Clinical applications, accuracy and limitations of guided endodontics: a systematic review

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Abstract


Background The novel concept of guided endodontics has been reported as an effective method to obtain safe and reliable results during several endodontic treatments.

Aim To evaluate by means of a systematic review the clinical applications, accuracy and limitations of guided endodontic treatment.

Data sources A search of the literature was performed on PubMed, Embase, Web of Science and Cochrane Library databases, until 25 April 2019. No language or year restrictions were applied.

Study eligibility criteria Articles that answered the research question, including case reports, in vitro and ex vivo studies were included. Data extraction was performed independently by two reviewers.

Study appraisal Quality assessment was done using STROBE, CARE and Modified CONSORT guidelines for observational, case reports and pre-clinical studies, respectively.

Results A total of 22 articles, including fifteen case reports, six pre-clinical studies (in vitro and ex vivo studies) and one observational study, were included.

Limitations and Conclusions Even though the level of evidence is low, and the methodology described among studies heterogeneous, all articles describe guided access cavity preparation and guided surgery as being highly accurate and successful techniques when comparing the drilled path to the planned treatment. More studies with a larger number of patients are necessary to obtain significant conclusions.

Keywords: 3D printed template, cone beam computed tomography, guided access, guided endodontics, guided surgery.

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Introduction

Pulp canal obliteration (PCO) is the deposition of hard tissue within the root canal space (McCabe & Dummer 2012). It is commonly associated with teeth having a history of trauma (Holcomb & Gregory 1967, Andreasen et al. 1987, Oginni et al. 2009, McCabe & Dummer 2012), following orthodontic treatment (Delivanis & Sauer 1982, Andreasen et al. 1987), in response to pulpal injuries (Agamy et al. 2004), dental caries (Saeygh & Reed 1968), restorative procedures or abfractions (Fleig et al. 2017), and in teeth of elderly patients (Saeygh & Reed 1968, Johnstone & Parashos 2015, Kiefner et al. 2017).

In such cases, if root canal treatment is indicated, the treatment is more challenging compared to a tooth with a wide and patent canal (Robertson et al. 1996). The access cavity will be difficult to align
On the other hand, accessing the apical third of the root during periapical surgery can also be challenging, as it requires precision to reach the apical target without damaging the neighbouring anatomical structures. Hence, the use of cone beam computed tomography (CBCT) is indicated in some cases (Anderson et al. 2018).

Cone beam computed tomography can be used in difficult cases in which conventional radiographs do not provide sufficient information on the morphology of the tooth and its surroundings (Patel et al. 2010, 2019). This 3D information can be merged with the surface information of the teeth acquired with an intraoral scanner in order to design and 3D print a guide for treatment (Dawood et al. 2015, Anderson et al. 2018).

Recently, the concept of guided endodontics has been reported, in which computer-designed guides are used for access cavity preparation (van der Meer et al. 2016, Krastl et al. 2016) and endodontic surgery (Strbac et al. 2017), in order to achieve predictable and safe results (Anderson et al. 2018). Pre-clinical studies have reported a high accuracy of the procedure when comparing the drilled path to the planned treatment without being influenced by the operator’s experience. Additionally, the use of a guide for treatment may reduce chair time (Zehnder et al. 2016, Connert et al. 2019).

This novel concept could help clinicians during treatments, it may avoid unnecessary removal of tissue, avoiding complications and therefore, improving the prognosis of treatment (Zehnder et al. 2016, Connert et al. 2018). Nevertheless, a review and quality assessment of the literature is needed to compile all available information and give an overview on what is known about this treatment concept.

The purpose of this systematic review is to assess the literature regarding the clinical applications, accuracy and limitations of Guided Endodontic treatment, focusing specifically on guided endodontics access cavity preparation and guided endodontic surgery.

General objectives are as follows:
- Describe the clinical applications of guided endodontics.
- Describe the limitations of guided endodontics.

Specific objectives are as follows:
- Describe the methodology used for each clinical application.
- Summarize the protocol for the design of 3D guides.

The components of the PICO question were as follows: (patients) patients (or teeth) with difficult access to the canals (calcified canals or teeth with malformations) or apical lesions, (Intervention) Guided endodontic treatment or guided apical surgery, (comparison) compare protocols between the articles (Material and Methods), (outcome) assessment of clinical applications, accuracy and limitations of guided endodontics.

Materials and methods

Protocol and registration

The material and method was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Liberati et al. 2009). The methodology was previously registered in the PROSPERO (International prospective register of systematic reviews) database under the protocol number: CRD42018117561.

Information sources and search strategy

A search strategy of the literature was performed on PubMed, no MeSH terms were found for ‘guided endodontics’, it was adapted later to Embase, Web of Science and Cochrane Library databases. The search was performed until 25 April 2019. No language or year restrictions were applied. Duplicates were removed manually with help from a reference manager. After the selection of the articles, a manual search was conducted from the reference lists. Other articles were then added by hand searching of the literature.

