Guided Endodontics: Redefining accuracy in Endodontic treatment

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ABSTRACT:
Guided endodontics has emerged as a transformative approach in modern endodontic care, particularly for cases involving complex anatomical challenges such as pulp canal obliteration and calcified root canals. This study explores the principles, clinical applications, and future directions of guided endodontics, with a focus on static/template-guided techniques. By integrating cone-beam computed tomography (CBCT), digital planning software, and 3D printing technologies, guided endodontics offers superior precision, reduced procedural errors, and enhanced preservation of tooth structure compared to conventional methods. The study also highlights the benefits of minimally invasive dentistry, demonstrating improved outcomes for patients and a significant reduction in operator dependency. However, challenges such as limited applicability in curved canals, high equipment costs, and the steep learning curve for dynamic systems remain barriers to widespread adoption. Future advancements, including the integration of artificial intelligence, augmented reality, and improved biocompatible materials, hold promise for expanding the clinical utility of guided endodontics. High-quality clinical studies and cost-effective innovations are needed to address current limitations and establish guided endodontics as a standard of care. This comprehensive review underscores the potential of guided endodonticsto redefine the field by enhancing precision, efficiency, and patient outcomes in endodontic procedures.

Introduction

Pulp obliteration (PO) is the excessive formation of dentine after trauma, visible as a calcified canal on radiographs. Also called pulp calcification, it can be total (root canals are not visible) or partial (root canals are narrowed but visible). Calcific metamorphosis refers to the rapid deposition of hard tissue in the pulp space due to trauma, making the pulp space appear filled with mineralized tissue, though some pulp may remain.[1]

Pulp canal obliteration are typical late sequelae after dental trauma. They occur in 15%–40% of cases after luxation injuries. While the formation of tertiary dentine indicates a vital pulp, root canal treatment may still be needed over time due to apical periodontitis or pulpitis. The extent of PCO can make root canal treatment difficult, even for experienced endodontic specialists. A study from 40 years ago examined the success of root canal treatments in incisors with post-traumatic pulp canal obliteration and periapical lesions. In cases with total obliteration, technical failures like root perforation, file fracture, or inaccessible canals occurred in one-third of treatments, resulting in significantly lower healing rates.[2]

During endodontic microsurgery (EMS), accurately locating the root apex can be difficult due to factors like a thick buccal plate or anatomical obstacles, such as the mental foramen or maxillary sinus, which may affect the prognosis.[3]In these clinical scenarios, creating a proper access cavity and locating the root canal orifices can be challenging and may lead to excessive tooth structure loss, increasing the risk of fractures. Preoperative planning and the use of three-dimensional (3D) imaging are highly recommended to mitigate these issues.[4]

In late 2006 and early 2007, the idea of adapting surgical guides for endodontic procedures emerged. Guided endodontics (GE) was introduced six years ago as an alternative to traditional access cavity preparation for teeth with pulp canal obliteration (PCO) and apical pathosis or irreversible pulpitis. By combining cone-beam computed tomography (CBCT) and digital surface scans, software can virtually plan optimal access to the calcified root canal.

Creating an endodontic access guide (EAG) begins with thorough planning. The clinician takes a high-quality CBCT scan, ideally covering the full arch, and obtains either a physical model of the patient's teeth or an intraoral scan. The DICOM files from the CBCT and the STL file of the model are then uploaded into specialized software for further planning.[5]

Cone-beam computed tomography (CBCT) is a valuable, noninvasive tool for diagnosing and planning treatment in endodontics, particularly for managing pulp canal obliteration (PCO). Computer-aided static (SN) and dynamic navigation (DN) techniques, using CBCT data, are emerging alternatives for precise access cavity preparation in complex endodontic cases. SN uses fixed guides made with CAD/CAM, while DN involves real-time motion-tracking cameras to guide drilling. These techniques are useful for managing calcified canals, anomalous teeth, post removal, and other challenging scenarios in endodontics. These modern techniques have improved the predictability of endodontic access cavities preparation and root canal location with several studies reporting a higher volume of dental tissue preservation with the digitally guided over conventional freehand access.[6]

