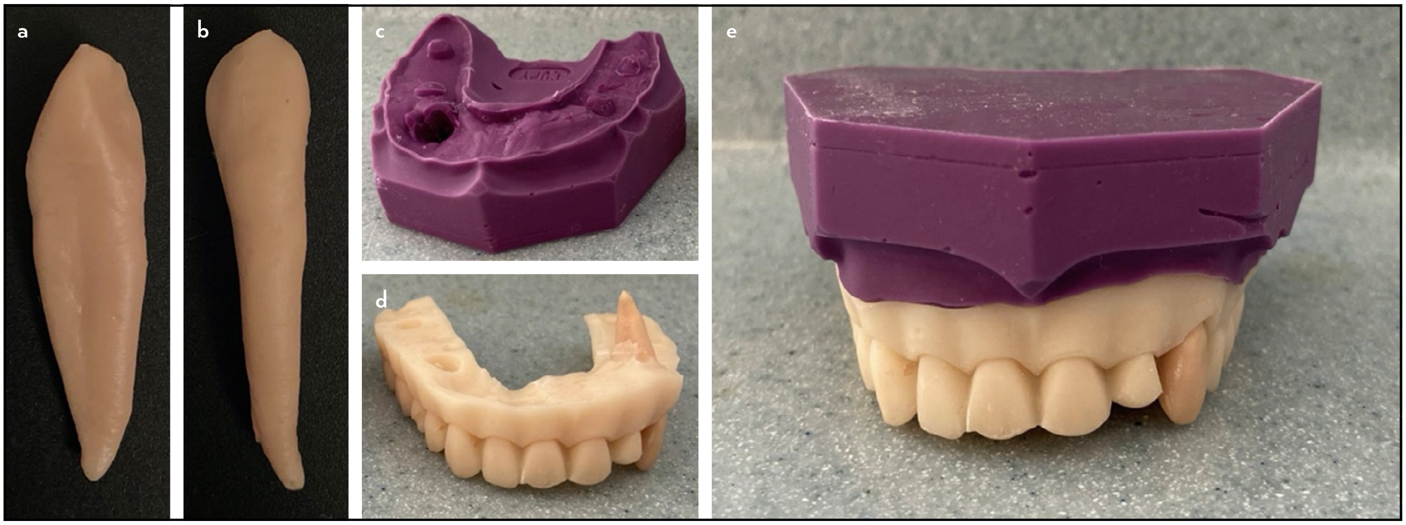

Figure 1. Printed canine in proximal (a) and vestibular (b) views. Removable base in putty silicone (c). Resin-bonded printed canine (d). Study model assembled (e)

