KU Leuven
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OMFS-IMPATH Research Group

KU LEUVEN

DOCTORAL SCHOOL
BIOMEDICAL SCIENCES

Guided Endodontics

A critical evaluation by means of in vitro studies and a clinical trial

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Promotor
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Guided Endodontics

Een kritische evaluatie door middel van in-vitro-onderzoeken en een klinische studie

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tot het behalen van de graad van
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For Ellen, Ana, Adrián and …

"Doubt is the origin of wisdom."
René Descartes

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List of abbreviations

3D	Three dimensional
6DOF	Six degrees of freedom
AR	Augmented reality
AP	Apical periodontitis
CBCT	Cone beam computed tomography
CCT	Controlled clinical trial
DICOM	Digital imaging and communications in medicine
DN	Dynamic navigation
EMS	Endodontic microsurgery
FOV	Field of view
GE	Guided endodontics
IMU	Inertial measurement unit
IOS	Intraoral scan
LiDAR	Light detection and ranging
PCO	Pulp canal obliteration
POI	Points of interest
STL	Standard tessellation language
TDI	Traumatic dental injuries
TEMS	Targeted endodontic microsurgery
VIO	Visual-inertial odometry

Introduction and aims

Pulp Canal Obliteration (PCO) or Calcific Metamorphosis is a process characterized by the deposition of hard tissue within the root canal [1]. It presents most commonly as a sequelae of traumatic dental injuries (TDI), and is reported to develop more often in teeth following concussion and subluxation injuries [2]. It can also present as a result of caries, tooth surface loss or operative procedures and rarely orthodontic treatment [1]. Also, in elderly patients, a lifelong apposition of secondary or tertiary dentin, can end up in a severe PCO [3].

Traumatic dental injuries are highly common and account for 85% of patients presenting with injuries to the oral region. They affect one billion people globally with a prevalence of 15.2% in permanent dentition [4]. Most often, patients suffering from TDI in the past, present years after the accident with a single discolored tooth. This discoloration may be the result of PCO, the pulp cavity being filled with dark tertiary dentine resulting in a darker hue, loss of translucency and yellowish appearance of the crown which is detected clinically (Figure 1) [2, 5]. Although the exact mechanism of PCO is still unknown, damage to the neurovascular supply of the pulp is probably related to this process [5-7].

Furthermore, teeth presenting PCO after trauma could develop pulpal necrosis and apical periodontitis (AP) in a range from 1% up to 27% of the cases [8-14]. Only when the tooth presents symptoms or radiographic signs of AP endodontic treatment should be indicated [5].

The main goal of endodontic treatment is the treatment and prevention of apical periodontitis (AP) trough thorough cleaning and shaping of the root canal system and its complete filling with an inert material to achieve periapical healing [15, 16]. However, localizing canals that present PCO can be a difficult and long task, taking from 15 minutes up to 1 hour [3]. In such cases, achieving a predictable treatment outcome, avoiding technical failures, will be challenging for even the most experienced practitioner [12].

A technical failure in endodontics refers to a situation where the root canal treatment does not achieve its intended goal due to problems related to the technical aspects of the treatment. In the case of teeth presenting with PCO, technical failures could involve not finding the root canal, instrument fracture, and root perforation, all of which may prevent complete chemomechanical debridement of the canal system, thus preventing effective elimination of bacteria and compromising the treatment outcome [17].

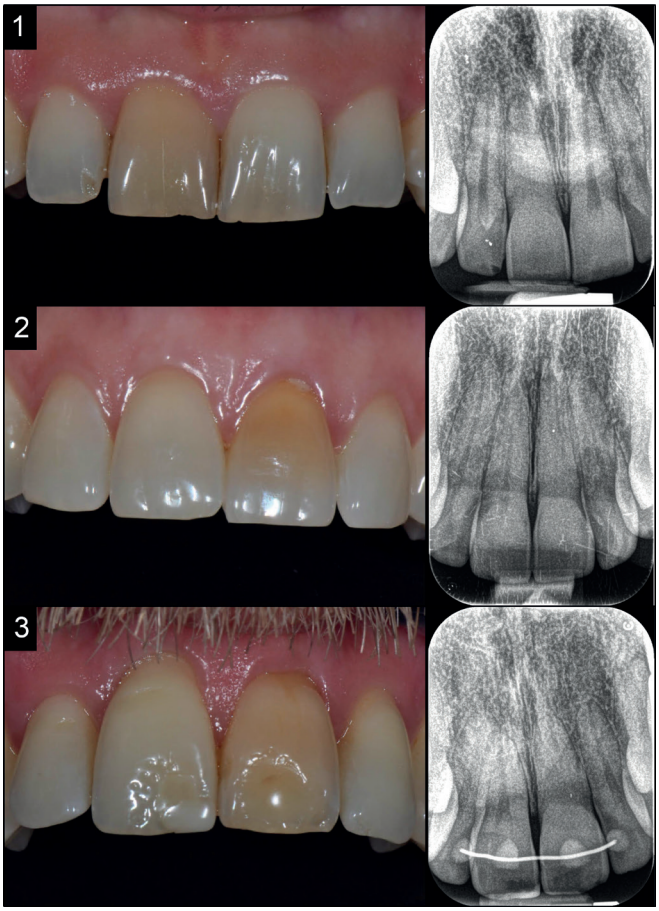

Figure 1. Clinical photos and periapical radiographs of teeth presenting with PCO. (1 – 3, left) Clinical examples of patients suffering from TDI in the past presenting at the dental practice, years after the accident, with a single discolored tooth with a yellowish appearance.
(1 – 3, right) Periapical radiographs of every case showing a severely calcified pulp canal without evidence of apical periodontitis.

In a study from Cvek [18] the total frequency of technical failures (perforation, fracture of a file or not finding the root canal) when performing an endodontic treatment on incisors presenting PCO was 14.3%. Moreover, when comparing upper and lower incisors without or only partially visible root canal, 71% of the treatments of lower incisors failed in comparison to 17% for upper incisors. Additionally, only 50% of the cases presenting a technical failure during treatment healed after 4-year follow-up.

Limited field of view Cone-Beam Computed Tomography (CBCT), is a universally accepted method for imaging hard tissues in the maxilla and mandible and it is beneficial in such cases for intra-appointment identification and localization of

calcified canals [19]. Root morphology can be visualized in three dimensions, as can the number of root canals and their exact location in the root [20]. This may help the clinician to establish a customized strategy with which to approach the canal prior to treatment, which could potentially reduce treatment time.

Another alternative for the treatment of PCO is the concept of Guided Endodontics (GE), in which a 3D printed guide is used to guide the bur up to the target location [21-25]. In this method, a digital impression of the patient's jaw is taken and registered to the data from the CBCT. Then, a path for the bur is created up to the target location (e.g. permeable portion of the root canal) as visualized on the CBCT. Finally, a guide is designed on the computer and 3D printed (Figure 2). This technique has been reported in the literature by several authors for the treatment of PCO [21-24, 26-28], dens evaginatus [29] and even during apicoectomy [28, 30, 31] in cases where otherwise extraction is the only option.

By using a 3D printed guide for endodontic treatment the chances of having technical failures, as iatrogenic damage or excessive loss of tooth structure, are reduced and the likelihood of finding the target is high, while reducing also treatment time [24, 26, 27, 32]. It has been shown that the mean substance loss is 5 times more when

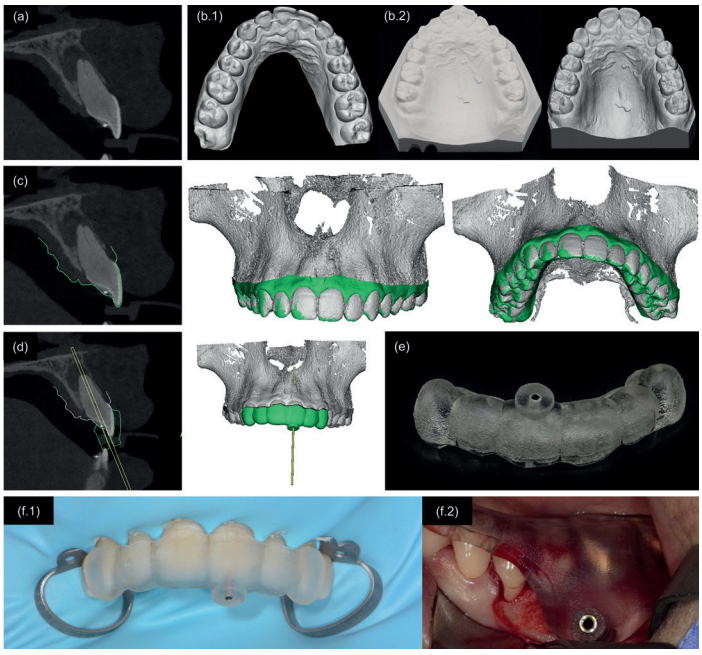

Figure 2. Workflow for guided endodontics. A CBCT from the patient is acquired (a) as well as a digital intraoral impression directly (b.1) or indirectly (b.2). The information from both sources is combined and registered in a digital planning software (c). Then, a treatment guide is designed (d) and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

drilling free-handed in comparison to the guided technique regardless of the experience of the operators [33]. Additionally, 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 free-handed technique (42%, 10/24) [33].

Another advantage of this technique is that it gives the possibility to preoperatively visualize the canal location and design the access in detail without having to mentally transfer the planning to the clinical situation [23]. Moreover, the final preparation shape does not exceed the size of the last instrument used, resulting in a minimally invasive treatment while maintaining as much of the root's rigidity as possible [34].

This type of static guides used are tooth-supported. A drawback of this method is that once it is manufactured, the planned angulation, size, and depth, cannot be easily changed [35]. Other problems include that there is a time needed to plan and manufacture the guide, which makes difficult to immediately treat urgent cases. In addition, it may not be possible to use static guides in patients with limited mouth opening, or in posterior regions where space is limited [36].

Another approach, is the use of dynamic navigation. Dynamic guidance or dynamic navigation (DN) is based on computer-aided surgical navigation technology, an analogous to global positioning systems or satellite navigation. It has been used in a number of areas in dentistry, such as Maxillofacial Surgery and Periodontics [35, 37]. With dynamic guidance, the position of the virtual path, correlated to reference points, is planned using computer software and the imported preoperative CBCT data. A system of motion-tracking optical cameras and images of the position of the virtually planned path provides real-time dynamic and visual feedback to guide the bur during the procedure. Therefore, information that has been planned on the scan is transferred to the real life clinical situation and the exact position of the handpiece can be tracked (Figure 3) [36].

Clinical case reports in the literature [38] and in vitro studies demonstrate also the potential of using computer-aided dynamic navigation technology during guided endodontic treatment [39-41]. A number of benefits have been attributed to dynamic navigation systems. They reduce errors and are superior in accuracy to freehand treatment [35, 42, 43]. It has also been reported that the high accuracy of dynamic navigation minimizes the potential risk of damage to critical anatomical structures [44], including nerves or neighboring teeth, and increases intraoperative safety [37]. It does not require special burs, conventional drills and burs are easily used as they do not have to rotate within a guide sleeve. It does not require to wait for the manufacture process of a guide, the treatment can be done within short time after scanning the

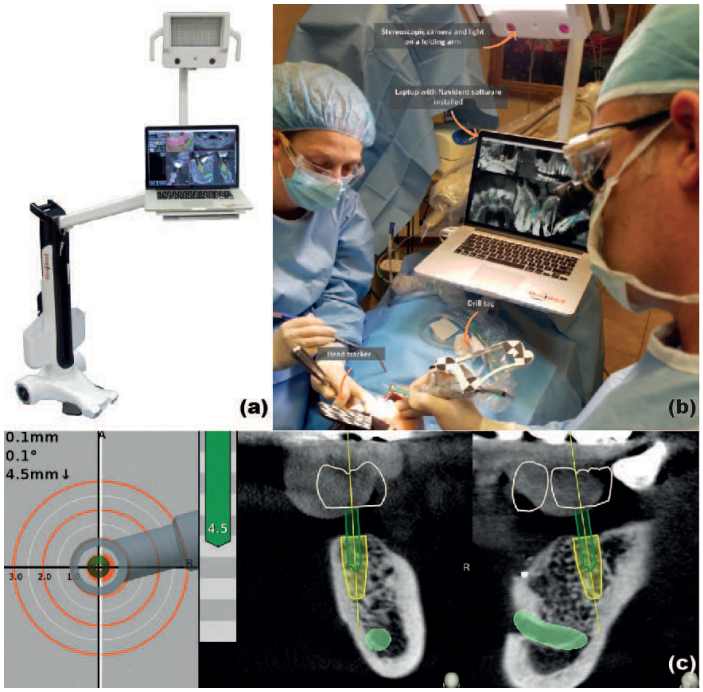

Figure 3. Dynamic navigation. Dynamic navigation device (example during implant placement) (a). A system of motion-tracking optical cameras (stereoscopic camera and light) track the position of the handpiece (drill tag) and head of the patient (head tracker), to provide the position of the drill in reference with the virtually planned path in real-time (b). The visual feedback is displayed as a target with crosshair reticule, with information on the apical deviation, angulation and drilling depth (c).

patient. Multiple drill paths in multi-canal teeth can be easily planned and executed, and it allows treatment changes to be made at the time of treatment so drill paths can be updated as new information is acquired during the procedure [35, 36, 38].

Although promising, there is a small number of studies assessing the "accuracy" of GE and DN. Accuracy measures how close results are to the true or known value, which in this case, can be extrapolated to the deviation of the drilled access cavity from the 3D planning. This measurement should be as small as possible when reaching the end point of the planning, thus improving the likelihood of localizing the root canal, avoiding deviations or technical failures that could compromise the outcome of the treatment and lead to a failed case [45].

Aim and objectives

The general aim of this PhD project was to investigate on the clinical applications and accuracy of the various methods for Guided Endodontics, and to provide an answer to the question: does guided endodontics treatment results in less technical failures compared to free-hand treatment?

We set up to accomplish this by dividing the PhD project in three Phases: Phase I comprises a systematic review of the literature, Phase II comprises in vitro studies on the accuracy of different techniques, and Phase III comprises a controlled clinical trial on guided endodontics. The following objectives were defined:

Phase I – Systematic Review of the literature.

General Aim: to provide a summary of the literature on the topic of Guided Endodontics and Dynamic Navigation.

General Hypothesis: Clinicians can benefit from the use of Guided Endodontics, either by using 3D printed templates or Dynamic Navigation, which can help preventing needless tooth tissue removal, technical complications during treatment, and ultimately improving the prognosis of the treatment.

Chapter 1 – Aim: 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.

Chapter 2 – Aim: to systematically review the available literature on the accuracy of non-surgical endodontic treatment procedures that are completed freehanded and using Dynamic Navigation.

Phase II – Accuracy assessment of different techniques for Guided Endodontics

General Aim: (1) To develop a protocol to be able to measure the accuracy of guided endodontics in-vivo. (2) To assess the accuracy and present data of different techniques for Guided Endodontics and Targeted Endodontic Microsurgery.

Chapter 3 – Aim: to validate a novel method using a post-operative intraoral scan (IOS) versus the gold standard, Cone Beam Computed Tomography (CBCT), on its ability to measure the accuracy of guided endodontics ex vivo.

Hypothesis: The accuracy measurements taken with a CBCT do not differ from the ones taken by IOS.

Chapter 4 – Aim: to assess the accuracy of sleeveless guided endodontics for guided root canal treatment of severe PCO in 3D printed jaws.

Hypothesis: sleeveless guides present a compelling alternative to conventional endodontic guides delivering comparable levels of accuracy while offering diverse advantages.

Chapter 5 – Aim: to evaluate the 3D accuracy and outcome of a dynamic navigation method for guided root canal treatment of severe PCO in 3D printed jaws in a laboratory setting.

Hypothesis: Dynamic Navigation, with its real-time guidance, is an accurate method for access cavity preparation in teeth presenting with severely calcified canals.

Chapter 6 – Aim: to evaluate the accuracy of Augmented Reality for guided access cavity preparation in 3D-printed jaws.

Hypothesis: Augmented Reality offers a precise and reliable method for guided endodontic access cavity preparation up to the pulp chamber.

Chapter 7 – Aim: to assess the accuracy of Targeted Endodontic Microsurgery in comparison to Endodontic Microsurgery. This approach aims to compare the drilled cavity to the planning with respect to nine parameters (deviation at entry point, end point, total deviation, depth, angle, root bevel, root resection, osteotomy volume and surgical time).

Hypothesis: TEMS is an accurate method for apical root resection in comparison to free-handed EMS, minimizing the risk of technical errors and complications, ultimately leading to more predictable and successful outcomes.

Phase III – Controlled Clinical Trial on Guided Endodontics

Chapter 8 – Aim: to assess the clinical outcome of guided endodontics for the treatment of teeth presenting with PCO in comparison to free-hand treatment. The main clinical research question is (PICO): in teeth presenting with PCO (P), does guided endodontics treatment (I) results in less technical failures (O) compared to free-hand treatment (C)?

Hypothesis: guided endodontics, by the use of 3D printed templates, presents less technical failures compared to free-handed treatment when treating teeth presenting with PCO.

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Conflict of interests

Authors declare that they have no conflict of interests.

Chapter 1

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

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Keywords

Cone-beam computed tomography
Guided access
Guided endodontics
Guided surgery
3D printed template

Abstract

Aim - The novel concept of guided endodontics has been reported as an effective method to obtain safe and reliable results in endodontic treatment. The aim of the present study is to evaluate by means of a systematic review the clinical applications, accuracy, and limitations of guided endodontic treatment. **Methods** - A search of the literature was performed on PubMed, EMBASE, Web of Science and Cochrane Library databases, until April 25th, 2019. No language or year restrictions were applied. 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. Quality assessment was done with STROBE, CARE and Modified CONSORT guidelines for observational, case reports and preclinical 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. **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.

1.1 Introduction

Pulp canal obliteration (PCO) is the deposition of hard tissue within the root canal space [1]. It is commonly associated in teeth with a history of trauma [1-4], following orthodontic treatment [2, 5], in response to pulpal injuries [6], dental caries [7], restorative procedures or abfractions [8], and in teeth of elderly patients [7, 9, 10].

In such cases, if root canal treatment is indicated, the treatment will be more challenging compared toa tooth with a wide and patent canal [11]. The access cavity will be difficult to align correctly [1, 12], and there is an increased probability of failure during treatment (20% according to Kvinnsland et al. [13] and Cvek et al. [14]).

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 neighboring anatomical structures. Hence, the use of Cone Beam Computed Tomography (CBCT) is indicated in some cases [15].

CBCT can be used in difficult cases in which conventional radiographs do not provide sufficient information on the morphology of the tooth and its surroundings [16, 17]. 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 [15, 18].

Recently, the concept of guided endodontics has been reported, in which computer-designed guides are used for access cavity preparation [19, 20] and endodontic surgery [21], in order to achieve predictable and safe results [15]. 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 [22, 23].

This novel concept could help clinicians during treatments, it may avoid unnecessary removal of tissue, avoiding complications and therefore, improving the prognosis of treatment [22, 24]. 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 specificallyon Guided Endodontic Access Cavity preparation and Guided Endodontic Surgery.

General objectives are:

- Describe the clinical applications of Guided Endodontics.
- Report on the accuracy of Guided Endodontics.
- Describe the limitations of Guided Endodontics.

Specific objectives are:

- Describe the methodology used for each clinical application.
- Summarize the protocol for the design of 3D guides.

The components of the PICO question were: (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.

1.2 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 [25]. 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 April 25th, 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, (1) applications of guided endodontics, (2) studies that assessed the accuracy of the treatment, (3) case reports and (4) in vitro or ex vivo studies that assessed the accuracy and limitations of guided endodontics. The exclusion criteria were: (1) articles in other languages than English, (2) narrative reviews, (3) experts' opinion, (4) guideline reports, (5) cases in which CBCT was used as mean of navigation technique (without the use of a guide), and (6) 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 meet 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 was obtained from the selected articles: (1) Study characteristics: Authors, Year of publication, (2) Methods: Endodontic application, teeth sample, (3) 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: (4) 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) [26] guideline was used for observational studies, CARE guideline (Case Report Guideline) [27] was used to evaluate case reports, and the "modified CONSORT checklist of items for reporting in vitro studies of dental materials" [28] was used for assessing the quality of preclinical 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.

1.3 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 were 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 3 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 [25] flow chart (Figure 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 Figure 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 [20, 24, 29-36] and 4 to guided endodontic surgery [21, 37-39]. The results of the case reports are shown in Tables 1 for access cavity and Table 2 for endodontic surgery. Nine articles performed access cavities in anterior one rooted teeth, seven of them were treatments for calcified canals [19, 20, 24, 29, 30, 32, 35] and two on teeth with anomalies such as dens invaginatus [36] and dens evaginatus [33]. The rest of the access cavities were made in calcified canals of maxillary [32] and

mandibular molars [34]. In the case of periapical surgery, they were performed on incisors, canines, premolars, and molars. Only 7 of the 15 case reports used intraoral scanners to obtain surface information in a single step [19-21, 24, 32, 34, 39], while the rest obtained impressions with alginate or silicone and the gypsum casts were later scanned with an optical scanner [29-31, 33, 35-38]. All articles used guides for the access cavity used burs, except for Shi et al. [34] who used ultrasonic tips to access the canal.

The observational study of 50 patients carried out by Buchgreitz et al. [40] was the only one of its kind found up to the date of this review. Patients who required endodontics in calcified teeth due to the presence of periapical lesion or because they needed a post were included. The method data is shown in Table 3. The authors report that they used a similar protocol to their previous publication [41]. The control of the treatment steps was done with intra-oral radiographs. At the end of the treatment, the precision was evaluated by means of two groups: one in which the path was perfectly centered 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 [41]. 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 [22, 23, 41, 42], while two focussed on guided endodontic surgery [43, 44]. 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 [35]. 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 Figure 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. [45] 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% [39] and a minimum score of 48% [20]. 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% [44]). 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).

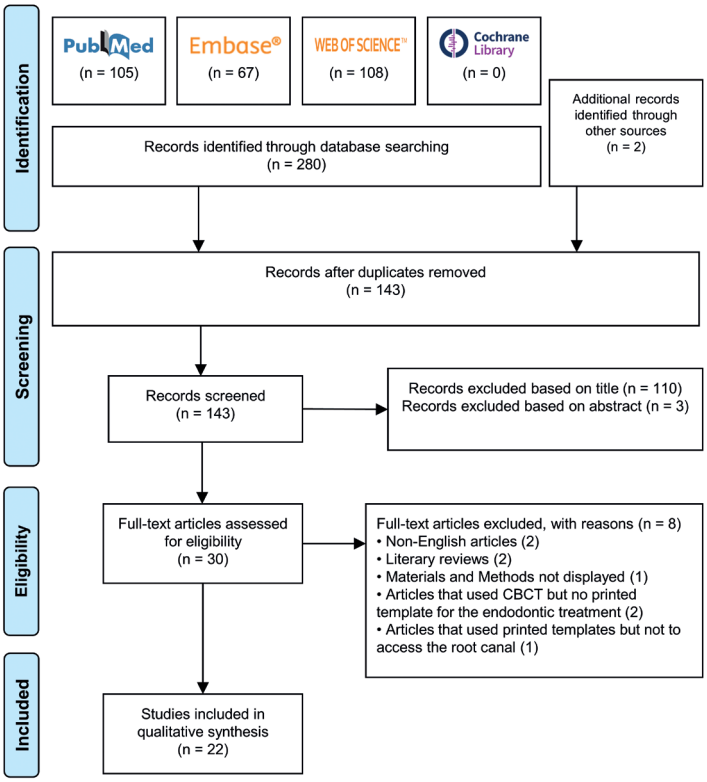

Figure 1. PRISMA flow chart (Liberati et al. 2009) of the selection process.

Material and Methods on Guided Endodontic Access Case Reports

N°	Authors	Teeth	CBCT	FOV	Voxel Size	Impression	
						Intraoral	Optical scanner
1	Connert et al. (2018)	Mandibular Central Incisors	Morita Accuitomo 80 (J Morita Mfg. Corp., USA)	Undisclosed	Undisclosed	iTero (Align Technology Inc., USA)	N/A
2	Fonseca-Tavares et al. (2018)	Maxillary Central Incisor	Undisclosed	Undisclosed	Undisclosed	Silicone impression	3Shape R700 Desktop Scanner (3Shape, USA)
3	Krastl et al. (2016)	Maxillary Central Incisor	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	50x50mm	0.08mm	iTero (Align Technology Inc., USA)	N/A
4	Lara-Mendes et al. (2018)	Maxillary Central Incisor	iCAT (Imaging Sciences International, USA)	Undisclosed	0.12mm	Intraoral impression (Material undisclosed)	3Shape R700 Desktop Scanner (3Shape, USA)
5	Lara-Mendes et al. (2018)	Second and Third Maxillary Molars	iCAT (Imaging Sciences International, USA)	Undisclosed	0.12mm	Intraoral impression (Material undisclosed)	3Shape R700 Desktop Scanner (3Shape, USA)
6	Maia et al. (2019)	Maxillary First Molar and Second Premolars	iCAT (Imaging Sciences International, USA)	Undisclosed	Undisclosed	TRIOS Color Pod (3Shape, Denmark)	N/A
7	Mena-Álvarez et al. (2017)	Maxillary Central Incisor	White Fox (Acteón Medico-Dental Iberica S.A.U.-Satelec, France)	60x60mm	Undisclosed	Undisclosed	Undisclosed
8	Shi et al. (2018)	First Mandibular Molar	ICAT 17-19 (Imaging Sciences International, USA)	Undisclosed	Undisclosed	CEREC AC (Sirona Dental Systems, Germany)	N/A
9	Torres et al. (2018)	Maxillary Lateral Incisor	NewTom VGi evo (NewTom, Italy)	100x100mm	0.2mm	Alginate impression	Activity 885 (SmartOptics, Germany)
10	van der Meer et al. (2016)	Maxillary Anterior Teeth	3D exam (KAVO, The Netherlands)	Undisclosed	0.3mm	Lava COS (3M Espe, Zoeterwoude, The Netherlands)	N/A
11	Zubizarreta et al. (2015)	Maxillary Lateral Incisor	WhiteFox, (Acteón Médico-Dental Ibérica S.A.U.-Satelec, France)	150x130mm	Undisclosed	Alginate impression	D710 scanner (3Shape, USA)

Table 1. Data extraction of Case Reports on Guided Endodontic Access. Letter coding: N/A: Not Applicable, L: Length, D: diameter, TL: total length, WL: working length, ID: inner diameter, ED: external diameter.

Planning Software	Printer	Bur			Template sleeve	Template Material
		Type	Specifications	Speed		
CoDiagnostiX, version undisclosed (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd., USA)	Specially designed miniaturized bur (Gebr. Brasseler GmbH & Co. KG, Germany)	0.85mm D	10,000rpm	Dimensions undisclosed (steco-system-technik GmbH & Co. KG, Germany)	Med610 (Stratasys Ltd., USA)
Simplant Version 11 (Materialise Dental, Belgium)	Objet Eden 260V (Stratasys Ltd., USA)	Neodent Drill for Tempimplants (Ref: 103179, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	1.3mm D, 20mm TL, 12mm WL	10,000rpm	Undisclosed	FullCure 720 (Stratasys Ltd., USA)
CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet Eden 260V (Stratasys Ltd., USA)	Straumann Drill for Tempimplants, (Ref.: 80381, Straumann, Switzerland)	37mm TL, 18,5mm WL, 1.5mm D	10,000rpm	6mm L, 2,8mm ED, 1,5mm ID (Fabricated by CNC technology)	Med610 (Stratasys Ltd., USA)
Simplant Version 11 (Materialise Dental-Technologielaan, Belgium)	Objet Eden 260V (Stratasys Ltd., USA)	Neodent Drill for Tempimplants (Ref: 103179, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	1.3mm D, 20mm TL, 12mm WL	1,200rpm	8,0mm L, 3,0 mm ED, 1,4mm ID (Ref: 102110, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	FullCure 720 (Stratasys Ltd., USA)
Simplant Version 11 (Materialise Dental-Technologielaan, Belgium)	Objet Eden 260V (Stratasys Ltd., USA)	Neodent Drill for Tempimplants (Ref: 103179, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	1.3mm D, 20mm TL, 12mm WL	1,200rpm	8,0mm L, 3,0 mm ED, 1,4mm ID (Ref: 102110, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	FullCure 720 (Stratasys Ltd., USA)
CoDiagnostiX, version undisclosed (Dental Wings Inc., Germany)	Objet Eden 260V (Stratasys Ltd., USA)	Neodent Drill for Tempimplants (Ref: 103044, 103179, JJGC Ind e Comercio de Materiais Dentarios SA, Brazil)	1.1mm D for Molar, 1,3mm D for Premolars	350rpm	Undisclosed	Med610 (Stratasys Ltd., USA)
SIMPLANT (Dentsply Implants, Belgium)	Projet 6000 (3D Systems, USA)	Diamond bur (Ref.: 882 314 012, Komet Medical, Germany)	1.2mm D, 14mm TL	Undisclosed	5mm L, 1,3mm ID	Medical-use resin
3 Matic 9.0 (Materialise, Belgium) and ZBursh (Pixologic Inc, USA)	3510SD (3D System Corporation, USA)	Ultrasonic Tips (SATELEC, ACTEON, France)	ET20 and ET25	Undisclosed	1,2mm ID	UV-curable plastic (VisiJet M3, 3Dsystem, USA)
Mimics 19.0 and 3 Matic 11.0 (Materialise, Belgium)	Object Connex 350 (Stratasys Ltd., USA)	Munce bur (CJM Engineering Inc., USA)	Size 1 0.8mm D, 34mm TL	10,000rpm	7mm L, 1mm ID	Med610 (Stratasys Ltd., USA)
3ds Max Software (Autodesk, USA)	Undisclosed	Munce bur (CJM Engineering Inc., USA)	Size 2 1mm D, 34mm TL	Undisclosed	3mm ID, 2,4mm ID	Undisclosed
SIMPLANT (Dentsplay Implants, Belgium)	Projet 6000 (3D Systems, USA)	Diamond bur (Ref.: 882 314 012, Komet Medical, Germany)	1.2mm D, 14mm TL	Undisclosed	5mm L, 1,3mm ID	Medical-use resin

Material and Methods on Guided Endodontic Surgery Case Reports							
N°	Authors	Teeth	CBCT	FOV	Voxel Size	Impression	
						Intraoral	Extraoral
1	Ahn et al. (2018)	First Mandibular Molar	Alphrad 3030 (Asahi Roentgen Ind Ltd., Japan)	Undisclosed	Undisclosed	Alginate impression	Identica Blue (Medit, Korea)
2	Giacomino et al. (2018)	Maxillary First and Second Molars and Mandibular Second Premolar	3D Accuitomo 170 (J Morita Mfg. Corp., USA)	80x80mm	Undisclosed	Polyvinyl siloxane impression (Aquasil Ultra, Dentsply Caulk, USA)	3Shape D1000 (Whip Mix Corp., USA)
3	Strbac et al. (2017)	Maxillary First Molar and Second Premolar	Siemens Somatom Sensation 4 (Siemens Healthcare GmbH, Germany)	Undisclosed	0.18x0.18x 0.5mm*	iTero (Align Technology Inc., USA)	N/A
4	Ye et al. (2018)	Maxillary Lateral Incisor and Canine	ICAT 17-19 (Imaging Sciences International, USA)	Undisclosed	Undisclosed	3Shape (Denmark)	N/A

Table 2. Data extraction of Case reports on Guided Endodontic Surgery. *Anisotropic voxel because of the use of a MSCT scan. Letter coding: N/A: Not Applicable, L: Length, D: diameter, TL: total length, WL: working length, ID: inner diameter, ED: external diameter, min: minimum.

Material and Methods on Guided Endodontic Access Case Reports							
N°	Authors	Sample	CBCT	FOV	Voxel Size	Impression	
						Intraoral	Extraoral
1	Buchgreitz et al. (2018)	50 patients	Orthophos XG 3D unit (Sirona Dental Systems, Germany)	Undisclosed	0.5mm	CEREC (Sirona Dental Systems, Germany)	N/A

Table 3. Data extraction of observational studies. Letter coding: N/A: Not Applicable, L: Length, D: diameter, TL: total length, WL: working length, ID: inner diameter, ED: external diameter, min: minimum.

Planning Software	Printer	Bur			Template sleeve	Template Material
		Type	Specifications	Speed		
Ondemand3D (Cybermed Co., Korea)	Objet Eden 260V (Stratasys Ltd., USA)	Anchor drill	20mm T, 1.5mm D	Undisclosed	Undisclosed	Med610 (Stratasys Ltd., USA)
Mimics (Materialise, Leuven, Belgium) or Blue Sky Plan 3 (Blue Sky Bio, LLC, USA)	Objet 260 Connex3 (Stratasys Ltd., USA)	Hollow trephine (Biomet 3i, LLC, USA)	5 or 6mm D	1200rpm	Min 7mm L with irrigation window	Undisclosed
CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)	Objet 350 Connex 3 (Stratasys Ltd., USA)	Piezoelectric saw (Piezomed Instruments, Piezomed, W&H Dentalwerk GmbH, Austria)	B7 (Piezomed instrument)	Undisclosed	N/A	Med610 (Stratasys Ltd., USA)
SIMPLANT (Dentsply Implants, Belgium)	3510SD (3D system Corporation, USA)	Trephine (Meisinger, Germany)	4mm D	Undisclosed	2mm L, 4.2mm ID	Undisclosed

Planning Software	Printer	Bur		Template	Template Material
		Type	Specifications		
Galaxis/ Galileos Implant, (Sirona Dental Systems, Germany)	No printer. CNC technology (SICAT optiguide, Germany)	Modified spiral bur (Busch, Germany)	1.2mm D, 22mm WL	4mm L, 1.2mm ID	Undisclosed

Material and Methods on Guided Endodontics: In vitro **and** Ex vivo **studies**

N°	Authors	Endodontic Application	Sample size (n)	CBCT	Voxel Size	Impression	Planning Software
1	Ackerman et al. (2019)	Guided Endodontic Surgery	48 roots (surgical access cavities)	iCAT FLX (Dental Imaging Technologies Corp., USA)	0,2 mm	Trios (3Shape, USA)	Blue Sky Bio (LLC., USA)
2	Buchgreitz et al. (2016)	Guided Endodontic Access	38 teeth	Orthophos XG 3D unit (Sirona Dental Systems, Germany)	Undis-closed	CEREC (Sirona Dental Systems, Germany)	Galaxis/ Galileos Implant, (Sirona Dental Systems, Germany)
3	Connert et al. (2017)	Guided Endodontic Access	59 teeth (Mandib-ular incisors and canines)	Morita Accuitomo 80 (J Morita Mfg. Corp, USA)	0,08 mm	iTero (Align Technology Inc., USA)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)
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., USA)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)
5	Pinsky et al. (2007)	Guided Endodontic Surgery	110 surgical access cavities	iCAT (Imaging Sciences International, USA)	Undis-closed	Non-used	CADImplant Inc.
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., USA)	CoDiagnostiX version 9.2 (Dental Wings Inc., Canada)

Results on Guided Endodontics's experimental studies

N°	Authors		Method	Accuracy analysis method
1	Ackerman et al. (2019)		Compare accuracy of freehand drilling versus virtual planned osteotomies	Drilled osteotomies were registered to virtual osteotomies and differenc-es were measured.
2	Buchgreitz et al. (2016)		Drill in bulk of dentin 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.
3	Connert et al. (2017)		Access to the root canal	Registration pre-CBCT with post-CBCT. Analysis automatically via the software.
4	Connert et al. (2019)		Compare accuracy of conventional tech-nique to guided access cavities.	Registration pre-CBCT with post-CBCT. Analysis automatically via the software.
5	Pinsky et al. (2007)		Compare accuracy of freehand drilling versus virtual planned osteotomies	Drilled osteotomies were registered to virtual osteotomies and differenc-es were measured.
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.

Table 4. Data extraction on Experimental Studies (continued). Color code study type: Green: Ex vivo studies, Yellow: In vitro studies.
Letter coding: BO: buccal-oral direction, MD: mesial-distal direction, AC: apical-coronal direction, SD: Standard Deviation.

Printer	Bur			Guide		Template Material
	Type	Specifications	Speed	Type	Sleeve	
Form 2 (Formlabs Inc., USA)	Surgical Lindemann bur (Meisinger, Germany)	<2mm D	Undisclosed	3D Printed	2mm ID Variable L	Dental SG Resin (Formlabs Inc., USA)
Non-used	Modified spiral bur (Busch, Germany)	1.2mm D, 22mm WL	250 rpm	CNC technology (SICAT optiguide, Germany)	4mm L, 1.2mm ID	Undisclosed
Objet Eden 260V (Stratasys Ltd., USA)	Specially designed bur (Gebr. Brasseler GmbH & Co KG, Germany)	0.85mm D, 20mm WL, 28mm TL	10.000 rpm	3D Printed	6mm L, 0.88mm ID, 4mm ED	Med610 (Stratasys Ltd., USA)
Objet Eden 260V (Stratasys Ltd., USA)	Specially designed bur (Gebr. Brasseler GmbH & Co KG, Germany)	0.85mm D, 20mm WL, 28mm TL	10.000 rpm	3D Printed	6mm L, 0.88mm ID, 4mm ED	Med610 (Stratasys Ltd., USA)
Non-used	Undisclosed	1.8mm D	Undisclosed	Computer driven drilling (Scanno-graphic guide)	Undisclosed	Acrylic material (Tri-ad, Dentsply, USA)
Objet Eden 260V (Stratasys Ltd., USA)	Straumann Drill for Tem-pimplants, (Ref.: 80381, Straumann, Switzerland)	1.5mm D, 18,5mm WL, 37mm TL	10.000 rpm	3D Printed	6mm L, 1.5mm ID, 2.8mm ED	Med610 (Stratasys Ltd., USA)

Deviation at base of bur	Deviation at tip of bur	Deviation angle	Success rate	Clinical Applicability
-	1.473mm mean (± 0.751 SD) using guide, 2.638mm mean (± 1.387 SD) freehand	-	100% of targets reached within 4mm (using guide)	
-	Mean 0.46mm	-	-	
BO: 0.13mm mean (0 – 0.4mm) MD: 0.12mm mean (0 – 0.54mm) AC: 0.12mm mean (0 – 0.41mm)	BO: 0.34mm mean (0 – 1.26mm) MD: 0.14mm mean (0 – 0.99mm) AC: 0.12mm mean (0 – 0.4mm)	1.59° mean (0 – 5.3°)	100%	
-	-	-	91,7% (22 of 24 root canals were achieved)	
-	0.79mm mean (± 0.33 SD) using guide, 2.27mm mean (± 1.46 SD) freehand	-	88% of targets reached within 1mm (using guide)	
	BO: 0.47mm mean (0 – 1.59mm) MD: 0.29mm mean (0 – 1.34mm) AC: 0.17mm mean (0 – 0.75mm)	1.81˚ mean (0 – 5.6˚)	100%	

STROBE Statement Checklist

Author	1		2	3	4	5	6		7	8	9	10	11	12				
	a	b					a	b						a	b	c	d	e
Buchgreitz et al. (2018)	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	Y	Y	N	N

Table 5. STROBE checklist. 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 annex section.

