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REVIEW

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

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Abstract

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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 (Sayegh & Reed 1968), restorative procedures or abfractions (Fleig *et al.* 2017), and in teeth of elderly patients (Sayegh & 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

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correctly (European Society of Endodontology 2006, McCabe & Dummer 2012), and there is an increased probability of failure during treatment (20% according to Kvinnsland *et al.* (1989) and Cvek *et al.* (1982)).

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.
- Report on the accuracy 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

'Guided Endodontics'[Mesh] OR guided endodontic*[tiab] OR (guided technique*[tiab] AND endodontic*[tiab]) OR ((endodontic*[tiab] OR endodontic treatment*[tiab] OR root canal*[tiab]) AND (guided access*[tiab] OR computer guided*[tiab] OR computer aided*[tiab] OR printed template*[tiab] OR 3D printed template*[tiab])) OR (pulp canal calcification*[tiab] AND (guided access*[tiab] OR computer guided*[tiab]

OR computer aided*[tiab] OR printed template*[tiab] OR 3D printed template*[tiab]))

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 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

From the total of 15 case reports, 11 of them corresponded to guided endodontic access cavity (Zubizarreta Macho *et al.* 2015, van der Meer *et al.* 2016, Krastl *et al.* 2016, Mena-Alvarez *et al.* 2017, Connert *et al.* 2018, Shi *et al.* 2018, Lara-Mendes *et al.* 2018a, Fonseca Tavares *et al.* 2018, Lara-Mendes *et al.* 2018b, Torres *et al.* 2018, Maia *et al.* 2019) and 4 to guided endodontic surgery (Strbac *et al.* 2017, Ahn *et al.* 2018, Giacomino *et al.* 2018, Ye