The search strategy used in PubMed is displayed below, the adapted versions used on each database can be found in the Supplementary Information.

PubMed

Eligibility criteria

Studies that answered the research question were included (i) applications of guided endodontics, (ii) studies that assessed the accuracy of the treatment, (iii) case reports and (iv) in vitro or ex vivo studies that assessed the accuracy and limitations of guided endodontics. The exclusion criteria were as follows: (i) articles in other languages than English, (ii) narrative reviews, (iii) experts’ opinion, (iv) guideline reports, (v) cases in which CBCT was used as mean of navigation technique (without the use of a guide) and (vi) cases that used a printed template but for other reasons than to access the root canal or apical lesion.

Study selection

Two researchers (CM and AT) reviewed independently the complete list of articles and selected first by title and then by abstract the articles that were potentially relevant. Later, full-text screening was performed to identify the articles that met the inclusion and exclusion criteria. In case of discrepancies, differences were discussed until agreement was reached or a third author with more experience was asked (RJ).

Data extraction

The data extraction was carried out by one author (CM) and later reviewed by a second author (AT), disagreements were solved by discussion. The following data were obtained from the selected articles: (i) study characteristics: authors, year of publication, (ii) methods: endodontic application, teeth sample, (iii) intervention characteristics: type of CBCT, voxel size, field of view (FOV), type of impression, planning software used, printer, type of bur and specifications and characteristics of the printed guide used. For observational, in vitro and ex vivo studies results were also noted: (iv) outcome: accuracy analysis method, deviation at base of bur, deviation at tip of bur, deviation angle and success rate.

Quality of the evidence assessment

For the evaluation of the quality of the report of the articles, STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) (Vandenbroucke et al. 2007) guideline was used for observational studies, CARE guideline (Case Report Guideline) (Riley et al. 2017) was used to evaluate case reports, and the ‘modified CONSORT checklist of items for reporting in vitro studies of dental materials’ (Faggion 2012) was used for assessing the quality of pre-clinical in vitro and ex vivo studies. The three checklists are displayed in the Supplementary Information. After applying the checklist, the average compliance of all the articles was recorded, as well as the minimum and maximum. In addition, the compliance percentage of each parameter was calculated.

Results

Search results

Once the search of the evidence in PubMed, Embase, Web of Science and Cochrane Library databases was made, 105, 67, 108 and 0 results were found, respectively. The total sum of 280 articles was stored in a reference manager, two results that were found by hand searching on the reference lists from the articles and due to other sources were added. Duplicates were removed manually with a reference manager, resulting in 143 unique articles. Thirty-three articles were selected by title that seemed to be related to the main search topic. These articles were revised by abstract, and three of them were later excluded. Finally, 30 articles were eligible for full-text screening. The years of the publications range from 2007 to 2019. The selection process can be seen in the PRISMA (Liberati et al. 2009) flow chart (Fig. 1). Full-text screening was performed resulting in 22 articles that were found by hand searching on the reference lists from the articles and due to other sources were added. Duplicates were removed manually with a reference manager, resulting in 143 unique articles. Thirty-three articles were selected by title that seemed to be related to the main search topic. These articles were revised by abstract, and three of them were later excluded. Finally, 30 articles were eligible for full-text screening. The years of the publications range from 2007 to 2019. The selection process can be seen in the PRISMA (Liberati et al. 2009) flow chart (Fig. 1). Full-text screening was performed resulting in 22 articles that were considered eligible to be evaluated by qualitative analysis. The reasons for the exclusions are listed in Fig. 1. Within the included manuscripts, there were 15 case reports, 6 experimental studies (2 in vitro and 4 ex vivo studies) and 1 observational study.

Study characteristics

et al. 2018). The results of the case reports are shown in Table 1 for access cavity and Table 2 for endodontic surgery. Nine articles performed access cavities in anterior single-rooted teeth. Seven of them were treatments for calcified canals (van der Meer et al. 2016, Krastl et al. 2016, Connert et al. 2018, Fonseca Tavares et al. 2018, Lara-Mendes et al. 2018b, Torres et al. 2018, Maia et al. 2019) and two on teeth with anomalies such as dens invaginatus (Zubizarreta Macho et al. 2015) and dens evaginatus (Mena-Alvarez et al. 2017). The rest of the access cavities was made in calcified canals of maxillary (Lara-Mendes et al. 2018a, Maia et al. 2019) and mandibular molars (Shi et al. 2018). In the case of periapical surgery, they were performed on incisors, canines, premolars and molars. Only 7 of the 15 case reports