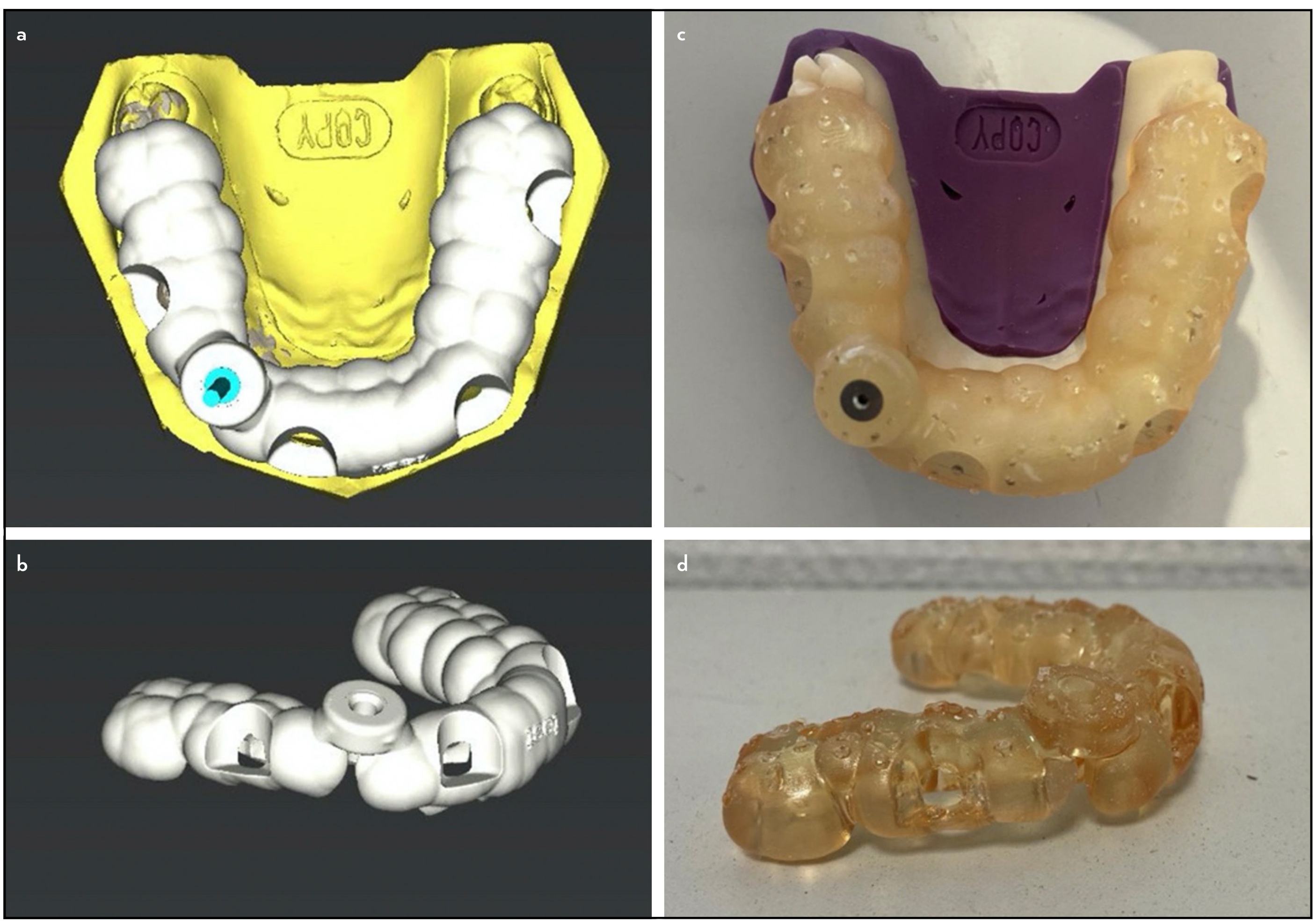

Figure 2. Virtual (a, b) and 3D printed (c, d) guide for guided endodontic access

ulate removal of enamel prior to drilling and avoid misalignment of the bur. After careful positioning of the guide, the bur (O.27.28.B044.052, Steco-system-technik GmbH) was mounted on a contra-angle, aligned with the sleeve and drilling was carried out at 10 000/min rotational speed, without cooling with pumping movements until the drill shank reached the sleeve.

Postoperative CBCT scans of the study models were acquired (high resolution: 80 µm). Data were superimposed with the virtual planning data relative to each study model (CoDiagnostix software). The software allowed automated evaluation of the deviation between planned and performed access cavities. At the level of the deepest bur penetration, angular and linear

TABLE 1. Experimental groups according to CBCT and 3D printing resolutions and drilling depth

Groups	CBCT resolution	3D printing resolution	Drilling depth
Reference	080μm	050μm	14 mm
Low-resolution CBCT	120 μm	050 μm	14 mm
Low-resolution 3D printing	080 μm	100 μm	14 mm
Deep drilling	080 μm	050 μm	21 mm

CBCT: Cone-beam computed tomography

deviations were determined following the method described by Torres et al. (29) and adapted from Brief et al. (30). The total linear deviation was subdivided further into mesiodistal, buccolingual and axial (depth) direction to provide both 3D and 2D measurements (Fig. 3).