The cost and time involved in creating endodontic access guides (EAGs) can be significant, making their routine use hard to justify. However, the benefits, such as reduced chair time, lower risk of perforation, and decreased chance of tooth loss, often outweigh these costs. Van der Meer et al. noted that 3D-designed guides allow even less experienced clinicians to successfully treat complex cases with greater predictability. As technology advances, costs are expected to decrease, and ease of use will improve. Despite the advantages, guided endodontics has limitations. Its accuracy in cases with pulp canal calcification (PCC) is still uncertain, and it is most effective in straight roots or the straight sections of curved roots. Accessibility in posterior teeth is also challenging due to limited space for templates and drills.[7]

Digital tools, when combined with traditional endodontic planning, play a crucial role in guided endodontics, particularly in managing pulp obliteration (PO), a common issue in endodontics. This review paper aims to explore the advantages, disadvantages, and potential applications of these digital methods, defining and characterizing guided surgical endodontics based on the latest scientific literature.[8]

While CBCT offers detailed three-dimensional imaging, its resolution may still fall short in visualizing extremely calcified or narrow root canals. The larger voxel sizes in some CBCT devices limit their ability to detect fine anatomical structures, which can be critical in pulp obliteration cases. Additionally, patient-specific factors such as existing metallic restorations, dense materials, or anatomical variability may create artifacts in the images, further complicating diagnostic accuracy. These limitations highlight the need for advanced imaging protocols and tools to optimize CBCT's efficacy in such challenging scenarios.[9]

From a patient perspective, guided endodontics significantly enhances the overall treatment experience. It reduces chair time by streamlining the procedure, improves procedural predictability, and minimizes the risks associated with traditional exploratory techniques, such as perforations or excessive removal of healthy tooth structure. This not only contributes to better clinical outcomes but also fosters greater patient satisfaction by offering a more efficient and minimally invasive approach to endodontic care.[10]

In summary, guided endodontics represents a transformative advancement in managing complex cases such as pulp canal obliteration. By leveraging cutting-edge technologies like CBCT, digital planning, and 3D-printed templates, it addresses the limitations of traditional techniques while prioritizing accuracy, efficiency, and patient satisfaction.[11] Although challenges such as imaging constraints and accessibility persist, the continuous evolution of these technologies promises to further enhance the precision and reliability of endodontic treatments in the future.

Technological Foundation

The advent of digital technologies has significantly transformed the landscape of modern endodontics. Among the most impactful developments is the use of Cone-Beam Computed Tomography (CBCT), which has become a cornerstone for diagnostic precision and treatment planning in endodontic procedures. Through meticulous navigation of CBCT images, clinicians can achieve a comprehensive understanding of the internal anatomy of teeth and surrounding structures, enabling more accurate root canal treatments. This advancement, combined with complementary digital tools, has improved both the quality and efficiency of endodontic care.

CBCT as the Foundation of Digital Planning in Endodontics

Cone-beam computed tomography (CBCT) plays a pivotal role in endodontic planning by offering three-dimensional (3D) images of the tooth's internal structures, which are crucial for identifying complex anatomical features such as root canal systems, fractures, and resorption areas. Traditional radiography, which provides two-dimensional (2D) images, is limited in its ability to accurately depict the complexities of the root canal anatomy and its adjacent structures. In contrast, CBCT imaging offers high-resolution 3D visualization that significantly enhances diagnostic accuracy.[12]

Endodontic treatment often requires precise navigation of tiny structures within the tooth, such as accessory canals, ramifications, and dentinal fractures. These microanatomical features are typically difficult to visualize with conventional 2D X-rays, posing significant challenges in accurate diagnosis and treatment planning. CBCT's ability to capture fine details of the tooth and its surrounding structures has thus become invaluable in overcoming these challenges. High-resolution CBCT scans enable clinicians to detect and navigate through intricate canal systems, helping reduce the risk of under-filling, over-instrumentation, or missing accessory canals during treatment.[13,14]