Figure 1 PRISMA flow chart (Liberati et al. 2009) of the selection process.
<table>
<thead>
<tr>
<th>No</th>
<th>Authors</th>
<th>Teeth</th>
<th>CBCT</th>
<th>FOV</th>
<th>Voxel size</th>
<th>Implantation impression</th>
<th>Planning software</th>
<th>Printer</th>
<th>Bur</th>
<th>Type</th>
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<th>Speed</th>
<th>Template sleeve</th>
<th>Template material</th>
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<tr>
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<td>Convert et al. (2018)</td>
<td>Mandibular Central Incisors</td>
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<td>Undisclosed</td>
<td>iTero (Align Technology Inc., San Jose, CA, USA)</td>
<td>CoDiagnostiX, version undisclosed (Dental Wings Inc., Canada)</td>
<td>Objet Eden 260V (Stratasys Ltd., Minneapolis, MN, USA)</td>
<td>Specialty designed miniaturized bur (Gebr. Brasseler GmbH &amp; Co. KG, Germany)</td>
<td>0.85 mm D, 10 000 rpm</td>
<td>Dimensions undisclosed (Stecosystem-technik GmbH &amp; Co. KG, Germany)</td>
<td>Med610 (Stratasys Ltd., Minneapolis, MN, USA)</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Fonseca Tavares et al. (2018)</td>
<td>Maxillary Central Incisor</td>
<td>Undisclosed</td>
<td>Undisclosed</td>
<td>Silicone impression</td>
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<td>Simplant version 11 (Materialize Dental, Belgium)</td>
<td>Objet Eden 260 V (Stratasys Ltd.)</td>
<td>Neodent Drill for Tempimplants (Ref: 103179; JGC Ind e Comendio de Materiais Dentarios SA, Brazil)</td>
<td>1.3 mm D, 20 mm TL, 12 mm WL</td>
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<td>Objet Eden 260 V (Stratasys Ltd.)</td>
<td>Straumann Drill for Tempimplants (Ref: 30231; Straumann, Switzerland)</td>
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<td>Maxillary Central Incisor</td>
<td>iCAT (Imaging Sciences International, Hatfield, PA, USA)</td>
<td>Undisclosed</td>
<td>0.12 mm</td>
<td>Introral impression (Material undisclosed)</td>
<td>3Shape R750 Desktop Scanner (3Shape)</td>
<td>Simplant version 11 (Materialize Dental-Technologies AB)</td>
<td>Neodent Drill for Tempimplants (Ref: 103179; JGC Ind e Comendio de Materiais Dentarios SA)</td>
<td>1.3 mm D, 20 mm TL, 12 mm WL</td>
<td>1200 rpm</td>
<td>FullCure 720 (Stratasys Ltd.)</td>
<td></td>
<td></td>
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<td>Second and Third Maxillary Molars</td>
<td>iCAT (Imaging Sciences International)</td>
<td>Undisclosed</td>
<td>0.12 mm</td>
<td>Introral impression (Material undisclosed)</td>
<td>3Shape R750 Desktop Scanner (3Shape)</td>
<td>Simplant version 11 (Materialize Dental-Technologies AB)</td>
<td>Neodent Drill for Tempimplants (Ref: 103179; JGC Ind e Comendio de Materiais Dentarios SA)</td>
<td>1.3 mm D, 20 mm TL, 12 mm WL</td>
<td>1200 rpm</td>
<td>FullCure 720 (Stratasys Ltd.)</td>
<td></td>
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### Table 1 Continued