Drilling deviation data were analysed using GraphPad Prism version 5.1 (GraphPad Software, Boston, MA, USA) (α=5%). As the data were not normally distributed (according to Kolmogorov-Smirnov test), the non-parametric Mann-Whitney test was performed to analyse differences between the reference group and each test group (low-resolution CBCT, low-resolution 3D printing and deep drilling). Effect size was calculated using Cohen's d.

RESULTS

Median, Q1 and Q3 values for all parameters are shown in Table 2 and the effect size in Table 3. Angular deviation was significantly higher in the low-resolution CBCT group than in the reference group (median (Q1; Q3): 3.10° (2.30°; 5.00°) and 2.0° (0.78°; 2.60°) respectively, $p<0.01$). No significant differences in angular deviation were found between the low-resolution 3D printing and deep drilling groups compared to the reference group ($p>0.05$).

The total linear deviation was significantly higher in the low-resolution CBCT group than in the reference group (median (Q1; Q3): 1.41 mm (1.21 mm; 1.70 mm) and 1.06 mm (0.69 mm; 1.31 mm) respectively, $p<0.05$). No significant differences in total linear deviation were found between the remaining and the reference groups ($p>0.05$).

In the mesiodistal direction, there were no significant differences in linear deviation between tests groups and the reference group ($p>0.05$). In the buccolingual direction, the deviation was significantly higher in the low-resolution CBCT group than in the reference group (median (Q1; Q3): 0.77 mm (0.41 mm; 1.12 mm) and 0.41 mm (0.21 mm; 0.61 mm) respectively, $p<0.05$). Depth deviation was significantly higher in the low-resolution 3D printing group than in the reference group (median (Q1; Q3): 0.90 mm (0.52 mm; 1.08 mm) and 0.45 mm (0.25 mm; 0.62 mm) respectively, $p<0.01$). No other significant differences between tests groups and the reference group in mesiodistal, buccolingual or depth directions were noted ($p>0.05$).

The maximum deviation was higher in the experimental groups (maximum angular and total linear deviations: 5.6° and 2.61 mm; 7.1° and 6.29 mm; 5.7° and 6.25 mm in the low-resolution CBCT, low-resolution 3D printing and drilling depth groups, respectively) compared to the reference (maximum angular and total linear deviations: 3.5° and 1.65 mm).