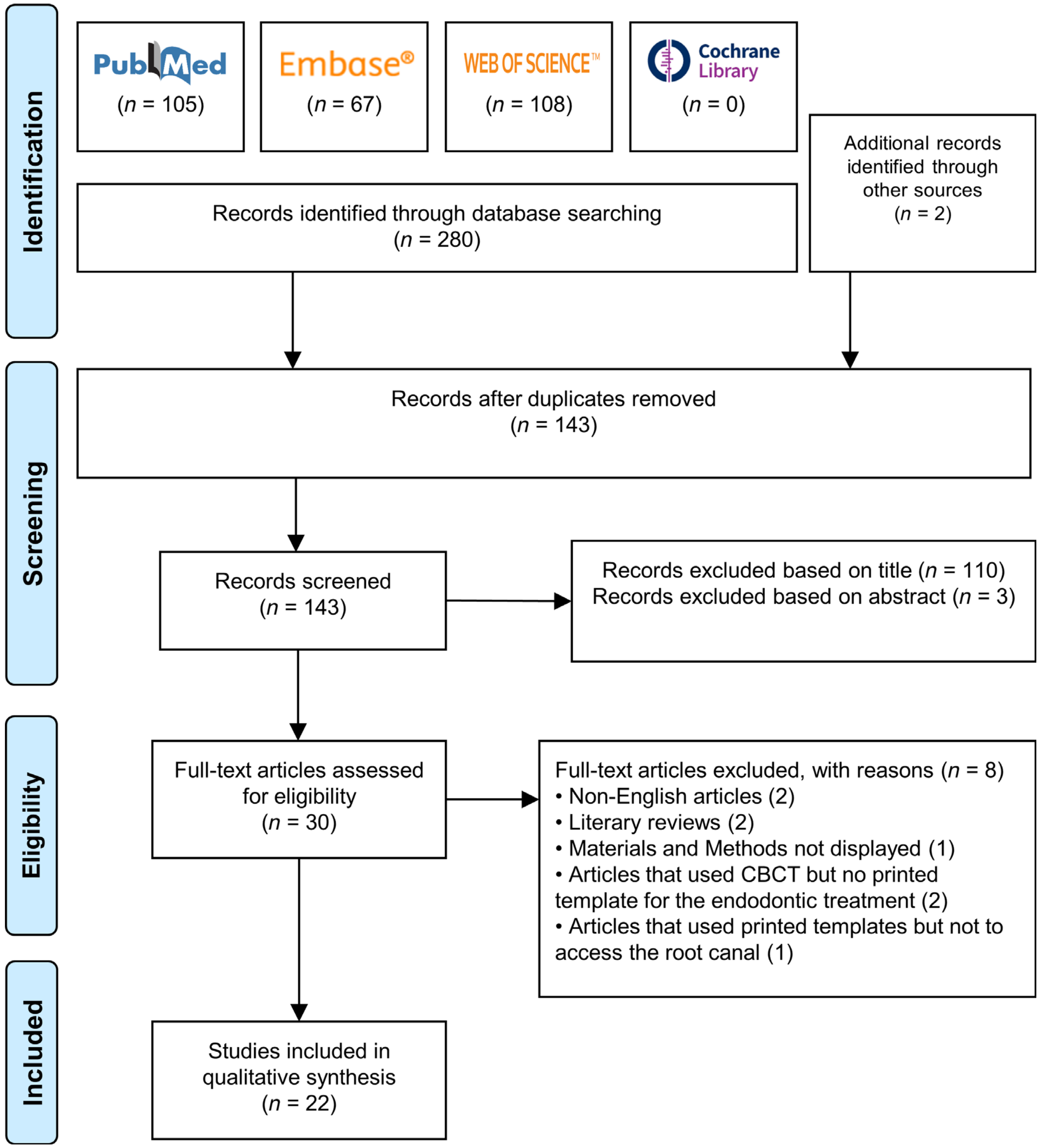

Figure 1 PRISMA flow chart (Liberati *et al.* 2009) of the selection process.

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

Table 1 Data extraction of case reports on guided endodontic access

Material and methods on guided endodontic access case reports

						Impression				Bur				
No	Authors	Teeth	CBCT	FOV	Voxel size	Intraoral	Optical scanner	Planning software	Printer	Type	Specifications	Speed	Template sleeve	Template material
1	Connert *et al.* (2018)	Mandibular Central Incisors	Morita Accuitomo 80 (J Morita Mfg. Corp., Irvine, CA, USA)	Undisclosed	Undisclosed	iTero (Align Technology Inc., San Jose, CA, USA)	N/A	CoDiagnostiX, version undisclosed (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd., Minneapolis, MN, USA)	Specially designed miniaturized bur (Gebr. Brasseler GmbH & Co. KG, Germany)	0.85 mm D	10 000 rpm	Dimensions undisclosed (Steco-system-technik GmbH & Co. KG, Germany)	Med610 (Stratasys Ltd, Minneapolis, MN, USA.)
2	Fonseca Tavares *et al.* (2018)	Maxillary Central Incisor	Undisclosed	Undisclosed	Undisclosed	Silicone impression	3Shape R700 Desktop Scanner (3Shape, Warren, NJ, USA)	Simplant version 11 (Materialize Dental, Belgium)	Objet Eden 260 V (Stratasys Ltd.)	Neodent Drill for Tempimplants (Ref: 103179; JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	1.3 mm D, 20 mm TL, 12 mm WL	10 000 rpm	Undisclosed	FullCure 720 (Stratasys Ltd., Minneapolis, MN, USA)