<table>
<thead>
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<th>No</th>
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<th>Voxel size</th>
<th>Impression</th>
<th>Planning software</th>
<th>Printer</th>
<th>Bur</th>
<th>Speed</th>
<th>Template</th>
<th>Template material</th>
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<tr>
<td>6</td>
<td>Maia et al.</td>
<td>Maxillary First Molar and Second Premolars</td>
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<td>Undisclosed TRios Color Pod (3Shape, Denmark)</td>
<td>N/A</td>
<td>CoDiagnostiX, version undisclosed</td>
<td>Dentip Wings Inc., Germany</td>
<td>Med610 1.1 mm D Molar, 1.3 mm D Premolars</td>
<td>380 rpm</td>
<td>Undisclosed</td>
<td>(Stratasys Ltd.)</td>
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<td>Mena Alvarez et al.</td>
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<td>60 x 60 mm</td>
<td>Undisclosed</td>
<td>Undisclosed</td>
<td>SMPLANT Diamond bur (Dentsply Implants, Belgium)</td>
<td>3Matic 9.0 (Materialia, Belgium) and ZBrush (Pixologic Inc, Los Angeles, CA, USA)</td>
<td>1.2 mm D, 14 mm TL</td>
<td>Undisclosed</td>
<td>5 mm L, 1.3 mm ID</td>
<td>Medical use rein</td>
</tr>
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<td>8</td>
<td>Shi et al.</td>
<td>Mandibular Molar</td>
<td>ICAT 17-19 OMSI (Sirona Dental Systems, Hatfield, PA, USA)</td>
<td>Undisclosed</td>
<td>Undisclosed</td>
<td>CEREC AC (3Shape, Charlotte, NC, USA)</td>
<td>N/A</td>
<td>3Matic 9.0 (Materialia, Belgium) and 3Shape (3Shape, Charlotte, NC, USA)</td>
<td>Projet 6000 (3D Systems, USA)</td>
<td>3D Systems, USA</td>
<td>3510SD (3D Systems Corporation, Rock Hill, SC, USA)</td>
<td></td>
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<td>9</td>
<td>Torres et al.</td>
<td>Maxillary Lateral Incisor</td>
<td>NewTom VG Evo (NewTom, Italy)</td>
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<td>0.2 mm</td>
<td>Alginate impression</td>
<td>Activity 885 (SmartOptions, Germany)</td>
<td>Mimics 19.0 (Materialia, Belgium)</td>
<td>Manec bur (GUM Engineering Inc., Santa Barbara, CA, USA)</td>
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<td>10</td>
<td>van der Meek et al.</td>
<td>Maxillary Anterior Teeth</td>
<td>3D examination (KAVO, The Netherlands)</td>
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<td>0.3 mm</td>
<td>Lava COS 3M Espe, Zherkowskii, The Netherlands</td>
<td>N/A</td>
<td>3ds Max Software (Autodesk, San Rafael, CA, USA)</td>
<td>Manec bur (GUM Engineering Inc., USA)</td>
<td>Size 2: 1 mm D, 3.4 mm ID</td>
<td>3 mm D, 2.4 mm ID</td>
<td>Undisclosed</td>
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<td>11</td>
<td>Zubizarreta et al.</td>
<td>Maxillary Lateral Incisor</td>
<td>White Fox (Acteon)</td>
<td>100 x 130 mm</td>
<td>Undisclosed</td>
<td>Alginate impression</td>
<td>D700 scanner (3Shape, Warren, NJ, USA)</td>
<td>SIMPLANT Diamond bur (Dentsply Implants, Belgium)</td>
<td>Projet 6000 (3D Systems, Rick Hills, SC, USA)</td>
<td>1.2 mm D, 14 mm TL</td>
<td>Undisclosed</td>
<td>5 mm L, 1.3 mm ID</td>
</tr>
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</table>

Letter coding: D, diameter; ED, external diameter; ID, inner diameter; L, length; N/A, not Applicable; TL, total length; WL, working length.

The observational study of 50 patients carried out by Buchgreitz et al. (2019) was the only one of its kind found up to the date of this review. Patients who required root canal treatment in calcified teeth due to the presence of periapical lesion or because they needed a post were included. The method data are shown in Table 3. The authors reported that they used a similar protocol to their previous publication (Buchgreitz et al. 2016). The control of the treatment steps was done with intraoral radiographs. At the end of the treatment, the precision was evaluated by means of two groups: one in which the path was perfectly centred on the tooth, defined as having ‘optimal precision’, and another in which the access cavity to the canal was slightly deviated, defined as ‘acceptable precision’. Authors reported that all treatments were completed and there were no failures (Buchgreitz et al. 2016). Even the worse performance was clinically acceptable.

Of the in vitro and ex vivo studies, four of them assessed the precision and planning of guided endodontic access cavity preparation (Buchgreitz et al. 2016, Zehnder et al. 2016, Connert et al. 2017, 2019), while two focussed on guided endodontic surgery (Pinsky et al. 2007, Ackerman et al. 2019). Data extracted from each article is displayed in Table 4.

Protocol for the design of the 3D guide

Upon diagnosis, the planning procedure usually consisted of: first, a high-resolution CBCT of the patient was acquired. Then, a digital intraoral impression of the patient’s teeth was acquired either directly, with the use of an intraoral scanner, or indirectly by scanning the impression tray or plaster cast with an optical scanner (Torres et al. 2018). Next, both scans (CBCT and intraoral) were registered by surface registration, using specialized image processing software. After that, using 3D design software, a template or guide was designed according to the desired pathway for treatment. Finally, the guide was 3D printed or milled for use during treatment. An illustration of the treatment planning sequence is shown in Fig. 2. Furthermore, the use of a semi-automatic method for the generation of the pathway based on the segmentation of the calcified canal has been reported by Nayak et al. (2018) However, the methodology of the study was not suitable to be included in this review.

Quality of the evidence assessment

The detailed results of the evaluation of the quality of the evidence with the STROBE, CARE and modified CONSORT guidelines are presented in Tables 5, 6 and 7, respectively. There was only one observational study with an overall STROBE score of 71% (Table 5). For the case reports, the mean compliance was 76% with a maximum score of 93% (Ye et al. 2018) and a minimum score of 48% (van der Meer et al. 2016). The parameter ‘intervention adherence and tolerability’ was not fulfilled in any report. On the contrary, there were 12 parameters that were observed in all these studies (Table 6). For the pre-clinical studies, the mean compliance was 58% [all studies scored 60%, except for one that scored 47% (Pinsky et al. 2007)]. Five parameters were not observed in any study, three of them in relation to the blinding and the random allocation sequence. On the other hand, six parameters were observed in all of them (Table 7).