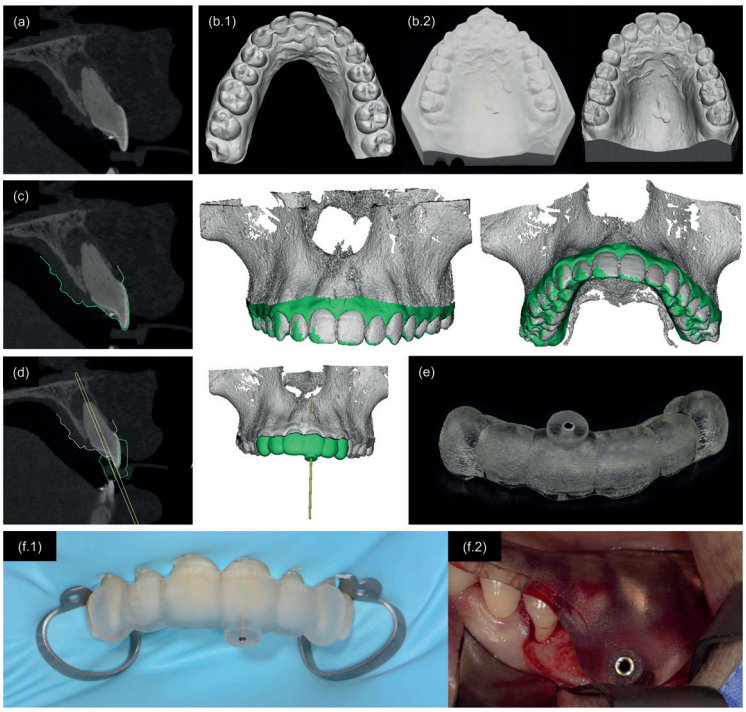

Figure 2. Workflow for guided endodontics. A CBCT from the patient is acquired (a) as well as a digital intraoral impression directly (b.1) or indirectly (b.2). The information from both sources is combined and registered in a digital planning software (c). Then, a treatment guide is designed (d) and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

CARE Checklist

Author
Ahn et al. (2018)
Connert et al. (2018)
Fonseca et al. (2018)
Giacomino et al. (2018)
Krastl et al. (2016)
Lara-Mendes et al. (2018)
Lara-Mendes et al. (2018)
Maia et al. (2019)
Mena-Alvarez et al. (2017)
Shi et al. (2018)
Strbac et al. (2017)
Torres et al. (2018)
van der Meer et al. (2016)
Ye et al. (2018)
Zubizarreta et al. (2015)

13			14			15	16			17	18	19	20	21	22	%
a	b	c	a	b	c		a	b	c							
Y	Y	N	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	Y	N	71%

1	2	3			4	5			6	7	8				9		10				11				12	13	%
		a	b	c		a	b	c			a	b	c	d	a	b	a	b	c	d	a	b	c	d			
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%
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%

Table 6. CARE checklist. 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 annex section.

Modified CONSORT checklist																
Author	**1**	**2**		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**%**
		a	**b**													
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%

Table 7. Modified CONSORT checklist. 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 annex section.

1.4 Discussion

Earlier reports on the literature addressed the complications that may present when treating teeth with PCO. According to Kvinnsland et al. [13], 20% of the perforations reported in the study were due to attempts to negotiate calcified canals. Similar results were found in a study from Cvek et al. [14], 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 [22, 23, 41, 42, 44]. Furthermore, there were no reports of root perforations when performing guided endodontic access [19-21, 24, 29-39].

The accuracy of guided-access cavity preparation seems to be reliable as reported on pre-clinical studies (see Table 4). Buchgreitz et al. [41] 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. [22] 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. [42] 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 differ-

ences 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. [41] 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. [46]. Tahmaseb et al. [47] 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 higher 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. [23] 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 $9.8mm^3$ (SD±3.0) for the guided technique and $49.9mm^3$ (SD±7.7) for the conventional approach by all operators [23]. 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 it was previously indicated in pre-clinical studies [22, 42].

Accuracy-measuring methods in the ex vivo studies are heterogeneous. Buchgreitz et al. [41] 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 2 observers. This may have led to small errors on the calculations. On the other hand, a different methodology was used by Zehnder et al. [22] and Connert et al. [42], 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 higher 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 [22, 23, 42] use teeth without complete calcifications. Therefore, the influence of PCO on the accuracy remains unclear [23]. Also, the time required to treat a tooth with PCO might be slightly longer [9]. Buchgreitz et al. [41]

assessed this issue by performing access cavities on the bulk of dentin 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-dentin.

In a recent observational study on 50 patients treated using this technique, Buchgreitz et al. [40] 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 a guide, the loss of tissue and the possibility of failure would be much greater than what is lost when straightening the cavity [19, 21, 23, 24, 30].
When assessing the accuracy of guided surgery, only 2 studies were found (see Table 4). Pinsky et al. [44] and Ackerman et al. [43] 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. [44]. As for Ackerman et al. [43], all procedures done with the guide had a successful result, meaning that the end of all drilled paths were within the apical 4mm 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 [39]. This minimally invasive procedure reduces the risk of intra- and postoperative complications such as bleeding or damaging neighboring anatomical structures. It also shortens the healing time and improves prognosis [37, 39].

The accuracy of the intraoral scanner has an added value when used during guided endodontic planning, as it reduces the number of steps [29]. 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 [29-31, 35-38]. 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 [48]. 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 [20].

One of the limitations of the technique for guided access cavity preparation, as mentioned by Buchgreitz et al. [40], is that the spatial resolution of the CBCT does not always allow visualization of the canal. There is a wide variability of CBCT ma-

chines 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 [49].

Another limitation regarding the imaging technique, is that in many cases intra-oral 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 [40], as well as the healing of the periapical lesion [50]. Fonseca Tavares et al. [29] 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 [51], the additional dose and cost related to the use of a preoperative CBCT, can be justified by the lower risk of iatrogenic errors [24].

When planning for a guided-access cavity, it should be noted that the technique is limited to straight canals [19, 41]. 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 [24, 31]. However, it is possible to apply the technique in molars that tend to have greater curvatures [31, 34], as most of the curvatures would be localized in the apical third [52], while calcifications would initially begin in the coronal third and extend apically. The latter would allow access to the canal in its straight portion [31]. Yet, in cases where the curvature would prevent a safe access to the target region, apical surgery would be indicated [19, 29, 31].

It should be mentioned that a reduced mouth opening could impose a limitation when trying to implement this technique in the posterior region [24, 31, 35, 42]. 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 [19]. Thinner drills are then necessary as suggested by different authors [24, 42].

It is of concern that the forces generated by the tip of the bur can generate cracks on the tooth surface [19, 29, 53], as well as produce excessive heat that can be harmful to the periodontal ligament and alveolar bone [54]. 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 the accuracy.

Planning time invested on the preparation of the guide has been discussed in several studies [19, 20, 22-24, 29, 35, 37, 39, 42, 54]. Connert et al. [42] reported that the average planning time, including digital intraoral impression, virtual planning and design of the template takes on average 9.4 minutes (ranging from 7 to 12.8 minutes). A second pre-clinical study by the same authors assessed the mean treatment duration which was reported to be 11.3 (SD±4.6) minutes when using the guide and 21.8 (SD±5.9) minutes otherwise [23]. 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 seconds on average (ranging from 9 to 208 seconds). All authors agree that although it may seem to be time-consuming, chair-side operating times and excessive loss of tooth structure are reduced, and the risk of iatrogenic damage is avoided [19, 20, 23, 24, 35, 37, 39, 42]. This is the first systematic review done on Guided Endodontics. Concerning the strengths of the study, it was possibleto 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 analyzed critically since the accuracy measuring methods are heterogeneous between studies. Additionally, the number of teeth in experimental studies are 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 preclinical 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 de 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 [27].

Considering the limitations of guided endodontics and the review itself, it must be acknowledged that this technique may be a promising method for the endodontical or surgical treatment of complex cases. The use of a guide eases the work of the clinician, reducing the working time and obtaining a more reliable outcome [23]. Moreover, the technology used to design and elaborate the guides is today available worldwide [43]. Thus, in the future, Guided Endodontics may be more widely used in clinical practice [19, 24], at least when treating PCO teeth and complex surgical treatment.

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

1.5 Conclusion

In 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 chair-side 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.

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Chapter 2

Accuracy of dynamic navigation for non-surgical endodontic treatment: a systematic review

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Keywords

Endodontics
Dynamic navigation
Guided endodontics
Real-time tracking

Abstract

Aim - In recent years, the application of Guided Endodontics has gained interest for non-surgical endodontic treatment and retreatment. The newest research focuses on the accuracy of Dynamic Navigation (DN). This article systematically reviewed existing data on the accuracy of non-surgical endodontic treatment procedures that were completed using DN. **Methods** - Following the PRISMA criteria, an electronic database search was conducted in PubMed, Web of Science, Scopus, and Cochrane Library. Studies comparing the accuracy of non-surgical endodontic treatment using DN and the conventional freehand technique were eligible. **Results** - The literature search resulted in 176 preliminary records. After the selection process six studies were included. The risk of bias was evaluated using the modified Cochrane Collaboration Risk of Bias 2.0 tool. Five studies examined the aid of DN for planning and executing endodontic access cavities, and one for fiber post removal. In two studies, endodontic access cavities were performed in teeth with pulp canal obliteration. The main outcomes that were measured in the included studies were preparation time, global coronal entry point and apical endpoint deviations, angular deviation, tooth substance loss, qualitative precision, number of unsuccessful attempts or procedural mishaps. The risk of bias was rated from low to raising some concerns. **Conclusions** - Overall, DN showed increased accuracy compared to the freehanded technique and could be especially helpful in treating highly difficult endodontic cases. Clinical studies are needed to confirm the published in vitro data.

2.1 Introduction

Traditionally, endodontic access cavity is prepared freehanded, according to the operator's clinical experience and knowledge of tooth anatomy. The anatomical laws of the pulp chamber which were formulated by Krasner and Rankow are used to aid in locating the canal [1]. Moreover, a dental operating microscope can be used during this treatment step to reduce the possibility of iatrogenic mishaps [2]. However, some clinical conditions, such as canal obliteration can prolong the location of a canal up to 60 min even using a dental operating microscope [3]. Further, technical failures, including missed canals, crown or root perforations, canal transportation, or weakened tooth structure, can reduce treatment success or lead to tooth extraction [4, 5]. Furthermore, due to some systemic conditions, e.g., patients taking bisphosphonates, tooth extraction is contraindicated, thus making locating even severely obliterated tooth canals essential in the case of apical periodontitis [6]. Therefore, to facilitate the management of difficult and complicated endodontic cases, the concept of Guided Endodontics was introduced [7]. This method allowed static navigation of the bur using a 3D printed template while preparing the endodontic access cavity. However, the concept has some drawbacks: increased planning time, the possible inaccuracies of pre-operative cone-beam computed tomographic (CBCT) or intra-oral scanning, difficult application in premolar and molar regions due to limited vertical space, and the requirement of straight-line access to the root canal [8]. These drawbacks limit the use of static guides to anterior teeth.

In 2000, dynamic navigation (DN) was implemented to increase accuracy in dental implant placement by providing the operator with a real-time navigation tool [9]. DN uses preoperative CBCT data for pre-treatment virtual planning and real-time guidance of bur positioning during the procedure. Recently, DN gained interest in the field of Guided Endodontics as it has some advantages over static guides: it can be used in posterior regions, it allows a change in the drilling path due to real-time tracking, and the patient can be treated in the same appointment [8-10].

The aim of this study is to systematically review the available literature on the accuracy of non-surgical endodontic treatment procedures that are completed freehanded and using DN.

2.2 Materials and methods

Study Design

The present systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systemic Reviews and Meta-Analyses) guidelines. The detailed PICO principles were defined as follows:

- Population – human teeth or three-dimensional (3D) printed teeth;
- Intervention – non-surgical endodontic treatment using the dynamic navigation system;
- Comparison – non-surgical endodontic treatment using the conventional freehand technique;
- Outcome – accuracy and efficiency of non-surgical endodontic treatment. The protocol was registered in PROSPERO (International Prospective Register of Systematic Reviews; registration number of CRD42021287170).

Search Strategy

The relevant studies were searched in the following databases: PubMed,Web of Science, Scopus, and Cochrane Library, by two independent reviewers (E.M.J. and G.B.). The search covered all the literature that was published from the inception of each database to September 2021, with no language or regional restrictions. The search strategy used in PubMed was as follows: "Surgical navigation systems"[Mesh] OR "Dynamic navigation" OR "Guided endodontic" OR "Computer-assisted treatment" OR "Computer-aided navigation" OR "Image-guided treatment" OR "Navigation system" OR "Real-time tracking" OR "Dynamic guide" AND "Endodontics"[Mesh] OR "Root canal therapy"[Mesh] OR "Dental pulp calcification"[Mesh] OR "Dental pulp"[Mesh] OR "Dental pulp cavity"[Mesh] OR "Access cavit*" OR "Pulp canal calcification" OR "Root canal treatment" OR "Endodontic*" OR "Minimally invasive dentistry" OR "Obliterat*" OR "Conservative endodontic access" OR "minimally invasive access". The same terms were used in adapted versions of the search strategy for each database. An additional manual search was performed to identify the potentially eligible studies that were not indexed in the databases mentioned above.

Study Selection

The titles, abstracts and full texts of the identified studies were independently screened for eligibility by two reviewers (E.M.J. and G.B.). Literature reviews and clinical cases were excluded at the initial stage of screening. The inclusion criteria involved the following:

- Randomized experimental trials (RETs) or clinical trials (RCTs);
- Non-surgical endodontic treatment using a dynamic navigation system;
- Outcomes compared to conventional freehand technique;
- Articles available in full text.

The exclusion criteria were as follows: case reports, reviews, non-English language articles, studies using CBCT as mean of navigation technique, performing surgical endodontic treatment or having no control group.

The inter-reviewer agreement on the study selection was determined by the value of Cohen's kappa. Any disagreement on the study selection was resolved by discussion until a consensus was reached. The third reviewer (S.D.) was involved when necessary.

Data Extraction

The data extraction from each eligible study was accomplished by two reviewers (E.M.J. and G.B.) separately. No differences between the collected information consisting of references (authors, year of publication, country), study design, sample size, type of teeth, measured parameters and results were observed at the end of data extraction.

In cases of multiple experimental groups, the data conforming to PICO were collected. When the data were missing or unclear, the corresponding authors of the relevant studies were contacted.

Quality Assessment

The quality of the selected studies was assessed by two independent reviewers (E.M.J. and G.B.) using the modified Cochrane Risk of Bias 2.0 tool (version 2, Cochrane Collaboration, London, UK) for randomized trials (RoB 2). All the domains (randomization process, deviations from the intended interventions, missing outcome data, measurement of the outcome and selection of the reported result) were classified as low, unclear, or high risk of bias. Studies with at least one domain of a high risk of bias were overall rated as a high risk of bias. The unclear risk of bias was attributed to studies with no high- risk domains and at least one domain of unclear risk.

The lack of agreement between the two reviewers was resolved by discussion with the third reviewer (S.D.).

2.3 Results

Study Selection

Our search identified an initial number of 176 articles. The selection strategy is shown in the PRISMA flow chart (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Figure 1) [11]. After the elimination of duplicates, 117 articles were screened by the reviewers. After filtering through titles and reading the abstracts, nine articles were selected for full-text reading, and six articles were considered to be eligible for inclusion in this systematic review. Cohen's-value for the inter-rater agreement was 0.92.

Study Characteristics

The main characteristics of the articles that were included in this review are summarized in Table 1. All the included articles were in vitro studies that were published in the years 2020 and 2021. Three studies used freshly extracted human teeth [12-14] and three used resin teeth [15-17]; the former studies used single-rooted teeth. Gambarini et al. [15] used resin upper first molars, whereas Connert et al. [17] and Jain et al. [16] used singlerooted printed teeth. The teeth in their correct anatomical position were either embedded in artificial jaw models [14-17] or in cadaver maxillae or mandibles [12, 13]. Dianat et al. [13], selected teeth with pulp canal obliteration and Jain et al. [16] 3D printed teeth with stimulated canal obliteration.

All the studies compared DN to conventional freehand preparation (FH) techniques, except Zubizarreta et al. [14], who also included a guided technique group. Five studies [13-17] examined the aid of DN for planning and executing endodontic access cavities and one for fiber post removal [12]. Two studies also compared the influence of the operator's experience on the results [13, 17].

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Quality Assessment

Overall, the risk of bias was rated as low in three included studies [13, 14, 16] and as raising some concerns in the remaining three studies [12, 15, 17]. In addition, some concerns emerged from the randomization process [12] and the selection of the reported results [15, 17]. Detailed results regarding the risk of bias of the included studies are presented in Figure 2.

Study	Sample size	DN System	Specimens
Gambarini et al. 2020 (Italy) (15)	20 (n=10)	Navident (Claronav)	Artificial, made of resin upper right first molars
Janabi et al. 2021 (USA) (12)	26 (n=13)	X-guide system (X-Nav Technologies)	Extracted human maxillary single-rooted teeth (incisors and canines). Teeth were endodontically treated and restored with fiber post.
Connert et al. 2021 (Switzerland) (17)	72 (n=18)	DENACAM system (Mininavident AG)	3D printed using resin maxillary single-rooted teeth (incisors and canines).
Jain et al. 2020 (USA) (16)	40 (n=20)	Navident (ClaroNav)	3D printed single-rooted teeth with simulated pulp canal obliteration. (maxillary and mandibular central incisors).
Dianat et al. 2020 (USA) (13)	60 (n=15)	X-guide system (X-Nav Technologies)	Extracted human single-rooted teeth with pulp canal obliteration (maxillary and mandibular incisors, canines and premolars).
Zubizarreta et al. 2020 (Spain) (14)	30 (n=10)	Navident (ClaroNav)	Extracted human single-rooted teeth (lower central incisors).

Table 1. Studies characteristics and results. * Significant pair-wise comparison between DN and FH Techniques.

Outcome measure	DN Technique Results ± SD (95% CI)	FH Technique Results ± SD (95% CI)
1. Preparation time. 2. Maximum distance between planned and prepared access cavity at the orifice level. 3. Access cavity angular deviation. 4. Ability to locate a canal.	1. 11.5 ± 2.4 sec. 2. 0.34 ± 0.19 mm * 3. DN 4.8° ± 1.8° * 4. All canals were located.	1. 12.2 ± 3.2 sec. 2. 0.88 ± 0.41mm * 3. 19.2° ± 8.9° * 4. All canal were located.
1. Preparation time. 2. Drilling trajectory global coronal deviation. 3. Drilling trajectory global apical deviation. 4. Access cavity angular deviation. 5. The volume of tooth structure before and after preparation. 6. Procedural mishaps.	1. 241.8 ± 25.8 s * 2. 0.91 ± 0.65 mm * 3. 1.17 ± 0.64 mm * 4. 1.75° ± 0.63° * 5. Before 542.50 ± 81.97 mm^3 After 487.87 ± 74.70 mm^3 * 6. No perforations.	1. 498 ± 279 s * 2. 1.13 ± 0.83 mm * 3. 1.68 ± 0.85 mm * 4. 4.49° ± 2.10° * 5. Before 571.34 ± 133.12 mm^3 After 533.16 ± 133.12 mm^3 * 6. No perforations.
1. Preparation time. 2. Tooth substance volume loss. 3. Procedural mishaps.	1. 195 (135 – 254) s 2. 10.5 (7.6 – 13.3) mm^3 * 3. One perforated canal.	1. 193 (164 – 222) s 2. 29.7 (24.2 – 35.2) mm^3 * 3. One perforated canal.
1. Preparation time. 2. Tooth substance volume loss. 3. Qualitative precision: optimal, suboptimal or unacceptable.	1. 136.1 (101.4 – 170.8) s * 2. 27.2 (22.0 – 32.5) mm^3 * 3. 75% optimal 15% suboptimal 10% unacceptable (one perforation)	1. 424.8 (289.4 – 560.2) s* 2. 40.7 (29.1 – 52.2) mm^3 * 3. 45% optimal 40% suboptimal 15% unacceptable (two perforations)
1. Preparation time. 2. Access cavity linear deviation (in the BL and MD directions). 3. Reduced dentin thickness (at the CEJ level and at the end of the drilling point (EDP)). 4. Access cavity angular deviation. 5. Successfully located canals. 6. Procedural mishaps.	1. 227 ± 97 s * 2. BL 0.19 ± 0.21 mm * MD 0.12 ± 0.14 mm 3. CEJ 1.06 ± 0.18 mm * EDP 1.18 ± 0.17 mm * 4. 2.39° ± 0.85° * 5. 96.6% (29/30) 6. One gouging *	1. 405 ± 246 s * 2. BL 0.81 ± 0.74 mm * MD 0.31 ± 0.35 mm 3. CEJ 1.55 ± 0.55 mm * EDP 1.47 ± 0.49 mm * 4. 7.25° ± 4.2° * 5. 83.3% (25/30) 6. Five perforations, three gouging *
1. Access cavity angular deviation. 2. Access cavity linear deviation (measured at the coronal entry point (CEP) and the end of the drilling point (EDP).	1. 5.58° ± 3.23° * 2. CEP 3.14 ±0.86 mm * EDP 2.48 ± 0.94 mm *	1. 14.95° ± 11.15° * 2. CEP 4.03 ± 1.93 mm * EDP 2.43 ± 1.23 mm *

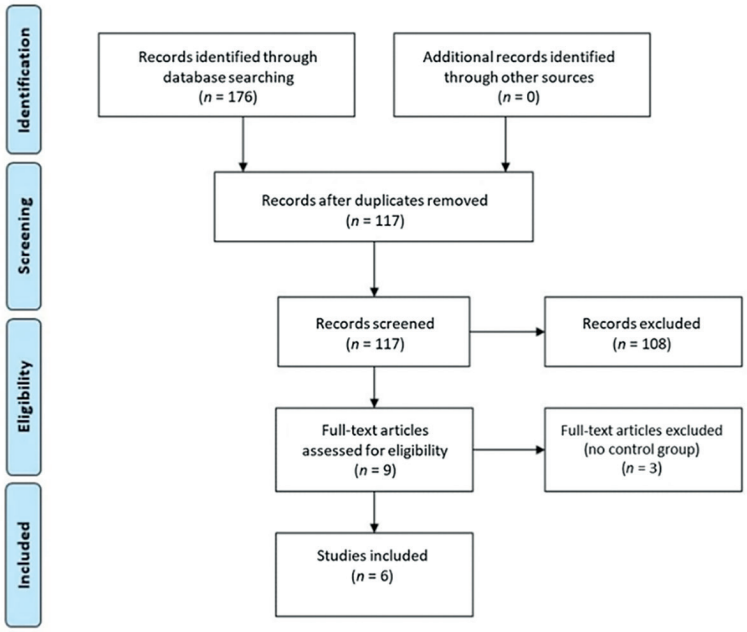

Figure 1. The review search and selection flowchart.

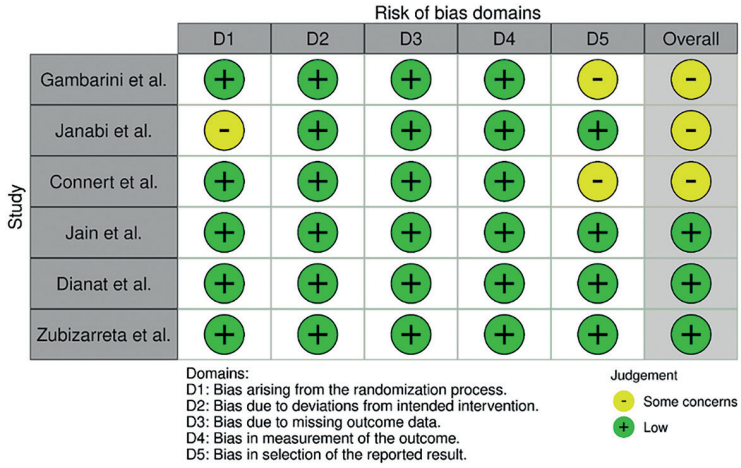

Figure 2. Risk of bias assessment using the modified RoB 2.0 tool. Gambarini et al. [15]; Janabi et al. [12]; Connert et al. [17]; Jain et al. [16]; Dianat et al. [13]; Zubi-zarreta et al., 2020 (Spain) [14].

2.4 Discussion

The present systematic review aimed to analyze the aid of DN to increase accuracy in endodontic procedures. It is now accepted that the loss of structural integrity that is associated with access cavity preparation and dentin removal, particularly in the peri-cervical region, are major causes of fracture in endodontically treated teeth [18]. Therefore, accurate access cavity preparation can reduce substance loss on endodontic treated tooth [12, 16, 17]. All the studies in this review reported increased accuracy and less volumetric loss of tooth structure when using DN. Furthermore, DN led to fewer iatrogenic errors. Among the studies, 119 teeth were treated using DN, in which two incidents of perforations and one case of gouging were reported. The most common procedural mishaps and errors were artifacts in the CBCT scan from restorations containing metal, planning errors, incorrect calibration, faulty transfer of the anatomic landmarks during registration, misfit of tracking components, inadequate systems check during the treatment and practitioner hand tremor [9, 19]. Thus, it is essential to ensure accuracy at each step to avoid the accumulation of errors. Further, there is a long learning curve for the practitioner when working with the DN because the technique requires a certain level of technical skill, hand-eye coordination and manual dexterity [9, 19, 20]. Torres et al. [20] observed accuracy result differences between operators during training, however, there were no statistically significant differences when the post-training treatment was carried out. They concluded that training is essential to achieve predictable results. Only two studies, included in this review, reported using 20 teeth to train the operator before the experiment [12, 13].

The time required to perform an endodontic treatment is essential for the patient and dental practitioner. Preparation time was recorded in five of the included studies [12, 13, 15-17]. Statistically significant differences in time between the DN and FH groups were found in the preparation of access cavities in teeth with root canal obliteration and fiber post removal [12, 13, 16]. Time differences between the studies can be explained by different measuring start and endpoints, simulated clinical situations, and research method differences. For example, Gambarini et al. [15] and Janabi et al. [12] did not specify start and end measurement points. In comparison, Jain et al. [16] used different endpoints of preparation time measurement for the FH and DN groups. The endpoint in the FH group was set as the successful canal negotiation or when the access depth was suspected to reach the estimated measurement to the canal space; the endpoint in the DN group was selected when the bur reached the end of the planned drill path. Root canal obliteration can be caused by dental trauma, carious lesions, orthodontic treatment, regenerative endodontic procedures and individual aging, and it is becoming more frequent [21, 22]. Fiber posts have also been increasingly used to restore endodontically treated teeth because of high survival rates and improved esthetics, compared to metal posts [23, 24]. According

to the American Association of Endodontists (AAE), root canal obliteration and fiber post removal are considered to be high difficulty endodontic cases which should be considered for referral [25]. Dianat et al. [13] found that using DN for locating obliterated canals allowed to avoid tooth perforation. Consequently, DN could be a superior choice when dealing with clinically challenging cases.

Two studies compared clinicians of different experience levels [13, 17]. Connert et al. [17] found that less experienced operators removed significantly more tooth structure using the FH technique than more experienced clinicians. There were no statistically significant differences between the operators when using DN. Dianat et al. reported a statistically significant difference between a board-certified endodontist and a third-year endodontic resident for the time that was required to locate the canal using the FH technique [13]. Again, there was no statistically significant difference in the DN group. Torres et al. [20] compared three operators with varying experience levels for access cavity preparation in teeth with severe root canal obliteration using DN. They found that 93% of canals were located irrespective of the operator's experience in endodontics, after appropriate training sessions with the device. These results suggest that DN can be beneficial for novice practitioners to combat high difficulty endodontic cases. Moreover, some studies evaluated the impact of DN on training dental students in dental implant placement. The results show that DN can be a valuable tool to improve the training of novice operators [26, 27].

Half of the included studies used extracted human teeth [12-14], while the other half used 3D printed tooth replicas [15-17] for the experiments. Natural extracted human teeth contain anatomical landmarks, such as a pulp chamber floor map and tertiary dentin color, which are important for freehanded endodontic access preparation and obliterated root canal location. In contrast, 3D printed resin teeth do not possess such qualities [1]. Therefore, a freehanded search for obliterated root canals in 3D printed teeth can be misleading. Moreover, the operator can become familiar with tooth anatomy and canal location. To overcome this drawback of 3D printed teeth, Jain et al. [16] recommend at least a one-week interval between treatment sessions.

Since DN was first introduced for dental implant placement, many studies have evaluated the accuracy and efficiency of DN in dental implantology, both in vitro and in clinical investigations. A recent systematic review and meta-analysis [28], which included in vitro and clinical studies, reported that clinical studies demonstrate slightly higher deviations than in vitro studies. The mean overall angular deviations were 2.01 (95% CI: 1.95 to 2.07) in in vitro studies and 3.68 (95% CI: 3.61 to 3.74) in clinical studies. Further, more than 1 mm deviations were observed in some clinical studies. These deviations can be of great importance in endodontics.

However, currently there are just a few case reports of applying DN for access cavity preparation and endodontic microsurgery [29-32]. Therefore, clinical trials are necessary to confirm the published in vitro data of DN accuracy in endodontics.

Only one included study compared DN with static guidance [14]. Static guides are 3D printed templates which are manufactured using preoperative CBCT and intraoral scanning data [7]. Results show that DN was more accurate than a static guide for endodontic access cavity preparation in an absolute value. However, the results showed no statistically significant differences.

The strength of the present systematic review is robust inclusion criteria, which were used to focus on the topic and decrease the possibility of bias arising from study selection. Another advantage is the overall low risk of bias of the included studies. Therefore, the limitations include the possibility of missing related articles, although this was decreased by searching four databases. Other potential limitations are the small number of included studies, the range of the study designs and the outcome measures which impede comparison. Although a meta-analysis was not attempted due to these limitations, this systematic review can provide some directions for the near future to standardize outcome measures.

2.5 Conclusions

Within the limitations of this systematic review, it can be concluded that the dynamic navigation system demonstrated increased accuracy, compared to the freehanded technique, and can be helpful in managing complicated endodontic cases after proper training with the device. However, well-designed clinical trials are necessary to confirm published in vitro data in the future.

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Clinical significance
The use of an IOS does not involve additional radiation exposure. A safety margin of at least 1 mm around the planned trajectory should be respected when planning the case to minimize the possibility of root perforation.

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Chapter 3

Ex vivo and in-vivo validation of a novel measuring protocol for guided endodontics

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Keywords

3-Dimensional printing
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Dental pulp calcification
Guided endodontics
Intraoral scanner

Abstract

Aim - To (1) validate the use of a post-operative intraoral scan (IOS) versus Cone Beam Computed Tomography (CBCT), gold standard, on its ability to measure the accuracy of guided endodontics, and (2) present clinical data on the accuracy of guided endodontics. **Methods** - Four models, including 10 extracted teeth each, were created. Forty guided access cavities were planned on dentin to simulate pulp canal obliteration (PCO). Two operators performed guided access cavities. A post-operative CBCT and IOS were acquired. The deviation coronally, apically, and angular deviation was measured with CBCT and IOS. Clinical accuracy was measured using an IOS acquired immediately after drilling the access cavity with the aid of a guide. Data analysis was performed using multiway Anova and corrected for simultaneous hypothesis testing according to Tukey. $P \leq 0.05$ was considered statistically significant. Descriptive statistics on the clinical accuracy of guided endodontics were performed. **Results** - Thirty-eight cavities were assessed with a mean length of 13.8 mm. No statistical difference between operators and methods was found for all parameters ($P > 0.05$). Thirty-three patients were treated with guided endodontics and measured using an IOS. Results show an average coronal, apical, and angular deviation of 0.2 mm, 0.45 mm, and 1.91° respectively. The average length of the access cavities was 12.5 mm. **Conclusions** - An IOS can be used to measure the accuracy of guided endodontics. Clinical data showed high accuracy of guided endodontics with a mean apical deviation smaller than 0.5 mm and a mean angular deviation of less than 2°.

3.1 Introduction

Endodontic treatment of teeth with pulp canal obliteration (PCO) is a challenging, time-consuming task [1, 2]. Even for experienced endodontists, it is difficult to maintain the correct alignment of the bur, and there is an increased probability of failure [3, 4].

Guided Endodontics, the use of computer-designed tooth-supported guides for access cavity preparation, may offer a better option than freehand drilling, as its outcome is highly predictable and the risk of iatrogenic damage is lowered [5, 6]. Additionally, minimally invasive treatment can be performed, and chairside time can be reduced [6-12].

Although promising, questions have been raised about the reliability and accuracy of guided endodontics to replicate the planned access cavity. Similar to the accuracy assessment performed for guided implant placement [13], in vitro and ex vivo studies have measured the accuracy of guided endodontics by superimposing pre-operative and post-operative Cone Beam Computed Tomography (CBCT) data [7, 9, 14-17]. However, such protocols involve unnecessary radiation exposure and cannot be clinically justified. That is why, in the case of guided implant placement, alternative non-radiologic methods have been proposed by using a CBCT of the master cast with implant replicas [18] or a digitalized version of the conventional impression of the implant [19].

Guided endodontics has already shown its potential in in vitro and ex vivo studies [6, 7, 9, 14-17]. However, its accuracy in vivo needs further investigation as the clinical setting may vary from the experimental set-up of a laboratory study.

Therefore, a method to clinically verify the accuracy of guided endodontics by comparing the trajectory of the access cavity to the digitally planned trajectory is proposed. By acquiring a post-operative intraoral scan (IOS) of the patient's tooth with the bur inside the access cavity, the axis of the bur can be calculated and compared to the planned trajectory using 3D computer software. Such devices, already used during planning, do not expose the patient to additional radiation.

Aim: This study aims (1) to validate a novel method using a post-operative intraoral scan (IOS) versus the gold standard, Cone Beam Computed Tomography (CBCT), on its ability to measure the accuracy of guided endodontics ex vivo, and (2) to present clinical data on the accuracy of guided endodontics. The null hypothesis states that mean results between IOS and CBCT do not differ.

3.2 Materials and methods

The study was divided into two phases: first, a validation of the measuring protocol ex vivo, and secondly, an accuracy analysis in vivo.

Ex vivo study

Model design and tooth selection

A model tray able to fit on a dental phantom head was designed using 3-Matic Medical software 15.0 (Materialise, Leuven, Vlaams Brabant, Belgium) with enough space to contain a full arch of teeth up to the second molar. A total of 4 model trays were 3D printed using the Objet Connex 350 3D printer (Stratasys, Eden Prairie, MN, USA) on a transparent material (VeroClear, Stratasys).

A total of 40 extracted teeth were collected immediately after extraction (16 incisors, 8 canines and 16 single-rooted premolars). The teeth were extracted for reasons unrelated to this study and needed to fulfill the following inclusion criteria: no caries, no fillings or presence of a small restoration, and a complete root without fractures. The use of extracted human teeth was approved by the Ethics Committee of the University Hospitals Leuven, Belgium (S64350).

All selected teeth were cleaned from any dental plaque or calculus. Then, a total of 4 models, 2 maxillary and 2 mandibular, were created, including 10 extracted teeth each from central incisor to second premolar on each side. Additionally, a first and a second plastic Frasaco molar teeth (Frasaco, Tettnang, Baden-Württemberg, Germany) were placed distally on each side to simulate a full arch. Finally, all extracted teeth roots were covered with a thin layer of modelling Wax (Cavex, Haarlem, Noord-Holland, The Netherlands) and fixated to the model tray with gypsum (Instant Stone, Cavex). The wax around the roots provided a contrast between the root and gypsum on the CBCT scan (Figure 1A, B).

Virtual planning and guide design

A pre-operative CBCT and IOS of every model were taken using the NewTom VGi evo (Cefla, Imola, Italy) operating at 110 kVp and 3 mA with a FOV of 8 x 8 cm and voxel size 0.125 mm and a Trios intraoral scanner (3Shape, Copenhagen, Hovedstaden, Denmark). DICOM images were imported together with the STL file from the intraoral scanner into Mimics Medical software 23.0 (Materialise). The registration of the IOS to the CBCT volume was first performed by using a 3-point registration method to approximate both structures. Subsequently, an automatic global registration was repeated for final registration until no further movement was possible. The correct registration was confirmed visually on the software (Figure 1D, white contour line).

Virtual planning of the access cavities was performed with the same software from right to left second premolar. Cavities were planned as a cylinder of 1 mm diameter aimed at the apical portion of the root and always on dentin trying to avoid the root canal to simulate PCO. One access cavity was planned per tooth, with a total of 40 cavities. Then, a threshold was applied to segment all teeth, and a 3D model was created. The 3D teeth models were exported as an STL file and imported, together with the virtual planning and the IOS, into 3-Matic Medical software 15.0 (Materialise) for the guide design (Figure 1C, D).

A total of four tooth-supported guides, one guide per model, were designed and 3D printed in a biocompatible material (MED 610) to simulate a clinical treatment, using the Objet Connex 350 3D printer (Stratasys) (Figure 1E, F).

Access cavity drilling

All models were mounted into a phantom head. Two operators with different levels of experience in endodontics performed guided access cavities using the 3D-printed guides. Operator 1 is an experienced Endodontic specialist with more than 5 years of experience, and Operator 2 is a second-year resident from the department of Endodontics at the KU Leuven, Leuven, Belgium. All guides were checked to fit passively on the crowns. Each operator performed guided access cavities on 1 set of models (upper and lower jaw). Every guide had an outer sleeve (REF M.27.02.D350L5, Steco System-Technik, Hamburg, Hamburg, Germany) per tooth bonded to it. An inner sleeve (Figure 1F, arrow) was then repetitively used (REF M.27.28.D100L5, Steco) in combination with a 1 mm diameter carbide bur, with 21 mm working length and 35 mm total length (REF O.27.28.B044.051, Steco) to drill the access cavities. The bur was changed every 5 cavities. Enamel was first removed by hand with a diamond bur and the entry point was marked with a mechanical pencil through the inner sleeve.

Ex vivo Accuracy analysis

After treatment, a post-operative CBCT was taken for each model using the NewTom VGi evo (Cefla) operating at the same parameters mentioned before. Additionally, after drilling every cavity, a sandblasted bur, the same as the one used during treatment, was placed inside of the cavity. A snug fit of the bur inside of the cavity was checked, and an IOS (Trios, 3Shape) of the model was taken with the bur in place. This way, a total of 10 IOSs and 1 post-operative CBCT were taken per model (Figure 2A, B).
DICOM images from the post-operative CBCT were imported into Mimics Medical software 23.0 (Materialise) where the teeth were segmented as described previously. Then, the 3D teeth models were exported as an STL file and imported, together with all post-operative IOSs, into 3-Matic Medical software 15.0 (Materialise). Registration

of the post-operative 3D teeth models to the pre-operative model was performed initially by using 3-point registration and later global surface registration as described before. In the same way, the post-operative IOSs were registered to the pre-operative IOS (Figure 2B).