3	Krastl *et al.* (2016)	Maxillary Central Incisor	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	50 × 50 mm	0.08 mm	iTero (Align Technology Inc.)	N/A	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet Eden 260 V (Stratasys Ltd.)	Straumann Drill for Tempimplants, (Ref: 80381; Straumann, Switzerland)	37 mm TL, 18.5 mm WL, 1.5 mm D	10 000 rpm	6 mm L, 2.8 mm ED, 1.5 mm ID (Fabricated by CNC technology)	Med610 (Stratasys Ltd.)
4	Lara-Mendes *et al.* (2018a)	Maxillary Central Incisor	iCAT (Imaging Sciences International, Hatfield, PA, USA)	Undisclosed	0.12 mm	Intraoral impression (Material undisclosed)	3Shape R700 Desktop Scanner (3Shape)	Simplant version 11 (Materialize Dental-Technologielaan)	Objet Eden 260 V (Stratasys Ltd.)	Neodent Drill for Tempimplants (Ref: 103179; JJGC Ind e Comercio de Materiais Dentarios SA)	1.3 mm D, 20 mm TL, 12 mm WL	1200 rpm	8.0 mm L, 3.0 mm ED, 1.4 mm ID (Ref: 102110; JJGC Ind e Comercio de Materiais Dentarios SA)	FullCure 720 (Stratasys Ltd.)
5	Lara-Mendes *et al.* (2018b)	Second and Third Maxillary Molars	iCAT (Imaging Sciences International)	Undisclosed	0.12 mm	Intraoral impression (Material undisclosed)	3Shape R700 Desktop Scanner (3Shape)	Simplant version 11 (Materialize Dental-Technologielaan)	Objet Eden 260 V (Stratasys Ltd.)	Neodent Drill for Tempimplants (Ref: 103179; JJGC Ind e Comercio de Materiais Dentarios SA)	1.3 mm D, 20 mm TL, 12 mm WL	1200 rpm	8.0 mm L, 3.0 mm ED, 1.4 mm ID (Ref: 102110; JJGC Ind e Comercio de Materiais Dentarios SA)	FullCure 720 (Stratasys Ltd.)