Discussion

Earlier reports on the literature addressed the complications that may present when treating teeth with PCO. According to Kvinnsland et al. (1989), 20% of the perforations reported in the study were due to attempts to locate and negotiate calcified canals. Similar results were found in a study from Cvek et al. (1982), with a total frequency of failures (perforation of the root, fracture of a file or root canal not found) of 20%, when performing root canal treatment on incisors with PCO.

Guided endodontic treatment seems to be a reliable alternative when treating calcified canals and anatomical variations or to improve the accuracy of apical surgery. All articles described guided surgery and guided access cavity preparation as highly accurate techniques when comparing the real cavity to the virtual planning (Pinsky et al. 2007, Buchgreitz...
<table>
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<tr>
<th>No</th>
<th>Authors</th>
<th>Teeth</th>
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<td>1</td>
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<td>First Mandibular Molar</td>
<td>Alpha 3000</td>
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<td>Identica Blue (Medix, Korea)</td>
<td>Onedemand3D (Cybermed Co., Korea)</td>
<td>Objet Eden 260V (Stratasys Ltd.)</td>
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<td>20 mm T, 1.5 mm D</td>
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<td>Onedemand3D (Cybermed Co., Korea)</td>
<td>Objet Eden 260V (Stratasys Ltd.)</td>
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<td>iTero 17-19</td>
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<td>SIMPLANT (Dentistry, Belgium)</td>
<td>3510SD (3D System Corporation)</td>
<td>Tephine (Masinger, Germany)</td>
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<td>2 mm L, 4.2 mm ID</td>
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</table>

Letter coding: D, diameter; ED, external diameter; ID, inner diameter; L, length; min, minimum; N/A, not Applicable; TL, total length; WL, working length.

*Anisotropic voxel because of the use of a MSCT scan.

The accuracy of guided access cavity preparation seems to be reliable as reported on pre-clinical studies (Table 4). Buchgreitz et al. (2016) reported an average deviation of 0.46 mm of the tip of the bur. However, no other data on distance measurements or angle deviations were provided by the authors. Zehnder et al. (2016) reported a mean angle deviation of 1.81°, with a mean mesial/distal deviation at the tip of the bur of 0.29 mm, buccal/oral of 0.47 mm and apical/coronal of 0.17 mm. Connert et al. (2017) reported lower values, with a mean angle deviation of 1.59°, a mean mesial/distal deviation at the tip of the bur of 0.14 mm, buccal/oral of 0.34 mm and apical/coronal of 0.12 mm. Additionally, the last two authors reported no statistical differences between access cavities performed by two different operators, which shows that the technique is reproducible between different operators. However, neither of these reports measured the true deviation as reported by Buchgreitz et al. (2016). Instead, a deviation on a mesial/distal and buccal/oral direction was given.

Compared with guided-implant placement, the mean angle deviation when placing implants using a tooth-supported template is much higher: 5.26° as reported in a systematic review by Schneider et al. (2009). Tahmaseb et al. (2014) reported more accurate results for implants, with a mean angle deviation of 3.89° and a mean deviation of 1.39 mm at the apex of the implant. However, these deviations are still greater compared to those in a guided access cavity preparation, probably because of the use of multiple sleeves and burs.

One in vitro study, using 3D printed teeth, conducted by Connert et al. (2019) compared a guided endodontic procedure with conventional access preparation using three operators: a 9-year experienced endodontist, a 3-year experienced general dentist and a newly graduated dentist. Results show that the mean substance loss was 9.8 mm³ (SD ± 3.0) for the guided technique and 49.9 mm³ (SD ± 7.7) for the conventional approach by all operators (Connert et al., et al. 2016, Zehnder et al. 2016, Connert et al. 2017, 2019).
Table 4 Data extraction on experimental studies