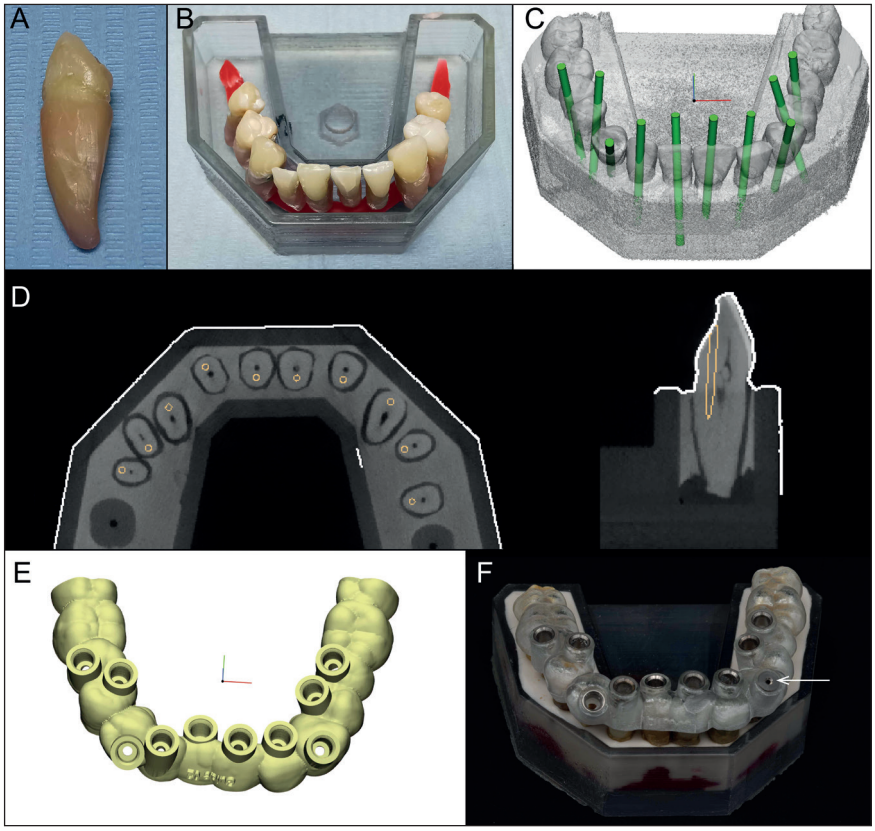

Figure 1. Model design, virtual planning, and guide design. (A) Example of a canine covered with a thin layer of wax (Modelling Wax, Cavex, Haarlem, The Netherlands). (B) A total of 10 extracted teeth from central incisor to second premolar placed in the 3D printed model tray. (C) 3D model from the pre-operative CBCT with the planned trajectory shown as green cylinders. (D) Left: axial slice from the pre-operative CBCT with the planned trajectory of access cavities in dentin to simulate PCO, and Right: example of an access cavity on an incisor shown on a sagittal slice. The pre-operative IOS was registered to the CBCT, and the correct registration was confirmed visually on the software (white contour line). Note the contrast between the wax around the roots and gypsum on the CBCT scan. (E) 3D model of a tooth supported guide and (F) 3D printed guide placed on the model with outer sleeves bonded to it and an inner sleeve (arrow) placed on one of the canines.

All post-operative 3D teeth models from the CBCT were registered to allow subtracting from the pre-operative model and obtain all access cavities. This method was previously described and validated by Torres et. al. [20]. The software automatically fitted a line on the central axis of each access cavity. First, two points were projected in the direction of the axis of the cavity up to the most coronal and most apical points of the access cavity. Then, two planes were created: a plane perpendicular to the planned trajectory passing through the coronal entry point and a second plane also perpendicular to the planned trajectory passing through the apical point of the access cavity. Finally, points were projected in the direction of the planned trajectory, up to the planes, and distances in relation to the planned trajectory were measured between points. The length of all access cavities was also recorded (Figure 2D1, D2).

On the post-operative IOS, the bur was manually separated from the rest of the scan, and the software automatically fitted a line on the central axis of the bur. A point was projected through the axis of the bur up to the surface of the pre-operative IOS to locate the coronal entry point. From this point, the axis line was extended according to the measured length of the cavity. The endpoint of the line corresponded to the apical point. Finally, as with the CBCT analysis, two planes were created: one perpendicular to the planned trajectory passing through the coronal entry point and a second plane passing through the apical point, also perpendicular to the planned trajectory. Points were then projected in the direction of the planned trajectory, up to the planes, and distances were measured (Figure 2C1, C2).

Angular deviation was measured between the planned trajectory and the axis of the segmented cavity on the CBCT or the axis of the bur on the IOS (Figure 2C, D).

In vivo analysis

After successfully validating the proposed method ex vivo, a clinical accuracy analysis of guided endodontics was performed. Virtual planning, guide design, access cavity drilling, and measuring protocols were the same for the treatment of the patients as described for the ex vivo protocol.

In vivo Accuracy Analysis

Between February 2020 and July 2022, a total of 33 patients referred to the Endodontic Department at the University Hospitals of Leuven, KU Leuven, Belgium, for endodontic treatment in teeth presenting with different levels of PCO and signs or symptoms of apical periodontitis were selected for inclusion. All patients had a thorough intraoral examination. Then, after PCO was confirm on a periapical radiograph, a pre-operative CBCT scan was taken for further assessment using the NewTom VGi

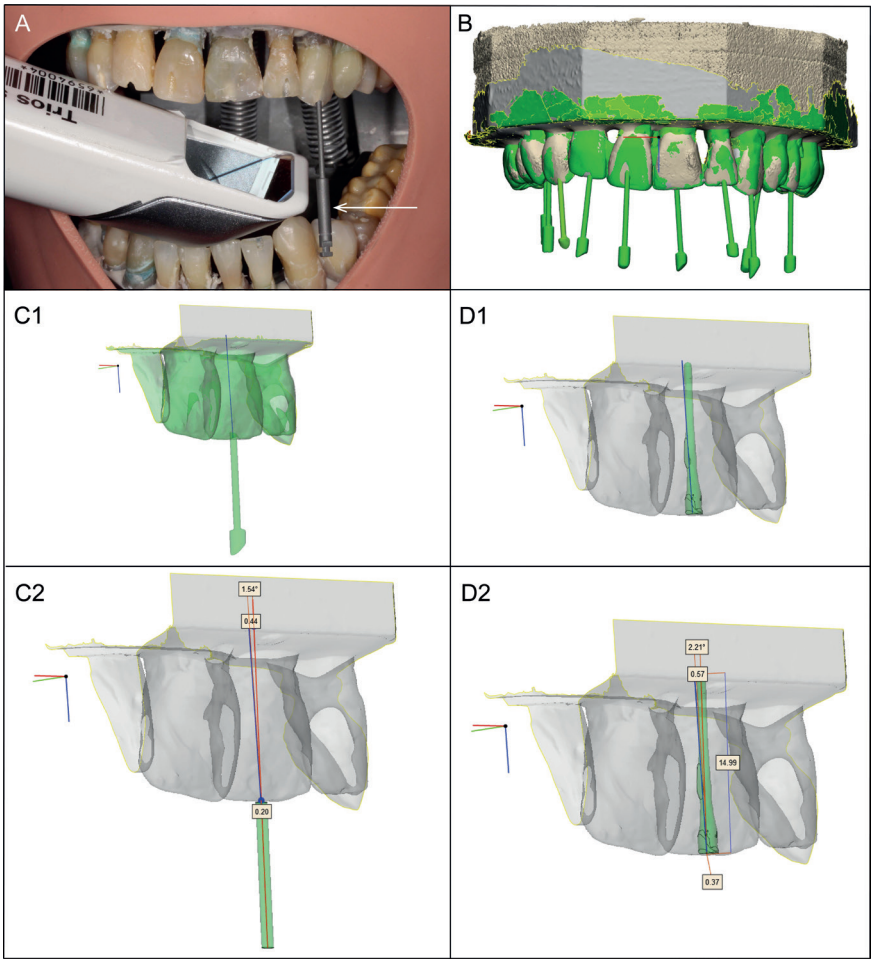

Figure 2. Accuracy analysis. (A) After drilling every cavity, a sandblasted bur, was placed inside the cavity (arrow), and an IOS was taken. (B) A total of 10 IOSs (green) were taken and registered to the pre-operative IOS (grey). The preoperative CBCT model is shown in light yellow. (C1) Registered post-operative IOS (green) with pre-operative IOS (grey) and planned trajectory (blue line). (C2) The bur was manually separated from the rest of the scan and a line was automatically fitted by the software on the central axis of the bur (red line) and extended apically (the length of the cavity was known by the measurement on the post-operative CBCT). (D1) Segmented cavity from the same tooth (green) and pre-operative IOS (grey) with planned trajectory (blue line). (D2) A line was automatically fitted by the software on the central axis of the access cavity (red line). The distance deviation from the planned trajectory in mm at the coronal and apical point is shown for both methods together with the angular deviation (in degrees) and length of access cavity (in mm).

evo (Cefla). If the CBCT volume confirmed the initial diagnosis of PCO, and the clinician evaluated the case as being of high difficulty [21], patients were planned for treatment with a 3D printed guide. Patients unwilling or unable to comply with the endodontic treatment, with a tooth in need of extraction, or with an unfavourable prognosis were excluded.

An IOS was taken for planning using the Trios intraoral scanner (3Shape). A safety margin of at least 1 mm around the planned trajectory was respected when planning each case (Figure 3). All guides were 3D printed in biocompatible material (MED

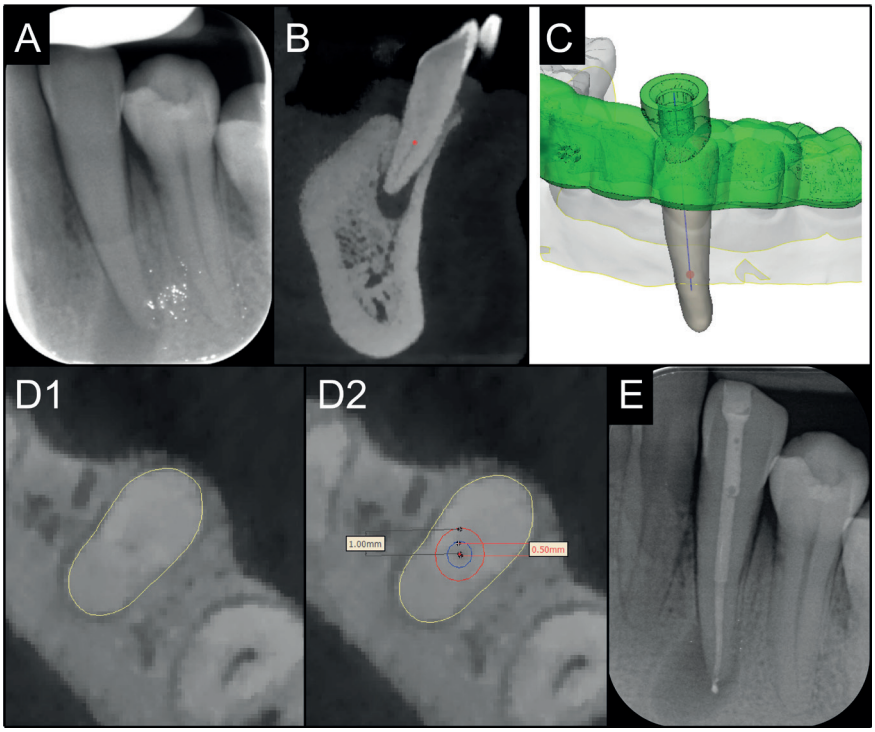

Figure 3. Safety margin during planning. (A) Intraoral radiograph showing a lower left canine with apical periodontitis and PCO. (B) Sagittal view from the same tooth on the CBCT showing severe PCO with the presence of apical periodontitis. The most coronal permeable point of the canal is marked with a red point. (C) 3D planning of the case; the segmented canine is shown in the middle with the planned trajectory (blue line) passing through the most coronal permeable point of the canal as marked on the CBCT (red point). The 3D guide is shown in green with the IOS from the patient in light grey. (D1) Axial view on the CBCT with the outer contour of the root marked in yellow, (D2) the planned trajectory passes through the center of the canal (red point), the circumference of a 1 mm diameter bur is visualized (blue line), and a safety margin of at least 1 mm (red line) around the planned trajectory was respected when planning the case. (E) Intraoral radiograph immediately after completion of the case.

610), using the Objet Connex 350 3D printer (Stratasys). Subsequently, an inner sleeve (REF M.27.28.D100L5, Steco) was bonded to the guide, and a 1 mm diameter carbide bur with 21 mm working length and 35 mm total length (REF O.27.28. B044.051, Steco) was used to drill the access cavities. All patients were treated by the same operator.

Immediately after drilling the access cavity with the aid of a guide and upon reaching the target point as planned, an IOS was taken with a sandblasted bur inside the cavity. The clinical outcome, evaluated as (1) canal found, (2) canal not found, or (3) perforation, and the length of the access cavity were assessed immediately during treatment. In addition, using the proposed method, the accuracy of the guiding system was assessed as follows: deviation from the planned trajectory in mm at the coronal entry point (C), apical point (A), and angular deviation (D). The treatment of patients with Guided Endodontics has been approved by the Ethics Committee of the University Hospitals Leuven, Belgium (S64630).

Statistical Analysis

All statistical analysis was done in S+ software, version 8.0 (TIBCO Software, Palo Alto, CA, USA). Differences between the variables (operators and measuring methods) were assessed for every parameter (C, A, and D) by a linear mixed model with the model as a random factor and operator and method and their interaction as crossed fixed factors. Initially, a residual analysis was performed by means of a normal quantile plot and residual dot plot. Then, if data were not normally distributed, a square root or log transformation was applied, or outliers were removed, and the normal quantile plot of the residual values was checked again.

As there were no significant interactions between variables found with multiway Anova, the variables were compared for all combinations of levels of the other variables and a correction for simultaneous hypothesis testing according to Tukey was applied. $P \leq 0.05$ was considered statistically significant.

Additionally, descriptive statistics on the accuracy of guided endodontics during the treatment of patients were performed for every parameter: C, A, D, and cavity length.

3.3 Results

In total, each operator drilled guided access cavities on 20 teeth: 10 on the upper jaw and 10 on the lower jaw. Two teeth, namely tooth number 43 on operator 1 and tooth number 41 on operator 2, came loose during drilling and were removed from

analysis. A total of 19 access cavities per operator were assessed. The mean length of the access cavities was 13.76 mm (min 10.56 mm – max 17.62 mm). The mean difference between planned drilling length and access cavity length was 0,54 mm (min 0,01 mm – max 1,36 mm).

Parameter	Comparison	Difference	*p*-value
Coronal entry point (C)	CBCT vs IOS	0.0492	0.138
	Op. 1 vs 2	0.0586	0.2318
Apical point (A)	CBCT vs IOS	0.0599	0.6505
	Op. 1 vs 2	0.2282	0.3044
Angular deviation (D)	CBCT vs IOS	-0.004	0.9934
	Op. 1 vs 2	0.4398	0.6543

Table 1. Differences between methods and operators per parameter. Letter coding: CBCT: Cone-Beam Computed Tomography, IOS: Intraoral Scan, Op: Operator. Differences in mm between the averages as calculated by the linear mixed model.

Differences between measuring methods, CBCT versus IOS, and both operators were assessed for every parameter: coronal entry point (C), apical point (A), and angular deviation (D). The null hypothesis stating that mean results between IOS and CBCT do not differ was not rejected. Additionally, the null hypothesis stating that mean results between operators do not differ was also not rejected. Results are shown in Table 1.

After successful statistical analysis of the proposed method ex vivo, 33 patients referred for endodontic treatment in teeth presenting PCO and signs or symptoms of apical periodontitis were included for analysis. All canals were found with the aid of guided endodontics. No perforations were recorded. Access cavities had an average length of 12.5 mm inside the tooth with a mean coronal deviation of 0.2 mm (min 0 mm – max 0.84 mm), mean apical deviation of 0.45 mm (min 0 mm – max 1.21 mm), and mean angular deviation of 1,91º (min 0.36º – max 5.19º). Examples of the cases and a schematic summary of the measurements are shown in Figure 4.

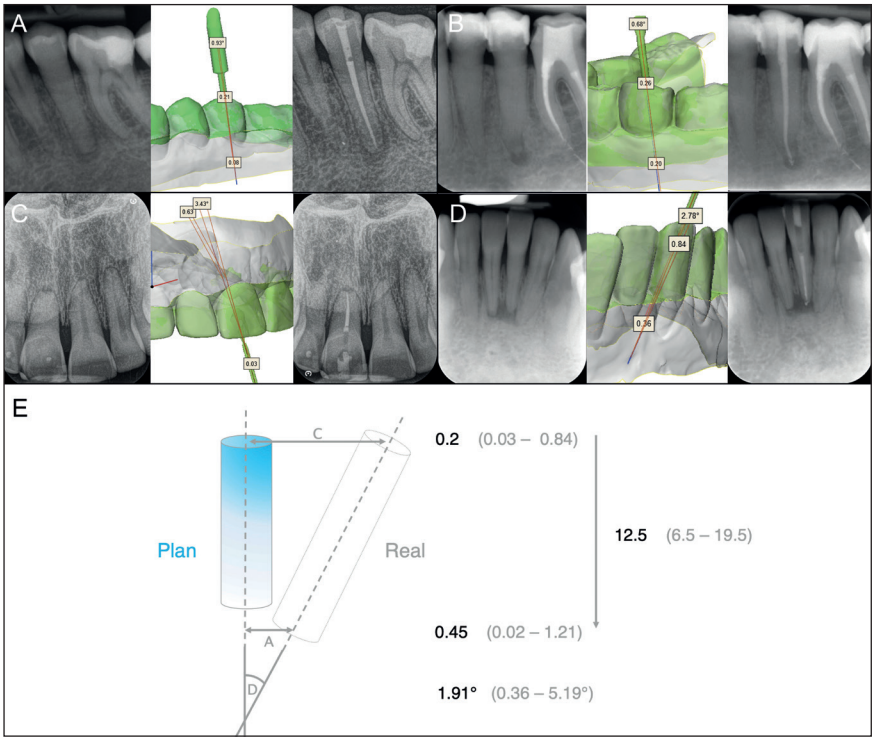

Figure 4. Clinical deviation measurements. (A - D), intraoral radiographs (left: pre-operative and right: post-operative) of clinical cases treated with guided endodontics. Center: deviation measurements assessed with IOS method, values (in mm) are shown for deviation at the coronal and apical point together with the angular deviation (in degrees). (E) Average deviation results (min and max shown between brackets) from n=33 patients at the C: Coronal entry point (average 0.2 mm, 0.03 – 0.84 mm) , A: Apical point (average 0.45 mm, 0.02 – 1.21 mm), D: Angular deviation (average 1.91□, 0.36□ – 5.19□). The length was measured clinically, and results are shown at the right side (average 12.5 mm, 6.5 – 19.5 mm).

3.4 Discussion

The first aim of this study was to validate a novel method using a post-operative intraoral scan (IOS) versus the gold standard, CBCT, on its ability to measure the accuracy of guided endodontics ex vivo. No statistical difference was found between measuring methods for all parameters ($P > 0.05$, Table 1). Therefore, the null hypothesis stating that mean accuracy measurements between IOS and CBCT do not differ was not rejected. Additionally, no statistical difference between operators was found ($P > 0.05$, Table 1), which confirms the reliability of the use of a guide for treatment, as the operator's experience does not influence the outcome. Other studies have demonstrated similar results [7, 15].

An intraoral scanner is an essential tool during digital planning and workflow for guided endodontics, in combination with a high-resolution CBCT [6]. Important to note is that an IOS's accuracy depends on the optical scanning technology, the capture principle, the version of software used, and a periodical calibration of the hardware when needed. Additionally, to decrease the chance of scan inaccuracies, the correct control of clinical factors by the clinician is mandatory. These include: avoiding the presence of saliva or blood over the scan surfaces, using retractors for soft tissues, and ensuring correct lighting conditions while scanning [22].

The intraoral scanner used in the present study (Trios, 3Shape) uses confocal microscopy as scanning technology with a video sequence as acquisition method [23]. Although there is no clear consensus about which technology would lead to more reliable results, this type of scanner has a high resolution (higher numbers of polygons per unit area) with favorable trueness and precision results reported in the literature [22, 23]. However, accuracy measurements may vary when using other types of scanners which could be a limitation [22]. Additionally, it is important to note that the bur placed inside of the cavity for post-op scanning acquisition was previously sandblasted (50 µm alumina powder at 2 bar) to improve surface roughness, reduce reflection and facilitate the scanning process, a concept used for scan bodies and single crowns [24-26].

Laboratory studies have reported a high accuracy of guided endodontics when comparing the actual path of the access cavity to the virtually planned trajectory through the superimposition of pre-operative and post-operative CBCT data [9, 14-17]. However, data from laboratory studies might not replicate all clinical variables and such results must be interpreted with caution when extrapolating to a clinical situation.

Several case reports [5, 8, 10-12, 27, 28] and an observational study on 50 patients [29] have shown the potential of guided endodontics as a reliable alternative for the treatment of complex endodontic cases. However, up to date there is no available data on the clinical accuracy of the method.

Therefore, the second aim of the study was to present clinical data on the accuracy of guided endodontics. After successful statistical analysis of the proposed method *ex vivo*, a total of 33 patients referred for endodontic treatment in teeth presenting PCO and signs or symptoms of apical periodontitis were included for analysis. All canals were found with the aid of a guide. Access cavities had an average length of 12.5 mm inside the tooth with a mean apical deviation of 0.45 mm and mean angular deviation of 1,9º.

By acquiring an IOS of the patient's tooth with the bur inside of the access cavity, the axis of the bur can be calculated and compared to the planned trajectory using 3D computer software without the need for a post-operative CBCT and additional radiation for the patient. A pre-operative IOS is available from the planning, and the acquisition of the post-operative IOS can be made in a short amount of time, during treatment, without moving the patient from the dental chair. Additionally, the registration process between a pre- and post-operative IOS is faster than for CBCT volumes since it requires less processing power.

During the treatment of the patients, the cavity length was measured with a periodontal probe or endodontic file upon its completion and recorded for analysis. Later, the bur axis line was extended in the software to the measured length to calculate the apical deviation. All measurements and points were calculated by the 3D analysis software, and no handmade measurements were needed.

Based on the current clinical results, to minimize the possibility of root perforation, a safety margin of at least 1 mm around the planned trajectory should be respected when planning the case, given that an average deviation of the center of the bur close to 0.5 mm can occur.

3.5 Conclusion

An IOS can be used to measure the accuracy of guided endodontics. It is as effective as the CBCT, and it does not involve additional exposure to radiation for the patient. Furthermore, clinical data showed high accuracy of guided endodontics with a mean apical deviation smaller than 0.5 mm and a mean angular deviation of less than 2º. A safety margin of at least 1 mm around the planned trajectory should be respected when planning the case to minimize the possibility of root perforation.

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Author Contributions
Conceptualization, A.T.; methodology, A.T. and M.D.; software, A.T.; validation, A.T., M.D., W.C.; formal analysis, A.T., and W.C.; investigation, A.T., M.D.; resources, A.T. and R.J.; data curation, A.T.; writing—original draft preparation, A.T.; writing—review and editing, A.T., M.D., W.C., MS.P., P.L., R.J.; visualization, A.T. and R.J.; supervision, A.T., P.L., R.J.; project administration, A.T.. All authors have read and agreed to the published version of the manuscript.

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Clinical significance
This method offers a valuable alternative to conventional endodontic guides with similar accuracy results.

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Chapter 4

In vitro study on the accuracy of sleeveless guided endodontics and treatment of a complex upper lateral incisor

Authors

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Keywords

3-dimensional printing
Accuracy
Cone beam computed tomography
Dental pulp calcification
Guided endodontics

Abstract

Aim - A sleeveless guide design reduces vertical space improving accessibility in posterior teeth, with direct visibility of the tooth during treatment, and better water cooling. Additionally, since no sleeve is used, the total cost is reduced, and there is no need for a dedicated bur. However, no data on its accuracy is available. Therefore, this study aims to assess the accuracy of sleeveless guided endodontics for guided root canal treatment of severe pulp canal obliteration (PCO) in 3D printed jaws. Additionally, the treatment of a complex lateral incisor is presented to illustrate the use of sleeveless guides in a clinical situation. **Methods** - Two cone-beam computed tomography (CBCT) volumes of an upper and lower jaw were selected to design 3D printed models with PCO. Virtual planning of the access cavities was performed from right to left second premolar. Then, the models were mounted into a phantom head to simulate an actual patient. Two operators with different levels of experience in endodontics performed guided access cavities. The handpiece was guided by guiding rails placed against each other on the sides of the tooth. A post-operative CBCT scan was taken for analysis. **Results** - Eighty-eight guided access cavities (44 per operator) were drilled on eight 3D printed models. The mean length of the access cavities was 15.3 mm, with a mean coronal and apical deviation of 0.5 mm and 0.7 mm respectively. The mean angular deviation was 1.5º. No statistically significant difference was found between operators for the three measured parameters. **Conclusions** - This study demonstrates, within its limitations, that this is an accurate method for guided endodontic treatment. No statistically significant difference between operators was found when using the guide.

4.1 Introduction

Guided endodontics offers an alternative to conventional access cavity preparation for teeth with pulp canal obliteration (PCO) and apical pathosis or irreversible pulpitis [1]. PCO is usually associated with luxation injuries after dental trauma [2-4]. It may also occur as a pulpal response to carious lesions [5], coronal restorations [6], after vital pulp therapy procedures [7], as apposition of secondary dentin over time in elderly patients [8, 9], or as an adverse effect to orthodontic forces [10, 11].

This technique uses tooth supported guides or templates analogous to guided implantology for the location of calcified canals [12]. The use of a guide can be advantageous in teeth where endodontic treatment can be challenging, and it can reduce the chance of iatrogenic damage [1, 12-15]. Additionally, it may save chair time [9, 14, 16] and provide minimally invasive access to the canal, avoiding unnecessary removal of dentin, which can compromise the tooth [16].

The most common guided endodontics technique involves the use of a metal sleeve bonded to a tooth-supported guide which leads the bur during drilling. However, some of the drawbacks of this technique are the blockage of direct vision during treatment, and limited water cooling, as there is no space to cool the drill properly. Moreover, vertical space can be an issue when treating posterior teeth or patients with limited mouth opening, as enough space is needed to place the guide and bur on top of the tooth [13, 17].

Recently, a sleeveless 3D printed guide was used to treat an upper premolar [18]. Instead of using a metal sleeve to guide the bur, the handpiece is guided by guiding rails placed against each other on the sides of the tooth. As a result, (1) vertical space is reduced, which (2) improves accessibility in posterior teeth, (3) there is direct visibility of the tooth during treatment, and (4) better water cooling [18]. Additionally, since no sleeve is used, the (5) total cost of the guide is reduced. There is (6) no need for a dedicated bur; therefore, the procedure can be fully guided with the use of diamond burs to drill first on enamel and later longer carbide burs to further drill on dentin.

Although promising, no data is currently available concerning its accuracy. Therefore, this study aims to assess the accuracy of sleeveless guided endodontics for guided root canal treatment of severe PCO in 3D printed jaws. Additionally, a sleeveless guided endodontic treatment of a complex lateral incisor is presented to illustrate the use of the guide in a clinical situation.

4.2 Materials and methods

This manuscript was written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (Figure 1) [19].

3D model design

For the design of the 3D models, two CBCT volumes were selected, one upper and one lower jaw, from the database of the Oral Imaging Center of the Department of Oral Health Science at the University Hospital of the KU Leuven, Leuven, Belgium. Patients were referred for CBCT scanning for clinical indications not related to the study. Teeth from the central incisor up to the second premolar, in both jaws, were segmented with an artificial intelligence driven automated tooth segmentation tool [20]. A threshold segmentation was performed to segment the bone in both jaws using Mimics Medical software 24.0 (Materialise, Leuven, Belgium). Finally, the 3D models of teeth and bone tissue were imported into 3-matic Medical software 16.0 (Materialise) where the final model was designed with a base able to fit on a dental phantom. This protocol was validated in a study on dynamic navigation [21].

Canals were created starting at 15 mm depth from the incisal edge or occlusal surface to simulate severe PCO. All teeth had 1 canal, except for teeth 14 and 24, which had 2 roots and 2 canals. In total, 12 and 10 canals were created for the upper and lower jaw respectively. All models were 3D printed in white resin material (VeroWhite; Stratasys, Eden Prairie, MN, USA) using the Objet Connex 350 3D printer (Stratasys).

Virtual planning

A pre-operative high resolution CBCT scan using the NewTom VGi evo (Cefla, Imola, Italy) with a voxel size of 0.125 mm was taken for each model together with an intraoral surface scan (Trios; 3shape, Copenhagen, Denmark). Both files, DICOM images from the CBCT and the STL file from the intraoral surface scan, were imported and registered using SMOP software (version 2.20.0, Swissmeda AG, Baar, Switzerland). The treatment was planned on the same software by creating a path for the bur maintaining straight-line access up to the root canal (Figure 2). Finally, 3D guides were designed using a double rail system placed on the sides of the tooth to guide the handpiece head (2INGIS, Brussels, Belgium). The guides were printed in Try-in material (3D Systems, Rock Hill, South Carolina, United States) using the NextDent 5100 3D printer (3D Systems).

Rationale

There is no data on the accuracy of sleeveless guide endodontics.

Aim

To assess the accuracy of sleeveless guided endodontics in 3D printed jaws.

Ethical approval

S64630

Samples per operator (2 operators)

Two sets of 3D printed models based on a real patient with 12 (upper jaw) and 10 (lower jaw) planned acces cavities (one per tooth up to second premolar on each side; first upper premolar one buccal and one palatal).

Groups

Operator 1 (44 acces cavities).

Operator 2 (44 acces cavities).

Outcomes assesed

Length of acces cavity, and deviation at the coronal entry point (C), apical point (A), and angular deviation (D).

Method used

Semiautomatic measuring protocol (previously validated by Torres et al (Torres et al. 2021)).

Results

88 acces cavities: Mean length of 15.3 mm, mean coronal and apical deviation of 0.5 mm and 0.7 mm respectively. Mean angular deviation of 1.5º. No statistically significant difference was found between operators.

Conclusion

Sleeveless guided endodontics is an accurate method for guided access treatment of teeth presenting PCO and can offer a valuable alternative to conventional endodontic guides.

Funding details

No funding.

Conflicts of interest

The authors deny any conflict of interest.

Figure 1. PRILE Flowchart. Adapted from Nagendrababu et al. 2021.

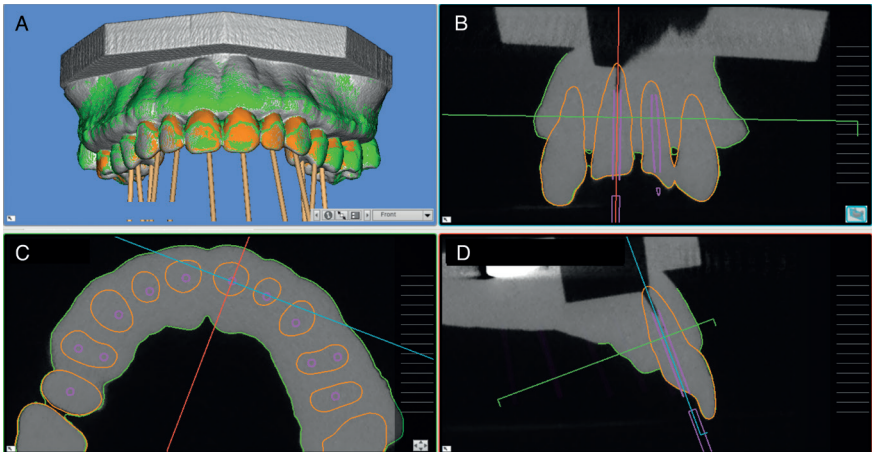

Figure 2. Virtual planning. Images from SMOP software (version 2.20.0). A: Registration of the pre-operative CBCT of the 3D model (grey) with the STL file from the intraoral scan (green). Note the planning of the access cavity path (orange cylinders). B: Coronal view of tooth 21 (upper left central incisor). Green contour line: registered intraoral scan. Orange contour line: 3D model of segmented teeth (registered to the CBCT to visualize the root). Purple contour line: path for the bur maintaining straight-line access up to the root canal. C: Axial view of the planning and contour lines. D: Sagittal view of tooth 21.

Access cavity drilling

All models were mounted into a phantom head to simulate a real patient. Two operators with different levels of experience in endodontics performed guided access cavities on 2 sets of models (upper and lower). Operator 1 is an experienced Endodontic specialist with more than 5 years of experience, and Operator 2 is a second-year resident from the department of Endodontics at the KU Leuven, Leuven, Belgium. A leg system (2INGIS) was firmly attached to the handpiece head (W&H WS-75 L handpiece, W&H, Bürmoos, Austria). These legs fit on the 3D printed guide's rails and guided the handpiece during treatment. The handpiece was used with a flat end cylinder diamond bur of 1 mm diameter mounted on an FG to RA converter mandrel adapter to simulate its clinical use during the drilling of enamel in the first 2 mm depth. Then, a 1 mm diameter carbide bur (working length: 21 mm, total length: 35 mm, REF O.27.28.B044.051, Steco System-Technik GmbH, Hamburg, Germany) was used at a maximum of 10.000 rpm with a pumping movement. The bur was replaced every 5 cavities (Figure 3).

Accuracy analysis

After treatment, a post-operative high resolution CBCT scan was taken for each model using the NewTom VGi evo (Cefla) operating at the same parameters mentioned before.

Pre- and post-operative CBCT volumes were imported into Mimics Medical software 24.0 (Materialise). A threshold segmentation was performed for both models, and they were then exported as an STL file into 3-Matic Medical software 16.0 (Materialise), where the post-operative model was registered to the pre-operative model (Figure 4A).

After registration, both models were duplicated, and the post-operative model was subtracted from the pre-operative model. As a result, all access cavities were obtained (Figure 4B and C). The software then fitted a line on the central axis of each access cavity. The deviation at the coronal entry point (C), apical point (A), and angular deviation (D) were measured in comparison to the virtual planning. Two planes were created to measure C and A: a plane perpendicular to the planning at the coronal access point and a second plane also perpendicular to the planning passing through the apical point of the access cavity. Finally, points were projected in the direction of the planning axis up to the planes, and distances in relation to the planning were measured (Figure 4D, E and F). The length of each access cavity was also recorded. This method was previously described and validated by Torres et. al. [21].

Clinical case report

A 72-year-old male patient, ASA I, was referred to the Endodontic Department at the University Hospitals of the KU Leuven, Leuven, Belgium, with an asymptomatic apical radiolucency on tooth number 12. The apical lesion was detected after the radiological checkup after cementation of the crowns. Clinically, the patient had no complains and there was no sinus tract. The patient was partially edentulous with metal porcelain crowns on all upper teeth (tooth number 16, 14, 13, 12, 11) and 2 implants with ball attachments on region 23 and 26 for the retention of a removable denture (Figure 5A and B). The periapical radiograph revealed an apical radiolucency on tooth 12 with an obliterated root canal. Tooth 12 was diagnosed with pulp necrosis and asymptomatic apical periodontitis.

Due to the degree of PCO on a thin root and presence of a crown with a precision attachment for a removable denture, guided endodontic treatment was scheduled. Guided endodontic treatment was approved by the ethical committee of the university hospitals (S64630) and informed consent was obtained. Ideally, a small access cavity had to be drilled trough the metal porcelain crown and located between the incisal border and the precision attachment on the palatal side. However, the presence of metal in the mouth presented a challenge for the registration of a digital impression to the CBCT for guided endodontic treatment planning.

Therefore, a Lego brick (Lego Brick 2x3, ID: 4211386/3002, Lego, Billund, Denmark) was fixed to a plastic impression tray, and an intraoral impression was taken

using the modified tray with Impregum Penta soft (3M ESPE, Seefeld, Germany) (Figure 5C and D). Directly after hardening of the impression material, a CBCT was taken with the tray inside of the mouth, using the NewTom VGi evo (Cefla) operating at 110 kVp, 3.0 mA with a FOV of 10 x 10 cm and voxel size 0.125 mm.

The impression tray was later scanned with a high-resolution optical scanner (Activity 885, SmartOptics, Bochum, Germany). The DICOM images from the CBCT, and the STL file from the digitalized impression were exported into Smop (Swissmeda AG). First, the quality of the CBCT was controlled by the correct registration of a standard 3D model of the Lego brick to the one on the CBCT. After checking and validating the data, the STL file from the digitalized impression was registered to the CBCT by registration of the Lego bricks, obtaining as a result the registration of the teeth surface (Figure 5E, F, G and H). Then, a path for the bur was created maintaining straight-line access up to the root canal (Figure 5H), and finally a 3D sleeveless guide was designed, and 3D printed in Try-in material (3D Systems) using the NextDent 5100 3D printer (3D Systems).

A leg system (2INGIS) was firmly attached to the handpiece head (W&H WS-75 L handpiece). The 3D printed guide was placed on the upper teeth, and treatment was initiated with a transmetal bur (Dentsply Sirona, Ballaigues, Switzerland) placed on an FG to RA converter mandrel adapter. After initial access through the metal was achieved, a 1 mm diameter carbide bur, with 21 mm working length and 35 mm total length (REF O.27.28.B044.051, Steco) was used to drill the rest of the access cavity. When the target point was reached, the tooth was immediately isolated and examined under the dental microscope.

After glide path was achieved with a size 15 K-File (Dentsply Sirona) instrumentation of the canal was performed with Waveone Gold files (Dentsply Sirona). Waveone Gold Medium (size 35, .06 taper) was selected as final file, apical patency was controlled during the whole procedure with the help of a size 10 K-File (Dentsply Sirona). During treatment, the root canal was rinsed with 20 ml of 5% NaOCl in combination with sonic activation using EDDY (VDW, Munich, Germany), then a final irrigation protocol was applied using EDDY and 17% EDTA, and a final rinse with 5% NaOCl. The root was dried using paper points and filled using a vertical condensation technique with warm gutta-percha and an epoxy sealer (TopSeal sealer, Dentsply De Trey, Konstanz, Germany). The access cavity was then filled with composite, occlusion was controlled, and the restoration was polished. A periapical radiograph was taken after treatment and the patient was scheduled for recall.

A follow-up periapical radiograph 1 year after treatment revealed a completely healed apical area (Figure 6).

Statistical analysis

Descriptive statistics for each parameter were performed. Differences between operators were assessed for every parameter (Coronal, Apical and Angle) by a linear mixed model with model as a random factor and operator as a fixed factor. In the first instance, a residual analysis was performed by means of a normal quantile plot and a residual dot plot. If data were not normally distributed, a square root or log transformation was applied, and the normal quantile plot of the residual values was checked again. $P \leq 0.05$ was considered statistically significant.

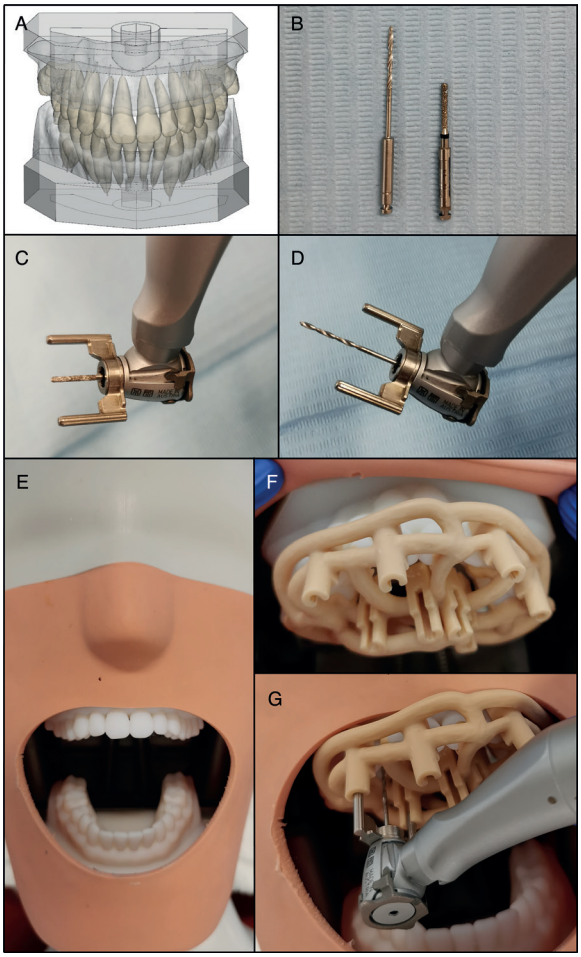

Figure 3. In vitro **experiment.**

A: 3D model replicas.
B: Left; 1 mm diameter carbide bur (REF O.27.28.B044.051, Steco). Right; flat end cylinder diamond bur of 1mm diameter mounted on an FG to RA converter mandrel adapter.
C: leg system (2INGIS) attached to the handpiece head (W&H) with diamond bur used to drill on the first 2mm to simulate the access through enamel.
D: same set-up with the carbide bur mounted on the handpiece (REF O.27.28.B044.051, Steco). E: Phantom mounted with 3D printed models to simulate a real patient. F: 3D printed guide placed on the upper jaw with rails for tooth 13, 11, 22 and 24 palatal. G: Guided access drilling of tooth 13 with carbide bur (Steco).