Table 1 Continued

Material and methods on guided endodontic access case reports

No	Authors	Teeth	CBCT	FOV	Voxel size	Impression		Planning software	Printer	Bur			Template sleeve	Template material
						Intraoral	Optical scanner			Type	Specifications	Speed		
6	Maia *et al.* (2019)	Maxillary First Molar and Second Premolars	iCAT (Imaging Sciences International)	Undisclosed	Undisclosed	TRIOS Color Pod (3Shape, Denmark)	N/A	CoDiagnostiX, version undisclosed (Dental Wings Inc., Germany)	Objet Eden 260 V (Stratasys Ltd.)	Neodent Drill for Tempimplants (Ref: 103044; 103179; JJGC Ind e Comercio de Materiais Dentarios SA)	1.1 mm D for Molar, 1.3 mm D for Premolars	350 rpm	Undisclosed	Med610 (Stratasys Ltd.)
7	Mena-Alvarez *et al.* (2017)	Maxillary Central Incisor	White Fox (Acteón Medico-Dental Iberica S.A.U.-Satelec, France)	60 × 60 mm	Undisclosed	Undisclosed	Undisclosed	SIMPLANT (Dentsply Implants, Belgium)	Projet 6000 (3D Systems, USA)	Diamond bur (Ref: 882314012; Komet Medical, Germany)	1.2 mm D, 14 mm TL	Undisclosed	5 mm L, 1.3 mm ID	Medical-use resin
8	Shi *et al.* (2018)	First	Mandibular Molar	ICAT 17-19 (Imaging Sciences International, Hatfield, PA, USA)	Undisclosed	Undisclosed	CEREC AC (Sirona Dental Systems, Germany)	N/A	3 Matic 9.0 (Materialize, Belgium) and ZBursh (it is ZBrush) (Pixologic Inc, Los Angeles, CA, USA)	3510SD (3D System				
			Corporation, Rock Hills, SC, USA)	Ultrasonic Tips (SATELEC, ACTEON, France)	ET20 and ET25	Undisclosed	1.2 mm ID	UV-curable plastic (VisiJet M3; 3Dsystem, Rock Hills, SC, USA)						
9	Torres *et al.* (2018)	Maxillary Lateral Incisor	NewTom VGi evo (NewTom, Italy)	100 × 100 mm	0.2 mm	Alginate impression	Activity 885 (SmartOptics, Germany)	Mimics 19.0 and 3 Matic 11.0 (Materialize, Belgium)	Object Connex 350 (Stratasys Ltd., Minneapolis, MN, USA)	Munce bur (CJM Engineering Inc., Santa Barbara, CA, USA)	Size 1: 0.8 mm D, 34 mm TL	10 000 rpm	7 mm L, 1 mm ID	Med610 (Stratasys Ltd.)
10	van der Meer *et al.* (2016)	Maxillary Anterior Teeth	3D examination (KAVO, The Netherlands)	Undisclosed	0.3 mm	Lava COS (3M Espe, Zoeterwoude, The Netherlands)	N/A	3ds Max Software (Autodesk, San Rafael, CA, USA)	Undisclosed	Munce bur (CJM Engineering Inc., USA)	Size 2: 1 mm D, 34 mm TL	Undisclosed	3 mm ID, 2.4 mm ID	Undisclosed
11	Zubizarreta Macho *et al.* (2015)	Maxillary Lateral Incisor	WhiteFox, (Acteón Médico-Dental Ibérica S.A.U.-Satelec, France)	150 × 130 mm	Undisclosed	Alginate impression	D710 scanner (3Shape, Warren, NJ, USA)	SIMPLANT (Dentsplay Implants, Belgium)	Projet 6000 (3D Systems, Rock Hills, SC, USA)	Diamond bur (Ref: 882314012; Komet Medical)	1.2 mm D, 14 mm TL	Undisclosed	5 mm L, 1.3 mm ID	Medical-use resin