(a) Material and methods on guided endodontics: in vitro and ex vivo studies

<table>
<thead>
<tr>
<th>No</th>
<th>Authors</th>
<th>Endodontic application</th>
<th>Sample size (n)</th>
<th>CBCT</th>
<th>View size</th>
<th>Impression</th>
<th>Planning software</th>
<th>Printer</th>
<th>Type</th>
<th>Specifications</th>
<th>Speed</th>
<th>Guide</th>
<th>Type</th>
<th>Slew</th>
<th>Template material</th>
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<td>Guided Endodontic Surgery (surgical access cavities)</td>
<td>48 roots</td>
<td>ICAT FLX (Dental Imaging Technologies Corp., Hatfield, PA, USA)</td>
<td>0.2 mm</td>
<td>Trios (3Shape)</td>
<td>Blue Sky Bio (LLC, Greendale, IL, USA)</td>
<td>Form 2 (Formlabs Inc., Somerville, MA, USA)</td>
<td>Surgical Underrun bur (Meisinger, Germany)</td>
<td>~2 mm D</td>
<td>Undisclosed</td>
<td>3D Printed</td>
<td>2 mm ID</td>
<td>Variable L (Formlabs Inc., Somerville, MA, USA)</td>
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<td>2</td>
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<td>Guided Endodontic Access</td>
<td>38 teeth</td>
<td>Orthophos XG 3D unit (Sirona Dental Systems)</td>
<td>Undisclosed</td>
<td>CBREC (Sirona)</td>
<td>Galaxy/Galilero (Sirona Implant, (Sirona Dental Systems)</td>
<td>Specially designed bur (Busch)</td>
<td>Modified spiral bur (Busch)</td>
<td>1.2 mm D</td>
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<td>3D Printed</td>
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<td>3</td>
<td>Cornet et al. (2017)</td>
<td>Guided Endodontic Access (mandibular and maxillary canines)</td>
<td>59 teeth</td>
<td>Morita Accuitomo 80 (J Morita Mfg. Corp, USA)</td>
<td>0.08 mm</td>
<td>iTero (Align Technology Inc.)</td>
<td>CoDiagnostiX (Stratasys Germany)</td>
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<td>0.85 mm D</td>
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<td>Guided Endodontic Access (mandibular incisors and canines)</td>
<td>48 teeth</td>
<td>Morita Accuitomo 80 (J Morita Mfg. Corp, USA)</td>
<td>0.125 mm</td>
<td>iTero (Align Technology Inc.)</td>
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<td>Specially designed bur</td>
<td>0.85 mm D</td>
<td>10 000 rpm</td>
<td>3D Printed</td>
<td>6 mm L</td>
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(b) Results on guided endodontics’s experimental studies

<table>
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<th>No</th>
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<th>Accuracy analysis method</th>
<th>Deviation at base of bur</th>
<th>Deviation at tip of bur</th>
<th>Deviation angle</th>
<th>Success rate</th>
<th>Clinical applicability</th>
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<tr>
<td>1</td>
<td>Ackerman et al. (2019)</td>
<td>Compare accuracy of freed hand drilling versus virtual planned osteotomies</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.473 mm mean (±0.751 SD) using guide, 2.638 mm mean (±1.387) SD freehand</td>
<td>100% of targets</td>
</tr>
<tr>
<td>2</td>
<td>Buchgreitz et al. (2016)</td>
<td>Drill in bulk of dentine to the centre of apical target point (Gutta-percha size 30 on apical third)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Mean 0.46 mm</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Cornet et al. (2017)</td>
<td>Registration pre-CBCT with post-CBCT. Analysis automatically via the software</td>
<td>BO: 0.13 mm mean (0.0.4 mm)</td>
<td>MD: 0.12 mm mean (0.0.4 mm)</td>
<td>AC: 0.12 mm mean (0.0.41 mm)</td>
<td>100%</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Cornet et al. (2019)</td>
<td>Compare accuracy of conventional technique to guided access cavities</td>
<td>Registration pre-CBCT with post-CBCT. Analysis automatically via the software</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>91.7% (22 of 24 root canals were achieved)</td>
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The guided-treatment allowed the operators to find, regardless of their experience, 92% (22/24) of the canals, a statistically higher proportion compared with the traditional technique (42%, 10/24), confirming what was previously indicated in pre-clinical studies (Zehnder et al. 2016, Connert et al. 2017).

Accuracy measuring methods in the ex vivo studies are heterogeneous. Buchgreitz et al. (2016) measured the distance from the centre of the drilled path to the centre of an apical target point (gutta-percha with a diameter of 0.3 mm) without taking into account the virtually planned drill path. The centre of the drilled path was done automatically with computer software by registering the virtual drilled path on the performed drill path. However, the distance measurements to the centre of the target point were manually calculated by two observers. This may have led to small errors on the calculations. On the other hand, a different methodology was used by Zehnder et al. (2016) and Connert et al. (2017), both authors used computer software to automatically calculate the deviation between planned and performed access cavity preparations by registering preoperative and postoperative CBCT scans. For such small measurements, an automated measurement methodology seems best to prevent bias with the results.

More studies with larger numbers of samples and a more standardize methodology are needed to draw conclusions on the precision of guided endodontics. However, this may be difficult as ex vivo studies (Zehnder et al. 2016, Connert et al. 2017, 2019) use teeth without complete calcifications. Therefore, the influence of PCO on the accuracy remains unclear (Connert et al. 2019). Also, the time required to treat a tooth with PCO might be slightly longer (Kiefner et al. 2017). Buchgreitz et al. (2016) assessed this issue by performing access cavities on the bulk of dentine to reflect PCO without taking the actual pulp cavity and tooth type into account. It could be speculated that in a real-life scenario, a drill path along the axis of a calcified canal may perform at least as well, due to a softer texture of the calcified tissue laid down in the root compared to ortho-dentine.