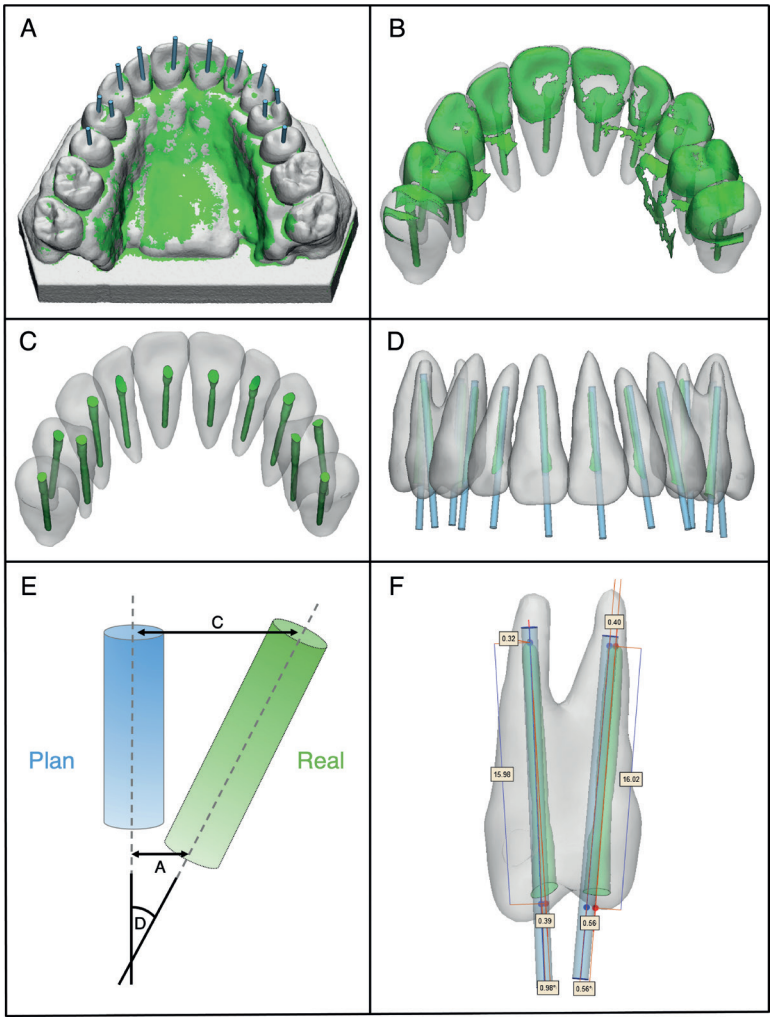

Figure 4. Accuracy analysis. Images from 3-Matic Medical software 16.0 (Materialise) A: Registration of pre-operative model (white) with post-operative model (green). Note the planning of the access cavity path (blue cylinders). B: The post-operative model was subtracted from the pre-operative model (result shown in green). The 3D model of the segmented teeth is shown in white for illustration purposes. C: All access cavities (green) after cleaning. D: Frontal view of the access cavities (green) and planning (blue) with segmented teeth (white). E: schematic representation of the accuracy measurements at the coronal entry point (C), apical point (A), and angular deviation (D). Measurements C and A are measured perpendicular to the planning at the coronal access point and apical point of the access cavity respectively. F: Example of the accuracy measurements of an upper premolar. The buccal cavity has a length of 15.98 mm, and deviation measurements of C: 0.39 mm, A: 0.32 mm, and D: 0.98º. The palatal cavity has a length of 16.02 mm, and deviation measurements of C: 0.56 mm, A: 0.40 mm, and D: 0.56º.

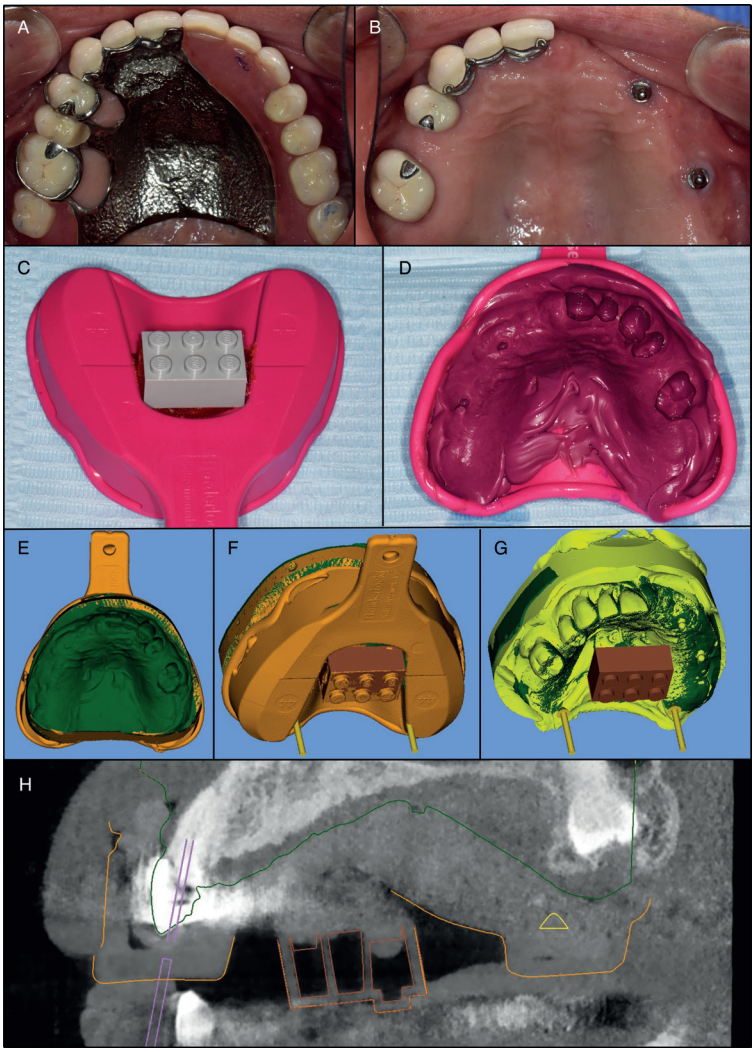

Figure 5. Virtual planning of clinical case. A: Clinical view of the upper jaw with removable prosthesis placed in the mouth supported by precision attachments on the right side and 2 implants with ball attachments on the left side. B: View of the upper jaw without prosthesis. C: Lego brick bonded to a plastic impression tray. D: Intraoral impression taken with Impregum Penta soft (3M ESPE). E: Digitalization of the intraoral impression after scanning with a high-resolution optical scanner (Activity 885, SmartOptics). F: View from below of the digitalized impression tray with Lego brick. G: View of the cast model (yellow) registered to intraoral impression (green). H: Sagittal view of tooth 12 with the registered contours of the impression tray and Lego brick (orange) and the intraoral impression (green). A path for the bur was created maintaining straight-line access up to the root canal (purple).

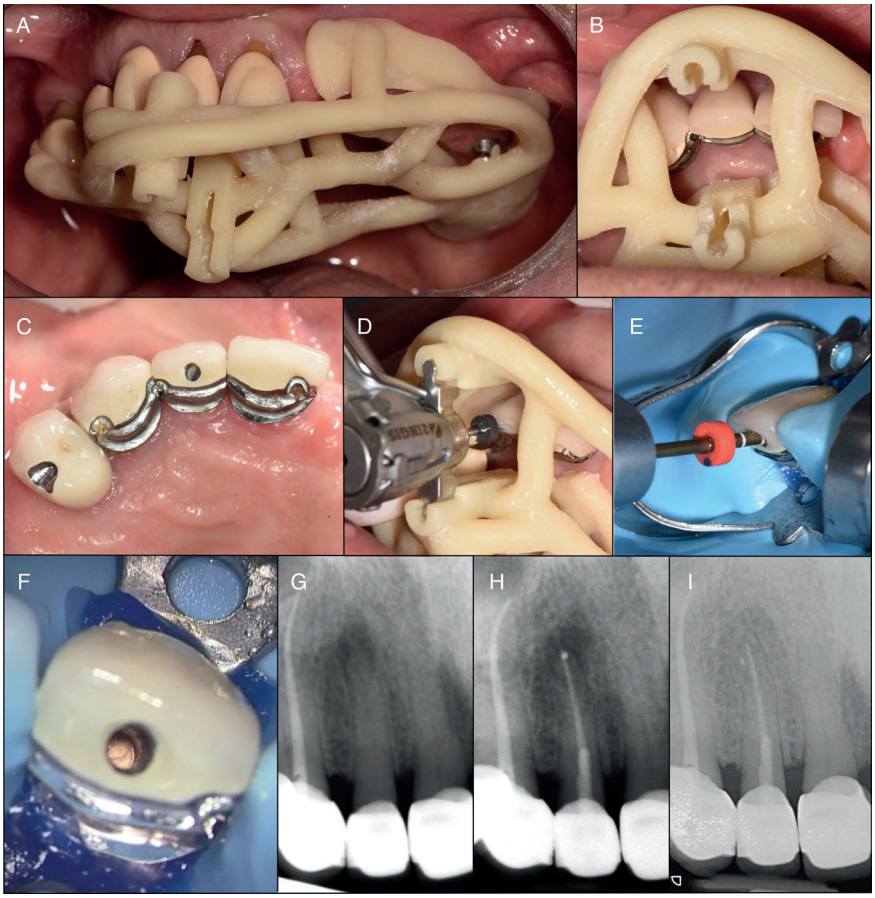

Figure 6. Clinical case. Clinical images during treatment; A: 3D sleeveless guide placed in the mouth supported by teeth on the right side and implants on the left side. B: View of tooth 12 with guiding rails on the sides of the tooth. C: Access cavity trough metal porcelain crown of tooth 12 after drilling with a transmetal bur. D: Guided access cavity drilling with carbide bur (Steco). A silicone stop ring (black) was placed on the bur up to the depth length of the target point. E: View during endodontic instrumentation with Waveone Gold Primary file (Dentsply). F: view from a dental microscope after filling of canal with gutta-percha. G: Pre-operative periapical radiograph before treatment revealing an apical radiolucency on tooth 12 with an obliterated root canal. Tooth 12 was diagnosed with pulp necrosis and asymptomatic apical periodontitis. H: Post-operative periapical radiograph after treatment, and I: follow-up periapical radiograph 1 year after treatment revealing a completely healed apical area.

4.3 Results

A total of 88 guided access cavities, 44 per operator, were drilled on eight 3D printed models. Each operator had four 3D models divided into 2 sets comprising an upper and a lower jaw. The mean length of the access cavities was 15.33 mm (min 10.76 mm – max 18.44 mm). The mean deviation values at the coronal entry point, apical point, and angular deviation, of both operators combined and apart are shown in Table 1.

A statistical analysis was performed to assess significant differences between the deviation values of both operators for every measured parameter. $P \leq 0.05$ was considered statistically significant. The following *p*-values were obtained: Coronal entry point: $p = 0.08$, Apical point: $p = 0.99$, and Angular deviation: $p = 0.56$.

	Coronal	Apical	Angle
Both Operators	0.50 mm (0.22 – 0.79)	0.68 mm (0.10 – 1.88)	1.54º (0.18 – 5.87)
Operator 1 (Experienced Endodontist)	0.47 mm (0.22 – 0.73)	0.66 mm (0.18 – 1.81)	1.47º (0.18 – 5.87)
Operator 2 (Second year resident)	0.54 mm (0.34 – 0.79)	0.70 mm (0.10 – 1.88)	1.61º (0.21 – 4.79)

Table 1. Mean deviation values of sleeveless guided endodontics with their minimum and maximum values between brackets.

4.4 Discussion

A sleeveless guide uses two cylinders, which are placed against each other on the sides of the tooth, to guide the handpiece instead of the bur. A two-legged adapter is firmly attached to the handpiece head which glides through the rails during treatment. Once inserted, the bur can only move in the direction of the drilling axis, while the adapter legs can rotate to find the best position for the handpiece [18, 22]. This results in a low-cost guide, as there is no additional cost for a sleeve and a specially dedicated bur. The adapter must be acquired once and can be reused.

The open design allows for (1) better visibility of the tooth, (2) direct control of the optimal fit of the guide in the mouth, and (3) water cooling during treatment. However, no previous study has investigated the influence of conventional and sleeveless guides on water cooling. Additionally, less vertical space is needed, as there is no sleeve and guide on top of the tooth, which allows for guided treatment on posterior

teeth or in cases when there is limited mouth opening [18, 23, 24]. One drawback is that it needs multiple anchor points to ensure its stability. Working with full mouth rubber dam isolation from the beginning of the treatment is an alternative option, but this could be uncomfortable for some patients [18].

The study aimed to assess the accuracy of sleeveless guided endodontics for guided root canal treatment of severe PCO in 3D printed jaws. In total, 88 guided access cavities were drilled with an average coronal and apical deviation of 0.5 mm and 0.7 mm respectively. The average angular deviation was 1.5º.

Although the more experience operator obtained slightly better accuracy values, no statistically significant difference between operators was found for the three measured parameters. This confirms that the use of a guide is not influenced by the operator's experience, as demonstrated in other studies [14, 16]. Nonetheless, a *p*-value close to 0.05 was obtained when comparing the coronal entry point between operators. Therefore, special attention should be paid when starting the treatment. The correct fitting of the guide must be inspected together with a fluent movement of the handpiece when placed inside the guiding rails. A couple of pumping movements can be practiced with the handpiece in place before the operator starts drilling to determine the correct axis without applying pressure in a direction that can compromise the bur's trajectory.

When placing implants, a sleeveless design seems to be clinically reliable, with good accuracy results showing a mean apical deviation of 0.8 mm and a mean angular deviation of 2.8° [24, 25]. Recently, a sleeveless guide was used for guided endodontic treatment of a first upper premolar [18]. The authors reported achieving minimally invasive access up to the middle of the root; however, no data was available regarding its accuracy. On the other hand, the accuracy of conventional guides used for guided endodontics has been assessed in several studies, showing mean apical deviation values smaller than 0.5 mm [13, 14, 26-28] with a mean angular deviation between 1.59° and 1.81° [13, 14]. Although it is difficult to compare the present study with other studies due to differences in the protocol and heterogeneous measuring methods, the deviation measurements obtained with a sleeveless guide do not seem to differ substantially from those of conventional guides. It is also important to consider the depth of the drilled cavities. The mean length of the access cavities was 15.33 mm, which was, on average, higher than those of previous studies. This can explain the slightly higher deviation values obtained apically. The average angular deviation was below the range reported by other authors [13, 14, 28].

The treatment of a complex lateral incisor was presented to illustrate the use of the guide in a clinical situation. Ideally, a small access cavity, located between the

incisal border and the precision attachment on the palatal side, had to be drilled through the metal porcelain crown to locate the canal presenting PCO. This motivated the use of a sleeveless guide because of the possibility of drilling guided through a metal porcelain crown using different types of burs. During planning, the presence of metal artefacts on the CBCT presented a challenge for the registration to the intraoral impression. For this reason, a Lego brick was used as a reference. It is a cost-effective method for the registration of the data. It is radio opaque, and has an accuracy of up to 5 µm, as claimed by the manufacturer [29]. Additionally, the correct registration of a standard 3D model of the Lego brick to the one on the CBCT allows for quality control of motion artefacts before planning.

4.5 Conclusions

In conclusion, notwithstanding its limitations, the present study has demonstrated that sleeveless guided endodontics is an accurate method for guided access treatment of teeth presenting PCO and can offer a valuable alternative to conventional endodontic guides. No statistically significant difference between operators was found when using the guide. However, clinical training is recommended to learn working with the system and avoid errors during treatment.

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Chapter 5

Dynamic navigation: a laboratory study on the accuracy and potential use of guided root canal treatment

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Keywords

Access cavity
Cone-beam computed tomography
Dynamic navigation
Dental pulp calcification
Guided endodontics

Abstract

Aim - To evaluate 3D accuracy and outcome of a dynamic navigation method for guided root canal treatment of severe pulp canal obliteration (PCO) in 3D printed jaws. **Methods** - Three operators with different levels of experience in Endodontics performed navigated access cavities, using the Navident system (ClaroNav, Toronto, Canada), in 2 sets (maxillary and mandibular) of 3D-printed jaw models with teeth presenting severe PCO. Models were mounted on a phantom to mimic a real clinical situation. After treatment, a post-operative high resolution CBCT scan (NewTom, Verona, Italy) was taken for each model and registered to the pre-operative model. All access cavities were then segmented using 3-Matic Medical software 15.0 (Materialise, Leuven, Belgium). Length and volume of each access cavity was measured, and a comparison was done by measuring the distance deviation in mm at the coronal entry point, apical point, vertical deviation, total deviation and angular deviation of the access cavity in comparison to the virtual planning. Additionally, all access cavities were scouted with a size 10 K-file and inspected on the CBCT to confirm that the canal was located. Descriptive statistics for each parameter were performed. Normality of the data was assessed; data were transformed if needed to make it normally distributed. One-way Analysis of Variance (ANOVA) was applied to assess differences between parameters for tooth type, jaw, and operators and corrected for simultaneous hypothesis testing according to Tukey. Significance level was set at 0.05. **Results** - After training with the system (28 cavities per operator), a total of 132 teeth and 168 access cavities (56 per operator) were prepared. All operators found a total of 156 canals, obtaining an overall success of 93% without difference between operator experience ($p > 0.05$). The mean deviation at the apical point was 0.63 mm (SD 0.35) and was significantly lower in anterior teeth in comparison to molars ($p < 0.05$). The mean angular deviation from the planning was 2.81° (SD 1.53). **Conclusions** - Dynamic navigation was an accurate approach for root canal treatment in teeth with severely calcified canals. However, the technique has a learning curve and requires extensive training prior to its use clinically.

5.1 Introduction

Conservative access cavity preparation on teeth with pulp canal obliteration (PCO) is challenging [1] as it is difficult to maintain the correct alignment of the bur and there is an increased probability of failure [2, 3]. Recently, the concept of guided endodontics has been introduced, in which computer-designed guides are used for conservative access cavity preparation [4, 5] of teeth with complex canal anatomy or PCO in order to achieve predictable and safe results [6].

In vitro and ex vivo studies have reported a high accuracy when comparing the actual path of the access cavity to the planning [7-9]. However, the use of static guides is challenging because of the limited mouth opening of the patient. Also, the time invested for the planning, design and fabrication of a guide has to be considered. Furthermore, there is limited visibility and water-cooling when using the guide and the planning cannot be modified during treatment. Other designs for static guides have been proposed to deal with some of these limitations by using a sleeveless guide [10], but it remains a static guide system.

On the other hand, computer-aided dynamic navigation systems use software to plan the treatment and a camera that detects tags fixed to the patient and the handpiece in order to track the movements of the bur relative to the patient's position, similar to a global positioning system in real time. In this technique, which has been already used in implant surgery [11, 12, b13, 14-19], movements of the bur, relative to the Cone-Beam Computer Tomography (CBCT) scan of the patient and the planning of the case, are then shown on a screen. This allow clinicians to visualize the position of the bur and its angulation during drilling, which can be adjusted in real time, increasing safety and predictability [14, 20]. Some of the advantages of this technique are:

1) The CBCT acquisition, planning and treatment can be performed in a single appointment
2) It can be used in cases of limited vertical space as a guide is not necessary
3) The planning is simplified as there is no need for a guide design
4) Visibility and water-cooling are improved as there is no barrier between the water source and the bur
5) Any bur can be used as there is no special coupling system
6) Guidance failures due to poorly fitting guides do not occur [19].

The drawbacks are:

1) A high initial investment in equipment is needed and may present a substantial change to the existing clinical workflow
2) It requires an initial calibration process prior to treatment
3) The operator has to be properly trained prior to treatment
4) Current deviation values seem slightly high compared to static guides

Nonetheless, dynamic navigation has the potential to be applied also for guided endodontics. However, studies are needed to test its accuracy.

Therefore, the aim of this study is to evaluate the 3D accuracy and outcome of a dynamic navigation method for guided root canal treatment of severe PCO in 3D printed jaws.

5.2 Materials and methods

Design of 3D model replicas

Two CBCT volumes were selected, maxillary and mandibular jaw, from the database of the Oral Imaging Center of the Department of Oral Health Science at the University Hospital of the KU Leuven, Leuven, Belgium, for the design of 3D model replicas. Patients were referred to the radiology centre for CBCT scanning in accordance with clinical indications not related to the study. For the maxilla an artificial intelligence driven automated tooth segmentation [21] was performed to segment and generate 3D models of teeth 15 to 25, the same algorithm was applied for segmentation of teeth 36 to 46 on the mandible. The bone tissue from both jaws was segmented by applying a threshold in Mimics Medical software 23.0 (Materialise, Leuven, Belgium). Finally, the teeth and bone tissue were imported into 3-matic Medical software 15.0 (Materialise) where a final model was designed.

Severe PCO was simulated on each tooth by placing canals at 15 mm depth from the incisal edge or occlusal surface. All teeth had 1 canal except for teeth 14 and 24 with 2 roots and 2 canals, and teeth 36 and 46 with 2 roots and 3 canals (2 mesial and 1 distal). In total, 12 and 16 canals were created for the maxillary and mandibular jaw respectively. All models were 3D printed in white resin material (VeroWhite; Stratasys, Eden Prairie, MN, USA) using the Objet Connex 350 3D printer (Stratasys) (Figure 1A).

Virtual planning protocol and treatment

A pre-operative high resolution CBCT scan using the NewTom VGi evo (NewTom, Verona, Italy) with a voxel size of 0.125 mm was taken for each model together with an intraoral surface scan (Trios; 3shape, Copenhagen, Denmark). The DICOM images from the CBCT and the STL file from the intraoral scanner were then imported into the Navident Software (ClaroNav; Toronto, Ontario, Canada) and registered to each other. Straight line access cavities/paths of 1 mm diameter were then planned in the same software up to the orifice of the canal.

The models were then placed in a phantom head including rubber cheeks to simulate a real patient. The *Jaw Tracker* from Navident (ClaroNav) was mounted in the model to be treated and fixed to the teeth using composite resin. Trace protocol was performed to register the CBCT volume to the model using the *Jaw Tracker* as reference. For the registration, a total of 6 reference points were placed on the surface of different teeth (3 on each side). Then, a calibrated *Tracer* tracked by the system's camera was initially placed on a reference point and then moved along the surface of the tooth, while the system sampled different points along its path. This group of points was then automatically registered by the software to the best possible fit with the surface of the tooth available from the intraoral scan. A final check to verify the registration accuracy was performed by tracing randomly selected teeth in all directions.

Prior to the navigated access cavity preparation, the axis and length of the bur was calibrated. First, a *Drill Tag* was firmly installed on the handpiece. The axis of the handpiece was then calibrated by inserting the handpiece head on the handpiece calibration pins from the *Calibrator Tool*. A gentle rotation movement from side to side around the calibrating pin's axis was performed to calibrate the axis of the bur. Then, the length of the bur was calibrated by placing the bur on the handpiece head and placing its tip in the dimple on top of the *Calibrator Tool*. Finally, the diameter of the tip was adjusted on the system software.

After the bur was calibrated, it is possible to visualize the tip of the bur in relation to the CBCT volume. An additional check was performed to verify the calibration accuracy by tracing randomly selected teeth with the tip of the bur in all directions.

Navigated access cavity preparation was performed using a combination of 2 burs. First, a round diamond bur of 1 mm diameter (Komet 801.314.010; Komet Brasseler, Lemgo, Germany), mounted on a WG-99 LT handpiece (W&H, Bümoos, Austria) was used to prepare up to 2 mm depth, in order to simulate the access through enamel. Then, a size 2 Munce Discovery bur (CJM Engineering, SantaBarbara, CA, USA) with a head and shaft diameter of 1 mm and a total length of 31 mm

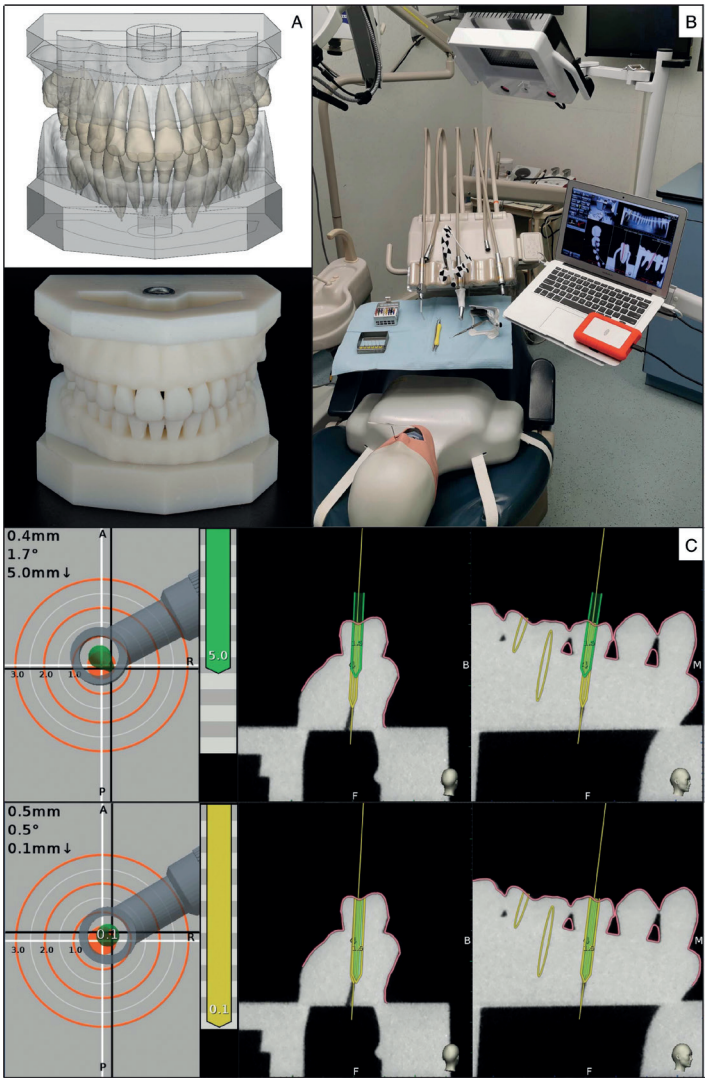

Figure 1. 3D model replicas and clinical set-up. (A) Top; 3D model design with segmented teeth and artificial canals with pulp canal obliteration (PCO) up to 15 mm depth. Bottom; 3D printed models in white resin material (VeroWhite). (B) Clinical set-up with the Navident unit and models placed in a phantom head to simulate a real clinical situation. (C) Views from the Navident software while drilling on a lower premolar (top) and upon reaching target (bottom). A "target" symbol is displayed on the left showing the deviation of the drill from the center of the planning, angular deviation and depth to target, additional views from the CBCT are provided on the right showing in live feed the position of the drill. Note: the color from the depth gauge changes from green to yellow when the drill is within 1 mm of the desired depth and from yellow to red when the correct depth is reached.

mounted on a WG-56 LT handpiece (W&H) was used in a pumping movement to prepare up to the orifice of the canal.

The movement and position of the handpiece in relation to the model was tracked via the mounted tags (*Drill Tag* and *Jaw Tracker*). Both tags are constantly and simultaneously detected by the built-in micron tracker camera, providing optical triangulation tracking. The operator can then visualize in real time the location and direction of the tip of the bur in relation to the CBCT of the model and the planned access cavity (Figure 1B, C).

Three operators with different levels of experience in Endodontics, a final year dentistry student (operator 1) and two endodontic specialists with more than 5 (operator 2) and 30 (operator 3) years of experience respectively, performed treatments on 2 pairs of models each (2 maxillary and 2 mandible models, with a total of 56 canals). One week prior to treatment, each operator trained with the system on 1 set of models (maxillary and mandible) preparing a total of 28 access cavities.

Accuracy analysis

After treatment, a post-operative high resolution CBCT scan was taken for each model using the NewTom VGi evo (NewTom) operating at the same parameters mentioned before. DICOM files from pre- and post-operative CBCT were imported into Mimics Medical software 23.0 (Materialise) where a segmentation of the model was performed by applying a threshold. Both models were then exported as an STL file into 3-Matic Medical software 15.0 (Materialise) where the post-operative model was registered to the pre-operative model by using a 3-point registration method to approximate both structures and later an automatic global registration was repeated, for final registration, until no further movement was possible.

After registration, both models were duplicated, and the post-operative model was subtracted from the pre-operative model obtaining all access cavities as a result. A line on the central axis of each access cavity was then automatically fitted by the software. The length and volume of each access cavity was measured, and a comparison was done by measuring the distance deviation in millimeters at the coronal entry point, apical point, vertical deviation, total deviation and angular deviation of the access cavity in comparison to the virtual planning (Figure 2). Additionally, visual inspection was done through the axial slides to assess for perforations. A successful outcome for the treatment was defined as being able to locate and scout the canal with a file after preparing the access cavity. The outcome was assessed for each treatment by scouting all access cavities with a size 10 K-file (Dentsply Sirona Endodontics, Ballaigues, Switzerland) and having visual confirmation of the file going

through the canal at the base of the model. This was later confirmed by inspecting the post-operative CBCT.

Statistical analysis

Descriptive statistics for each parameter were performed. Normality of the data was assessed by means of normal quantile plots. A square root of log-transformation was applied in order to make the data normally distributed. Outliers were identified after an eventual transformation by means of the Grubbs test.

One-way Analysis of Variance (ANOVA) was applied to assess the differences between parameters for tooth type (anterior, premolar, molar), jaw (maxillary and mandible), and operators. The significance level was set at 0.05. Differences between groups were made based on the results of the Anova model and corrected for simultaneous hypothesis testing according to Tukey.

To assess the differences between the operators's success rate during treatment, a general linear model for binary outcomes using a logit link was applied and the proportions of the three operators were compared with a correction for simultaneous hypothesis testing according to Tukey.

5.3 Results

A total of 168 access cavities (56 per operator) were prepared in 132 teeth (72 on anterior teeth, 60 on premolars, and 36 on molars). Mean, median, minimum, maximum and standard deviation values for all five accuracy parameters as well as for length and volume of the cavities are shown in Table 1.

All operators found a total of 156 from 168 canals, obtaining an overall success of 93%. A detailed view of the success rate per operator is shown in Table 2. Furthermore, from all 12 missed canals, 7 perforated the root.

When comparing the discrepancy of the five accuracy parameters between different tooth types (anterior, premolar and molars), a significant difference was found for the deviation at the apical point between anterior teeth and molars ($p = 0.0194$), and for the vertical deviation between anterior teeth and molars ($p = 0.0002$), as well as between premolars and molars ($p = 0.0103$) (Table 3). No significant difference was found when comparing the five accuracy parameters between jaws (maxillary vs mandible) (Table 3).

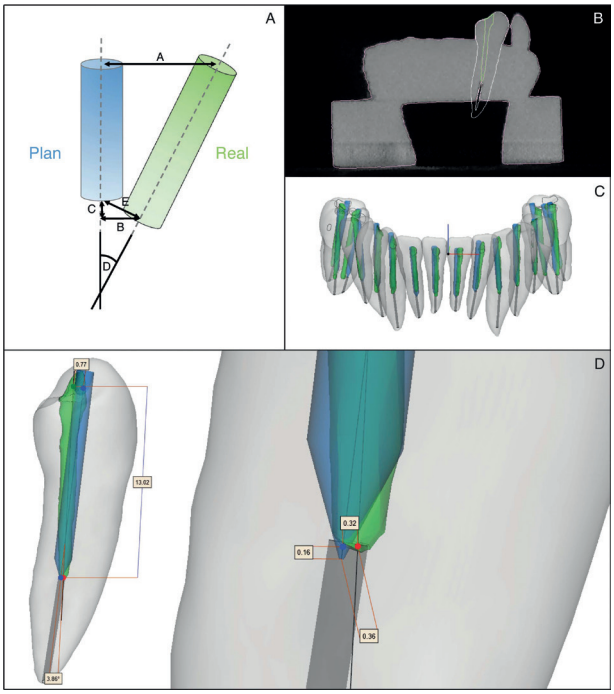

Figure 2. Accuracy analysis. (A) Accuracy deviation measurements for A, deviation at entry; B, apical deviation; C, vertical deviation; D, angular deviation; E, total deviation, adapted from [14]. (B) Image showing the registration of post-operative CBCT scan (pink contour line) to the pre-operative CBCT scan, and the segmented cavity of tooth #34 (green line) with the model of the tooth (white line). (C) 3D representation of all segmented cavities from a lower jaw model (green) with their respective planning (blue). (D) Left: Tooth #34 showing measurements for deviation at entry (0.77 mm), angular deviation (3.86°) and length of cavity (13.02 mm). Right: detail image of the apical portion showing the measurements for apical deviation (0.32 mm), vertical deviation (-0.16 mm) and total deviation (0.36 mm).

The length of the access cavities was shorter on anterior teeth (mean: 13.04 mm (9.59 – 17.12 mm)) compared to premolars and molars (mean: 15.46 mm (12.18 – 17.51 mm) and mean: 15.9 (14.78 – 17.05 mm), respectively).

A significant difference was found when comparing the different operators and their deviation at the apical point, vertical deviation and total deviation (Table 3). When assessing the cavity length and volume, operator 2 had the lowest mean length (13.86 mm (9.59 – 16.45 mm)) and volume (18.61 mm^3 (8.23 – 33.45 mm^3)), operator 1 had a mean length of 14.74 mm (10.86 – 17.51 mm) and operator 3 had 14.96 mm (11.1 – 17.12 mm), both operators had the same mean volume of 21.82 mm^3 (operator 1: 11.02 – 38.95 mm^3, operator 3: 12.11 – 39.63 mm^3). When comparing the discrepancy between the different operators for length and cavity volume, a significant difference was found for operator 2 when compared to either, operator 1 (length: $p = 0.0378$ and volume: $p = 0.0158$) or operator 3 (length: $p = 0.0051$ and volume: $p = 0.0052$).

An additional analysis was performed for single-rooted teeth containing a single canal. For these teeth, the percentage of substance loss was calculated by comparing the volume of the access cavity to the total volume of the tooth (Table 4). A significant difference was found when comparing the substance loss between mandibular incisors and maxillary canines (p = 0.0196), as well between mandibular incisors and mandibular canines (p = 0.0077). Additionally, a significant difference was found when comparing mandibular premolars and maxillary canines (p = 0.0195), as well between mandibular premolars and mandibular canines (p = 0.0076).

Parameter	Mean	Median	SD	Min	Max
A	0.67	0.60	0.34	0.02	1.85
B	0.63	0.58	0.35	0.07	1.86
C	1.37	1.08	1.01	0.01	5.12
D	2.81	2.60	1.53	0.2	9.42
E	1.60	1.36	0.95	0.22	5.28
Length (mm)	14.53	15.15	1.81	9.59	17.51
Volume (mm^3)	20.95	19.28	7.13	8.23	54.79

Table 1. Descriptive statistics for all five accuracy parameters as well for length and volume of the access cavities. Values in mm. Letter coding: SD, standard deviation; Min, minimum; Max, maximum; A, deviation at entry; B, apical deviation; C, vertical deviation; D, angular deviation; E, total deviation.

	Operator 1 (Last year student)		Operator 2 (Endodontist 5+ yrs. exp.)		Operator 3 (Endodontist 30+ yrs. exp.)	
	Training	Treatment	Training	Treatment	Training	Treatment
Canal found	23	51	26	52	5	53
Canal not found	5	5	2	4	23	3
Success	82%	91%	93%	93%	18%	95%
Improvement after training		9%		0%		77%
Comparison during treatment	**P - value**					
Op 1 vs Op 2	0.937					
Op 1 vs Op 3	0.752					
Op 2 vs Op 3	0.921					

Table 2. Success rate per operator for training and treatment, and comparison analysis.

Tooth Type									
Accuracy (mm)	**n**	**A**		**B**		**C**		**D**	
Anterior	72	0.61	0.11 – 1.45	0.57	0.07 – 1.12	1.62	0.18 – 5.12	2.68	0.2 – 6.14
Premolar	60	0.70	0.12 – 1.59	0.60	0.09 – 1.68	1.35	0.04 – 3.38	2.73	0.4 – 5.49
Molar	36	0.74	0.02 – 1.85	0.80	0.13 – 1.86	0.90	0.01 – 2.7	3.01	0.34 – 6.78
Comparison		**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**
A – PM		0.046	0.4137	0.021	0.8435	0.093	0.416	0.031	0.9242
A – M		0.059	0.3479	0.122	**0.0194**	0.355	**0.0002**	0.102	0.5416
PM – M		0.013	0.9538	0.100	0.078	0.262	**0.0103**	0.071	0.7557
Jaw type									
Accuracy (mm)	**n**	**A**		**B**		**C**		**D**	
Upper	72	0.67	0.13 – 1.59	0.58	0.1 – 1.21	1.23	0.04 – 3.09	2.73	0.4 – 5.64
Lower	96	0.66	0.02 – 1.85	0.66	0.07 – 1.86	1.48	0.01 – 5.12	2.79	0.2 – 6.78
Comparison		**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**
Upper - Lower		0.012	0.7168	0.037	0.2894	0.044	0.5236	0.002	0.9811
Operator									
Accuracy (mm)	**n**	**A**		**B**		**C**		**D**	
1	56	0.69	0.02 – 1.59	0.71	0.12 – 1.68	2.02	0.26 – 5.12	2.71	0.2 – 5.93
2	56	0.69	0.11 – 1.59	0.55	0.07 – 1.86	0.73	0.06 – 1.87	3.03	0.59 – 6.15
3	56	0.62	0.13 – 1.85	0.63	0.09 – 1.78	1.36	0.01 – 4.29	2.56	0.34 – 6.78
Comparison		**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**	**Difference**	***P*-value**
1 – 2		0.008	0.9761	0.111	**0.0214**	0.565	**0.0001**	0.109	0.4249
1 – 3		0.037	0.6147	0.051	0.4432	0.295	**0.0002**	0.064	0.7438
2 – 3		0.045	0.4838	0.061	0.3075	0.270	**0.0006**	0.174	0.1205

Tooth Type	**n**	**Mean**	**Median**	**SD**	**Min**	**Max**
All teeth	108	0.046	0.046	0.015	0.02	0.117
Upper I	24	0.045	0.044	0.017	0.02	0.081
Lower I	24	0.055	0.05	0.018	0.028	0.117
Upper C	12	0.038	0.035	0.01	0.024	0.054
Lower C	12	0.036	0.035	0.008	0.026	0.051
Upper PM	12	0.042	0.042	0.012	0.024	0.062
Lower PM	24	0.052	0.052	0.01	0.034	0.081

Table 4. Descriptive statistics and comparison analysis on substance loss (on single rooted teeth with one canal).