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

used intraoral scanners to obtain surface information in a single step (van der Meer *et al.* 2016, Krastl *et al.* 2016, Strbac *et al.* 2017, Connert *et al.* 2018, Shi *et al.* 2018, Ye *et al.* 2018, Maia *et al.* 2019,), while the rest obtained impressions with alginate or silicone and the gypsum casts were later scanned with an optical scanner (Zubizarreta Macho *et al.* 2015, Mena-Alvarez *et al.* 2017, Ahn *et al.* 2018, Giacomino *et al.* 2018, Fonseca Tavares *et al.* 2018, Lara-Mendes *et al.* 2018a,b, Torres *et al.* 2018). All articles that used guides for the access cavity used burs, except for Shi *et al.* (2018) who used ultrasonic tips to access the canal.

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 fulfiled 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 2 Data extraction of case reports on guided endodontic surgery

Material and methods on guided endodontic surgery case reports

						Impression				Bur				
No	Authors	Teeth	CBCT	FOV	Voxel Size	Intraoral	Extraoral	Planning software	Printer	Type	Specifications	Speed	Template sleeve	Template material
1	Ahn *et al.* (2018)	First Mandibular Molar	Alphrad 3030 (Asahi Roentgen Ind Ltd., Japan)	Undisclosed	Undisclosed	Alginate impression	Identica Blue (Medit, Korea)	Ondemand3D (Cybermed Co., Korea)	Objet Eden 260V (Stratasys Ltd.)	Anchor drill	20 mm T, 1.5 mm D	Undisclosed	Undisclosed	Med610 (Stratasys Ltd.)
2	Giacomino *et al.* (2018)	Maxillary First and Second Molars and Mandibular Second Premolar	3D Accuitomo 170 (J Morita Mfg. Corp., Irvine, CA, USA)	80 × 80 mm	Undisclosed	Polyvinyl siloxane impression (Aquasil Ultra, Dentsply Caulk, Milford, DE, USA)	3Shape D1000 (Whip Mix Corp., Lousville, KY, USA)	Mimics (Materialize, Leuven, Belgium) or Blue Sky Plan 3 (Blue Sky Bio, LLC, Grayslake, IL, USA)	Objet 260 Connex3 (Stratasys Ltd.)	Hollow trephine (Biomet 3i, LLC, Palm Beach Gardens, FL, USA)	5 or 6 mm D	1200 rpm	Min 7 mm L with irrigation window	Undisclosed
3	Strbac *et al.* (2017)	Maxillary First Molar and Second Premolar	Siemens Somatom Sensation 4 (Siemens Healthcare GmbH, Germany)	Undisclosed	$0.18 \times 0.18 \times 0.5mm^{a}$	iTero (Align Technology Inc.)	N/A	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet 350 Connex 3 (Stratasys Ltd.)	Piezoelectric saw (Piezomed Instruments, Piezomed, W&H Dentalwerk GmbH, Austria)	B7 (Piezomed instrument)	Undisclosed	N/A	Med610 (Stratasys Ltd.)
4	Ye *et al.* (2018)	Maxillary Lateral Incisor and Canine	ICAT 17-19 (Imaging Sciences International)	Undisclosed	Undisclosed	3Shape (Denmark)	N/A	SIMPLANT (Dentsply Implants, Belgium)	3510SD (3D system Corporation)	Trephine (Meisinger, Germany)	4 mm D	Undisclosed	2 mm L, 4.2 mm ID	Undisclosed