In a recent observational study on 50 patients treated using this technique, Buchgreitz et al. (2019) suggested that a reasonable deviation of the bur can be classified as ‘acceptable’ precision. The term ‘acceptable’ was used when there was some deviation, but the canal could still be located and instrumented, and when follow-up showed healing of the apical lesion. In contrast, when trying to access the canal without...
When assessing the accuracy of guided surgery, only 2 studies were found (see Table 4). Pinsky et al. (2007) and Ackerman et al. (2019) compared the use of a guide to a freehand procedure on the localization of the root apex. The results were significantly different to the control group in both studies. The use of a CAD/CAM guide yielded a mean distance of 0.79 mm from the apex, in contrast to the freehand osteotomies with a mean distance of 2.27 mm reported by Pinsky et al. (2007). As for Ackerman et al. (2019), all procedures done with the guide had a successful result, meaning that the end of all drilled paths was within the apical 4 mm of the teeth. Additionally, the use of guides for periapical surgery reduces the diameter of the osteotomy to a size slightly larger than the length of the resection (Ye et al. 2018). This minimally invasive procedure reduces the risk of intra- and
postoperative complications such as bleeding or damaging neighbouring anatomical structures. It also shortens the healing time and improves prognosis (Ahn et al. 2018, Ye et al. 2018).

The accuracy of the intraoral scanner has an added value when used during guided endodontic planning, as it reduces the number of steps (Fonseca Tavares et al. 2018). However, the clinical cases showed that it is not essential to achieve positive results. A conventional impression using alginate with a subsequent optical scan of the gypsum cast can also be used to achieve successful treatment (Zubizarreta Macho et al. 2015, Ahn et al. 2018, Giacomino et al. 2018, Lara-Mendes et al. 2018a, Fonseca Tavares et al. 2018, Lara-Mendes et al. 2018b, Torres et al. 2018). Indeed, it has been reported that the digital impression technique is clinically as good as or even better than the optical scanning of a gypsum cast compared to scanning natural teeth directly (Albdour et al. 2018). However, the optimal error value for clinical and digital impression acquisition for guided endodontics has not yet been described. Moreover, it should be noted that as more steps are taken, there will be a sum of the small errors in the final result (van der Meer et al. 2016).

One of the limitations of the technique for guided access cavity preparation, as mentioned by Buchgreitz et al. (2019), is that the spatial resolution of the CBCT does not always allow visualization of the canal. There is a wide variability of CBCT machines used in the included studies, and the voxel size is not always specified. Clinically, such calcified canals are initially negotiated using small diameter files size 06 or 08. However, this small diameter is not seen in the CBCT images as the voxel size is larger. In those cases, and when treating single-rooted teeth, the pathway can be established through the centre of the root as seen on the axial view. Since the root canal of single-rooted teeth is placed in the centre of the root, localizing the periphery of the root may be sufficient to estimate where the canal is likely to be. The acquired image should allow the evaluation of the apex and its surroundings but keeping in mind that as the spatial resolution is improved by decreasing the voxel size, the radiation dose would increase (Patel et al. 2015).

Another limitation regarding the imaging technique is that in many cases intraoral radiography is used during follow-up. Given the 2D nature of the image, the deviation of the access cavity may be underestimated in terms of its bucco-lingual position (Buchgreitz et al. 2019), as well as the healing of the

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**Table 5** STROBE checklist

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periapical lesion (Patel et al. 2012). Fonseca Tavares et al. (2018) recommended taking at least two radiographs with different angulations to ensure that the bur was not deviating from the axis of the canal. Although CBCT needs further justification considering the increased radiation burden (Patel et al. 2019), the additional dose and cost related to the use of a preoperative CBCT can be justified by the lower risk of iatrogenic errors (Connert et al. 2018).

When planning for a guided access cavity, it should be noted that the technique is limited to straight canals (Krastl et al. 2016, Buchgreitz et al. 2016). Because the drill is straight and not deformable, it should only be used on the straight portion of the canal and not beyond the curvature (Connert et al. 2018, Lara-Mendes et al. 2018a). However, it is possible to apply the technique in molars that tend to have greater curvatures (Shi et al. 2018, Lara-Mendes et al. 2018a), as most of the curvatures would be localized in the apical third (Lee et al. 2006), while calcifications would initially begin in the coronal third and extend apically. The latter would allow access to the canal in its straight portion (Lara-Mendes et al. 2018a). Yet, in cases where the curvature would prevent safe access to the target region, apical surgery would be indicated (Krastl et al. 2016, Lara-Mendes et al. 2018a, Fonseca Tavares et al. 2018).