E	
1.77	0.22 – 5.28
1.54	0.29 – 3.62
1.37	0.28 – 3.06
Difference	***P*-value**
0.073	0.7841
0.263	0.1035
0.190	0.3256
E	
1.42	0.46 – 3.25
1.74	0.22 – 5.28
Difference	***P*-value**
0.086	0.132
E	
2.19	0.52 – 5.28
0.99	0.22 – 2.03
1.62	0.28 – 4.4
Difference	***P*-value**
0.471	**0.0001**
0.211	**0.0013**
0.260	**0.0001**

Table 3. Comparison analysis between all five accuracy parameters and Tooth type, Jaw type and Operator. Mean values with their respective minimum and maximum values are given (values in mm). Note: data were square root transformed for comparison analysis. Bold letters in the *p*-value indicate significant statistical difference ($p < 0.05$). A, deviation at entry; B, apical deviation; C, vertical deviation; D, angular deviation; E, total deviation.

When comparing the percentage of substance loss between maxillary and mandibular jaw (mean: 4.2% vs 4.9% respectively) a statistically significant difference was found ($p = 0.01$). Moreover, when comparing substance loss between operators (mean values; operator 1: 4.7%, operator 2: 4.1% and operator 3: 5%) a significant difference was found between operator 2 and 3 ($p = 0.0073$).

5.4 Discussion

In this laboratory study, three operators with different levels of experience in endodontics performed a total of 168 navigated access cavity preparations on 132 teeth. All canals were standardized and located at a depth of 15 mm from the incisal edge or occlusal surface to mimic the treatment of a difficult and severe PCO. In total, 156 of 168 canals were located, obtaining a success rate of almost 93% for the navigated access technique.

For the analysis, the postoperative CBCT volume was registered to the preoperative CBCT volume using a semiautomated protocol with a global registration parameter to minimize errors. A semiautomated process was used in which a line was automatically fitted by the software in the centre of the cavity. Then, two points were placed by the software, through the central axis line, on the coronal and apical aspect of the cavity to perform all measurements. The tridimensional distance deviation of all cavities was then assessed in comparison to the planning on 5 different parameters according to previous publications [14] (Figure 2). For such small measurements, an automated measurement protocol, as the one presented in this article, is of great importance to prevent errors on the results. It is also important to remark that such protocol allows for tridimensional measurements instead of a two-dimensional approximation.

The accuracy of dynamic navigation as a technique for implant placement has been already described in the literature [12, b13, 16, 18, 19]. It has a similar accuracy compared to that of static guides, and it is significantly better than freehand implant placement. With average deviation values at the apex of the implant of as low as 0.2 mm [16], this technique demonstrates potential to be used for the preparation of access cavities on teeth.

Two studies have assessed the accuracy of dynamic navigation for the preparation of access cavities, both using the same Navident (ClaroNav) unit as in the present study [20, 22]. Chong et al. [20], performed conservative access cavities on extracted teeth with intact crowns and roots, obtaining a success rate of 89% (41 canals located vs 5 not located) which is lower in comparison to the present study (93%). No additional accuracy measurements were performed by the authors. Jain et al. [22] performed conservative access cavities on 3D printed models composed of 84 teeth with 138 canals. The depth of the canals was not the same for all teeth, as in the present study (15 mm), and it was different for anterior and posterior teeth. Moreover, no reference was given to whether the canal was found or not. However, a thorough accuracy analysis was performed.

Jain et al. [22] obtained a mean apical deviation of 0.9 mm. In the present study, a lower mean apical deviation of 0.63 mm was obtained. These values were different when comparing anterior teeth, premolars and molars. Moreover, a significant difference was found between anterior teeth and molars (0.57 mm vs 0.8 mm, $p = 0.0194$), probably due to their position in the mouth which allows, in the case of anterior teeth, for a greater vertical space and better maneuverability while drilling. When comparing the present results to that of static guide systems with a mean deviation smaller than 0.5 mm [6], the values may still seem slightly high. For this reason, comparison studies that assess both techniques are needed.

In the present study, the mean cavity length and volume for all cavities, in the present study, was 14.5 mm and 21 mm^3 respectively. When assessing one-rooted teeth with one canal, this volume represents a mean substance loss of 4.7%, compared to the total volume of the tooth. Moreover, mandible incisors and premolars had the greatest mean substance loss which can be attributed to the small overall volume of the teeth. This contributed also to a significant difference between maxillary and mandible jaws ($p < 0.05$). In contrast maxillary and mandible canines presented the least mean substance loss. On the other hand, Connert et al. [23] reported a mean cavity volume of 9.8 mm^3 when using a static guide. The difference to the present study could be attributed to the higher degree of freedom that the operator has when using dynamic navigation, together with the small corrections that may be performed along the way, which can result in slightly larger cavities. Moreover, a wider bur was used in the present study with a diameter of 1 mm in comparison to the smaller diameter of 0.85 mm used in the study of Connert et al. [23]. Nevertheless, the substance loss with dynamic navigation is considerably less than that of free-handed drilling (49.9 mm^3) [23].

One of the advantages of the use of static guides for guided root canal treatment is that the success of the guided approach is not influenced by the experience of the

operator [23]. On the other hand, the use of dynamic navigation systems requires rigorous training because there is a learning curve. There is a certain level of technical skill, hand-eye coordination, and manual dexterity that must be maintained throughout the whole preparation of the access cavity while looking at the computer screen [20, 22]. Block et al. [13] observed that a surgeon who had prior experience with a navigation system obtained better accuracy outcomes and a flat learning curve compared with surgeons who had no experience with navigation systems. However, after 20 cases the authors only found minimal accuracy differences between surgeons. In the present study, all operators performed a total of 28 access cavities (12 on the maxillary jaw, 14 on the mandible jaw) as training. Although, accuracy result were very heterogenous during training, when the treatment was performed, all operators obtained similar success rates without any significant difference ($p > 0.05$, Table 2). However, the operator with the least experience had the lowest success rate and highest mean apical deviation, although they are non-significant (Tables 2 and 3).

The use of a dynamic navigation device in clinical practice may present a substantial change to the existing clinical workflow. Some of the drawbacks of this technique are that it requires an investment in equipment and training and, that the setup procedure is time-consuming, requiring the placement of the external monitors on a clear line of sight which must be carefully thought through. [19, 24]. However, a number of benefits have been attributed to dynamic navigation systems. They reduce errors and are superior in accuracy to freehand treatment [12, b13, 14]. Its accuracy can minimize the risk of iatrogenic damage and increase intraoperative safety [15, 17]. When compared to the use of a static guide for treatment, there is no need for the fabrication of a guide, so the treatment can be implemented on the same day after the acquisition of the CBCT and intraoral scan. This is of great advantage when dealing with endodontic urgencies and complex anatomy or PCO. Additionally, because there is no guide being placed on top of the teeth, the view of the operation field is improved, there is more vertical space, water cooling is possible, and any bur can be used, as it does not require special burs to rotate within a guide sleeve. Furthermore, multiple paths for the bur in multi-canal teeth can be planned and executed easily, and it allows for live feedback during treatment so corrections on the position of the bur can be made in real time [11, 12, 18, 19, 22].

5.5 Conclusion

In a laboratory study, the use of dynamic navigation was an accurate approach for access cavity preparation during root canal treatment in teeth with severely calcified canals. However, the technique requires a certain level of technical skill, hand-eye coordination, and manual dexterity, therefore proper training prior to treatment is essential.

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Conceptualization, M.F., A.T., R.J.; methodology, A.T.; software, M.F. and A.T.; vali-dation, M.F. and A.T.; formal analysis, A.T.; investigation, A.T., M.D.; resources, A.T. and R.J.; data curation, M.F. and A.T.; writing—original draft preparation, M.F. and A.T.; writing—review and editing, M.F., A.T., MS.P., R.J.; visualization, M.F. and A.T.; supervision, MS.P. and R.J.; project administration, M.F. and A.T.. All authors have read and agreed to the published version of the manuscript.

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Clinical significance

The present study introduces a new system for guided endodontics using visual-inertial odometry. The technology could unlock the possibility of performing augmented reality guided, minimally-invasive access cavities for the clinician.

Chapter 6

Novel method for augmented reality guided endodontics: an in vitro study

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Keywords

Visual-inertial odometry
Guided endodontics
Augmented reality
Cone-beam computed tomography
Minimal invasive endodontics

Abstract

Aim - To evaluate the accuracy in endodontics of a novel augmented reality (AR) method for guided access cavity preparation in 3D-printed jaws. **Methods** - Two operators with different levels of experience in endodontics performed pre-planned virtually guided access cavities through a novel markerless AR system developed by a team among the authors on three sets of 3D-printed jaw models using a 3D printer (Objet Connex 350, Stratasys) mounted on a phantom. After the treatment, a post-operative high-resolution CBCT scan (NewTom VGI Evo, Cefla) was taken for each model and registered to the pre-operative model. All the access cavities were then digitally reconstructed by filling the cavity area using 3D medical software (3-Matic 15.0, Materialise). For the anterior teeth and the premolars, the deviation at the coronal and apical entry points as well as the angular deviation of the access cavity were compared to the virtual plan. For the molars, the deviation at the coronal entry point was compared to the virtual plan. Additionally, the surface area of all access cavities at the entry point was measured and compared to the virtual plan. Descriptive statistics for each parameter were performed. A 95% confi-dence interval was calculated. **Results** - A total of 90 access cavities were drilled up to a depth of 4 mm inside the tooth. The mean deviation in the frontal teeth and in the premolars at the entry point was 0.51 mm and 0.77 mm at the apical point, with a mean angular deviation of 8.5° and a mean surface overlap of 57%. The mean deviation for the molars at the entry point was 0.63 mm, with a mean surface overlap of 82%. **Conclusions** - The use of AR as a digital guide for endodontic access cavity drilling on diffe-rent teeth showed promising results and might have potential for clinical use. How-ever, further development and research might be needed before in vivo validation to overcome the limitations of the study.

6.1 Introduction

Visual-inertial odometry (VIO) has been described as the process of estimating the egomotion of an agent using an inertial measurement unit (IMU), while egomotion is defined as the 3D motion of a camera within an environment relative to a rigid scene [1].

When VIO algorithms are applied to a device that displays digital elements on a rigid scene, the resulting composite view can be defined as augmented reality (AR). AR is a recent trend in digital dentistry, especially in the field of maxillofacial surgery [2], but its application also presents itself in a rapidly increasing number of new fields, for example, prosthetics [3] and aesthetic treatment [4]. It has been test-ed by the use of commonly available hardware devices such as the Oculus Rift S (Facebook Technologies, LLC, Menlo Park, CA, USA) [5] and Hololens (Microsoft, Redmond, WA, USA) [6], or by new, custom-made devices [7]. Moreover, cone-beam computed tomography (CBCT) images and digital guides can be displayed and matched to the patient's anatomy, offering an advantage to the clinician's view [8].

The most common hardware used in AR procedures are the "visors", namely head-mounted devices, which are usually combined with a marker system fixed to the patient's anatomy [9]. On the other side, different modalities of augmenting a clinical scene exist, such as half-silvered mirrors over a rigid scene, where an im-age is pro-jected [10], or double camera systems integrated with the use of a computer [11].

Depending on the field of application, the threshold for clinical usage of a new technology relies on the overall precision and accuracy of the system pro-posed. The threshold for success in implantology is considered to be in a range of about 2 mm [12]. The use of visors has achieved a range of precision of approxi-mately 0.50 mm and 2° to 3° in angular deviation for single implant placement in 2019 with the use of a Hololens (Hololens, Microsoft, USA). [9] Previous in vitro studies in implantology described a precision of a mean linear deviation of 1.5 mm and an angular deviation of 5.5° on mandibular models in 2018 [13], and a linear deviation of 0.50 mm to 1.1 mm and an angular deviation of 2.70° to 3.33° in 2015 with the use of other head-mounted displays [14]. On the other hand, in maxillo-facial surgery, an error of about 0.71 mm was described in a study published in 2014 by the use of a system with customized ste-reo cameras and real-time 3-D contour matching on a half-silvered mirror. The system was used to evaluate the overlay accuracy in vitro [15]. However, the evidence from in vivo clinical trials is still lacking. Similar tools have also been proposed for dental education, with signif-icant and promising results through the use of haptic and virtual reality simulation systems. The fields of interest were: periodontology, restorative den-tistry, maxillofa-cial surgery, prosthodontics, and enhanced simulation [16].

The first use of augmented reality in the field of endodontics was reported by Bruellmann et al. with the use of bi-dimensional images for the detection of pre-registered root canal orifices with a sensitivity of 94% and an accuracy range of 65% to 96.7%, depending on the canals observed [17]. The system relies on previ-ously described software for the automatic detection of root canal orifices from intra-oral images. Automatic detection significantly upgrades the view of the clinician in real time, making it potentially a useful technology for augmented vision [18, 19]. The use of a digital guide in endodontics is particularly useful to gain access to an obliterated canal and at the same time achieve a minimally invasive access cavity [20, 21]. The aim is to maintain as much pericervical dentin as possible to preserve the fracture resistance of root canal treated teeth [22, 23]. It can also be used for retreatment or the removal of fiberglass posts [24-26].

Besides AR, other alternative methodologies for digitally guided interven-tions are already available to clinicians: the use of static guides, for example, has been described as a highly accurate and successful technique by recent studies, with a deviation at the tip of the bur ranging from 0.14 mm to 0.46 mm [20]. This method uses digital planning and 3D printing to create a fully customized physical guide that guides the bur. The technique has set new standards for precision and repeatability; however, the planning procedure needed prior to the intervention re-quires additional time and costs compared to conventional techniques. It also re-quires the use of a 3D printer, which is a practice that has been questioned for its environmental impact [27].

Dynamic navigation, on the other hand, is another alternative for guided in-terventions. It requires software to digitally plan the treatment and a camera that detects tags (or markers) fixed both to the patient and to the handpiece, allowing the software to automatically track the movements of the bur relative to the patient's position, like a global positioning system, in real-time and to transfer the information to the digital plan [28]. This procedure allows the user to perform the planning and treatment in a single appointment without the need to design and print a guide. In endodontics, this procedure can achieve a success rate of 93% with a mean devia-tion of 0.63 mm at the end of the cavity [29]. It can also improve accuracy in root-end resection [30]. According to a systematic review, its increased accuracy com-pared to the freehanded technique can be helpful in managing complicated endo-dontic cases [28, 31]. However, it requires an initial calibration process prior to treatment, a high initial investment in equipment, substantial changes in workflow, and proper training with the device [28, 31].

Even though AR has not been tested yet for its application in guided en-dodontics, it has the potential to solve many of the problems related to static and dynamic guides, such as the need for additional appointments and the time and materials to fabricate the guides [7]. The system adopted in this research, in particu-lar, is imme-

diately available for the clinicians and does not require a pre-planned marker system, with the environment and the clinical scene themselves serving as guides for the visual-inertial odometry-based three-dimensional superimposition.

However, the overall precision has not been quantified yet. Therefore, the present study aims to evaluate the accuracy of AR for guided access cavity preparation in 3D-printed jaws.

6.2 Materials and methods

AR system

A novel system composed of hardware, custom software, and cloud storage was tested. For the hardware, an iPad Pro 2020 (Apple, Cupertino, USA) was used with the following components: a double camera system (1080p; 8 MP), a LiDAR scanner (Apple, Cupertino, USA), and a touch screen display (11", 2048x2732 pix-els). The software was developed by a team among the authors using the pro-gramming language C++. The development includes a platform that allows the user to visualize and easily interact with digital objects by regulating their six degrees of freedom, position, and transparency, such as CBCT-derived anatomical segmenta-tions and virtual access cavity paths loaded as standard triangulation language (STL) 3D objects. The digital objects are saved on a cloud server. Once the position of the digital objects is judged anatomically correct and well superimposed by the operator, the software automatically fixes them to the observed scene, which means that regardless of the device or the patient's movements, the superimposi-tion of the digital objects to the patient's anatomy remains unaltered. To do so, the software was designed to generate a set of reference points, called points of inter-est (POI), in real time and place them into the scene to keep the 3D objects fixed to their positions. The position is maintained through VIO algorithms previously de-scribed in the literature by various authors [1-3]. The same software connects the POI to the LiDAR scanner tracking system to increase the efficiency of the stabiliza-tion.

The software was then loaded into the hardware device through an Apple developer's account to make it accessible for usage.

Design of 3D models

Two CBCT volumes were selected, one for the maxillary jaw and one for the mandibular jaw, from the database of the Oral Imaging Center of the Department of Oral Health Science at the University Hospital (UZ Leuven, Leuven, Belgium) for the de-

sign of 3D model replicas. These volumes were previously selected for a study on dynamic navigation [29]. Patients were referred to the radiology center for CBCT scanning for reasons not related to the study. An artificial intelligence-driven, automated tooth segmentation was applied to generate 3D models of the teeth. This method was previously described and used by EzEldeen et al. [32] for tooth autotransplantation and later validated by Lahoud et al. [33]. It has also been used in several other studies [34-38]. The bone tissue from both jaws was segmented by applying a threshold in Mimics Medical software 23.0 (Materialise, Leuven, Bel-gium). Finally, the teeth and bone tissue were imported into 3-Matic Medical soft-ware 16.0 (Materialise, Leuven, Belgium) where a final model was designed.

All models were 3D printed in white resin material (VeroWhite; Stratasys, Eden Prairie, MN, USA) using the Objet Connex 350 3D printer (Stratasys, Eden Prairie, MN, USA). The gum tissue was later painted by hand in pink to resemble a real anatomical scene (Figure 1 A, B).

Virtual planning and treatment

An intraoral scan (IOS) of the models was taken using the Trios intraoral scanner (3Shape, Copenhagen, Denmark). The STL file was imported and regis-tered to the virtual model in 3-Matic Medical software 16.0 (Materialise, Leuven, Belgium). A straight-line access path was planned from the right to left second pre-molar as a cylinder of 1 mm diameter to the center of the root to serve as guidance during the drilling procedure. Upper first premolars had 2 separate access paths (one for each root, buccal and palatal). Additionally, minimally invasive occlusal access cavities were designed on the same software for the first and second mo-lars. All data (IOS and planning) were exported in STL and imported into the cloud server from the system (Figure 1C).

Two operators with different levels of experience in endodontics (operator #1: Ph.D student, endodontic specialist with 10 years of experience in endodontics; operator #2 Ph.D student with basic experience in endodontics) received the hard-ware with the preinstalled software (Test Flight, Apple, Cupertino, USA), access credentials, and an instructional meeting session. Then the models were placed in a phantom head to simulate a real patient. The digital data was retrieved from the storage in the cloud, which included multi-layered digital information divided into digital object/groups: the main virtual model (upper and lower, separately) and the virtual access cavities for the drilling session.

The scene was centered on the camera view and scanned through light movements (yaw, pitch, and roll) of the camera while points of interest (POI) were automatically generated by the software in a time span of approximately 30–60 s.

The virtual data was then selected and manually superimposed by the oper-ator by pinch gesture on the touch screen until satisfying overlap of the surgical scene and the digital models (Figure 1D). Then the data position was locked by the function of the software used and stabilized through the POI previously placed, after which the drilling of the cavities was started. A size 2 Munce Discovery bur (CJM Engineering, Santa Barbara, CA, USA) was used to drill the access cavities from the right to left second premolar, and a size 4 diamond-coated Endo-Access bur (Dentsply Maillefer, Ballaigues, Switzerland) was used for drilling the molars follow-ing the digital contour of the access cavity (Figure 1E).

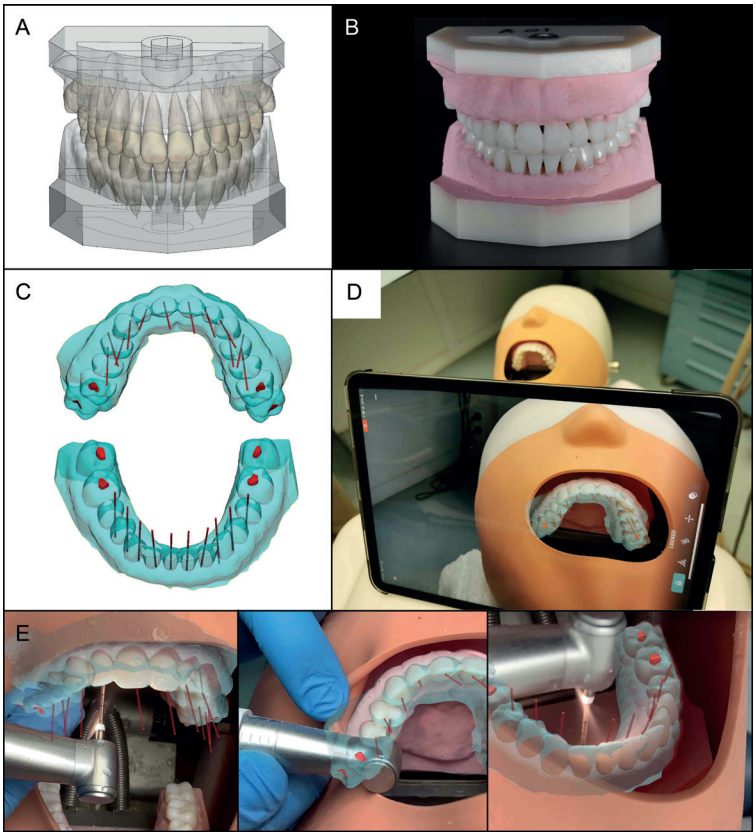

Figure 1. 3D Model, virtual planning, and treatment with AR. (A) 3D model design in 3-Matic Medical software 16.0 (Materialise). (B) 3D printed models in white resin material (VeroWhite; Stra-tasys, Eden Prairie, MN, USA). Note: the gum tissue was painted pink to resemble visually a real anatomical scene. (C) IOS (light blue) and virtual planning of access cavities (red). (D) Clinical set-up with digital data locked in position ready for treatment. (E) Drilling of guided access cavities with AR, from left to right; upper later incisor, upper first premolar, and lower lateral incisor.

Accuracy assessment

After treatment, a post-operative high-resolution CBCT (NewTom VGi evo, Cefla, Imola, Italy) with a voxel size of 0.125 mm was taken for each model. DICOM files were imported into Mimics Medical software 23.0 (Materialise, Leuven, Belgium) and segmented by applying a threshold. The post-operative models were then ex-ported as an STL file into 3-Matic Medical software 16.0 (Materialise, Leuven, Bel-gium) and registered to the pre-operative model first by using a 3-point registration method and later by automatic global registration until no further movement was possible. Finally, all access cavities were segmented using a method previously described by Torres et al. [29]. A line on the central axis of each access cavity was then automatically fitted by the software. For the molars, the center of the occlusal cavity was automatically calculated by the software.

Outcomes

For the anterior teeth and premolars, the deviation in mm at the coronal entry point (C) and apically at 4 mm depth (A) and the angular deviation (D) of the ac-cess cavity were compared to the virtual planning. For the molars, the distance de-viation in mm at the coronal entry point was compared. Additionally, the surface area of all access cavities at the entry point was measured in mm2 and compared to the plan. Finally, the percentage of overlap with the plan was calculated (Figure 2A, B).

Statistical Analysis

Descriptive statistics for each parameter were performed. Differences be-tween variables, operators, tooth types (anterior, premolars, molars), and jaws (upper, lower) were assessed for every parameter (C, A, and D) by a linear mixed model. First, a residual analysis was performed by means of a normal quantile plot and a residual dot plot. If the data was not normally distributed, a square root or log transformation was applied, or outliers were removed, and the normal quantile plot of the residual values was checked again.

As there were no significant interactions between variables found with the linear mixed model, the variables were compared for all the combinations of levels of the other variables. A correction for simultaneous hypothesis testing according to Tukey was applied. $P \leq 0.05$ was considered statistically significant. All statistical analysis was performed with S+ software, version 8.0 (TIBCO Software Inc., Palo Alto, CA, USA).

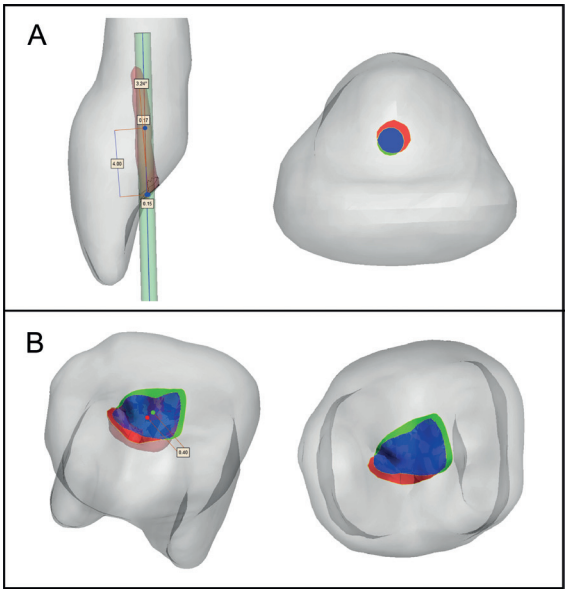

Figure 2. Accuracy assessment. (A) Upper central incisor. Left (interprox-imal view): Green cylin-der; Virtual planning with central axis (blue line), Red; segmented cavity from CBCT with central axis (red line), accuracy measurements at 4 mm depth (Cor-onal entry point: 0.15 mm, Apical 0.17 mm, Angular deviation 3.24°). Right (occlusal view): Surface area of access cavity (red) and over-lap (blue) with planning (green). (B) Lower first molar. Left: Red; segmented cavity from CBCT, Green; virtual planning, Blue; overlap of cavity surface with planning, Red dot; center of cavity, Green dot; center of planning, and coronal deviation of 0.4 mm. Right (occlusal view): Surface area of access cavity (red) and overlap (blue) with planning (green).

6.3 Results

A total of 90 endodontic access cavities were drilled (66 in front teeth and premolars and 24 in molars) by the two operators using the AR system. Each oper-ator drilled 45 cavities (33 in the front teeth and premolars, and 12 in the molars). Descriptive statistics results are shown in Table 1.

When assessing anterior teeth and premolars, no statistical difference was found between operators, tooth types, jaw types, operators and tooth type, or operators and jaw type. for the coronal entry point (C) or angular deviation (D). For the apical devi-ation at 4 mm depth (A), the anterior teeth had significantly higher devia-tion values (mean anterior: 0.91 mm vs. the premolars: 0.58 mm, $p = 0.0018$).

When assessing the cavity surface area vs. the virtually planned surface ar-ea, anterior teeth and premolars had significantly larger surface area deviations from the virtual plan (164% for anterior teeth and 168% for premolars) as compared to the de-viations for molars (125%) ($p = 0.0002$). Also, molars had significantly higher overlap with the virtual plan (82%) compared to anterior teeth (56%) and premolars (57%); (anterior vs. molars $p = 0.0044$, premolars vs. molars $p = 0.0068$).

Anterior teeth and premolars (n = 66)						Molars (n = 24)		
	Coronal (C)	Apical (4 mm depth) (A)	Angular deviation (D)	Cavity surface area vs plan	Overlap	Coronal (C)	Cavity surface area vs plan	Overlap
Mean	0.51 mm	0.77 mm	8.48°	166%	57%	0.63 mm	125%	82%
Min	0.08 mm	0.1 mm	1.1°	62%	0%	0.24 mm	87%	50%
Max	1.39 mm	1.95 mm	23.22°	291%	100%	1.23 mm	181%	98%

Table 1. Deviation measurements on AR

6.4 Discussion

The aim of the study was to evaluate the accuracy of AR for guided access cavity preparation in 3D-printed jaws in endodontics. To our knowledge, this is the first study using a custom-made 3D AR system for guided endodontic access cavi-ties. Other studies proposed the use of Hololens 2 internal software (Redmond, WA, USA) [39]. In total, 90 endodontic access cavities and 32 minimally invasive occlusal cavities were drilled by two operators. A minimum depth of 4 mm was set as the average needed to reach the pulpar horn in the anterior teeth and premolars [33]. On average, a deviation of 0.51 mm at the coronal entry point and 0.77 mm apically was achieved. However, the average angular deviation was 8.5°, which is high when compared to other guiding methods in endodontics [20, 29, 40]. This could be due to the fixed position of the device, which makes it difficult to control the angulation from different perspectives, and it could explain the higher apical devia-tion values on anterior teeth compared to premolars (0.9 mm vs. 0.6 mm). The posi-tion of the screen is therefore essential for achieving success.

AR works through the interaction between the components of the hardware and the software. The egomotion of the device is calculated in real-time with the support of the dual-camera system and the LiDAR scanner through a Kalman filter [41]. This set-up allows precise positioning of POIs on the anatomical view and the background scene in real-time through VIO, producing a 3D reference world that acts as a visual marker. The POIs are automatically generated by the movements of the hardware in 6 degrees of freedom and the support of the LIDAR scanner by simultaneous localization and mapping (SLAM) [42]. In this way, markers are not needed, making the system immediately available and reducing the costs.

Despite the promising implementation of custom systems from past studies [43], the use of augmented reality still needs a fully customized workflow to reduce pre-operative calibration time and minimize linear and angular error for clinical val-idation. A marker-less system offers the opportunity to reduce pre-operative timing compared

to available AR systems and unlocks fully virtual guidance on the com-posite view of the anatomical site. A flowchart of the set-up is shown in Figure 3.

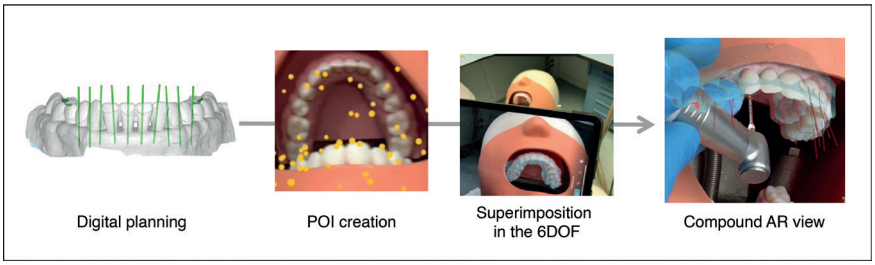

Figure 3. Set-up Flowchart. From left to right: First, the digital planning is imported into the VIO software through the cloud storage and POI are generated by moving the device around the scene. Then, the plan is superimposed in the 6DOF and locked to the scene. Finally, treatment can be initiated with a compound AR view.

When assessing the cavity surface area vs. the virtually planned surface ar-ea, anterior teeth and premolars had significantly larger surface areas compared to the virtual plan, whereas the molars did not. This could be due to the location of the access cavity, which in anterior teeth is located on an inclined plane (palatal sur-face) in comparison to a flatter surface (the occlusal plane of molars). A slightly big-ger cavity must be drilled in the anterior teeth to create a platform for drilling deeper.

Molars also had significantly higher overlap with the virtual plan compared to the anterior teeth and premolars. This finding, in combination with the achievement of smaller cavity surface areas, could suggest a promising application of AR as a strategy for conservative endodontic access cavity preparation in molars. The cavi-ties shown in this study were performed as planned, without modifying their shapes after the procedure, in order to obtain an accurate assessment of the deviation. Therefore, the planning of the cavity had a research purpose and not a clinical one. In a clinical situation, adjustments to the shape of the cavities can be made after reaching the target to improve cleaning and shaping procedures. Even though use-ful in some clinical situations (anterior teeth with extremely obliterated canals), a minimally invasive cavity design aims to maximize the preservation of tooth struc-ture. Nonetheless, clinicians must keep in mind that small cavity designs can com-promise canal detection, make proper cleaning and shaping of the canals difficult, cause canal transportation, and lengthen treatment time, jeopardizing the biologi-cal goal of endodontic therapy [44].

One of the advantages of AR is that it can be immediately available for treatment. There is no need for the fabrication of a guide [20]. The plan can be im-mediately visualized on the patient, and the treatment can be performed on the same day.

Another problem related to 3D-printed guides is the anatomical fit and vertical space—in fact, they can only be placed if the mouth opening allows it. Re-searchers also recently evidenced how the use of a physical guide might cause an increase in the temperature due to the interference with water cooling, however, it is still unclear as some other authors reported low temperature rise [45]. On the other hand, AR gives the clinician an immediately available tool where digital data derived from a CBCT can be overlapped on the patient and used as a guiding sys-tem, similar to dynamic navigation [29]. However, contrary to dynamic navigation, our AR system is specifically designed to avoid the use of physical markers [9]. The device used, a tablet, is commonly available on the market and can often be found in a medical center. The underlying technology is rapidly evolving, and the pro-gress in software engineering could improve the UX for the operator, resulting in higher precision [8].

Limitations of the study

Despite promising results, a few shortcomings should be considered. First, this is a study describing a novel custom software, and more studies should be car-ried out to validate the results before its clinical application can be recommended. Furthermore, this is an in vitro study, and although clinical conditions were simulat-ed using AI segmented 3D models from real patients mounted on a dental phan-tom, results must be interpreted with caution and cannot be directly extrapolated to a clinical situation. Also, minimally invasive cavities were planned and drilled with-out modifying their shape for accurate measurement assessment. Adjustments should be performed during the treatment of patients to improve cleaning and shaping procedures.

6.5 Conclusion

Under the limitations of the present in vitro study, the use of the new pro-posed AR system for the drilling of endodontic access cavities achieved a deviation at the coronal entrance point of 0.51 mm and 0.77 mm at 4 mm depth, with an an-gular deviation of 8.5°. The technology used allows clinicians to operate with new software that does not require additional visits or the use of printed guides. Addi-tionally, the hardware used is easily accessible on the market. This technology has the potential to be used for guided endodontic access cavity preparation. However, further research is needed to validate the safety of the proposed system before its clinical application can be recommended.

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Conceptualization, A.T. and C.MR.; methodology, A.T., E.DB., C.MR. O.S., V.P.; software, A.T. and E.DB.; validation, A.T. and E.DB.; formal analysis, A.T.; investigation, A.T., E.DB., C.MR. O.S., V.P.; resources, A.T., MS.P, R.J.; data curation, A.T., C.MR., E.DB.; writing—original draft preparation, A.T., E.DB., C.MR.; writing—review and editing, A.T., MS.P, P.L., R.J.; visualization, A.T. and R.J.; supervision, A.T., M.S.P., P.L., R.J.; project administration, A.T.. All authors have read and agreed to the published version of the manuscript.

In process of publication

Clinical significance
TEMS can minimize potential errors due to free hand drilling which can be beneficial in anatomically challenging places or with less experienced operators.

Conflicts of interest
Authors declare explicitly that there are no conflicts of interest.

Chapter 7

How accurate is targeted endodontic microsurgery? An in vitro study

Authors

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Keywords

Apicoectomy
Endodontic surgery
Guided endodontics
Osteotomy
Root resection

Abstract

Aim - Targeted endodontic microsurgery (TEMS) uses 3D printed guides in combination with a trephine bur for root end resection. The aim of this study is to assess the accuracy of TEMS in comparison to free-handed EMS with respect to 9 parameters: deviation at entry and end of cavity, total deviation, depth, angle deviation, root bevel, root resection, osteotomy volume and surgical time. **Methods** - Two cone-beam computed tomography (CBCT) volumes containing an upper and a lower jaw were selected to design 3D models. Virtual planning of the osteotomies was performed up to the first molar on both jaws and tooth supported guides were 3D printed. Two operators with different levels of experience performed EMS and TEMS while being timed. Upon completion, a post-operative CBCT scan was taken for analysis. **Results** - Each operator performed surgery on 56 roots (28 EMS and 28 TEMS) from 48 teeth (24 EMS and 24 TEMS). When comparing EMS vs TEMS to the virtual planning, results show a mean total angle deviation of 17° vs 5°, a mean total deviation of 1.4 mm vs 1.2 mm, a mean bevel of 12° vs 3°, a mean root resection of 2,7 mm vs 4 mm and mean total time of 175 s vs 38 s. **Conclusions** - TEMS showed overall less deviations, a root bevel closer to zero, more predictable root resection and shorter surgical time. However, slightly deeper osteotomies were obtained with greater volumes, the latter being dependent on the size of trephine bur used.

7.1 Introduction

The purpose of endodontic surgery is treating periapical pathologies that could not be solved with conventional root canal treatment [1]. This procedure is considered technically difficult, and, in the past, it was avoided because of its invasive nature and uncertain prognosis with inconsistent success rates ranging from 44% to 90% [2, 3]. Nowadays, with the use of microscope, illumination and micro-instruments, a new concept of endodontic microsurgery (EMS) has been developed which allows treatment to be performed with higher precision and obtain higher success rates (88.9% to 100%) [2-6].

Cone Beam Computed Tomography (CBCT) has several applications in endodontics, such as diagnosis of pathology, describing canal morphology, identifying neighboring structures and their relationship to the root, among others [7-10]. To perform endodontic surgery, tridimensional information is required to plan the access to the root end [11]. Ideally, a resected root bevel between 0˚ - 10˚, and 3 mm root-end resection is intended to remove apical ramifications by up to 98%, together with a minimally invasive osteotomy, ideally smaller than 5 mm diameter [2, 12]. A correlation has been shown between the length of the access window and volume of the crypt, and a successful healing outcome [2, 12, 13].

A novel approach to EMS was introduced by Pinsky et al. in which CAD/CAM surgical guides were used during EMS, obtaining a more accurate osteotomy and better correlation between operators [14]. Recently, the concept of targeted endodontic microsurgery (TEMS) has been introduced by Giacomino et. al. [15] with the use of 3D printed surgical guides (3DSG) and a trephine bur for osteotomy and root end resection. Furthermore, this technique has been published in several case reports in the last years [4, 15-19].

However, one of the major drawbacks when comparing the accuracy results with other studies on TEMS is that there is no standardize method for measurement and reporting. Additionally, some authors rely on manual measurements which can lead to errors [20]. The purpose of this study is to assess the accuracy of TEMS in comparison to EMS using a semiautomatic measuring protocol (based on Torres et al [21]). This approach aims to compare the drilled cavity to the planning with respect to nine parameters (deviation at entry point, end point, total deviation, depth, angle, root bevel, root resection, osteotomy volume and surgical time).

7.2 Materials and methods

This manuscript has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (Figure 1) [22].

Rationale

There is no comparison on the deviation between EMS and TEMS using a standardize measuring method.

Aim

To compare the drilled cavity to the planning with respect to nine parameters.

Ethical approval

S57587

Samples per operator (2 operators)

2 upper and lower jaw 3D printed models with 14 planned osteotomies on each jaw model up to first molar on each side (one osteotomy per tooth; first molar one for mesial and one for distal root).

Group per operator

Group 1 EMS (28 osteotomies).

Group 2 TEMS (28 osteotomies).

Outcomes assesed

9 parameters: deviation at entry point, end point, total deviation, depth, angle, root bevel, root resection, osteotomy volume and surgical time.

4 groups or variables (1) Surgery type (EMS vs TEMS); 2) Operators (Operator 1 vs 2); 3) Tooth type (Anterior vs Premolar vs Molar); and 4) Jaw type (Upper vs Lower jaw)).

Method used

Semiautomatic measuring protocol (previously validated by Torres et al (Torres et al. 2021)).

Results

When comparing EMS vs TEMS to the virtual planning, results show a mean total angle deviation of 17° vs 5°, a mean total deviation of 1.4 mm vs 1.2 mm, a mean bevel of 12° vs 3°, a mean root resection of 2,7 mm vs 4 mm and mean total time of 175 s vs 38 s.

Conclusion

TEMS can minimize potential errors due to free hand drilling which can be beneficial in anatomically challenging places or with less experienced operators.

Funding details

No funding.

Conflicts of interest

The authors deny any conflict of interest.

Figure 1. PRILE Flowchart. Adapted from Nagendrababu et al. 2021.

Model design

A search was carried out through the database of the Maxillofacial Radiology department at the University Hospitals of Leuven, KU Leuven, Belgium, to find a high resolution CBCT scan of an upper and lower jaw with a full set of teeth and no restorations. Two CBCT volumes containing an upper and a lower jaw that met the criteria were selected. Both CBCT were taken using the NewTom VGi evo (NewTom, Verona, Italy) operating at 110 kVp and 3 mA with a FOV of 10 x 10 cm and voxel size 0.125 mm for reasons not related to the study. The study was approved by the Ethical Review Board of the University Hospitals (S57587).