Letter coding: D, diameter; ED, external diameter; ID, inner diameter; L, length; min, minimum; N/A, not Applicable; TL, total length; WL, working length.
[a]Anisotropic voxel because of the use of a MSCT scan.

Table 3 Data extraction of observational studies

Material and methods on guided endodontic access case reports

No	Authors	Sample	CBCT	FOV	Voxel size	Impression		Planning software	Printer	Bur		Template	Template material
						Intraoral	Extraoral			Type	Specifications		
1	Buchgreitz *et al.* (2019)	50 patients	Orthophos XG 3D unit (Sirona Dental Systems)	Undisclosed	0.5 mm	CEREC (Sirona Dental Systems)	N/A	Galaxis/ Galileos Implant, (Sirona Dental Systems)	No printer. CNC technology (SICAT optiguide, Germany)	Modified spiral bur (Busch, Germany)	1.2 mm D, 22 mm WL	4 mm L, 1.2 mm ID	Undisclosed

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

et al. 2016, Zehnder *et al.* 2016, Connert *et al.* 2017, 2019). Furthermore, there were no reports of root perforations when performing guided endodontic access (Zubizarreta Macho *et al.* 2015, van der Meer *et al.* 2016, Krastl *et al.* 2016, Strbac *et al.* 2017, Mena-Alvarez *et al.* 2017, Connert *et al.* 2018, Ahn *et al.* 2018, Giacomino *et al.* 2018, Shi *et al.* 2018, Lara-Mendes *et al.* 2018a, Ye *et al.* 2018, Fonseca Tavares *et al.* 2018, Lara-Mendes *et al.* 2018b, Torres *et al.* 2018, Maia *et al.* 2019).

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 mm^3 (SD ± 3.0) for the guided technique and 49.9 mm^3 (SD ± 7.7) for the conventional approach by all operators (Connert *et al.*

Table 4 Data extraction on experimental studies

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

									Bur			Guide		
No	Authors	Endodontic application	Sample size (*n*)	CBCT	Voxel size	Impression	Planning software	Printer	Type	Specifications	Speed	Type	Sleeve	Template material
1	Ackerman *et al.* (2019)	Guided Endodontic Surgery	48 roots (surgical access cavities)	iCAT FLX (Dental Imaging Technologies Corp., Hatfield, PA, USA)	0.2 mm	Trios (3Shape)	Blue Sky Bio (LLC., Greyslake, IL,USA)	Form 2 (Formlabs Inc., Somerville, MA, USA)	Surgical Lindemann bur (Meisinger, Germany)	<2 mm D	Undisclosed	3D Printed	2 mm ID Variable L	Dental SG Resin (Formlabs Inc., Somerville, MA, USA)
2	Buchgreitz *et al.* (2016)	Guided Endodontic Access	38 teeth	Orthophos XG 3D unit (Sirona Dental Systems)	Undisclosed	CEREC (Sirona Dental Systems)	Galaxis/Galileos Implant, (Sirona Dental Systems)	Nonused	Modified spiral bur (Busch)	1.2 mm D, 22 mm WL	250 rpm	CNC technology (SICAT optiguide)	4 mm L, 1.2 mm ID	Undisclosed
3	Connert *et al.* (2017)	Guided Endodontic Access	59 teeth (Mandibular incisors and canines)	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	0.08 mm	iTero (Align Technology Inc.)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd.)	Specially designed bur (Gebr. Brasseler GmbH & Co KG, Germany)	0.85 mm D, 20 mm WL, 28 mm TL	10 000 rpm	3D Printed	6 mm L, 0.88 mm ID, 4 mm ED	Med610 (Stratasys Ltd.)
4	Connert *et al.* (2019)	Guided Endodontic Access	48 teeth (Maxillary and Mandibular Incisors)	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	0.125 mm	iTero (Align Technology Inc.)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd.)	Specially designed bur (Gebr. Brasseler GmbH & Co KG, Germany)	0.85 mm D, 20 mm WL, 28 mm TL	10 000 rpm	3D Printed	6 mm L, 0.88 mm ID, 4 mm ED	Med610 (Stratasys Ltd.)
5	Pinsky *et al.* (2007)	Guided Endodontic Surgery	110 surgical access cavities	iCAT (Imaging Sciences International)	Undisclosed	Nonused	CADImplant Inc.	Nonused	Undisclosed	1.8 mm D	Undisclosed	Computer driven drilling (Scannographic guide)	Undisclosed	Acrylic material (Triad, Dentsply, USA)
6	Zehnder *et al.* (2016)	Guided Endodontic Access	58 teeth (single rooted)	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	0.125 mm	iTero (Align Technology Inc.)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd.)	Straumann Drill for Tempimplants, (Ref: 80381; Straumann)	1.5 mm D, 18.5 mm WL, 37 mm TL	10 000 rpm	3D Printed	6 mm L, 1.5 mm ID, 2.8 mm ED	Med610 (Stratasys Ltd.)