It should be mentioned that reduced mouth opening could impose a limitation when trying to implement this technique in the posterior region (Connert et al. 2018).

Table 6 CARE checklist

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Letter code: Y, reported on the case report, N, not reported. Obtained from Checklist from CARE guidelines for case reports: explanation and elaboration document (Riley et al. 2017). The table with the detailed parameters to evaluate can be found in the Appendix section.
Not only space could be a limitation, but also the thickness of the root should be taken into account. This might be the case when planning an access cavity on mandibular incisors with smaller roots in comparison to central maxillary incisors (Krastl et al. 2016). Thinner drills are then necessary as suggested by various authors (Connert et al. 2017, 2018).

It is of concern that the forces generated by the tip of the bur can generate cracks on the tooth surface (Capar et al. 2015, Krastl et al. 2016, Fonseca Tavares et al. 2018), as well as produce excessive heat that can be harmful to the periodontal ligament and alveolar bone (Saunders & Saunders 1989). Therefore, cooling is of great importance while using the guide. However, providing sufficient space to allow the passage of irrigating solutions to the alveolar bone and access cavity may not always be possible as it may compromise accuracy.

Planning time invested on the preparation of the guide has been discussed in several studies (van der Meer et al. 2016, Krastl et al. 2016, Zehnder et al. 2016, Connert et al. 2017, 2018, 2019, Ahn et al. 2018, Ye et al. 2018, Torres et al. 2018.). Connert et al. (2017) reported that the average planning time, including digital intraoral impression, virtual planning and design of the template, takes on average 9.4 min (ranging from 7 to 12.8 min). A second pre-clinical study by the same authors assessed the mean treatment duration which was reported to be 11.3 (SD ± 4.6) min when using the guide and 21.8 (SD ± 5.9) min otherwise (Connert et al. 2019). Planning time may vary with different software, but it should not take long, considering a normal learning curve. Furthermore, the preparation of the access cavity by using the guide required only 30 s on average (ranging from 9 to 208 s). All authors agree that although it may seem to be time-consuming, chairside operating times and excessive loss of tooth structure are reduced, and the risk of iatrogenic damage is avoided (van der Meer et al. 2016, Krastl et al. 2016, Connert et al. 2017, 2018, 2019, Ahn et al. 2018, Ye et al. 2018, Torres et al. 2018).

This is the first systematic review on guided endodontics. Concerning the strengths of the study, it was possible to describe the clinical applications of guided endodontics, summarize a protocol for the design of a 3D guide and report on the accuracy of the method. However, reports on accuracy should be analysed critically since the accuracy measuring methods are heterogeneous between studies. Additionally, the number of teeth in experimental studies is chosen arbitrarily, and the outcomes vary between studies. It is hoped that in the future that a standardize measuring protocol to report on the accuracy of the technique will be developed to ease on the assessment and comparison of the different techniques and protocols.

The existing literature lacks high-quality studies and the level of evidence of the literature found is low, given that the majority of the available studies corresponds to pre-clinical studies and case reports. Moreover, the risk of bias is high and the checklists on quality of the study in no case comply with all the parameters that were evaluated. However, given the nature of the procedure, it is difficult to fulfill the checklist as some of the points may not be applicable for case reports or pre-clinical studies. Nevertheless, the average quality of the included case reports was
acceptable to our judgement, scoring an average of 76% on the CARE checklist (Riley et al. 2017).

Considering the limitations of guided endodontics and the review itself, it must be acknowledged that this technique may be a promising method for the endodontic or surgical treatment of complex cases. The use of a guide eases the work of the clinician, reducing the working time and results in a more reliable outcome (Connert et al. 2019). Moreover, the technology used to design and elaborate the guides is today available worldwide (Ackerman et al. 2019). Thus, in the future, guided endodontics may be more widely used in clinical practice (Krastl et al. 2016, Connert et al. 2018), at least when treating PCO teeth and complex surgical cases.

However, some questions were raised by this systematic review, as mentioned above, regarding the protocol steps and the technique itself and further research is needed. High-quality studies are essential to understand the technique, its strengths and limitations in order to offer the patient the best outcome.

Conclusion

Guided endodontic procedures are a promising technique offering a highly predictable outcome and lower risk of iatrogenic damage. Minimally invasive treatment can be performed, and chairside time can be reduced. However, this should be interpreted with care since it is based on limited and low-quality evidence from case reports, observational studies, in vitro and ex vivo studies. Larger population studies with longer follow-up periods are required, as well as standardized experimental studies with similar sample size, aim and a standardized measuring method.

Conflict of interests

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

References


Supporting Information
Additional Supporting Information may be found in the online version of this article:

Appendix S1. Adapted search strategies.
Appendix S2. STROBE statement checklist.
Appendix S3. CARE statement checklist.
Appendix S4. Modified CONSORT checklist.