Data was anonymized and the DICOM images were imported into Mimics Medical software 21.0 (Materialise, Leuven, Belgium) where a threshold was applied to segment bone and teeth. All inner gaps were later filled using the software tools to allow export of a solid structure as an STL file. This STL file was imported into 3-Matic Medical software 13.0 (Materialise), where the crowns were removed, only the bone structure was preserved. The initial DICOM file was loaded into MeVisLab 3.0.1 (MeVis Medical Solutions AG, Bremen, Germany), where teeth from right to left first molar were segmented using a custom-made network based on artificial intelligence, previously validated by Lahoud et. al. [23]. The STL files from the teeth, containing roots and crown, were then imported into 3-Matic Medical software 13.0 (Materialise) and superimposed to the previously segmented maxillary or mandible bone. A space of 0.2 mm around the last 5 mm of the root was manually designed on the software to simulate the periapical ligament and allow easy removal of the root during the procedure. The model was then exported as an STL file and 3D printed in two colors, one for the teeth (VeroWhitePlus, white color) and another for the bone (VeroDent MED670, peach color), using the Objet Connex 350 3D printer (Stratasys, Eden Prairie, MN, USA). The periapical ligament space contained support material (SUP705), (Figure 2A, B).

Virtual planning of treatment and guide

The virtual planning of the osteotomies was performed in 3-Matic Medical software 13.0 (Materialise) from right to left first molar on both jaws by an operator not involved in the operative procedures. The osteotomies were planned as a cylinder of 5 mm of diameter aimed to resect apically 3 mm of the root in a perpendicular angle (90˚, no bevel) to the longitudinal axis of the root (Figure 2C). Fourteen surgical sites were planned, seven on each side, first molars had two apart osteotomies for MB and DB roots. The surgical guides were tooth supported and designed to fit passively on the crowns. The sleeves of the guide had a variable length to achieve depth control while drilling when the handpiece head would touch the sleeve. An irrigation win-

dow was also designed as a small corridor on the cylindrical sleeve. Later, the guide was 3D printed in a biocompatible material (MED 610) using the Objet Connex 350 3D printer (Stratasys, Eden Prairie, MN, USA) (Figure 2D, E).

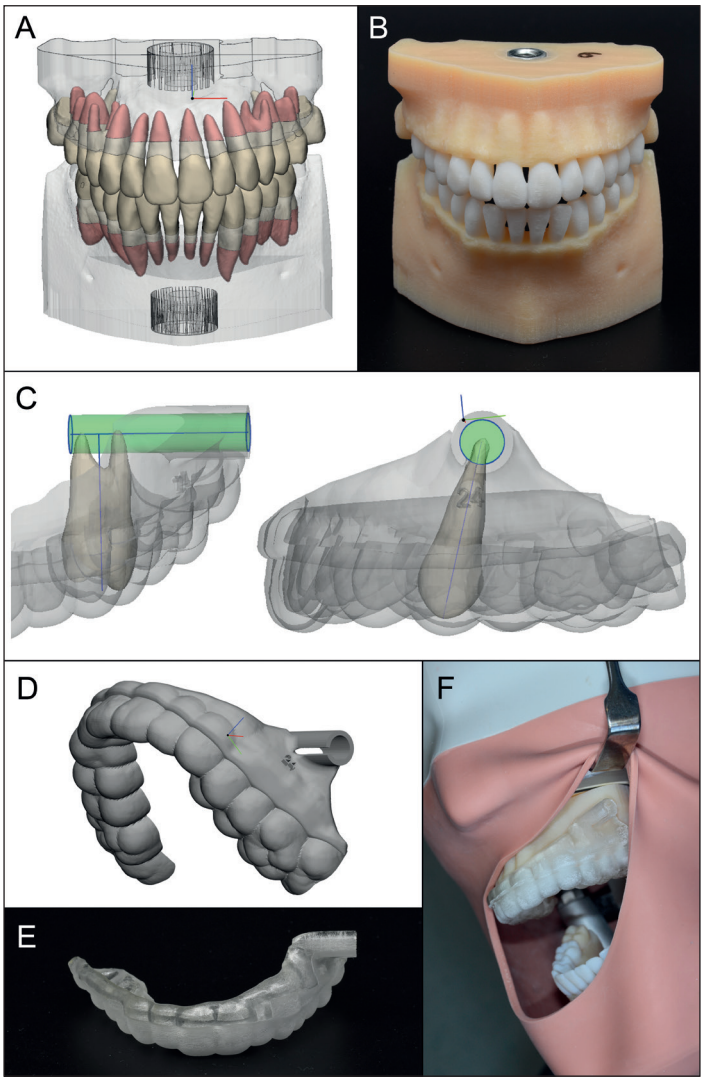

Figure 2. 3D model replicas and clinical set-up A. 3D Models of the upper and lower jaw with the segmented bone (white) and teeth (yellow). A space of 0.2 mm around the last 5 mm of the root was created (red) to simulate the periapical ligament. B. 3D printed model in two colors, one for the teeth (VeroWhitePlus, white color) and another for the bone (VeroDent MED670, peach color). C. Example of the planification of an osteotomy on tooth #24 on 3-Matic Medical software (Materialise). Osteotomy is planned as a cylinder of 5 mm of diameter aimed to resect apically 3 mm of the root in a perpendicular angle to the longitudinal axis of the root. D. 3D model of the 3DSG for the same tooth. Note the corridor on the sleeve to allow for water cooling during the procedure. E. 3D printed surgical guide. F. Models mounted in a phantom head with the 3DSG in place ready for TEMS.

Osteotomy and root resection

Prior to the procedure, a pre-operative CBCT scan from an upper and a lower 3D printed model was taken using the NewTom VGi evo (NewTom, Verona, Italy) operating at 110 kVp, 5 mA with a FOV of 8 x 8 cm and voxel size 0.125 mm and used as a master pre-operative scan. The models were then mounted into a phantom head.

Two operators with different levels of experience in endodontic microsurgery (Operator 1: a last year resident from the department of Endodontics at the KU Leuven, Leuven, Belgium, and Operator 2: an experienced Endodontist specialist with more than 5 years of experience in endodontic microsurgery) performed the osteotomies. Each operator performed osteotomies in every tooth on the upper and lower jaw model once freehanded (EMS) and once using the 3D-printed guide (TEMS). The osteotomies were divided over different models. The operators had access to the full CBCT volume and the 3D file with the planning (exported as a 3D PDF (Adobe Inc., San José, California, USA)). The aim of EMS was to perform one osteotomy aiming to resect 3 mm from the apex of the root trying not to enlarge the osteotomy more than 5 mm in diameter. The procedure was finished when a diamond-coated retro-tip of 3 mm length (AS3D, Acteon, Paris, France) could be placed inside of the osteotomy. EMS was performed using a round bur and a Lindemann bur (Meisinger, Neuss, Germany). The aim of the TEMS was to drill with the guide in a pumping motion until full depth was achieved (up to the handpiece head) and remove the resected material. A trephine drill with an inner diameter of 4 mm, an outer diameter of 5 mm and total working length of 18 mm (Meisinger) was used in combination with the 3D printed guide (Figure 2F).

Accuracy analysis

Upon completion, a post-operative CBCT scan was taken using NewTom VGi evo (NewTom) operating at the same parameters mentioned before. DICOM files from the master pre-operative CBCT and post-operative CBCT scans were loaded separately into Mimics Medical software 21.0 (Materialise, Leuven, Belgium) and a threshold was applied for segmentation. Both structures, pre- and post-operative models, were exported separately as STL files to 3-Matic Medical software 13.0 (Materialise). The post-operative model was then registered to the pre-operative model first by using the N-point registration tool from the software (with 3 points) to approximate the structure and later by using global surface registration until no further movement was achieved after 3 consecutive attempts.

After registration, both models were duplicated, and the post-operative model was subtracted from the pre-operative to obtain the performed osteotomies. A cylin-

der, automatically fitted by the software, was superimposed over the osteotomies. The central axis of the cylinder corresponded to the middle of the segmented osteotomy, following its direction.

The same operator involved in the planning performed the accuracy analysis. A comparison was done with the planning and a total of 9 parameters were measured: 1) A Deviation at the entry (mm); 2) B Deviation at the end (mm); 3) C Depth (mm),

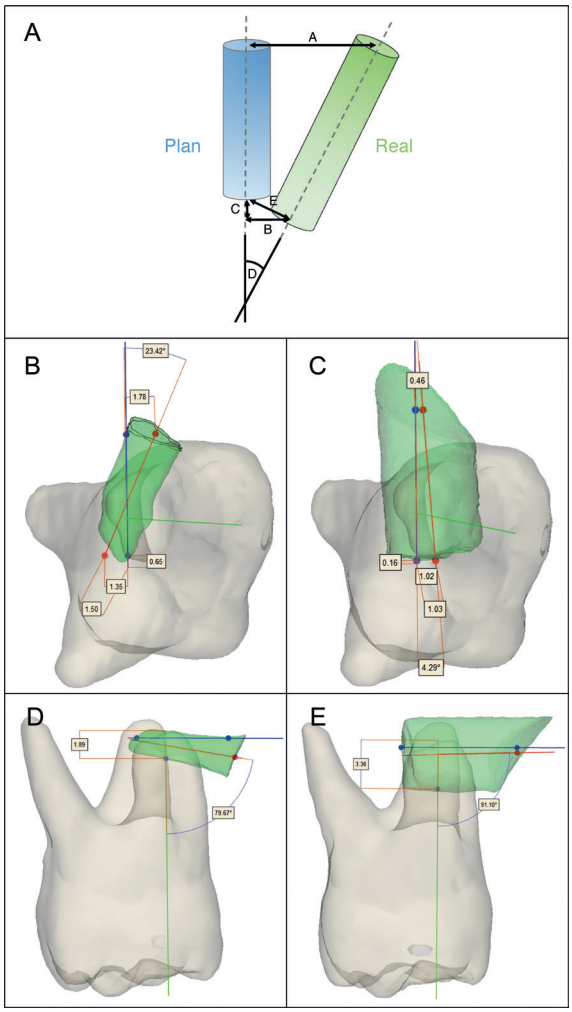

Figure 3. Accuracy analysis and example of tooth #26
A. Accuracy deviation measurements for (A) deviation at entry, (B) deviation at the end, (C) depth, (D) angle deviation, and (E) total deviation. From B. trough E. in green the segmented osteotomy with central axis in red vs planning axis in blue. Accuracy analysis for EMS: B. deviation at entry (1.78 mm), end (1.35 mm), depth (0.65 mm), angle (23.42°) and total deviation (1.50 mm). D. bevel of root resection (10.33°), root resection (1.89 mm). Accuracy analysis for TEMS: C. deviation at entry (0.46 mm), end (1.02 mm), depth (0.16 mm), angle (4.29°) and total deviation (1.03 mm). E. bevel of root resection (1.10°), root resection (3.36 mm).

presenting a negative value if the osteotomy had less depth than planned and a positive if it was beyond planning; 4) D Angle deviation (degrees); 5) E Total deviation (mm); 6) Bevel of root resection (90° = 0, no bevel); 7) Root resection (amount of root resected in mm, measured from the axis of the root); 8) Osteotomy volume (percentage value in comparison to planning); 9) Time (seconds) required to drill the osteotomy (Figure 3).

Statistical Analysis

Descriptive statistics for each parameter was performed. Differences between groups were assessed by a linear mixed model. In a first instance, a residual analysis was performed by means of a normal quantile plot and residual dot plot. If data were not normally distributed, a square root or log transformation was applied, or outliers were removed and the normal quantile plot of the residual values was checked again.

If the results of the linear mixed model showed that a significant interaction between a combination of variables existed, levels of one variable were compared for every combination of levels of the other variables apart and a correction for simultaneous hypothesis testing according to Sidak was applied. If no interaction existed, levels of one variable were compared for all level combinations of the other variables with a correction for simultaneous hypothesis testing according to Tukey.

7.3 Results

In total, each operator performed surgery on 56 roots (28 EMS and 28 TEMS) from 48 teeth (24 EMS and 24 TEMS). Descriptive statistic values between EMS and TEMS are shown in Tables 1 and 2.

Additionally, a statistical analysis was performed to find significant differences between four groups or variables (1) Surgery type (EMS vs TEMS); 2) Operators (Operator 1 vs 2); 3) Tooth type (Anterior vs Premolar vs Molar); and 4) Jaw type (Upper vs Lower jaw)). Since significant interactions were found between variables, levels of one variable were compared for every combination of levels of the other variables apart. All statistically significant results ($p < 0.05$) between the variables are described hereafter per parameter:

A Deviation at entry. TEMS was more accurate than EMS for posterior teeth (premolars and molars). Anterior lower teeth had higher deviation with EMS compared to anterior upper teeth.

B Deviation at end. No difference was found between surgery type. Operator 2 had more accurate values overall.

C Depth. TEMS had higher depth value. No difference was found between operators and tooth types.

D Angle. EMS had higher deviation angles than TEMS for Operator 2 on all tooth types, and for operator 1 only on anterior lower teeth.

E Total deviation. Operator 2 presented more accurate values overall. On EMS upper anterior teeth had less deviation than upper posterior teeth (premolars and molars).

Bevel. TEMS presented significant smaller values than EMS. No difference was found between operators or jaw types with TEMS.

Root resection. No difference was found between operators.

Osteotomy volume compared to planning. EMS had lower volumes than TEMS. No difference was found between tooth types for TEMS. Operator 2 had smaller volumes than operator 1 with EMS on all teeth except for lower premolars and molars.

Time. TEMS took less time than EMS. Upper anterior teeth took less time than upper posterior teeth (premolars and molars) with EMS.

	A (mm)	B (mm)	C (mm)	D (°)	E (mm)	Volume (mm^3)	Volume (%)
EMS	1.78 (0.37 – 3.43)	1.04 (0.23 – 5.11)	-0.63 (-3.37 – 0.97)	16.96 (0.5 – 62.62)	1.35 (0.47 – 6.12)	59.22 (13.88 – 152.53)	40.7 (16.6 – 87.7)
TEMS	0.67 (0.11 – 1.7)	1.12 (0.27 – 2.50)	0.06 (-0.71 – 1.26)	4.86 (0.21 – 17.23)	1.19 (0.29 – 2.51)	137.39 (73.99 – 226.92)	98.4 (83.3 – 113.2)

Table 1. Deviations of freehanded EMS vs TEMS in comparison to the virtual planning. General results. Mean values are given with their minimum and maximum values between brackets. Volume percentages are given in comparison to the planning. Letter coding: A: Deviation at entry, B: Deviation at end, C: Depth, D: Angle deviation, E: Total deviation.

Operator 1							
	A (mm)	**B (mm)**	**C (mm)**	**D (°)**	**E (mm)**	**Volume (mm^3)**	**Volume (%)**
EMS	1.55 (0.37 – 3.04)	1.17 (0.48 – 2.72)	-0.48 (-1.93 – 0.47)	11.78 (0.5 – 26.61)	1.38 (0.66 – 2.72)	71.07 (26.23 – 152.53)	48.7 (26.7 – 87.7)
TEMS	0.76 (0.25 – 1.7)	1.23 (0.27 – 2.5)	-0.03 (-0.71 – 0.8)	5.72 (1.15 – 17.23)	1.28 (0.29 – 2.51)	138.31 (78.48 – 226.92)	98.9 (84 – 113.2)
Operator 2							
	A (mm)	**B (mm)**	**C (mm)**	**D (°)**	**E (mm)**	**Volume (mm^3)**	**Volume (%)**
EMS	2.01 (0.79 – 3.43)	0.91 (0.23 – 5.11)	-0.77 (-3.37 – 0.97)	22.15 (6.07 – 62.62)	1.32 (0.47 – 6.12)	47.38 (13.88 – 86.54)	32.6 (16.6 – 54.5)
TEMS	0.58 (0.11 – 1.31)	1.01 (0.38 – 1.99)	0.15 (-0.46 – 1.26)	4.01 (0.21 – 7.81)	1.11 (0.39 – 2.15)	136.47 (73.99 – 194.95)	97.8 (83.3 -111.5)

Table 2. Deviations of freehanded EMS vs TEMS in comparison to the virtual planning. Results per operator. Mean values are given with their minimum and maximum values between brackets. Volume percentages are given in comparison to the planning. Letter coding: A: Deviation at entry, B: Deviation at end, C: Depth, D: Angle deviation, E: Total deviation.

7.4 Discussion

The purpose of this study was to assess the accuracy of TEMS in comparison to EMS using a semiautomatic measuring protocol (based on Torres et al (21)) with respect to nine parameters (deviation at entry point, end point, total deviation, depth, angle, root bevel, root resection, osteotomy volume and surgical time).

A need for a standardize measuring method as the one proposed in the present study is needed to compare results from accuracy studies. This method removes human hand error as all points are automatically placed by the software. Such method has also been used for accuracy measurements of guided endodontics [21] and is based on established accuracy studies from guided implant placement [24-28].

Bevel (°)	Root resection (mm)	Time (s)
11.76 (0.01 – 28.52)	2.66 (0.77 – 4.76)	175 (52 – 652)
3.20 (0.48 – 8.55)	4.17 (1.93 – 5.2)	38 (10 – 167)

Bevel (°)	Root resection (mm)	Time (s)
6.51 (0.01 – 17.5)	2.92 (0.77 – 4.76)	184 (88 -652)
3.28 (0.49 – 8.55)	4.30 (3.13 – 5.2)	29 (10 – 167)

Bevel (°)	Root resection (mm)	Time (s)
17.01 (4.61 – 28.52)	2.40 (1.38 – 4.11)	166 (52 – 568)
3.12 (0.48 – 7.81)	4.04 (1.93 – 4.09)	47 (19 – 110)

Recently, a similar study set-up was published by Hawkins, 2020 et. al. [29] comparing TEMS with EMS. However, the study focused more on volumetric measurements and does not assessed deviation. Additionally, in contrast to Hawkins 2020 et. al. [29], there was no simulation of periapical lesions in the models from the present study, this was done to be able to segment cylindrical shaped cavities for the accuracy analysis.

Upper molar teeth are usually more complex to treat due to its more posterior position and could be a place where the use of TEMS could improve reliability. T.K. Hawkins, 2020 et. al. [29] reported higher standard deviation on the values between both techniques mostly due to a fused DB-P root. In the present study, maxillary molars also showed the greatest difference between techniques. EMS showed a higher deviation at entry, total deviation, and bevel (compared to upper premolars), and less

root resection (when compared to upper anterior and premolars). Also, there was a significant longer surgical time when compared to upper anterior teeth.

When using a guide, the results are more predictable and have less variability between and within operators [14, 30]. In the present study more accurate and standardized osteotomies were observed on both upper and lower jaws with the use of TEMS, in comparison to EMS. The current results suggest that TEMS could reduce the experience gap between professionals. Furthermore, the use of a guide would allow a reliable access to a target point, this gives an advantage in difficult to reach places such as the palatal root of upper molars, a deep located root apex, or when the integrity of neighbor structures can be compromised [4, 14].

When comparing accuracy between procedures, Ackerman et al. [31] obtained 100% success when using a guide in comparison to the control side with only 45.8% of successful cases. Success was defined when the end of the cavity reached within 4 mm from the apex (1.5 mm (±0.8 SD) for the guided group and 2.6 mm (±1.4 SD) for the control group [31]). In the present study, a mean total deviation of the cavity of 1.2 mm (±0.6 SD) was found in the TEMS group in comparison to 1.4 mm (±0.8 SD) in the EMS group. These results are lower than the ones described by Ackerman et al. [31], possibly due to the different study design and measuring technique. However, the present study shows a higher contrast between techniques for the mean deviation at entry (TEMS: 0.7 mm (±0.3 SD) vs EMS: 1.8 mm (±0.7 SD)).

Another benefit of using a 3DSG is the decrease in surgical time [29]. In the present study we observed a mean total time of 38s (±27 SD) for TEMS compared to 175s (±112 SD) for EMS. Although the definition of surgical time was different, Hawkins et. al. also shows a significant reduced time when using TEMS from an average of 859s to 254s.

There was greater volume resected for TEMS than for EMS (this can be explained by the diameter of the burr). Hawkins et. al [29], shows that the total volume removed using TEMS was less than the volume removed using the free-handed technique. However, the volume was measured in bone and root volume; the volume of bone removed was greater when performing TEMS than EMS, the opposite was found for volume of root removed. Also, the volume deviations were greater for EMS than TEMS. This was again observed in the present study, with a greater variation between operators, tooth types and jaw types, for EMS.

Results from the present study should be interpreted with care. The 3D model was made based on a real patient, but the material colors and consistency are different than that of a real situation. The present study did not include replicas of periapical

lesions as by T.K. Hawkins, 2020 et. al. [29]. Neither gingival tissue was mimicked and there was no bleeding. Additionally, anatomical landmarks and neighbor structures were not replicated or considered in the planning. However, even though in-vivo conditions may be hard to replicate, mounting 3D models into a phantom head allows for excellent standardization. Which may give a greater advantage to EMS but not to TEMS, as with TEMS a 3DSG is used and as long it is properly placed, deviation from ideal under clinical conditions is minimized [29].

An important point to consider is that the sleeve of the guide will only allow one position of the handpiece and it may be difficult to fit in the patient's mouth [31]. This should be carefully considered during initial consultation with the patient and when designing the guide for treatment. Water cooling during drilling can be a challenge when using 3DSG [31], that is why, in the present study, an irrigation window in each sleeve was included [15].

7.5 Conclusion

In conclusion, a standardize measurement protocol was proposed based on nine parameters for the report of results that can make comparisons between studies in the future easier and more reliable. Within its limitations, the present study demonstrates that TEMS, in comparison to free-handed EMS, results in: less deviations, a root bevel closer to zero, more predictable root resection and shorter surgical time, however slightly deeper osteotomies are obtained with greater volumes, the latter being dependent on the size of trephine bur used. Additionally, a more predictable result may be achieved, minimizing potential errors which can be beneficial in anatomically challenging places.

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Chapter 8

Clinical outcome of guided endodontics vs freehand drilling: a nonrandomized controlled clinical trial

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Keywords

Controlled clinical trial
Guided endodontics
Cone beam computed tomography
Dental pulp calcification

Abstract

Aim - High-quality, prospective clinical studies are needed to increase evidence for guided endodontics. This study aims to assess the clinical outcome of guided endodontics for the treatment of teeth presenting with pulp canal obliteration (PCO) in comparison to free-hand treatment. **Methods** - This trial was registered in the ISRCTN.com registry (ISRCTN75277265) and designed as a Controlled Clinical Trial: Prospective, nonrandomized, single center study (ethical approval number S64630). Inclusion criteria were; tooth presenting with PCO and symptoms and/or signs of apical periodontitis (AP). An external control group was selected from clinical records of patients presenting the same criteria but treated free-handed. Guided root canal treatments were performed by the same operator on all patients. Free-handed treatments were performed by Endodontist specialists under microscope with pre-operative CBCT available. Primary outcome for both groups was evaluated as: canal found, canal not found, or perforation. As secondary outcome, the qualitative accuracy of the drill path, was assessed as: optimal precision, acceptable precision, or technical failure. Patients were followed-up yearly. Descriptive statistics on the study patient's demographics and healing outcome were performed and specific statistical analysis was performed on each outcome variable. **Results** - A total of 133 teeth were included (n = 60 guided, n = 73 free-handed) from 128 patients (n = 59 guided, n = 69 free-handed). The primary outcome for the guided group was: 59 teeth canal found, and 1 tooth canal not found. No perforations were recorded. In the free-handed group, the root canal was successfully found in 59 teeth, in 7 was not found, and 7 had a perforation. An analysis of all data showed that guided endodontics presented statistically significant better outcome than free-hand treatment ($P < 0.05$). **Conclusions** - Guided endodontics showed a statistically significant better outcome than free-handed treatment resulting in less technical failures. However, it is a complex procedure which should be carried out by an experienced endodontist with the aid of a dental microscope.

8.1 Introduction

Pulp canal obliteration (PCO), is a process characterized by the deposition of hard tissue within the root canal [1]. It can present mainly as a result of trauma [2] but also due to caries, tooth surface loss, operative procedures, orthodontic treatment or in elderly patients, due to a lifelong apposition of secondary or tertiary dentin [1, 3]. It is generally accepted that sensibility tests are unreliable in cases presenting with PCO [4-6]. Endodontic treatment of such cases should only be initiated if the tooth presents symptoms or radiographic signs of apical periodontitis [2].

The negotiation of root canals presenting with PCO has been classified in the moderate to high risk category by the American Association of Endodontics [7]. Localizing the canal can be a difficult and long task [3], and in such cases, there is a higher probability of failure which can compromise the outcome of the root canal treatment [8]. In this regard, the acquisition of limited field of view Cone-Beam Computed Tomography (CBCT) can be beneficial. It allows for a 3-dimensional visualization of the root canal and a better understanding of the tooth's anatomy, such as the number of root canals and their exact location in the root [9]. This allows the clinician to establish a customized strategy with which to approach the canal prior to treatment. Repeated intra-oral radiographs can be then taken during treatment to verify the access cavity path. CBCT can also be beneficial for intra-appointment identification and localization of calcified canals [10-12]. However, the acquisition of an extra CBCT volume for intra-appointment localization of the canals involves longer treatment time and additional exposure to radiation for the patient.

A current alternative for the treatment of PCO is the concept of "Guided Endodontics", in which a 3D printed guide is used to guide the bur up to the target location [13, 14]. It can reduce the chance of iatrogenic damage or excessive loss of tooth structure, and the likelihood of finding the canal is high, while reducing also treatment time [15-19]. Additionally, the outcome is not dependent on the operator's experience [19-21].

Recently, a systematic review of the literature reported that guided endodontics is an effective and predictable tool for locating calcified root canals [22]. After analysis of the literature, the authors included a total of 21 case reports, 11 case series and 1 observational cohort study on 50 patients. However, although the studies were classified as having low risk of bias, a potential publication bias should be considered as well as the impact of non-publication of failed cases [23].

Case reports are important when assessing new techniques where the success rate is not yet known or difficult to estimate [22]. Nevertheless, high-quality, prospective clinical studies are lacking. Such studies are needed to increase the evidence for

guided endodontics [22, 24]. Therefore, the aim of this controlled clinical trial is to assess the clinical outcome of guided endodontics for the treatment of teeth presenting with PCO in comparison to free-hand treatment. The main clinical research question is (PICO): in teeth presenting with PCO (P), does guided endodontics treatment (I) results in less technical failures (O) compared to free-hand treatment (C)?

8.2 Materials and methods

This clinical trial has been written according to Preferred Reporting Items for RAndomized Trials in Endodontics (PRIRATE) 2020 guidelines [25].

Study design

The study was designed as a Controlled Clinical Trial (CCT): Prospective, nonrandomized, single center study. With an external control group. The design was structured according to the ethical principles of the Declaration of Helsinki and Good Clinical Practice (GCP). The treatment of patients with Guided Endodontics has been approved by the Ethics Committee of the University Hospitals Leuven, Leuven, Belgium (S64630). Written informed consent was obtained prior to starting the treatment. Additionally, all participants received a verbal explanation in terms suited to their comprehension of the purposes, procedures, and potential risks of the study and of their rights as research participants. The Principal Investigator (AT) assured that no deviation from, or changes to the protocol were made except where necessary to eliminate an immediate hazard(s) to the trial participants. The trial was registered in the ISRCTN registry (ISRCTN75277265, https://www.isrctn.com).

Patient selection

Between April 2018 and October 2022 all patients referred for endodontic treatment at the Endodontic Department at the University Hospitals of Leuven, Leuven, Belgium, were screened for eligibility during the initial consultation. The inclusion criteria were as follows:

- Tooth presenting with PCO, (and)
- Symptoms and/or radiographic signs of apical periodontitis (AP).

All patients had a thorough intraoral examination. A periapical radiograph was taken for assessment. If the tooth presented PCO, a score was given based on the visibility of the canal on the periapical radiograph as: (1) root canal not visible (total PCO), (2) root canal visible up to apical root third, (3) root canal visible up to middle root third, (4) root canal visible up to coronal root third. Then, a pre-operative CBCT scan

was taken for further assessment using the NewTom VGi evo (Cefla, Imola, Italy) operating at 110 kVp and 3 mA. If the CBCT volume confirmed the initial diagnosis of PCO, and the clinician evaluated the case as being of high difficulty [7], patients were candidates for inclusion. The exclusion criteria were:

- Patients unwilling or unable to comply with the endodontic treatment.
- Tooth in need of extraction, or with an unfavourable prognosis.

Sample size

The sample size was calculated based on the probability of technical failure (perforation or canal not found) when drilling free-handed on teeth presenting PCO. Cvek et al. [8] reported a probability of technical failure (root canal not found or perforation) of 14.3% (7 out of 49 teeth) when drilling free-handed on anterior teeth with reduced pulpal lumen. Based on this data, a sample size calculation was performed with a power of 80% and a significance level of 0.05. Considering that the technical failure of Guided Endodontics was not known, an arbitrary technical failure rate of 2% was set to be clinically relevant. This would imply more than 10% improvement than drilling without guidance.

The sample size was calculated by the normal approximation to the comparison of proprotions using the TrialSize library from R in an iterative way, in which, for a new calculation, quantiles from an Studentized t-distribution were used, for which the degrees of freedom corresponded to the requested number of data from the previous calculation. According to the test, a sample size of 59 teeth was needed. This was rounded up to 60 teeth (Figure 1).

Randomization and blinding

Considering that 21 case reports, 11 case series and 1 observational cohort study on 50 patients [22] show that the use of guides for endodontic treatment offer a highly predictable outcome, with a low risk of iatrogenic damage, randomizing the treatments was not considered to be ethical as it would not guaranty the best quality standards of treatment to the patient [7]. As a result, an external (historical) control group was selected to assess the success rate of Guided Endodontics treatment. Blinding of the operator was not possible due to the study design.

Control group

A database search was carried out in the clinical management software (KWS, version 3.4.1, Cegeka, Hasselt, Belgium), for clinical records from the Endodontic Department at the University Hospitals of Leuven, Leuven, Belgium, on patients that

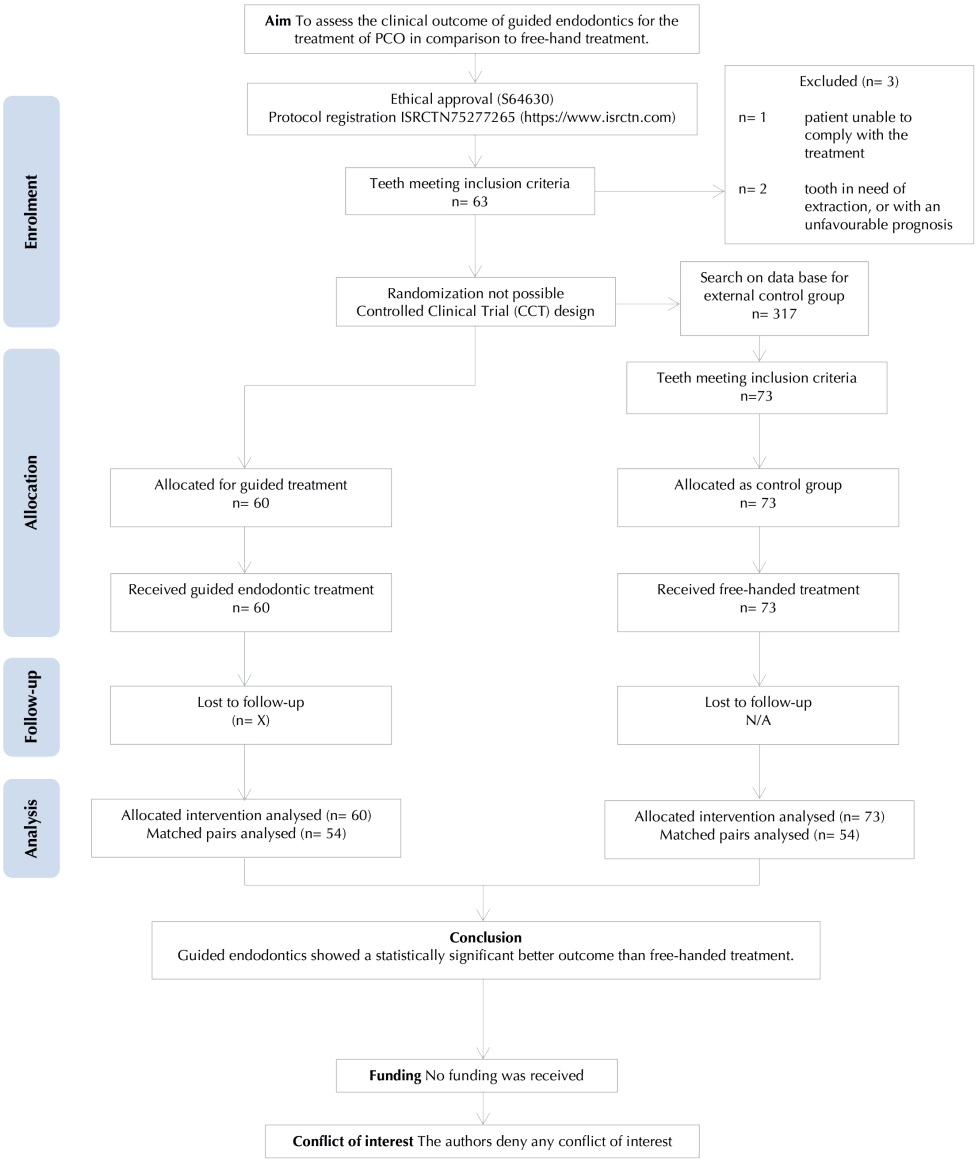

Figure 1. PRIRATE flowchart (Nagendrababu et al. 2020). Study design and flowchart of participants.

were treated without the use of any guiding system between January 2014 up to October 2022.

The following search terms were used to search on all consultation reports from the clinical database of the department of Endodontics: “calcified” OR “calcification” OR “obliterated” OR “obliteration” OR “small” OR “narrow” OR “perforated” OR “perforation” OR “not found” OR “not visible”.

After the search was completed, a second operator not related to the clinical treatments (MD) analyzed all dental reports and selected the patients for the control group. Patients presenting with all the following inclusion criteria were selected for inclusion:

- The patient was treated by an Endodontist specialist
- A dental microscope was used
- A CBCT was available before treatment
- The tooth presented PCO visible on a periapical radiograph
- The case can be classified as being of high difficulty [7]
- Symptoms and/or radiographic signs of AP were present at the time of treatment

Planning and Guide design

A pre-operative CBCT and IOS of every patient selected for guided endodontics treatment were taken using the NewTom VGi evo (Cefla) and a Trios intraoral scanner (3Shape, Copenhagen, Denmark). The DICOM images from the CBCT and STL file from the IOS were imported into Mimics Medical software 23.0 (Materialise, Leuven, Belgium). Then the upper or lower jaw, depending on the case, was segmented using the threshold tool, and a 3D model was created. The registration of the IOS to the segmented CBCT model was first performed by using a 3-point registration method to approximate both structures. Subsequently, the automatic global registration tool was applied and repeated for final registration until no further movement was possible. The correct registration was confirmed visually by checking the contour of the registered IOS on the CBCT images (Figure 2).

A path for the bur was created maintaining a straight-line access up to the root canal. Special attention was placed to avoid drilling on the incisal border or buccal side of the tooth when possible. Then, the registered IOS together with the planned trajectory were imported into 3-Matic medical software 14.0 (Materialise) where a tooth-supported guide was designed (Figure 2).

After completion of the design, an insertion axis was defined, and the undercut zones were removed by the software’s tool. Subsequently, the guide was 3D printed

in a biocompatible material (MED 610, Stratasys, Eden Prairie, MN, USA) using the Objet Connex 350 3D printer (Stratasys) and finally, a metallic inner sleeve (REF M.27.28.D100L5, Steco, Steco System-Technik, Hamburg, Germany) was bonded to the guide (Figure 3).

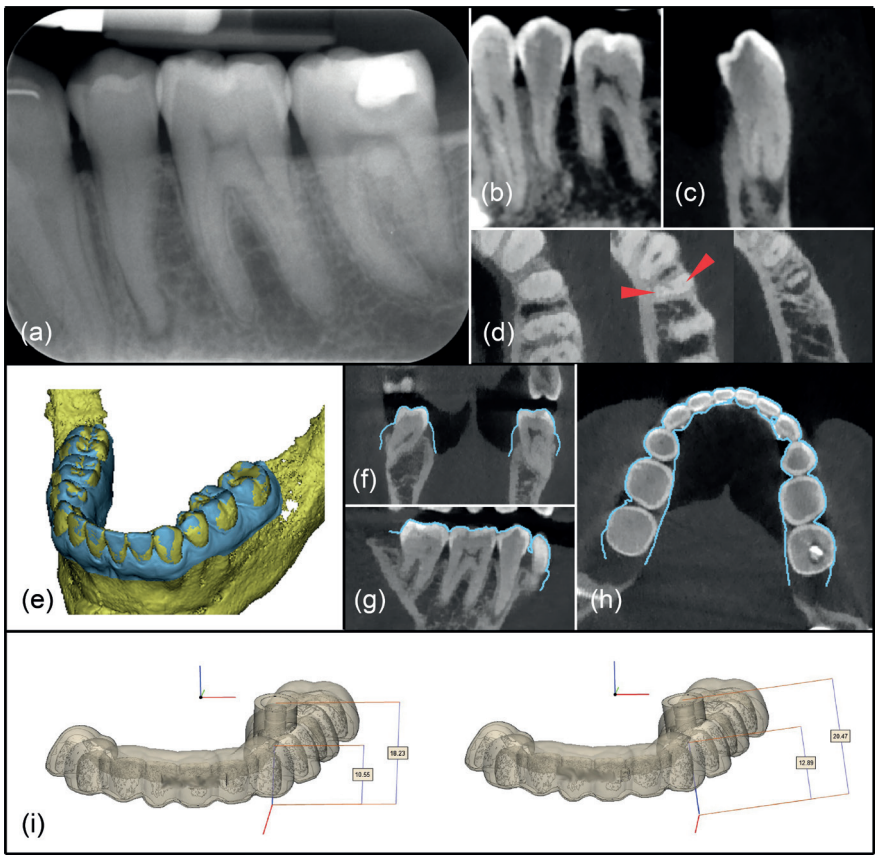

Figure 2. Planning and Guide design. Case of a 29-year-old female presenting with pain complains on the left lower jaw. (a) A periapical radiograph revealed PCO and apical periodontitis on tooth 34. The tooth was diagnosed with symptomatic apical periodontitis. (b, c) A pre-operative CBCT revealed the presence of PCO up to the middle root third with (d) 2 canals apically on the buccal and lingual side (red arrows) and apical periodontitis. (e) The DICOM images from the CBCT were imported into Mimics Medical software 23.0 (Materialise) where the lower jaw was segmented using the threshold tool creating a 3D model (yellow). The correct registration of the IOS (blue) was confirmed visually on the model and on every plane (f, g, h) by checking the contour of the registered IOS (blue line) on the CBCT images. (i) 3D model from 3-Matic medical software 14.0 (Materialise) of 2 tooth-supported guides used during treatment for the buccal and lingual canal. The length of the drill considering the height of the sleeve and drilling depth in the tooth up to the canal were measured before treatment (Left, guide for lingual canal: drill length 18 mm, drill depth in tooth 10.5 mm. Right, guide for buccal canal: drill length 20.5 mm, drill depth in tooth 13 mm. All measurements were rounded to the nearest half for treatment).