(b) Results on guided endodontics's experimental studies

No	Authors	Method	Accuracy analysis method	Deviation at base of bur	Deviation at tip of bur	Deviation angle	Success rate	Clinical applicability
1	Ackerman *et al.* (2019)	Compare accuracy of freehand drilling versus virtual planned osteotomies	Drilled osteotomies were registered to virtual osteotomies and differences were measured	–	1.473 mm mean (±0.751 SD) using guide, 2.638 mm mean (±1.387 SD) freehand	–	100% of targets reached within 4 mm (using guide)	✓
2	Buchgreitz *et al.* (2016)	Drill in bulk of dentine to the centre of apical target point (Gutta-percha size 30 on apical third)	Virtual drill path registered to performed drill path. Centre axis extended to target point and measure distance to centre of target	–	Mean 0.46 mm	–	–	✓
3	Connert *et al.* (2017)	Access to the root canal	Registration pre-CBCT with post-CBCT. Analysis automatically via the software	BO: 0.13 mm mean (0–0.4 mm) MD: 0.12 mm mean (0–0.54 mm) AC: 0.12 mm mean (0–0.41 mm)	BO: 0.34 mm mean (0–1.26 mm) MD: 0.14 mm mean (0–0.99 mm) AC: 0.12 mm mean (0–0.4 mm)	1.59° mean (0–5.3°)	100%	✓
4	Connert *et al.* (2019)	Compare accuracy of conventional technique to guided access cavities	Registration pre-CBCT with post-CBCT. Analysis automatically via the software	–	–	–	91.7% (22 of 24 root canals were achieved)	✓

Table 4 Continued

(b) Results on guided endodontics's experimental studies

No	Authors	Method	Accuracy analysis method	Deviation at base of bur	Deviation at tip of bur	Deviation angle	Success rate	Clinical applicability
5	Pinsky *et al.* (2007)	Compare accuracy of freehand drilling versus virtual planned osteotomies	Drilled osteotomies were registered to virtual osteotomies and differences were measured	–	0.79 mm mean (±0.33 SD) using guide, 2.27 mm mean (±1.46 SD) freehand	–	88% of targets reached within 1 mm (using guide)	✓
6	Zehnder *et al.* (2016)	Create access to the apical third of the root canal	Registration pre-CBCT with post-CBCT. Analysis automatically via the software	BO: 0.2 mm mean (0–0.76 mm) MD: 0.21 mm mean (0–0.75 mm) AC: 0.16 mm mean (0–0.76 mm)	BO: 0.47 mm mean (0–1.59 mm) MD: 0.29 mm mean (0–1.34 mm) AC: 0.17 mm mean (0–0.75 mm)	1.81° mean (0–5.6°)	100%	✓

(a) Letter coding: D, diameter, ED, external diameter; ID, inner diameter; L, length; TL, total length; WL, working length. (b) Colour code study type: Green: *ex vivo* studies, Yellow: *in vitro* studies. Letter coding: BO: buccal-oral direction, AC, apical-coronal direction; MD, mesial-distal direction; SD, Standard Deviation.