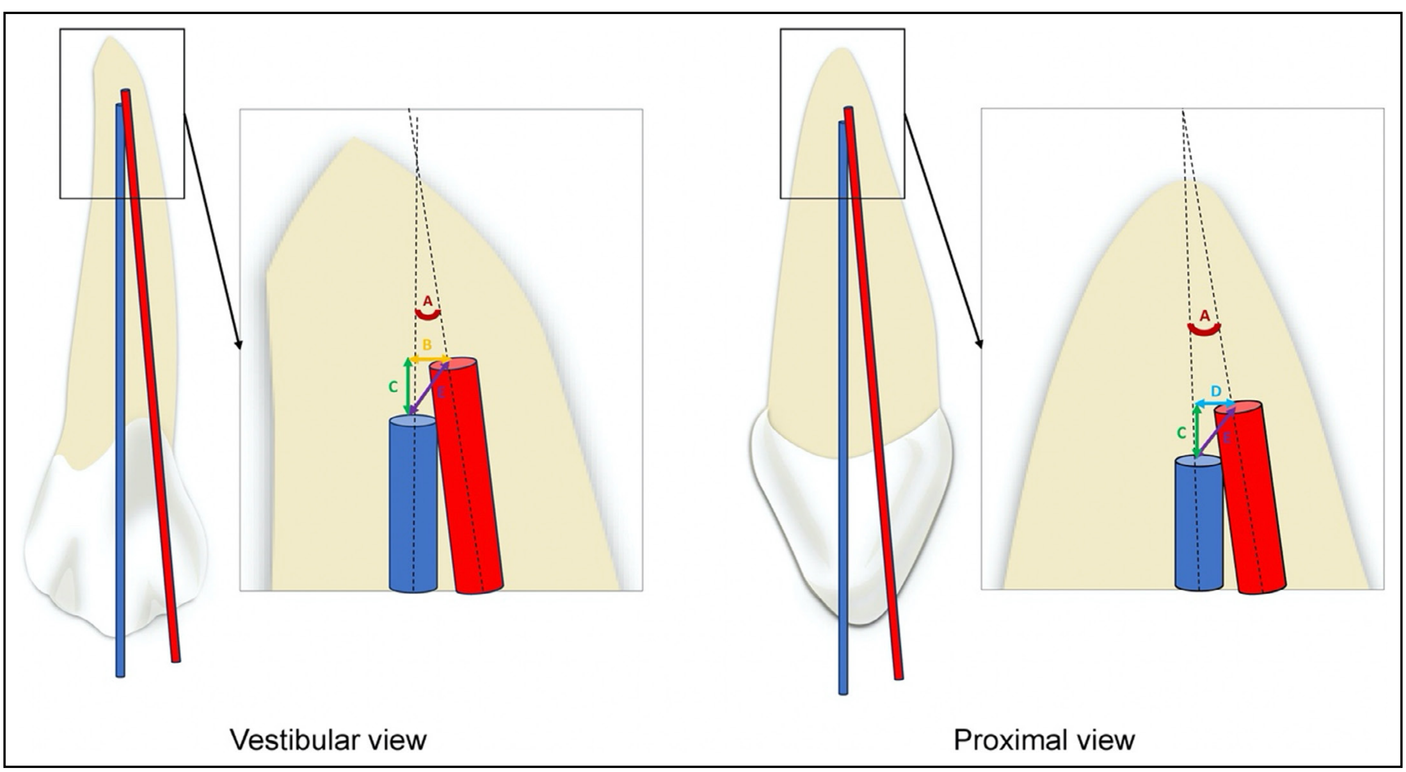

Figure 3. 3D (angular (a) and total (e) linear deviations) and 2D (mesiodistal (b), axial (c) and buccolingual (d) directions) measurements of deviation between planned (blue) and performed (red) cavities

TABLE 2. Deviation results (median (Q1; Q3) for the five parameters in the different groups

Groups	Angle (°)	Total linear (mm)	Mesiodistal (mm)	Buccolingual (mm)	Depth (mm)
Reference	2.00 (0.78; 2.60)[a]	1.06 (0.69; 1.31)[c]	0.68 (0.14; 1.10)[e]	0.41 (0.21; 0.61)[f]	0.45 (0.25; 0.62)[h]
Low-resolution CBCT	3.10 (2.30; 5.00)[b]	1.41 (1.21; 1.70)[d]	0.85 (0.47; 1.37)[e]	0.77 (0.41;1.12)[g]	0.19(0.14; 0.45)[h]
Low-resolution 3D printing	1.95 (1.00; 2.73)[a]	1.33 (1.09; 1.65)[c]	0.35 (0.10; 0.72)[e]	0.50 (0.21; 0.93)[f]	0.90 (0.52; 1.08)[i]
Deep drilling	1.55 (0.00; 2.23)[a]	0.98 (0.79; 1.75)[c]	0.47 (0.16; 1.12)[e]	0.26 (0.06; 0.42)[f]	0.40 (0.04; 1.07)[h]

Different superscripts indicate significant differences with the reference group ($p<0.05$). CBCT: Cone-beam computed tomography

TABLE 3. Effect size for the five parameters in the different groups compared to reference

Groups	Angle	Total linear	Mesiodistal	Buccolingual	Depth
Low-resolution CBCT	1.14	0.74	0.36	0.87	0.35
Low-resolution 3D printing	0.18	0.60	0.48	0.44	0.70
Deep drilling	0.16	0.50	0.05	0.45	0.52

DISCUSSION

To the best of knowledge this is the first study evaluating the impact of CBCT and 3D printing resolution and drilling depth on the deviation that occurs during guided access procedures. The present data demonstrate that the drilling precision in guided endodontic access is affected by planning parameters: the drilling accuracy was lower when a CBCT scan of low resolution was used, and also when 3D printing was done with lower resolution. The null hypothesis, stating that there is no influence of CBCT and 3D printing resolutions and drilling depth on drilling deviation, was rejected.