Guided root canal treatment was performed by the same operator (AT) on all patients, always adhering to the quality guidelines for endodontic treatment from the European Society of Endodontology [26].

First, full rubber dam isolation was placed, with the extension of the isolation field being determined by the extension of the guide. The guide was then placed on the patient's teeth and checked to fit passively on the crowns. Correct fit was checked on both ends of the guide (Figure 3). If needed, the interproximal interferences were removed manually from the guide until achieving a passive fit. The stability was checked visually by pressing on one side of the guide (left or right), if there was no movement on the opposite side, the guide was stable, and treatment started.

Two 1 mm diameter carbide burs with different lengths were available for guided treatment. One short with 21 mm working length and 35 mm total length (REF O.27.28.B044.051, Steco), and a longer one with 28 mm working length and 42 mm total length (REF O.27.28.B044.052, Steco). The decision to use a long or short drill was based upon the case. A new bur was used on every treatment. Before drilling, the entry point was marked with a mechanical pencil through the inner sleeve and enamel was removed by hand with a diamond bur. Then the access cavity was precisely drilled using the selected carbide bur (Steco) mounted on and a Blue W&H WE-56 LED G handpiece (W&H, Bürmoos, Austria) operated at 20.000 rpm using a pumping movement (Figure 3). During drilling, water was irrigated at the entrance of the sleeve using a Stropko Irrigator (Vista Apex, Racine, WI, USA).

When the target point was reached, the tooth was examined under the dental microscope. Small size K-Files (06 up to 10, Dentsply Sirona, Baillagues, Switserland) where used initially to negotiate the canal, and after glide path was achieved with a size 15 K-File (Dentsply Sirona), instrumentation of the canal was performed with Waveone Gold files (Dentsply Sirona) up to at least a Medium size (size 35, .06 taper) as final working file. Apical patency was controlled during the whole treatment with a size 10 K-File (Dentsply Sirona). During treatment, the root canal was rinsed with at least 20 ml of 5% NaOCl in combination with sonic activation using EDDY (VDW, Munich, Germany), then a final irrigation protocol was applied using EDDY and 17% EDTA, and a final rinse with 5% NaOCl. The root was dried using paper points and filled using a vertical compaction technique with warm gutta-percha and an epoxy sealer (AH Plus sealer, Dentsply Sirona). The access cavity was then filled with composite, occlusion was controlled, and the restoration was polished. A periapical radiograph was taken after treatment and the patient was scheduled for recall (Figure 3).

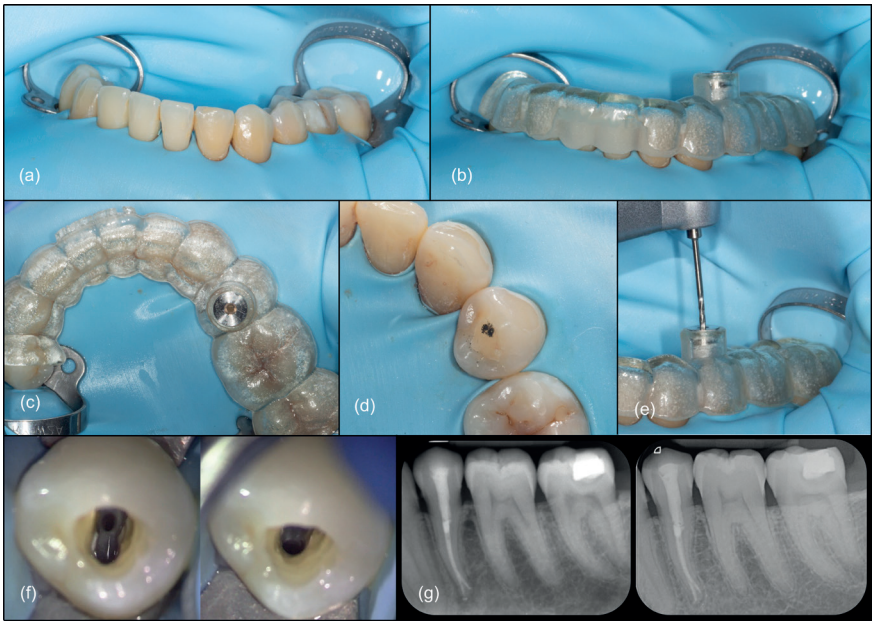

Figure 3. Guided Endodontic Treatment. Treatment of the same case from Fig. 2. (a) Full rubber dam isolation, the extension of the isolation field was determined by the extension of the guide. (b, c) Placement of the 3D printed guide on the patient's teeth, note that an inner sleeve (REF M.27.28.D100L5, Steco, Steco System-Technik, Hamburg, Germany) was bonded to the guide. The guide was checked to fit passively on the crowns. (d) Before drilling, the entry point was marked with a mechanical pencil through the inner sleeve and enamel was removed by hand with a diamond bur. (e) A new 1 mm diameter carbide bur was selected for treatment depending of the length needed (21 mm working length and 35 mm total length REF O.27.28. B044.051, or 28 mm working length and 42 mm total length REF O.27.28.B044.052, Steco). The access cavity was drilled using the selected bur and a Blue W&H WE-56 LED G handpiece (W&H) operating at 20.000 rpm using a pumping movement. (f) Images from the dental microscope of the buccal canal (left) and lingual canal (right) after root canal preparation was finished. (g) Left: periapical radiograph after treatment and 1 year follow-up showing full periapical healing. Note that there was a slight deviation of the drill path on the buccal side, this case was assessed as having acceptable precision on the qualitative accuracy assessment of the drill path.

Free-handed Treatment (control group)

Root canal treatment was performed by an Endodontist specialist not related to the study working at the time at the Endodontic Department at the University Hospitals of Leuven, Leuven, Belgium. Endodontic treatment complied to the quality guidelines for endodontic treatment from the European Society of Endodontology [26]. A dental microscope was used during the whole procedure, and a CBCT was available before treatment for planning and visual guidance during treatment.

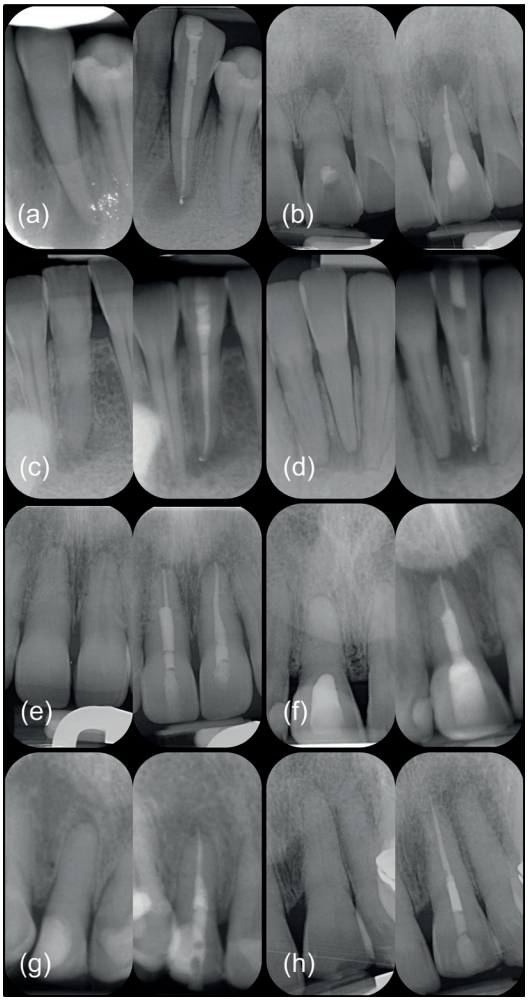

Figure 4. Qualitative accuracy assessment of the drill path. As secondary outcome, the qualitative accuracy of the drill path was assessed based on the clinical data and divided into 3 groups (adapted from Buchgreitz et. al. [27]): 1. Optimal precision: Drill path centered. 2. Acceptable precision: Drill path peripherally or tangentially transported. A manual correction was needed to find the canal. 3. Technical failure: Perforation or canal not found. (a – d) Cases having optimal precision with a centered drill path. (e – h) Cases having acceptable precision with a peripherally or tangentially transported drill path. A small correction was needed to find the canal. Note that case (h) was slightly deviated on the buccal-palatal direction which is not visible on a 2D radiograph. The classification was based on clinical data from every treatment.

Outcome measurements

During guided endodontic treatment the primary outcome was evaluated by the operator (AT) as:

1. Canal found
2. Canal not found
3. Perforation

As secondary outcome, the qualitative accuracy of the drill path was assessed based on the clinical data and divided into 3 groups (adapted from Buchgreitz et. al. [27]) (Figure 4):

1. Optimal precision: Drill path centered.
2. Acceptable precision: Drill path peripherally or tangentially transported. A manual correction was needed to find the canal.
3. Technical failure: Perforation or canal not found.

Additionally, the healing after root canal treatment was assessed clinically and radiologically, with periapical radiographs, at 1 year and yearly until periapical healing. A favorable outcome was defined as absence of pain, swelling and other symptoms, no sinus tract, no loss of function and radiological evidence of a normal periodontal ligament space around the root [26].

In the same manner as the guided treatment group, the primary outcome of the endodontic treatment from the control group was classified and recorded as:

1. Canal found
2. Canal not found
3. Perforation

Pairing of teeth for statistical analysis

The following variables were recorded on both treatment groups (guided treatment and control group) for matched pairing:

- Tooth number
- Tooth type: Anterior; incisors and canines, Posterior; premolars and molars.
- Tooth length in mm (measured on the CBCT)
- Canal depth in mm: distance in mm from incisal border or occlusal plane to the canal (measured on the CBCT)
- Canal depth percentage: percentage calculated dividing the canal depth by the tooth length.

Teeth were first matched to a pair from the other group based on the same tooth number and similar canal depths or depth percentages. If no match was found, matching was performed on tooth type (anterior and posterior) and similar canal depths or depth percentages.

Statistical Analysis

All statistical analysis was done in S+ software, version 8.0 (TIBCO Software, Palo Alto, CA, USA). A technical failure was defined by not finding the canal or having a perforation during treatment. The null hypothesis stated that; H0: there is no difference in technical failures between guided endodontics and free-handed treatment. Additionally, the alternative hypothesis stated that; Ha: Guided endodontics presents less technical failures compared to free-handed treatment.

An analysis including all data, without matching, was performed by a generalized linear model for binary data using a logit link function with the primary outcome (canal found or not found/perforation) as response variable and the technique (guided or free-handed) as explanatory variable. $P \leq 0.05$ was considered statistically significant. Data were also matched based on tooth type and canal depth. The primary outcome (canal found or not found/perforation) was analyzed by a Generalized Estimation Equations analysis for binomial data. Data were considered to be clustered per pair of control and matched teeth. Only teeth for which a matched pair was found were included in the analysis. $P \leq 0.05$ was considered statistically significant.

Additionally, descriptive statistics on the study patient's demographics and healing after root canal treatment were performed.

8.3 Results

A total of 60 teeth in 59 patients (22 males and 37 female) with median age of 48 (range: 14 – 85) received guided endodontic treatment. Three teeth were excluded from the study; one because the patient was unable to comply with the treatment, and two teeth were deemed to have unfavorable prognosis and, therefore, extraction was chosen instead of endodontic treatment (Figure 1).

For the selection of the control group (teeth with PCO treated free-handed), a database search was carried out in the clinical management software (KWS, Cegeka) for clinical records, from the Endodontic Department, using specific keywords leading to the treatment of calcified canals similarly as a classic literature search (see "Material and methods" section, subsection "Control group"). The search resulted in 317 potential patients to be included in the control group. After further analysis, 73 teeth in 69 patients (33 males and 36 females) with median age of 55 (range: 9 – 85) met the inclusion criteria and were selected for inclusion (Figure 1). Descriptive statistics on the demographics of the study patients are shown in Table 1.

	Guided Group		Control group	
Variables	**n**	**%**	**n**	**%**
Age in years				
Mean ± SD	49 ± 19.43		50 ± 20.95	
Gender				
Male	22	37.3	33	47.8
Female	37	62.7	36	52.2
Total	59	100	69	100
Tooth type				
Maxillary incisor	39	65	41	56.2
Maxillary canine	2	3.3	3	4.1
Maxillary premolar	3	5	16	21.9
Mandibular incisor	11	18.3	9	12.3
Mandibular canine	1	1.7	0	0
Mandibular premolar	4	6.7	4	5.5
Total	60	100	73	100
Canal visible in periapical radiograph				
No	15	25	12	16.4
Up to apical root third	16	26.7	9	12.3
Up to middle root third	20	33.3	37	50.7
Up to coronal root third	9	15	15	20.6
Canal depth on CBCT in mm				
Mean ± SD	12.05 ± 3.45		10.62 ± 3.43	

Table 1. Demographics of the study patients.

After consultation with a professional statistician (WC) and to increase the power of the study, teeth from the guided endodontics group were matched to a similar pair from the control group based on tooth number or tooth type and canal depth or depth percentage. A total of 54 matches were found with an average difference in canal depth of 1 mm ± 1.3, and average difference in depth percentage of 6.5% ± 5.4 (Tables 2 and 3).

Guided Endodontics group				Free-handed control group			
Case number	Tooth number	Canal depth (mm)	Canal depth (%)	Case number	Tooth number	Canal depth (mm)	Canal depth (%)
1	22	9	51.4	**68**	22	9	37.5
2	21	10	48.8	**31**	11	10	47.6
3	11	11.5	62.2	**15**	11	12	63.2
4	32	10.5	56.8	**22**	31	11	59.5
5	22	9	42.9	**52**	12	9	45
6	14	9.5	47.5	**9**	14	9	43.9
7	21	14	70	**24**	11	14	66.7
8	11	11	46.8	**59**	11	10.5	44.7
9	21	11.5	56.1	**61**	21	12	57.1
10	31	9	48.6	**58**	42	10	47.6
11	42	10	50	**65**	42	10	45.5
12	13	18	69.2	**70**	11	15	69.8
13	11	11.5	56.1	**49**	21	11.5	53.5
14	11	11	61.1	**73**	21	11	52.4
15	35	15	78.9	**63**	45	15	68.2
16	11	13	57.8	**60**	11	12.5	62.5
17	11	9	37.5	**57**	12	9	45
18	12	9	54.5	**8**	11	14	53.8
19	12	14.5	74.4	**5**	21	15	65.2
20	11	17.5	87.5	**13**	11	17	75.6
21	35	11	46.8	**33**	45	9.5	44.2
22	21	11	56.4	**42**	23	11.5	42.6
23	25	11.5	76.7	**21**	14	14.5	67.4
24	11	10	62.5	**38**	11	10	45.5
25	11	14	73.7	**50**	11	14	60.9
26	41	7.5	34.9	**28**	41	6	31.6
27	11	9	40	**72**	21	8	39
28	21	7.5	30	**17**	11	7	36.8
29	21	8	55.2	**46**	22	8	42.1
30	31	17.5	83.3	**64**	31	14	70

Table 2. Overview of matched pairs of guided treated teeth to free-handed control group. Matching was done based mainly on similar canal depths and secondary on similar depth percentages.

Guided Endodontics group				Free-handed control group			
Case number	Tooth number	Canal depth (mm)	Canal depth (%)	Case number	Tooth number	Canal depth (mm)	Canal depth (%)
31	35	9.5	42.2	**23**	45	9	40.9
32	35	9.5	46.3	**3**	44	8	38.1
33	21	10	62.5	**4**	22	10	43.5
34	21	17.5	74.5	**16**	21	13	76.5
35	12	12.5	52.1	**51**	23	13	52
36	23	20	87	**2**	12	19.5	72.2
37	22	10	47.6	**44**	21	6.5	48.1
38	21	12.5	69.4	**6**	21	13	59.1
39	22	16	72.7	**1**	11	16.5	70.2
40	22	11.5	59	**69**	22	12	60
41	21	7	43.8	**7**	12	7	46.7
42	31	10	46.5	**19**	42	12	57.1
43	12	8.5	39.5	**39**	22	5	38.5
44	33	17.5	72.9	**20**	42	13.5	58.7
45	21	12	46.2	**37**	11	12.5	51
46	32	11	59.5	**18**	32	13	57.8
47	12	15	71.4	**30**	11	14.5	55.8
48	25	9.5	45.2	**12**	24	10	50
49	11	8	39	**40**	12	6	37.5
50	32	11	47.8	**62**	41	12	57.1
51	41	13	61.9				
52	42	6.5	38.2				
53	41	10	50				
54	21	18	73.5	**71**	21	16	61.5
55	12	16	69.6	**53**	13	16	56.1
56	11	14.5	63	**27**	21	13	53.1
57	21	8	42.1	**45**	22	7	46.7
58	22	15.5	79.5				
59	11	19	76				
60	21	14	54.9				

Free-handed control group			
Case number	Tooth number	Canal depth (mm)	Canal depth (%)
10	12	4.5	25
11	12	4.5	22.5
14	14	10	52.6
25	25	15	65.2
26	24	10.5	44.7
29	22	5	35.7
32	25	8.5	32.1
34	24	8	53.3
35	14	12.5	65.8
36	24	8	43.2
41	24	8	42.1
43	14	13	59.1
47	14	9.5	55.9
48	14	10.5	52.5
54	22	5	22.7
55	15	9.5	39.6
56	12	4.5	31
66	15	6.5	40.6
67	21	5	29.4

Table 3. Overview of non-matched controls.

Outcome of Guided Endodontics and free-handed control group

In the experimental group (guided endodontics), the root canal was found in 59 out of 60 teeth (98%). In only 1 case (maxillary canine), the root canal was not found, and the patient was scheduled for endodontic microsurgery. No perforations were recorded. In the control group (free-handed treatment), the root canal was successfully found in 59 out of 73 teeth (81%). In 7 teeth, the root canal was not found, and 7 teeth had a perforation.

An analysis of all data, without matching, for the assessment of the outcome of guided endodontics in comparison to free-hand treatment, showed that guided endodontics presented statistically significant better outcome than free-hand treatment ($P < 0.05$; Table 4). The same result was obtained when assessing only matched pairs of teeth (n= 54) and excluding the unmatched data ($P < 0.05$; Table 4). The null hy-

pothesis stating that; H0: there is no difference in technical failures between guided endodontics and free-handed treatment, was therefore rejected.

Analysis of all data (Guided Endodontics n=60 vs Free-handed Control n=73)		
	Failure	**Canal found**
Free-handed control	14	59
Guided Endodontics	1	59
Comparison	**Difference***	**P-value**
Free-handed vs Guided	-2.64	0.014
Analysis of matched pairs only (n= 54)		
	Failure	**Canal found**
Free-handed control	12	42
Guided Endodontics	1	53
Comparison	**Difference***	**P-value**
Free-handed vs Guided	-2.72	0.0105

Table 4. Assessment of the outcome of guided endodontics in comparison to free-handed treatment. *Difference as calculated by the generalized linear model for binary data (all data) and generalized estimation equations analysis for binomial data (matched pairs).

Moreover, from all 60 teeth treated with guided endodontics, 49 presented an optimal precision with a center drill path. On 10 teeth (8 maxillary incisors and 2 lower premolars) an acceptable precision was obtained, and a correction was needed to find the canal. One technical failure was registered where the root canal was not found.

8.4 Discussion

The primary outcome of guided endodontic treatment was defined and registered after drilling as: canal found, canal not found, or perforation. After assessment of all data, and further matched pair analysis, guided endodontics presented a statistically significant better outcome than free-handed treatment ($P \leq 0.05$; Table 4). The null hypothesis was therefore rejected, and data favor the alternative hypothesis stating that guided endodontics presents less technical failures compared to free-handed treatment.

Guided endodontics has been introduced in the literature in 2016 as a technique to approach teeth presenting PCO and AP [14, 15]. Since then, several case reports and case series had shown its potential [22]. However, high-quality prospective clinical studies are needed to increase the evidence for guided endodontics [22, 24]. While randomized control trials are the gold standard, randomizing the treatments in the present study was not considered to be ethical as the current evidence show that the use of guides for endodontic treatment offers a highly predictable outcome, with a low risk of iatrogenic damage [22]. Non-randomized control trials, on the other hand, allow the comparison between a group receiving an intervention with an historical/external control group. Therefore, this study was designed as a Controlled Clinical Trial (CCT): prospective, nonrandomized, single center study, with an external control group selected from the database of the same center.

Although, the frequency of pulpal necrosis and AP in teeth presenting with PCO is reported to vary from 1 to 27% [4-6, 28-31], most of the studies suggest that pulpal necrosis and AP are not a common complication of teeth presenting with PCO. The presence of PCO alone should not be considered an indication for endodontic treatment [2]. Therefore, all patients included in the study had a thorough intraoral examination and were scheduled for root canal treatment only when presenting with symptoms and/or radiographic signs of AP. Three teeth were excluded from the study (Figure 1), one because the patient was unable to comply with the treatment; after initial examination, the patient did not attend to the scheduled appointment for treatment. Two teeth had an unfavorable prognosis and were scheduled for extraction.

A qualitative assessment of the accuracy of the drill path, adapted from Buchgreitz et. al. [27], was performed based on clinical data recorded during treatment. If the canal was located without correcting the trajectory of the access cavity after the use of the guide, an optimal precision was registered. If a manual correction was needed, an acceptable precision was registered. The present results showed a total of 49 teeth with an optimal precision, and 10 teeth with an acceptable precision (Figure 4). In only 1 case the root canal was not found. On the other hand, Buchgreitz et. al. [27] found that, in a total of 50 patients, 22 presented an optimal precision, and 28 an acceptable precision. However, the authors classified the teeth based exclusively on the appearance of the drill path on the final periapical radiograph and divided them in two groups: drill path centred (optimal precision), and drill path peripherally or tangentially transported (acceptable precision). Such method may underestimate tangential deviations on the bucco-lingual direction due to the 2-dimensional nature of the periapical radiograph. Nevertheless, from the 50 patients treated, no manual corrections to the direction of the drill path were mentioned, which correlates with the results from the present study (n = 49 optimal precision).

However, there were cases when after initial drilling to the planned depth, there was no trace of the canal visible under the dental microscope. When this was the case, an intra-operative periapical radiograph was taken for evaluation. Then, the operator could decide to drill deeper with the use of the guide or, in the case where a tangential deviation was visible on the radiograph, to manually correct the path with a long neck bur or ultrasonic tip in the search for the permeable portion of the root canal. All these corrections were small, as shown by data on the clinical accuracy of guided endodontics previously measured and reported by the authors [32]. Results show an average apical deviation of 0.45 mm (min 0 mm – max 1.2 mm). In either case, guided endodontics led to a predictable and efficient location of the obliterated canal, allowing for a conservative access, deep inside the root, with minimal substance loss as stated previously by Connert et. al. in an in vitro study [19].

Buchgreitz et. al. [27] found that in mandibular front teeth, where the length of pulp space obliteration was shorter than in maxillary teeth, optimal precision was most frequently achieved. However, in the present study, no difference was found between canal depths measured on CBCT from maxillary incisors (mean 12 mm) in comparison to mandibular incisors (mean 11.4 mm). Manual correction was more frequently needed in maxillary incisors (acceptable precision), and this may be explained due to the higher overall prevalence of maxillary incisors treated in the present study (65% vs 18%, Table 1). Nevertheless, deviations from the planned drilled path could be explained due to small errors during acquisition of the intraoral model, 3D printing of the guide, or inadequate fit of the guide in the mouth [33]. Additionally, the bur should be correctly positioned and introduced within the sleeve, no resistance should be experienced when introducing the bur inside of the sleeve. This can be controlled by performing a pecking motion with the bur inside of the sleeve before drilling.

One of the major advantages of guided endodontics in comparison to free-handed treatment is that it allows for a conservative access minimizing the risk of iatrogenic damage (perforation) to the root [22, 34, 35]. This was also observed in the present study, with no perforations recorded in the guided group in comparison to 7 perforations (9.6%) recorded in the control group. This is of utmost importance, as several long term studies on the outcome of nonsurgical root canal treatment have shown that the presence of root perforation can negatively impact the success rate of root canal treatment [36-39]. The message for clinicians is clearly that caution must be an important aspect during treatment, as such complications can lead to tooth extraction [36, 37, 39].

Although no perforations were recorded in the experimental group (guided endodontics), in 1 case the root canal was not found. The canal was visualized on the CBCT at a depth of 20 mm on a 23 mm long maxillary canine. Upon drilling with the aid of a 3D printed guide, no trace of the root canal could be visualized under the dental microscope. A control periapical radiograph revealed the deviation of the drill path from the original trajectory. Due to the cavity depth and high difficulty of the case, decision was taken to acquire an intra-operative limited field of view CBCT scan to visualize the position of the access cavity inside of the root on 3-dimensions. Upon assessment of the CBCT, the operator decided to stop the treatment as further drilling could lead to the perforation of the root. The patient was then scheduled for endodontic microsurgery and followed-up until healing (Figure 5). A similar approach was also reported by Fonseca Tavares et. al. [33] for the management of an unsuccessful case of technical failure (perforation) after guided endodontics was used. The authors state that endodontic microsurgery should be considered the treatment of choice when guided endodontics cannot be used safely or fails.

On the other hand, retrograde root canal treatment though endodontic microsurgery could be the initial treatment option on teeth presenting with apical periodontitis and PCO. On a prospective study [40], a total of 57 patients, presenting with limited orthograde access to the root canal, were endodontically treated from the root apex though endodontic microsurgery. After initial removal of the root apex, the canals were instrumented with files, irrigated with 0.5% sodium hypochlorite, and filled with an epoxy base sealer and thermo-plasticized gutta-percha. Retrograde root canal treatment was successful in 90% of cases after 2-year follow-up. This could be an alternative treatment option in cases presenting PCO, where accessing the canal apically could result in a less invasive approach, from a tooth perspective, considering the amount of coronal dentin that needs to be removed to reach the root canal and the possibility of a technical failure during orthograde treatment. Moreover, the use of modern filling materials, such as MTA, would improve healing due to its favorable tissue response and sealing properties over time.

One of the limitations of the current clinical trial is that there was no randomization of the patients. Instead, a control group was selected from the database from the same center. Although all root canal treatments from the control group were performed by an Endodontist specialist with the aid of a dental microscope and a CBCT prior to treatment, there was no control on how the treatments were performed and the outcome of the treatment can depend on the operator's experience. However, Connert et. al. [19] showed that an endodontist specialist had the highest scores when detecting canals with simulated PCO, compared to a general dentist and a dental student.

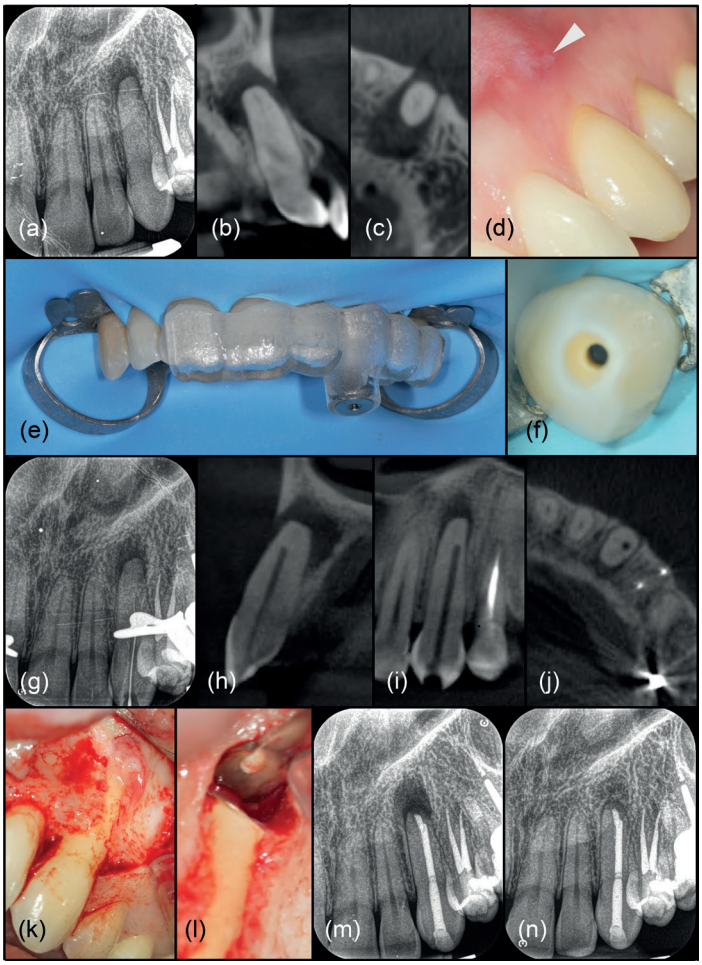

Figure 5. Failed case of a left maxillary canine. Case of a 38-year-old female presenting with pain complains on the right upper jaw. (a) A periapical radiograph revealed PCO and apical periodontitis on tooth 23. The tooth was diagnosed with symptomatic apical periodontitis. (b, c) A pre-operative CBCT revealed the presence of severe PCO up to the apical root third and apical periodontitis. The canal was visualized on the CBCT at a depth of 20 mm on a 23 mm long maxillary canine. (d) The tooth presented clinically a fistula on the buccal side (white arrow). (e) Placement of the 3D printed guide under full rubber dam isolation. (f) Upon drilling, no trace of the root canal could be visualized under the dental microscope. (g) A control periapical radiograph revealed the deviation of the drill path from the original trajectory. (h – j) An intra-operative limited field of view CBCT revealed a disto-buccal deviation of the access cavity. The operator decided to stop the treatment as further drilling could lead to root perforation. The patient was then scheduled for endodontic microsurgery. (k) Flap elevation and (l) root resection showing a retrograde MTA filling on the root canal. (m) Periapical radiograph after surgical treatment and (n) 1 year follow-up showing full periapical healing.

To account for nonrandomization and perform a strong analysis, a matched pair analysis was performed. However, it is not possible to always find a perfect match. In a first instance a search was carried out to find matching tooth numbers, but later the teeth were divided in tooth types to allow further matching. Additionally, value ranges from the canal depths or depth percentages were used to facilitate matching, though this introduces some variation within the teeth in each pair.

At the same time, to improve the quality of the evidence and remove additional variables, all guided endodontic treatments were performed by a single operator. Moreover, it has been shown in the literature that this technique is not dependent on the operator's experience [17, 19, 21].

The results from the current clinical trial are in line with similar studies [22, 34]. Many of the known benefits of guided endodontics were observed during treatment of the patients. Such benefits are: a reduce probability of iatrogenic damage together with a high accuracy (likelihood of finding the canal), a conservative access cavity up to the canal can be created allowing for a minimally invasive treatment while maintaining as much of the root's rigidity as possible [41], reduction of chair time, and it allows the preoperative visualization of the case and detailed planification without having to mentally transfer the planning to the clinical situation [13].

These advantages are hard to be overlooked when deciding the best treatment option for an otherwise highly complex case, where the risk of technical failure would be high by treating on a conventional manner and could precipitate the extraction of the tooth [8, 36-39]. However, although the use of a 3D printed guide can facilitate treatment, it is still a complex procedure which should be carried out by an experienced Endodontist with the aid of a dental microscope. It still presents limitations, as it has been shown here previously by a failed case of an upper canine and in a recently published case report [33].

In contrast to static guidance, other techniques, such as the use of dynamic navigation can also be of benefit for the treatment of PCO in the future [42-44]. However, this technique requires a high acquisition cost for the device and extensive training is needed prior to its clinical use [44]. An alternative can be the use of augmented reality. Yet, despite showing promising results for potential clinical use, it needs further development and research [45].

8.5 Conclusion

Guided endodontics showed a statistically significant better outcome than free-handed treatment. It resulted in less technical failures compared to conventional treatment. However, it is a complex procedure which should be carried out by an experienced endodontist with the aid of a dental microscope.

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General discussion and future perspectives

The general aim of this PhD project was to investigate on the clinical applications and accuracy of the various methods for Guided Endodontics (GE), and to provide an answer to the question: does guided endodontics treatment results in less technical failures compared to free-hand treatment?

We set up to accomplish this by dividing the PhD project in three Phases: Phase I comprises a systematic review of the literature, Phase II comprises in vitro studies on the accuracy of different techniques, and Phase III comprises a controlled clinical trial on guided endodontics.

Phase I – Systematic Review of the literature

The general aim of this first Phase of the PhD was to provide a summary of the literature on the topic of GE and Dynamic Navigation (DN). The secondary aim was to identify research gaps and challenges to structure a working plan for the PhD project.

The first chapter focused on GE, strictly using 3D printed guides, as an alternative for the treatment of PCO or endodontic microsurgery. The aim was to assess the literature regarding the clinical applications, accuracy, and limitations of guided endodontic treatment.

All articles described guided access cavity preparation and guided surgery as highly accurate techniques when comparing the real cavity to the virtual planning [1-5]. However, there was a lack of high-quality studies and the level of evidence of the literature found was low, given that most of the available studies corresponded to laboratory studies and case reports. Moreover, the risk of bias was high and the checklists on quality of the study in no case complied with all the parameters that were evaluated. Nevertheless, the average quality of the included case reports was acceptable to our judgement, scoring an average of 76% on the CARE checklist [6].

The accuracy of guided-access cavity preparation seems to be reliable as reported on laboratory studies with a mean apical deviation smaller than 0.5 mm and mean angular deviation up to 1.8□ [1, 3, 5]. This 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 [7].

One of the limitations of studies measuring accuracy is that the methods are heterogeneous. Some measurements were performed manually [1] which may lead to small errors on the calculations. Others used computer software to automatically calculate the deviation between planned and performed access cavity preparations but measured the deviation in 2D planes [3, 5]. For such small measurements, an automated 3D measurement protocol would be best to prevent bias within the results.

The use of a guide for guided access cavity preparation showed many benefits when compared to free-hand treatment; it has high accuracy, there is a reduction of mean substance loss of up to 5 times less for the guided access cavity in comparison to conventional access cavity, it is a technique that is not dependent on the experience of the operator [2, 3, 5], less chair time is required when using a guide [8], iatrogenic damage to the root can be reduced and a more reliable outcome can be obtained [2].

Likewise, when using a guide during Targeted Endodontic Microsurgery (TEMS) for the localization of the root apex a significantly better accuracy than free-hand treatment can be achieved [4, 9]. Additionally, the diameter of the osteotomy is reduced to a size slightly larger than the length of the resection [10]. This minimally invasive procedure reduces the risk of intra- and postoperative complications such as bleeding or damaging neighboring anatomical structures. It also shortens the healing time and improves prognosis [10, 11].

Within its disadvantages, the use of a guide is limited to the straight portion of the canal and cannot be used beyond the curvature [1, 12-14]. Additionally, there is a need for vertical space to place the guide and the bur on top of the tooth, which can limit its use on the posterior region [3, 13-15]. The thickness of the root should also be considered when planning an access cavity on teeth with small roots [12] as thinner drills may be necessary [3, 13]. Cooling is of great importance while using the guide. However, providing sufficient space to allow the passage of irrigating solutions to the tooth or alveolar bone may not always be possible as it may compromise the accuracy. The design and production of a guide requires time, however all authors agree that although it may seem to be time-consuming, chair-side operating times and excessive loss of tooth structure are reduced, and the risk of iatrogenic damage is avoided [2, 3, 5, 10, 11, 13, 15-17].

Concerning the strengths of the study, it was possible to describe the clinical applications of guided endodontics, outline the benefits and disadvantages, summarize a protocol for the design of a 3D guide, and report on the accuracy of the method. However, there was a need for an automated 3D measurement protocol, there was no clinical data available on its accuracy, and

high-quality clinical studies were needed to better understand the technique, its strengths and limitations, in order to offer the patient the best outcome.

In the second chapter we focused on the concept of DN, more specifically we aimed to systematically review the literature on the accuracy of non-surgical endodontic treatment completed freehanded and with Dynamic Navigation (DN).

Dynamic navigation was first implemented to increase accuracy in dental implant placement by providing the operator with a real-time navigation tool [18]. It uses CBCT data for virtual planning and real-time guidance of the bur during the procedure. This technique has gained interest in the field of Guided Endodontics as it has some advantages over static guides; the CBCT acquisition, planning and treatment can be performed in a single appointment, it can be used in cases of limited vertical space as a guide is not necessary, the planning is simplified as there is no need for a guide design, visibility and water-cooling are improved as there is no barrier between the water source and the bur, any bur can be used, and guidance failures due to poorly fitting guides do not occur [18-22].

The drawbacks are that; it requires a high initial investment in equipment and may present a substantial change to the existing clinical workflow, it requires an initial calibration process prior to treatment, and the operator must be properly trained prior to treatment.

All the studies reviewed reported increased accuracy and less volumetric loss of tooth structure when using DN. Furthermore, DN led to fewer iatrogenic errors. The most common procedural mishaps and errors were artifacts in the CBCT scan from restorations containing metal, planning errors, incorrect calibration, faulty transfer of the anatomic landmarks during registration, misfit of tracking components, inadequate systems check during the treatment and hand tremor from the operator [18, 23]. Thus, it is essential to check each step to avoid the accumulation of errors.

There is a long learning curve for the practitioner when working with DN because the technique requires a certain level of technical skill, hand-eye coordination, and manual dexterity [18, 20, 23]. However, there is no statistically significant difference in accuracy between operators after training [20].

In comparison to free-hand treatment, DN resulted in a minimally invasive access cavity [24], it required less time to locate the root canal [25], and no difference was seen before operators, with different experience levels, after proper training [20]. These findings suggest that DN could be a superior choice when dealing with clinically challenging cases [25]. Moreover, it can be beneficial for novice practitioners to combat high difficulty endodontic cases.

All studies included in this systematic review were laboratory studies using either extracted or 3D printed teeth. Just a few case reports were found in the literature using DN for access cavity preparation and endodontic microsurgery [26-29]. Therefore, high quality clinical studies are necessary to assess the accuracy of DN for endodontic treatment.

One of the strengths of this systematic review was the robust inclusion criteria, which focused on the topic and decreased the possibility of bias arising from study selection. Another advantage was the overall low risk of bias of the included studies. On the other hand, the small number of included studies can be a potential limitation, also the variability of the study designs and the outcomes measured hindered comparison. Although a meta-analysis was not attempted due to these limitations, this systematic review can provide some directions for the near future to standardize outcome measures.

Within the limitations of both systematic reviews, guided endodontics and DN are promising techniques offering a highly predictable outcome and lower risk of iatrogenic damage, in comparison to free-hand treatment, for the treatment of high difficulty cases. Each method presents its own advantages and limitations, however both methods can achieve a minimally invasive treatment with reduced chair-side time. Nevertheless, this should be interpreted with care since it is based on limited and low-quality evidence from laboratory studies and case reports. Standardize experimental studies with similar sample size, aim, and a standardize measuring protocol are needed together with high quality clinical studies.

Phase II – Accuracy assessment of different techniques for Guided Endodontics

The general aim of this phase was to fill some of the gaps on GE. We aimed to (1) develop a measuring protocol to measure the accuracy of guided endodontics in-vivo and to (2) assess the accuracy and present data of different techniques for GE and TEMS.

During this phase a semiautomated protocol was developed for the analysis of the results using 3-Matic Medical Software (Materialise, Leuven, Belgium). First the post-operative CBCT was registered to the pre-operative CBCT using a global registration parameter. A semiautomated process was used in which a line was automatically fitted by the software in the center of the cavity. Then, two points were placed by the software, through the central axis line, on the coronal and apical aspect of the cavity to perform all measurements. The distance deviation of all cavities was then assessed in comparison to the planning on 5 different parameters [30]. With such small measurements (fractions of a millimeter), it was important to develop an automated mea-

surement protocol to prevent errors on the results. Such protocol allowed for true 3D measurements instead of a 2D approximation (Zehnder et al. (2016) and Connert et al. (2017)) as discussed previously in chapter 1.