Factors Influencing CBCT Image Quality

The effectiveness of CBCT in diagnosing endodontic conditions is highly dependent on several factors, including the characteristics of the CBCT device, acquisition settings, and patient positioning. CBCT systems differ in their ability to capture high-resolution images, which is crucial for detecting small anatomical features. In particular, the focal point and resolution of the scanner are of paramount importance. Clinicians must prioritize image acquisition using high-resolution scanners with better focal capabilities, as opposed to devices that focus on larger volumes or wider areas.[15]

Additionally, the presence of dense materials, such as restorations or metal objects, within the patient's mouth can interfere with image clarity by causing artifacts. These artifacts may obscure critical anatomical details, compromising diagnostic accuracy. To mitigate these issues, advanced image processing software is essential. Software such as e-Vol DX (CDT Software, São José dos Campos, Brazil) is specifically designed to work with CBCT images and offers features like Blooming Artifact Reduction (BAR) and Accessory Canal Identification/Navigation (ACI). These tools help improve image quality by reducing artifacts and enhancing the visibility of intricate canal structures.[16]

Furthermore, Cinematic Rendering, a technique used in CBCT software, enables the generation of photorealistic 3D images that mimic the appearance of natural tissue, offering clinicians a more intuitive view of the tooth's microanatomy. This enhanced visualization improves diagnostic accuracy and provides valuable insights into complex cases, leading to better-informed clinical decisions.[17]

Digital Planning and the Development of Endodontic Guides

The use of digital planning software has been instrumental in advancing guided endodontics, a technique that combines CBCT data with computer-aided design (CAD) tools to create precise treatment plans and surgical guides. In this process, CBCT images are imported into digital planning software, which allows clinicians to virtually plan every stage of the procedure, from access openings to root canal preparation. The software analyzes the 3D CBCT data to map the optimal path for instrumentation, ensuring that the treatment follows the most efficient and safe route.[18]

Once the digital treatment plan is established, it is used to design custom surgical guides. These guides, which direct the placement of instruments during the procedure, are created using 3D printing technology. The process begins by converting the CBCT data into a digital model, typically in STL (Standard

Tesselation Language) format, which can be used by 3D printing machines to create the physical guide. The digital model, obtained through intraoral scanning, is synchronized with the DICOM (Digital Imaging and Communications in Medicine) data from the CBCT scan, ensuring that the guide is tailored to the patient's unique anatomy.[19]

3D printed guides offer a high level of precision, as they are designed to fit perfectly into the patient's oral cavity. This reduces the risk of human error during treatment and enhances the predictability of the outcome. The process of Stereolithography (SLA) or Direct Light Processing (DLP) technology allows for the production of highly accurate guides with a superior cost-benefit ratio. With smaller slice thicknesses in the STL files, the reliability of the printed guides is improved, though the printing time is prolonged. As a result, endodontists can ensure that the guide provides accurate guidance for canal preparation, minimizing the potential for procedural mistakes.[20,21]

The Role of 3D Printing in Endodontics

In addition to CBCT and digital planning software, 3D printing technology has emerged as a crucial tool in modern endodontics. It allows for the creation of highly accurate and customizable surgical guides that aid in the precise execution of root canal procedures. The guides are produced from light-curing resin using DLP (Direct Light Processing) or SLA techniques, which offer high precision in terms of fit and accuracy. 3D printing also reduces the reliance on traditional, less precise methods of creating surgical guides, ensuring that clinicians can achieve optimal outcomes in complex or difficult cases.[22]

While the time required for 3D printing can vary depending on the resolution and complexity of the guide, the result is a highly detailed and reliable tool that aids in the efficiency and success of the procedure. As 3D printing technology continues to advance, it is expected that the cost of these devices will decrease, making them increasingly accessible to a broader range of clinicians.[23]