2019). 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

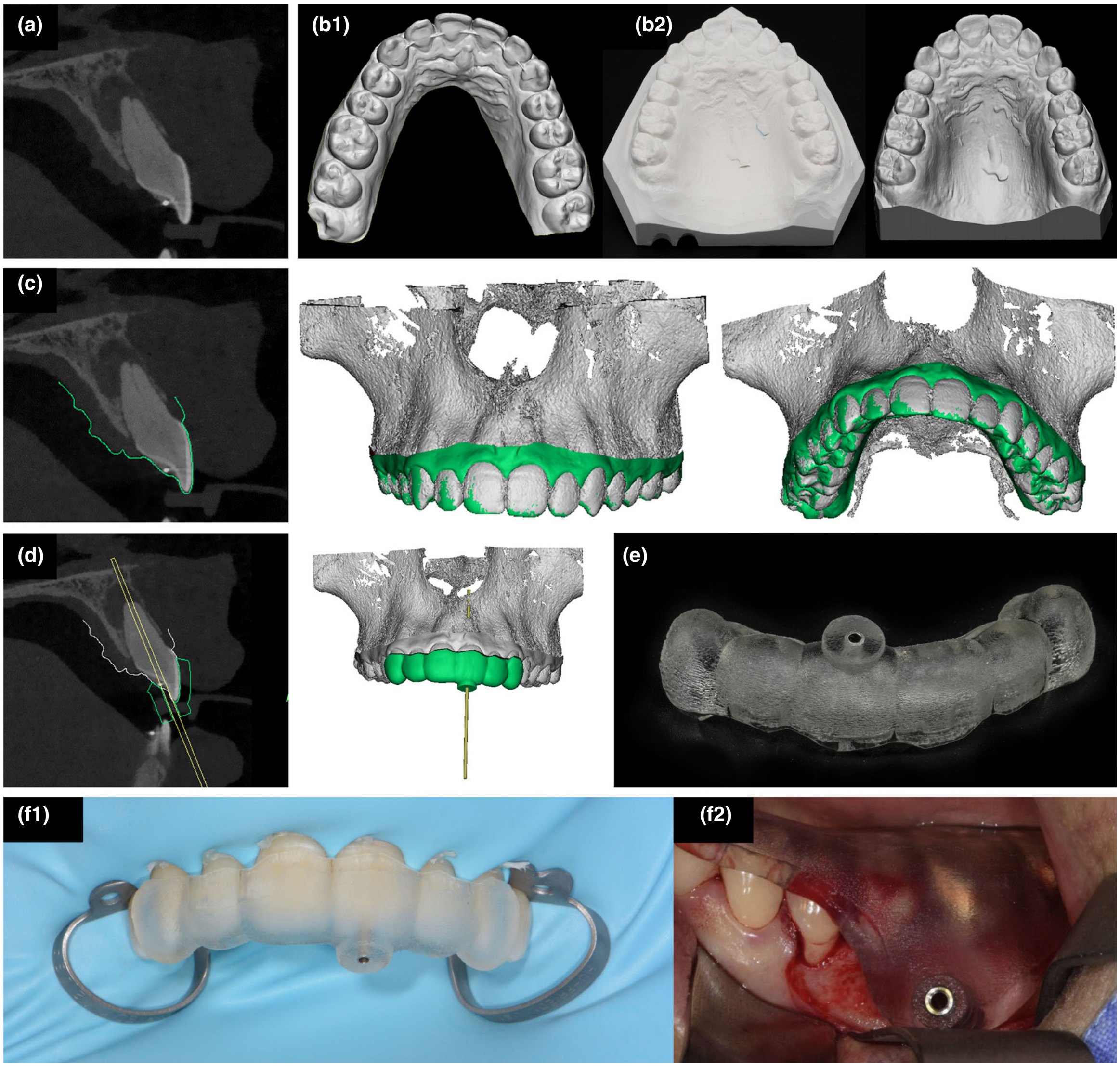

Figure 2 Workflow for guided endodontics. A CBCT from the patient is acquired (a) as well as a digital intraoral impression directly (b.1) or indirectly (b.2). The information from both sources is combined and registered in a digital planning software (c). Then, a treatment guide is designed (d) and fabricated (e). Finally, the guide is either used during guided access cavity preparation (f.1) or apical surgery (f.2: image adapted from Ahn et al. 2018).

a guide, the loss of tissue and the possibility of failure would be much greater than what is lost when straightening the cavity (Krastl *et al.* 2016, Strbac *et al.* 2017, Connert *et al.* 2018, Lara-Mendes *et al.* 2018b, Connert *et al.* 2019).

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

Table 5 STROBE checklist

STROBE statement checklist	1		2	3	4	5	6		7	8	9	10	11	12					13			14			15	16			17	18	19	20	21	22	%
Author	a	b					a	b						a	b	c	d	e	a	b	c	a	b	c		a	b	c							
Buchgreitz *et al.* (2019)	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	Y	N	71%

Letter code: Y, reported on the article, N, not reported. Obtained from the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guideline, Explanation and Elaboration (Vandenbroucke *et al.* 2007). The table with the detailed parameters to evaluate can be found in the Appendix section.

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

Table 6 CARE checklist

CARE checklist			3				5					8				9		10				11						
Author	1	2	a	b	c	4	a	b	c	6	7	a	b	c	d	a	b	a	b	c	d	a	b	c	d	12	13	%
Ahn *et al.* (2018)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N	85
Connert *et al.* (2018)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	74
Fonseca Tavares *et al.* (2018)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	78
Giacomino *et al.* (2018)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N	81
Krastl *et al.* (2016)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	74
Lara-Mendes *et al.* (2018a)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	81
Lara-Mendes *et al.* (2018b)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N	78
Maia *et al.* (2019)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	78
Mena-Alvarez *et al.* (2017)	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	70
Shi *et al.* (2018)	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	67
Strbac *et al.* (2017)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	81
Torres *et al.* (2018)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	81
van der Meer *et al.* (2016)	N	Y	Y	N	Y	Y	N	N	N	N	Y	N	N	N	N	Y	Y	Y	N	N	N	Y	Y	Y	Y	N	Y	48
Ye *et al.* (2018)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	93
Zubizarreta Macho *et al.* (2015)	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	70

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.

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.*

Table 7 Modified CONSORT checklist

Modified CONSORT checklist																
		2														
Author	1	a	b	3	4	5	6	7	8	9	10	11	12	13	14	%
Ackerman *et al.* (2019)	Y	Y	Y	N	Y	N	N	N	N	Y	Y	Y	Y	Y	N	60
Buchgreitz *et al.* (2016)	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	60
Connert *et al.* (2017)	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	60
Connert *et al.* (2019)	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	60
Pinsky *et al.* (2007)	N	Y	Y	Y	Y	N	N	N	N	N	Y	Y	N	Y	N	47
Zehnder *et al.* (2016)	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	60

Letter code: Y, reported on the article, N, not reported. Obtained from Checklist from Guidelines for Reporting Pre-Clinical In-Vitro Studies on Dental Materials (Faggion 2012). The table with the detailed parameters to evaluate can be found in the Appendix section.

2017, 2018, Lara-Mendes *et al.* 2018a, Torres *et al.* 2018). 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 (Çapar *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, Fonseca Tavares *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 $\pm$ 4.6) min when using the guide and 21.8 (SD $\pm$ 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 fulfil 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 standardize experimental studies with similar sample size, aim and a standardize measuring method.

Conflict of interests

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

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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.