Printed canines were developed and used to obtain a high level of standardisation and to help overcome the problems inherent to morphological variability of natural teeth (15). The 3D printed teeth were also adequately fixated in the upper jaw models to minimize any change in their position relative to the dental arch. However, the retention of the printed canines was limited to their cervical area, leaving a possibility of coronal or apical mobility, which could be a source of inaccuracies (15, 19). Another drawback of these models concerns the absence of variation in consistency, lacking the differential composition of enamel and dentine. On the other hand, the use of a standardized material for the teeth removes any variation in the mechanical properties between samples, which is the case with dentine of natural teeth.

Successful access to a calcified canal during root canal treatment heavily relies on minimizing deviation from the ideal axis that occurs during drilling. Indeed, any deviation can lead to iatrogenic errors such as extensive loss of dentine or even perforation. This may finally result in endodontic failure (9, 10), tooth fracture (11) or even tooth loss (16). The present experimental setup involved a high degree of standardization, allowing the precise and differentiating comparison between the different test conditions. In addition to anatomical and material standardization of the models, the endodontic templates were prepared uniformly, with the incorporation of a sleeve intended to ensure the reliability of the drilling (19). The fit between the bur and the sleeve is important: a tight contact can result in excessive heat generation, while a loose fit can cause greater angular inaccuracies (31). Studies on the use of printed templates for guided implantology have shown that drilling accuracy improves with a tight sleeve-bur fit and an increase in the height of the sleeve (32). In the present study, a compatible sleeve-bur combination was used. However, the influence of the sleeve-bur fit and the sleeve height seems to deserve further investigation.

The deviation measurement technique used in this study has been validated and has been widely documented in the field of implantology (33) and more recently in endodontics (31). Krug et al. (19) have shown that the CoDiagnostix software is suitable for performing this type of analysis. In implantology, the angular deviation of drilling reported by Tahmaseb et al. (34) (angle: 3.5°) is higher than the values usually reported in endodontics. These greater inaccuracies can be attributed to the fact that the implant guide may rely on mucosal support, which results in a loose tissue-guide adaptation and template displacement, as opposed to endodontic guides that rely on dental support. In addition, the preparation of the implant cavity involves the use of several successive burs with varying diameters, while in endodontic guided access, only one bur is necessary (17).

CBCT has become increasingly important in endodontics (35), especially in static guided access (17, 19, 36, 37). This 3D radiographic technique is accurate, enables the visualization of pre-operative anatomy, and is non-destructive (38). It is particularly useful in planning the theoretical axis to the root canal and evaluating drilling deviation comparing pre- and post-operative data. Following the 'ALARA"-principle ('as low as reasonably achievable'), the systematic use of CBCT prior to root canal treatment is not recommended (35). Nevertheless, the European Society of Endodontology recommends a CBCT scan in cases where radiographic evidence indicates severe root canal calcification and apical periodontitis. To minimize exposure to radiation, Leontiev et al. (39) have suggested replacing CBCT with MRI (Magnetic Resonance Imaging) for virtual planning of guided endodontics. These authors conclude that MRI can serve as a viable technical replacement for CBCT, but the latter still holds its position as the preferred option due to economic and practical considerations.