The first chapter of this second phase (Chapter 3) aimed (1) to validate a method using a post-operative intraoral scan (IOS) to measure the accuracy of guided endodontics ex vivo, and (2) to present clinical data on the accuracy of guided endodontics.

We know from previous studies (as discussed on Chapter 1) that guided endodontics presents a high accuracy when comparing the actual path of the access cavity to the virtually planned trajectory through the superimposition of pre-operative and post-operative CBCT data [1, 3, 5, 31, 32]. However, data from laboratory studies might not replicate all clinical variables and such results must be interpreted with caution when extrapolating to a clinical situation.

A validation of a novel measuring method ex vivo was carried out first using four models, including 10 extracted teeth each. Forty guided access cavities were planned and drilled on dentin to simulate PCO. A post-operative CBCT (gold standard) and IOS were acquired. The deviation coronally, apically, and angular deviation was measured with CBCT and IOS.

We found no statistical difference between measuring methods for all parameters ($P > 0.05$). Therefore, the null hypothesis was accepted stating that mean accuracy measurements between IOS and CBCT do not differ. Additionally, no statistical difference was found between operators ($P > 0.05$), which confirms once more the reliability of the use of a guide for treatment regardless of the operator's experience [2, 5].

After successful validation of the proposed method ex vivo, a total of 33 patients treated with the aid of a guide were assessed with the IOS measuring protocol. All canals were found with the aid of a guide. Access cavities had an average depth of 12.5 mm with a mean apical deviation of 0.45 mm and mean angular deviation of 1,9□. The acquisition of an IOS with the bur inside of the access cavity, allowed for an accuracy assessment without the need for a post-operative CBCT and additional radiation for the patient. A pre-operative IOS is available from the planning, and the acquisition of the post-operative IOS can be made in a short amount of time, during treatment, without moving the patient from the dental chair. Additionally, the registration process between IOS's is faster than for CBCT volumes and requires less processing power.

This study demonstrated that an IOS can be used to measure the accuracy of guided endodontics. It is as effective as the CBCT, and it does not involve additional exposure to radiation for the patient. Furthermore, clinical data showed high accuracy of GE with a mean apical deviation smaller than 0.5 mm and a mean angular deviation of less than 2□. Based on this clinical data, we could conclude that a safety margin of at least 1 mm around the planned trajectory should be respected when planning the case to minimize the possibility of root perforation.

On Chapters 4, 5 and 6 we aimed to assess the accuracy of a "sleeveless guide", Dynamic Navigation (DN), and Augmented Reality (AR), respectively, for guided root canal treatment.

When using a sleeveless guide (Chapter 4), an average apical deviation of 0.7 mm was obtained. The average angular deviation was 1.5□. In cavities with a mean depth of 15.3 mm. These results are somewhat comparable to the clinical measurements obtained from Chapter 3 when using conventional guides (mean apical deviation of 0.45 mm, mean angular deviation of 1,9□, in cavities of 12.5 mm depth). The apical deviation obtained clinically with conventional guides was lower than sleeveless guides, but the cavities were shorter, which could explain the smaller deviations. However, the angular deviation from the sleeveless guides was lower, yet this was an in vitro study. Nevertheless, the results obtained, demonstrate that sleeveless guides offer a valuable alternative to conventional endodontic guides with similar accuracy results.

On the other hand, with the use of DN (Chapter 5), three operators with different levels of experience in endodontics were able to localize 93% of the canals (156 of 168 canals). This was higher than the results from Chong et al. with a success rate of 89% (41 of 46 canals) [22]. The mean deviation at the apical point was 0.6 mm, with a mean angular deviation of 2.8°, and a mean depth of the cavities of 14.5 mm. When comparing our results to the ones from Jain et al. [33], a lower mean apical deviation of 0.6 mm (vs 0.9 mm) was obtained.

When comparing DN to the use of a 3D printed guide (Chapter 3 and 4), although it presents a comparable low mean apical deviation of 0.6 mm, a slightly higher angular deviation of 1° higher was obtained. Additionally, the values were different when comparing anterior teeth, premolars, and molars. A significant difference was found between anterior teeth and molars (0.57 mm vs 0.8 mm, $P < 0.05$), probably due to their position in the mouth which allows, in the case of anterior teeth, for a greater vertical space and better maneuverability while drilling. This can be explained since DN allows the bur to move "without restrictions" in contrast to the movement of a bur or handpiece through a 3D printed template. This can lead to technical failures if not trained properly.

Another interesting technology is the use of AR (Chapter 6), which is a recent trend in digital dentistry, especially in the field of maxillofacial surgery [34], but its application also presents itself in a rapidly increasing number of new fields like prosthetics [35] and aesthetic treatment [36]. Since it is still in development, our goal was to reach the pulp chamber. To achieve that, a minimum depth of 4 mm was defined [37]. On average, an apical deviation of 0.8 mm, with an angular deviation of 8.5° was observed.

The results were somewhat high when compared to other guiding techniques evaluated in previous chapters. This could be due to the fixed position of the device's screen, which makes it difficult to control the angulation from different perspectives. However, when assessing the surface area of the cavities drilled, the molars presented significantly higher overlap with the virtual plan compared to the anterior teeth and premolars. These findings could suggest a promising application of AR as a strategy for conservative endodontic access cavity in molars. Yet, further research is needed to validate the safety of the proposed system before its clinical application.

Three different methods for guided endodontic treatment have been assessed and discussed, either using guides, which could be conventional (Chapter 3) or sleeveless (Chapter 4), the use of DN (Chapter 5) or AR (Chapter 6). The results show that 3D printed templates and DN navigation can achieve similar outcomes, and AR needs further research and development.

When using a guide, despite of the design (Chapter 3 and 4), no statistically significant difference between operators was found. This confirms that the use of a guide is not influenced by the operator's experience [2, 5]. Moreover, a sleeveless guide design presents some advantages over a conventional guide; with (1) better visibility of the tooth, (2) direct control of the optimal fit of the guide in the mouth, (3) water cooling during treatment, and (4) less vertical space is needed, allowing for guided treatment on posterior teeth or in cases when there is limited mouth opening [38-40]. One drawback is that it needs multiple anchor points to ensure its stability [40]. Additionally, special attention should be paid when starting the treatment. The correct fitting of the guide must be inspected together with a fluent movement of the handpiece when placed inside the guiding rails. A couple of pumping movements can be practiced with the handpiece in place before the operator starts drilling to determine the correct axis without applying pressure in a direction that can compromise the bur's trajectory.

On the other hand, with the use of DN for guided endodontic treatment, (1) the CBCT acquisition, planning and treatment can be performed in a single appointment, (2) it can be used in cases of limited vertical space as a guide is not necessary, (3)

the planning is simplified as there is no need for a guide design, (4) visibility and water-cooling are improved as there is no barrier between the water source and the bur, (5) any bur can be used as there is no special coupling system, and (6) guidance technical failures due to poorly fitting guides do not occur [19].

However, DN is a system that requires rigorous training as it requires a certain level of technical skill, hand-eye coordination, and manual dexterity that must be maintained throughout the whole procedure while looking at a computer screen [22, 33]. Additionally, a high initial investment in equipment is needed, and it may present a substantial change to the existing clinical workflow.

Thus, the choice of a type of guide or technique remains a decision from the clinician, considering the advantages and disadvantages of each method, together with his own experience and expertise.

In some cases when periapical pathologies cannot be solved with conventional root canal treatment, endodontic microsurgery (EMS) can provide a valuable treatment option [41]. Furthermore, 3D printed surgical guides, for targeted endodontic microsurgery (TEMS), can be used to obtain a more accurate osteotomy and better correlation between operators [4]. Therefore, the aim of the final chapter of phase II (Chapter 7) was to assess the accuracy of TEMS in comparison to EMS. This approach aimed to compare the drilled cavity to the planning with respect to nine parameters (deviation at entry point, end point, total deviation, depth, angle, root bevel, root resection, osteotomy volume and surgical time.

Upper molar teeth are usually more complex to treat due to its more posterior position and could be a place where the use of TEMS could improve reliability [42]. In our study, maxillary molars also showed the greatest difference between techniques. EMS showed a higher deviation at entry, total deviation and bevel, and less root resection. Also, a significant longer surgical time was needed when compared to upper anterior teeth.

When using a guide, as confirmed in previous chapters, the results are more predictable and have less variability between and within operators [2, 4]. In our study more accurate and standardized osteotomies were observed with the use of TEMS, in comparison to EMS. These findings suggest that TEMS could reduce the experience gap between professionals. Furthermore, the use of a guide would allow a reliable access to a target point, giving an advantage in difficult to reach places such as the palatal root of upper molars, a deep located root apex, or when the integrity of neighbor structures can be compromised [4, 11].

When comparing accuracy between procedures, a mean total deviation of the cavity of 1,19mm (±0.55 SD) was found in the TEMS group in comparison to 1,35mm (±0.82 SD) in the EMS group. This difference is lower than the one described by Ackerman et al. [9], possibly due to the different study design and measuring technique. However, the present study shows a higher contrast between techniques for the mean deviation at the entry point (TEMS: 0,67mm (±0,31 SD) vs EMS: 1,78mm (±0,72 SD)).

Another benefit is a decrease in surgical time [42]. We observed a mean total time of 38s (±27 SD) for TEMS compared to 175s (±112 SD) for EMS. Although the definition of surgical time was different, Hawkins et. al. also showed a significant reduced time when using TEMS from an average of 859s (EMS) to 254s (TEMS).

One of the limitations of the study was that it is an in vitro study, and although the 3D model was made based on a real patient, the material colors and consistency are different than that of a real situation. We did not included replicas of periapical lesions as by T.K. Hawkins, 2020 et. al. [42]. Neither gingival tissue was mimicked and there was no bleeding. Additionally, anatomical landmarks and neighbor structures were not replicated or considered in the planning. However, even though in-vivo conditions may be hard to replicate, it may give a greater advantage to EMS but not to TEMS, as with TEMS a guide is used and as long it is properly placed, deviation from the planning under clinical conditions is minimized [42]. Additionally, mounting 3D models into a phantom head allows for excellent standardization.

Therefore, within its limitations, this study demonstrated that TEMS, in comparison to free-handed EMS, results in: less deviations, a root bevel closer to zero, more predictable root resection and shorter surgical time, however slightly deeper osteotomies are obtained with greater volumes, the latter being dependent on the size of trephine bur used. Additionally, a more predictable result may be achieved, minimizing potential errors which can be beneficial in anatomically challenging places.

Phase III – Controlled Clinical Trial on Guided Endodontics

One of the knowledge gaps in GE literature was, as seen on Phase I, the lack of high-quality, prospective clinical studies. Therefore, during the last Phase of this PhD project (Chapter 8), the focus was to set up a Controlled Clinical Trial for GE. We aimed to assess the clinical outcome of guided endodontics for the treatment of teeth presenting with PCO in comparison to free-hand treatment.

After assessment of all data, and further matched pair analysis, guided endodontics presented a statistically significant better outcome than free-handed treatment ($P \leq 0.05$; Table 4). The null hypothesis was therefore rejected, and data favor the

alternative hypothesis stating that guided endodontics presents less technical failures compared to free-handed treatment.

Randomized control trials are the gold standard, however, we did not considered to be ethical to randomize the treatments in our study, as the current evidence show that the use of guides for endodontic treatment offers a highly predictable outcome, with a low risk of iatrogenic damage (also demonstrated in Phases I and II) [43]. Non-randomized control trials, on the other hand, allow the comparison between a group receiving an intervention with an historical/external control group. Therefore, this study was designed as a Controlled Clinical Trial (CCT): prospective, nonrandomized, single center study, with an external control group selected from the database of the same center.

Additionally, a qualitative assessment of the accuracy of the drill path, adapted from Buchgreitz et. al. [7], was performed based on clinical data recorded during treatment. If the canal was located without correcting the trajectory of the access cavity after the use of the guide, an optimal precision was registered. If a manual correction was needed, an acceptable precision was registered. The present results showed a total of 49 teeth with an optimal precision, and 10 teeth with an acceptable precision. In only 1 case the root canal was not found. Buchgreitz et. al. [7] found that, in a total of 50 patients, 22 presented an optimal precision, and 28 an acceptable precision. However, the authors classified the teeth based exclusively on the appearance of the drill path on the final periapical radiograph. Such method may underestimate tangential deviations on the bucco-lingual direction due to the 2-dimensional nature of the periapical radiograph. Nevertheless, from the 50 patients treated, no manual corrections to the direction of the drill path were mentioned, which correlates with the results from the present study (n = 49 optimal precision).

When there were cases when after initial drilling to the planned depth there was no trace of the canal visible under the dental microscope, an intra-operative periapical radiograph was taken for evaluation. The operator could then decide to drill deeper with the use of the guide or, in the case where a tangential deviation was visible on the radiograph, to manually correct the path with a long neck bur or ultrasonic tip in the search for the permeable portion of the root canal. All these corrections were small, as shown by data on the clinical accuracy of guided endodontics previously measured and reported on Chapter 3. Deviations from the planned drilled path could be explained due to small errors during acquisition of the intraoral model, 3D printing of the guide, or inadequate fit of the guide in the mouth [44]. In either case, guided endodontics led to a predictable and efficient location of the obliterated canal, allowing for a conservative access, deep inside the root, with minimal substance loss as stated previously by Connert et. al. in an in vitro study [2].

One of the mayor advantages of guided endodontics in comparison to free-handed treatment is that not only it allows for a conservative access, but also it minimizes the risk of iatrogenic damage (perforation) to the root [43, 45, 46]. This was observed in our study. No root perforations were recorded in the guided group in comparison to 7 perforations (9.6%) recorded in the control group. This is of utmost importance, as several long-term studies on the outcome of nonsurgical root canal treatment have shown that the presence of root perforation can negatively impact the success rate of root canal treatment [47-50]. The message for clinicians is clearly that caution must be an important aspect during treatment, as such complications can lead to tooth extraction [47, 48, 50].

One of the limitations of the current clinical trial is that there was no possible randomization of the patients. Instead, an external control group was selected, and although all root canal treatments were performed by an Endodontist specialist (with the aid of a dental microscope and a CBCT), there was no control on how the treatments were performed, as the outcome of the treatment can depend on the operator's experience. On the other hand, Connert et. al. [2] showed that an endodontist specialist had the highest scores when detecting canals with simulated PCO, compared to a general dentist and a dental student.

To account for this nonrandomization and still be able to perform a strong statistical analysis, a matched pair analysis was performed. However, it is not possible to always find a perfect match, and value ranges from the canal depths or depth percentages were used to facilitate matching. This could introduce some variation within in each pair.

At the same time, to improve the quality of the evidence and remove additional variables, all guided endodontic treatments were performed by a single operator. Moreover, it has been shown in the literature and throughout Phase II of this PhD project, that this technique is not dependent on the operator's experience [2, 5, 51]. With the results of this CCT on GE, we could provide with concluding evidence that GE shows a statistically significant better outcome than free-handed treatment. It resulted in less technical failures compared to conventional treatment. However, we would like to emphasize, that GE is a procedure used to facilitate the treatment of already highly complex cases, therefore it should be carried out by an experienced endodontist with the aid of a dental microscope.

Future Perspectives

In the previous chapters, we have shown that with the help of GE or DN complex clinical cases, which were otherwise doomed for failure or extraction, can be successfully treated.

The use of 3D printed guides facilitate treatment and reduce the likelihood of iatrogenic damage. Not only that, but it can also reduce the experience gap between operators. This technique is already relatively mature [21], however there is not a wide range of drills commercially available which can limit the use of the technique in some cases. There are alternatives available like the use of a sleeveless guide, as shown in chapter 4, where guidance is performed on the hand piece allowing for a free choice of burs depending on the case. However, sets of burs variating in length and diameter would be desirable in the future to make a more patient-oriented approach [21].

On the other hand, one of the current limiting factors of DN is that it requires a high initial investment in equipment, also, the devices can be big and may present a substantial change to the existing clinical workflow. However, this technology is rapidly evolving and companies like DENACAM are developing miniaturized versions like the MiniNavident (DENACAM, Liestal, Switzerland) which allows greater flexibility and enhanced patient and operator comfort [24]. In the future a reduction in size and price would not only improve the handling of the devices but its implementation in more dental practices.

It would be ideal if DN systems could orient itself using the existing anatomical structures instead of markers. That is where AR can be an interesting step towards simplification and improvement of the operator's experience. Moreover, the integration of AR to overlay images such as planning trajectories, or anatomy from CBCT scans into wearable head-up displays or dental microscopes can be a desirable step forward in endodontics. It would then allow for a dynamic visualization of the operative field instead of the use of a fixed screen, as presented in chapter 6, which can improve its accuracy.

It is undeniable that the continuous improvement in 3D imaging, 3D printing technologies and virtual planning are promoting an era of digitalization in dentistry. This ultimately results in an optimized treatment outcome and improvement of patient's comfort. Additionally, the use of 3D printing provides potential benefits for

education. As knowledge moves forward, endodontic postgraduate programs should consider implementing 3D printing and digitalization as part of their curriculum [52].

On the other hand, as the uses for 3D printing are increasing, so does the global plastics pollution. This technology is also the origin of residues, in the form of nanoparticles, from the cleaning procedure at the end of each printing. These nanoparticles are usually not correctly disposed, and thus could be released to the environment and become a public health risk [53]. There is a need for more research in order to help develop sustainable, environment-friendly 3D printing materials and technologies [54].

Artificial intelligence (AI) has also made its way into digital dentistry. As CBCT images are commonly acquired to assist in diagnosis, treatment planning, and surgical treatment, large databases are available for training AI models [55]. In endodontics, AI can be used for detection and segmentation of periapical lesions [56, 57], detection of vertical root fractures [58] and tooth segmentation [37]. Other purposes like segmentation of the mandibular nerve canal [59], maxillary sinus segmentation [60], and segmentation of the maxillofacial complex [61], can also be useful for non-surgical and surgical planning. It seems then possible that in the future the use of AI would allow for pulp canal segmentation. Furthermore, its application could potentially streamline and expedite the planning workflow for GE reducing the clinician's workload.

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Summary

The general aim of this PhD project was to investigate on the clinical applications and accuracy of the various methods for Guided Endodontics (GE), and to provide an answer to the question: does GE treatment results in less failures compared to free-hand treatment?

We set up to accomplish this by dividing the PhD project in three Phases: **Phase I** comprises a systematic review of the literature, **Phase II** comprises in vitro studies on the accuracy of different techniques, and **Phase III** comprises a controlled clinical trial on guided endodontics.

Phase I was further divided into two different chapters, each one comprising a systematic review, one on GE and the second one on Dynamic Navigation (DN). The aim of **Chapter 1** was to evaluate by means of a systematic review the clinical applications, accuracy, and limitations of guided endodontic treatment. 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. Even though the level of evidence was low, and the methodology described among studies heterogeneous, all articles described guided access cavity preparation and guided surgery as being highly accurate and successful techniques when comparing the drilled path to the planned treatment. However, there was a need for more studies with a larger number of patients to obtain significant conclusions.

Chapter 2 was set up to review systematically existing data on the accuracy of non-surgical endodontic treatment procedures that were completed using DN. We selected only studies comparing the accuracy of non-surgical endodontic treatment using DN with conventional freehanded access. After the selection process six studies were included. The risk of bias was rated from low to raising some concerns. Overall, DN showed increased accuracy compared to freehanded access and could be especially helpful in treating highly difficult endodontic cases. However, clinical studies are needed to confirm the published in vitro studies.

After systematically reviewing the literature and evaluating the gaps in the literature, **Phase II** was design to further test the accuracy of different guidance techniques in vitro.

In **Chapter 3** we aimed first to validate the use of a post-operative intraoral scan (IOS) versus CBCT on its ability to measure the accuracy of guided endodontics,

and second to present clinical data on the accuracy of guided endodontics. In vitro validation showed that an IOS can be used to measure the accuracy of GE without involving additional exposure to radiation. Using this method, clinical accuracy measurements were performed on thirty-three patients, showing high accuracy of GE with a mean apical deviation smaller than 0.5 mm and a mean angular deviation of less than 2°.

During **Chapter 4** we focused on a novel guide design, the sleeveless guide. Since no data on its accuracy was available, we aimed to assess its accuracy for guided root canal treatment of severe PCO in 3D printed jaws. Additionally, the treatment of a complex lateral incisor was presented to illustrate the use of this guide in a clinical situation. This study demonstrated, within its limitations, that a sleeveless guide is also an accurate method for GE treatment (mean apical deviation of 0.7 mm and mean angular deviation of 1.5°), offering a valuable alternative to conventional endodontic guides with similar accuracy results. Additionally, no statistically significant difference between operators was found when using the guide.

Chapter 5 aimed to evaluate the accuracy and outcome of DN for guided root canal treatment of severe PCO in 3D printed jaws. After training with the system, three operators with different levels of experience performed a total of 168 access (56 per operator) obtaining an overall success of 93% without difference between operator experience ($p > 0.05$). Dynamic navigation showed to be an accurate approach for root canal treatment in teeth with severely calcified canals (mean apical deviation 0.6 mm and mean angular deviation 2.8°). However, the technique has a learning curve and requires extensive training prior to its use clinically.

In **Chapter 6** we set up to evaluate the accuracy of a novel AR method for guided access cavity preparation in 3D-printed jaws. We defined a standard depth, needed to reach the pulp chamber, of 4 mm inside the tooth. The mean apical deviation was 0.8 mm and a mean angular deviation of 8.5°. The use of AR as a digital guide for endodontic access cavity drilling showed promising results and might have potential for clinical use. However, further development and research might be needed before in-vivo validation.

During the final chapter of Phase II (**Chapter 7**) we focused on the use of guides for surgical endodontic treatment or TEMS. The aim of this study was to assess the accuracy of TEMS in comparison to free-handed EMS. When comparing EMS vs TEMS to the virtual planning, results show a mean total angle deviation of 17° vs 5°, a mean total deviation of 1.4 mm vs 1.2 mm, a mean bevel of 12° vs 3°, a mean root resection of 2,7 mm vs 4 mm and mean total time of 175 s vs 38 s. In conclusion TEMS showed overall less deviations, a root bevel closer to zero, more predictable

root resection and shorter surgical time. However, slightly deeper osteotomies were obtained with greater volumes, the latter being dependent on the size of trephine bur used. The use of a guide can minimize potential errors due to free hand drilling which can be beneficial in anatomically challenging places or with less experienced operators.

In the last phase of the PhD project (**Phase III**, **Chapter 8**) a controlled clinical trial on guided endodontics was performed. The aim of this trial was to assess the clinical outcome of GE for the treatment of teeth presenting with PCO in comparison to free-hand treatment. An external control group was selected from clinical records of patients presenting the same criteria but treated free-handed. The primary outcome for the guided group was: 59 teeth canal found, and 1 tooth canal not found. No perforations were recorded. In the free-handed group, the root canal was successfully found in 59 teeth, in 7 was not found, and 7 had a perforation. Guided endodontics showed a statistically significant better outcome than free-handed treatment resulting in less failures ($P < 0.05$). However, it is a complex procedure which should be carried out by an experienced endodontist with the aid of a dental microscope.

Based on the abovementioned findings, the following general conclusions can be drawn:

1. An IOS can be used to measure the clinical accuracy of GE without involving additional exposure to radiation to the patient.
2. GE shows a statistically significant better outcome than free-handed treatment resulting in less failures, for the treatment of teeth presenting PCO.
3. Other guidance methods, like the use of a sleeveless guide or DN offer a valuable alternative to conventional endodontic guides with similar accuracy results.
4. TEMS showed overall less deviations, a root bevel closer to zero, more predictable root resection and shorter surgical time. It can minimize potential errors due to free hand drilling in anatomically challenging places or with less experienced operators.
5. The use of AR shows promising results for GE. However, further development and research is needed before its clinical use.

Samenvatting

Het algemene doel van dit PhD-project was het onderzoeken van de klinische toepassingen en nauwkeurigheid van de verschillende methoden voor Guided Endodontics (GE), en een antwoord te geven op de vraag: leidt behandeling met behulp van GE tot minder faling in vergelijking met behandeling uit de vrije hand?

Dit wilden we bereiken door het doctoraatsproject in drie fasen op te delen: **Fase I** omvat een systematisch overzicht van de literatuur, **Fase II** omvat in vitro studies naar de nauwkeurigheid van verschillende technieken, en **Fase III** omvat een gecontroleerde klinische studie naar GE.

Fase I was verder verdeeld in twee verschillende hoofdstukken, elk bestaande uit een systematische review, één over GE en één over Dynamic Navigation (DN). Het doel van **hoofdstuk 1** was om door middel van een systematische review de klinische toepassingen, nauwkeurigheid en beperkingen van GE te evalueren. In totaal werden 22 artikels opgenomen, waaronder vijftien case reports, zes preklinische studies (in vitro en ex vivo studies) en één observationele studie. Hoewel het niveau van bewijs laag was, en de beschreven methodologie in de studies heterogeen, beschreven alle artikels geleide caviteitspreparatie en geleide chirurgie als zeer nauwkeurige en succesvolle technieken bij het vergelijken van de geboorde caviteit met de geplande behandeling. Er was echter behoefte aan meer studies met een groter aantal patiënten om significante conclusies te kunnen trekken.

Hoofdstuk 2 werd opgezet om de bestaande gegevens over de nauwkeurigheid van niet-chirurgische endodontische behandelingsprocedures die met behulp van DN werden uitgevoerd, systematisch te beoordelen. Wij selecteerden alleen studies waarin de nauwkeurigheid van niet-chirurgische endodontische behandeling met behulp van DN werd vergeleken met conventionele toegang preparatie uit de vrije hand. Na het selectieproces werden zes studies geïncludeerd. Het risico van bias werd beoordeeld van laag tot enigszins zorgwekkend. In het algemeen bleek DN een grotere nauwkeurigheid te bieden dan vrije hand toegang en zou het vooral nuttig kunnen zijn bij de behandeling van zeer moeilijke endodontische gevallen. Er zijn echter klinische studies nodig om de gepubliceerde in vitro studies te bevestigen.

Na een systematisch onderzoek van de literatuur en een evaluatie van de lacunes in de literatuur werd **fase II** opgezet om de nauwkeurigheid van verschillende geleidingstechnieken in vitro verder te testen.

In **hoofdstuk 3** wilden wij ten eerste het gebruik van een postoperatieve intraorale scan (IOS) versus CBCT valideren op zijn vermogen om de nauwkeurigheid van geleide endodontie te meten, en ten tweede klinische gegevens presenteren over de nauwkeurigheid van geleide endodontie. In vitro validatie toonde aan dat een IOS kan worden gebruikt om de nauwkeurigheid van GE te meten zonder extra blootstelling aan straling. Met deze methode werden klinische nauwkeurigheidsmetingen uitgevoerd bij 33 patiënten, waarbij een hoge nauwkeurigheid van GE werd aangetoond met een gemiddelde apicale afwijking kleiner dan 0,5 mm en een gemiddelde hoekafwijking van minder dan 2°.

In **hoofdstuk 4** hebben we ons gericht op een nieuw ontwerp voor de guide, zonder sleeve/sleeveless guide. Omdat er geen gegevens beschikbaar waren over de nauwkeurigheid ervan, wilden we de nauwkeurigheid ervan beoordelen voor geleide wortelkanaalbehandeling van ernstige PCO in 3D-geprinte kaken. Daarnaast werd de behandeling van een complexe laterale snijtand gepresenteerd om het gebruik van deze geleider in een klinische situatie te illustreren. Deze studie toonde, binnen haar beperkingen, aan dat een sleeveles guide ook een nauwkeurige methode is voor GE-behandeling (gemiddelde apicale afwijking van 0,7 mm en gemiddelde hoekafwijking van 1,5°), en een waardevol alternatief biedt voor conventionele endodontische geleiders met vergelijkbare nauwkeurigheidsresultaten. Bovendien werd geen statistisch significant verschil gevonden tussen operatoren bij het gebruik van het sjabloon.

Hoofdstuk 5 had tot doel de nauwkeurigheid en het resultaat van DN voor geleide wortelkanaalbehandeling van ernstige PCO in 3D-geprinte kaken te evalueren. Na training met het systeem voerden drie operators met verschillende ervaringsniveaus in totaal 168 ingrepen uit (56 per operator), waarbij een algemeen succes van 93% werd behaald zonder verschil in ervaring tussen de operators ($P > 0,05$). Dynamische navigatie bleek een nauwkeurige benadering te zijn voor wortelkanaalbehandeling in tanden met ernstig verkalkte kanalen (gemiddelde apicale afwijking 0,6 mm en gemiddelde hoekafwijking 2,8°). De techniek heeft echter een leercurve en vereist uitgebreide training voordat deze klinisch kan worden toegepast.

In hoofdstuk 6 evalueren we de nauwkeurigheid van een nieuwe AR-methode voor geleide toegang tot caviteiten in 3D-geprinte kaken. We bepaalden een standaarddiepte, nodig om de pulpakamer te bereiken, van 4 mm in de tand. De gemiddelde apicale afwijking was 0,8 mm en een gemiddelde hoekafwijking van 8,5°. Het gebruik van AR als een digitale gids voor endodontische toegangsholteboren toonde veelbelovende resultaten en zou potentieel kunnen hebben voor klinisch gebruik. Verdere ontwikkeling en onderzoek zijn echter nodig voor in-vivo validatie.

In het laatste hoofdstuk van fase II (**hoofdstuk 7**) richtten wij ons op het gebruik van geleiders voor chirurgische endodontische behandeling of TEMS. Het doel van deze studie was de nauwkeurigheid van TEMS te beoordelen in vergelijking met EMS uit de vrije hand. Bij vergelijking van EMS vs TEMS met de virtuele planning laten de resultaten een gemiddelde totale hoekafwijking zien van 17° vs 5° , een gemiddelde totale afwijking van 1,4 mm vs 1,2 mm, een gemiddelde afschuining van 12° vs 3°, een gemiddelde wortelresectie van 2,7 mm vs 4 mm en een gemiddelde totale tijd van 175 s vs 38 s. Concluderend bleek TEMS over het geheel genomen minder afwijkingen te vertonen, een bevel van de resectie dichter bij nul, een meer voorspelbare wortelresectie en een kortere operatietijd. Er werden echter iets diepere osteotomieën verkregen met grotere volumes, dit laatste afhankelijk van de grootte van de gebruikte trepaanboor. Het gebruik van een guide kan potentiële fouten als gevolg van boren uit de vrije hand tot een minimum beperken, wat gunstig kan zijn op anatomisch moeilijke plaatsen of bij minder ervaren operatoren.

In de laatste fase van het PhD-project (**Fase III**, **Hoofdstuk 8**) werd een gecontroleerd klinisch onderzoek naar geleide endodontie uitgevoerd. Het doel van dit onderzoek was het beoordelen van het klinische resultaat van GE voor de behandeling van tanden met PCO in vergelijking met behandeling uit de vrije hand. Een externe controlegroep werd geselecteerd uit klinische dossiers van patiënten met dezelfde criteria, maar behandeld met de vrije hand. Het primaire resultaat voor de geleide groep was: 59 wortelkanalen gevonden, en 1 wortelkanaal niet gevonden. Er werden geen perforaties geregistreerd. In de free-handed groep werd het wortelkanaal succesvol gevonden in 59 tanden, in 7 werd het niet gevonden, en 7 hadden een perforatie. Geleide endodontie liet een statistisch significant beter resultaat zien dan behandeling met vrije hand, met minder faling ($P < 0,05$). Het is echter een complexe procedure die moet worden uitgevoerd door een ervaren endodontoloog met behulp van een tandheelkundige microscoop.

Op basis van bovenstaande bevindingen kunnen de volgende algemene conclusies worden getrokken:

1. Een IOS kan worden gebruikt om de klinische nauwkeurigheid van GE te meten zonder extra blootstelling van de patiënt aan straling.
2. GE toont een statistisch significant beter resultaat dan de behandeling met de vrije hand, wat resulteert in minder faling voor de behandeling van tanden met PCO.
3. Andere geleidingsmethoden, zoals het gebruik van een sleeveless guide of DN, bieden een waardevol alternatief voor conventionele endodontische guides met vergelijkbare nauwkeurigheidsresultaten.

4. TEMS vertoonde in het algemeen minder afwijkingen, een wortelafschuining dichter bij nul, meer voorspelbare wortelresectie en een kortere operatietijd. Het kan potentiële fouten als gevolg van boren uit de vrije hand op anatomisch moeilijke plaatsen of met minder ervaren operatoren tot een minimum beperken.
5. Het gebruik van AR toont veelbelovende resultaten voor GE. Er is echter verdere ontwikkeling en onderzoek nodig voordat het klinisch kan worden gebruikt.

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This PhD thesis is written by the PhD student Andrés Torres and properly revised by the promotor Prof. Dr. Reinhilde Jacobs and the co-promotor Prof. Dr. Em. Paul Lambrechts.

All experiments were performed by or under supervision of the PhD candidate with the collaboration and technical support from other researchers and colleagues.

All the manuscripts from this thesis, with the exception of Chapter 2, were written by the PhD candidate and revised by all co-authors.

Conflict of interest

The authors declare that they have **NO** affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this work.

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Curriculum vitae and list of publications

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Born on July 4th, 1988, in Bogotá, Colombia

Andrés Torres obtained his degree as General Dentist in 2012 from the University of Los Andes, Santiago, Chile. During his dental training, he participated twice in a research internship on CBCT in Endodontics at the KU Leuven, Leuven, Belgium, led by Professor Reinhilde Jacobs. In March 2014 he achieved the equivalence of foreign diploma "Titulo de Cirujano Dentista" with the Flemish degree of "Master of Science in Dentistry". In 2015 he obtained the diploma of Postgraduate studies in Advance Medical Imaging at the KU Leuven. Further, he obtained a specialization degree in Endodontics in July 2017, under the guidance of Professor Paul Lambrechts at the KU Leuven.

He currently works as an Endodontic specialist in private practice. He is also instructor of the Endodontic postgraduate program at KU Leuven. Currently he is a PhD candidate (OMFS-IMPATH, KU Leuven) with Professor Reinhilde Jacobs as his promoter and Professor Paul Lambrechts as his co-promoter.

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August 2019 – today	**Endodontist at Tandartsenpraktijk Radix** (private practice, Heist-op-den-Berg, Belgium)
August 2018 – today	**Instructor in Endodontics** at the Endodontic Department, KU Leuven, Belgium
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Education

- **PhD in Biomedical Sciences,**
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- **Postgraduate in Endodontology,**
  KU Leuven, Belgium, June 2017
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- **Master in specialist oral health care,**
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- **Postgraduate studies in Advance Medical Imaging,**
  KU Leuven, Belgium, July 2015
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- **Postgraduate studies in General Dentistry**
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- **Dentistry**
  Universidad de los Andes, Santiago, Chile, December 2012

- **High School**
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List of international peer-reviewed publications

- **Torres A**, Dierickx M, Coucke W, Pedano MS, Lambrechts P, Jacobs R. J Dent. May 2023. Ex vivo **and in-vivo validation of a novel measuring protocol for guided endodontics.**

- Farronato M, **Torres A**, Pedano MS, Jacobs R. J Dent. March 2023. **Novel method for augmented reality guided endodontics: An in vitro study.**

- **Torres A**, Dierickx M, Coucke W, Pedano MS, Lambrechts P, Jacobs R. J Dent. Feb 2023. In vitro study on the accuracy of sleeveless guided endodontics and treatment of a complex upper lateral incisor.

- Jonaityte EM, Bilvinaite G, Drukteinis S, **Torres A**. J Clin Med. Jun 2022. **Accuracy of Dynamic Navigation for Non-Surgical Endodontic Treatment: A Systematic Review.**

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- Moreno-Rabié C, **Torres A**, Lambrechts P, Jacobs R. Int Endod J. Feb 2020. **Clinical applications, accuracy, and limitations of guided endodontics: a systematic review.**

- **Torres A**, Shaheen E, Lambrechts P, Politis C, Jacobs R. Int Endod J. Apr 2019. **Microguided Endodontics: a case report of a maxillary lateral incisor with pulp canal obliteration and apical periodontitis.**

- Martínez I, **Torres A**, Jacobs R, Lepe A, Jara D, Ramírez V, Concha G, Briner A and Brizuela C. Austin J Radiol. Nov 2018. **Root Canal Morphology of Mandibular Incisors Using Cone-Beam Computed Tomography in Two Population Samples: A Cross-Sectional Study.**

- Pedemonte E, Cabrera C, **Torres A**, Jacobs R, Harnisch A, Ramírez V, Concha G, Briner A, Brizuela C. Oral Radiol. May 2018. **Root and canal morphology of mandibular premolars using cone-beam computed tomography in a Chilean and Belgian subpopulation: a cross-sectional study.**

- **Torres A**, Jacobs R, Lambrechts P, Brizuela C, Cabrera C, Concha G, Pedemonte ME. Imaging Sci Dent. Jun 2015. **Characterization of mandibular molar root and canal morphology using cone beam computed tomography and its variability in Belgian and Chilean population samples.**

List of contributions to (inter)national conferences in the field

- July 2023 – IADMFR World Tour congress, Brussels, Belgium. **Keynote presentation**: "Digitalization and automation in Endodontics".

- September 2022 – 20th ESE Biennial Congress, Budapest, Hungary. **Oral presentation** "Digital scanning as an effective tool to clinically assess the accuracy of guided endodontics".

- 2018, 2019, 2020, 2022 – Post academical education course, Leuven, Belgium. **Lecture** in: "CBCT in Endodontics".

- December 2021 – 1st Digital Dentistry Society Congress Belgium, Ghent, Belgium. **Keynote presentation**: "The digital dentist, Endodontics".

- September 2021 – Oral Health Research Congress IADR, Brussels, Belgium. **Oral presentation** and **winner of IADR Travel Grant**: "Accuracy of Virtually-guided access cavity preparation through Augmented Reality".

- September 2019 – 19th ESE Biennial Congress, Vienna, Austria. **Clinical video presentation**: "A Novel Guided Endodontics method for the treatment of a maxillary premolar with pulp canal obliteration and apical periodontitis".

- July 2019 – 3D Medical Conference & Expo, Perugia, Italy. **Oral Presentation**: "3D Guided Endodontics".

- September 2017 – 18th ESE Biennial Congress, Brussels, Belgium. **Clinical poster oral prize presentation** "Guided Endodontics: A case report".

- **Moderator** of Coltène lecture "Nickel-Titanium instrumentation: clinical applications of endodontic files properties in the heat-treatments' era." from Eugenio Pedullà and Ultradent Lecture "What is the best kinematics to be applied during instrumentation? Reciprocation, rotary or both? Matching endodontic literacy with the clinical reality." from Carlos A. Spironelli Ramos.

- October 2016 – **Participant** 2nd Research and Postgraduate Student Meeting, European Society Endodontology, Amsterdam, Holland.

- April 2016 – **Coaching** at the workshop "Canal Obturation", PAV KU Leuven, Leuven, Belgium.

- Augustus 2015 - 20th IADMFR Congress, Santiago, Chile. **Oral presentation** "3-Dimensional volumetric changes of apical radiolucencies after 1 vs 2 visit endodontic retreatment: a pilot study."

- May 2015 – **Coaching** at the workshop "Successful Endodontics", PAV KU Leuven, Leuven, Belgium.

- February 2014 – **Participant** 1st EADMFR Junior Meeting, Umea, Sweden.

- Juni 2013 - 19th IADMFR Congress, Bergen, Noorwegen. **Oral presentation** "Use of Cone-Beam Computed Tomography to evaluate root and canal morphology of mandibular molars."