Drilling deviation was observed in all of the studied test groups. Resolutions of 80 and 120 µm were selected to provide high- and low-resolution CBCT images comparable to previous works (15, 31). The present data demonstrate that the lower the CBCT resolution, the higher the angular and total linear deviation of the drilling during guided access procedures. This total linear deviation occurred mostly in the buccolingual direction. These findings confirm the hypothesis put forth by Llaquet Pujol et al. (26) and Fonseca Tavares et al. (27) that low CBCT resolution significantly reduces the safety of drilling during endodontic guided access. However, their hypothesis was not supported by experimental data. These results are not surprising, since reduced preoperative volume data inevitably results in inaccuracies that accumulate during the planning process. This leads to a gap between the planned and performed access cavities. Our results are comparable to those of Zehnder et al. (17) and Connert et al. (31), as they also reported similar levels of angular deviation ranging from 1.81° to 1.59±1.22°. Zubizarreta-Macho et al. (40) measured a higher level of angular deviation at 10.04±5.20°. However, their results can be attributed to the use of a CBCT with a low resolution (300 µm), which may have led to an increased drilling deviation.

This study showed that using low resolution 3D printing resulted in an increase in linear deviation (depth) during the drilling procedure. This confirms the significant impact of 3D printing resolution on drilling accuracy. Koch et al. (25) obtained similar results in their study, which compared the use of different stereolithographic devices with varying resolutions (between 25 and 150 µm) for the manufacturing of endodontic guides. However, their results don't allow direct incrimination of the 3D printing resolution, as the deviation was evaluated using different devices with specific technologies and resolutions for each, which troubles intergroup comparison. Similar to the case of a CBCT scan, the use of low-resolution 3D printing for fabrication of endodontic access guides may result in faster processing time, but it also leads to inaccuracies that can accumulate during the drilling process. On the other hand, high resolution 3D printing is more time consuming and poses a significant risk of shaping failure due to increased number of layers required for manufacturing (25). Zehnder et al. (17) and Connert et al. (31) observed lower depth deviation (0.16 mm and 0.12±0.12 mm, respectively) than those reported in the present study when the 3D printing resolution was low. This could be explained by the potential higher resolution offered by polyjet technology (up to 16 µm) compared to SLA equipment used in the present work (up to 50 µm).

High variability including higher maximum deviation values was observed in the experimental groups compared to the reference, showing more cases with large and probably clinically unacceptable deviation. These data support the fact that low CBCT and 3D printing resolutions may increase iatrogenic risk during guided access procedures. While the difference between the 2 printing resolutions (50 and 100µm) equalled 100%, the difference between the 2 CBCT resolutions (80 and 120 µm) was only 50%. However, an increase of CBCT resolution of 100 % (80 to 160 µm) is quite distant from clinical reality. Therefore, the gap between the 2 CBCT resolutions was reduced to make the results more clinically relevant. For printing resolutions, a range of 50–100 µm was selected, which includes the highest available resolution as well as the step just below the threshold in the settings.

The drilling depth in this work did not impact angular or total linear deviation. This contrasts the findings by Matsumara et al. (22), who showed that this parameter was critical for the preparation of an implant bed. Once again, these differences can be explained by the differences between drilling protocol in endodontics and in implantology, which requires the use of successive burs.

CONCLUSION

Within the limitations of this laboratory study, it is possible to conclude that both CBCT and 3D printing resolutions have a significant impact on the drilling accuracy during a guided access procedure. Higher CBCT resolution results in lower angular and total linear drilling deviation. Total linear deviation in case of low CBCT resolution occurred mostly in the buccolingual direction. Higher 3D printing resolution yielded lower vertical linear deviation.

Disclosures

Authorship Contributions: Concept – M.H., L.R.; Design – M.H., L.R., M.M.; Supervision – M.H., L.R.; Data collection and/or processing – M.H.; Data analysis and/or interpretation – M.H., L.R., M.M.; Literature search – M.H., L.R., M.M., J.V.; Writing – M.H., L.R., M.M., J.V.; Critical review – M.H., L.R., M.M., J.V.

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