The digital workflow, from CBCT imaging to 3D-printed guides, offers a more streamlined and less invasive experience for patients. Reduced treatment time and predictable outcomes not only improve patient satisfaction but also build greater trust in the treatment process. The precision and reliability of these digital tools help alleviate patient anxiety and provide a more comfortable overall experience.[24]

Principles of Guided Endodontics

Although straight-line access to the root canal is recommended,[17,18] minimally invasive concepts are also being considered.[25–27] Contracted endodontic cavities (CECs) are based on the concept of minimally invasive dentistry. To maintain the mechanical stability of the tooth, they are an alternative to traditional endodontic access cavities (TECs). Minimally invasive endodontics (MIE) aims to preserve maximum healthy coronal, cervical, and radicular tooth structure during the endodontic treatment. The concept of CEC is based on the preservation of pericervical dentin (PCD). In the conventional deroofing process, much of PCD is lost, which decreases the fracture resistance of the tooth. A more conservative approach can help in the preservation of PCD. Guided endodontics helps in the preservation of PCD and offers the most conservative approach for cases with high difficulty levels: calcified canals. Adequate root canal treatment in pulp canal obliteration (PCO) cases is challenging and associated with various risks. In these cases, even the most experienced clinicians can encounter difficulties preparing an adequate access cavity. Guided endodontics is extremely helpful for predictable, minimally invasive, and successful endodontic treatment of such cases.

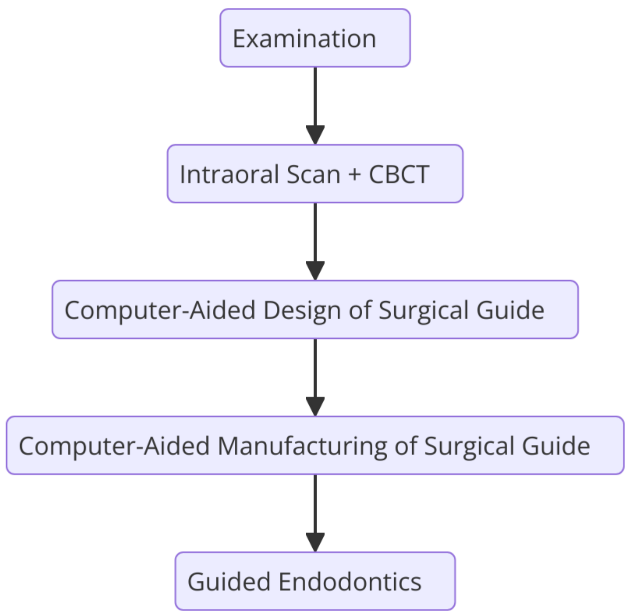
Guided Endodontics is also termed Targeted Endodontic Treatment (TET). In casesof calcified canals and endodontic microsurgery, Guided endodontics can delivermore predictable treatment outcomes compared to conventional treatment strategies.Guided approach can be static or dynamic. "Static guided Endodontics" is a way touse CBCT merged with an optical impression, creating the platform for the design ofa virtual drill path subsequent to the clinical procedure of drilling using a guide.A CBCT scan is an excellent measure for localizing the root canals in order tomake an orthograde root canal treatment of seemingly obliterated root canals.A virtual drill path can be made at the scan with the use of appropriatesoftware. If this virtual drill path has to be converted into a real drill path, some kindof surface guiding based on the CBCT scan is necessary.[28] It could be a dynamicguiding or a static guiding. A static guiding is made by using a guide made from acombination of a CBCT scan and a surface scan, whereas the dynamic guiding usesthe CBCT data in combination with recordings of the drill movements running realtime. Navigation can support several aspects of endodontic treatment, from localization of calcified canals to guiding the osteotomy for apicoectomy.

Targeted endodontic microsurgery (TEMS) was introduced recently which has been beneficial in anatomically challenging scenarios (Giacomino et al., 2018), demonstrating precise osteotomy site, angulation depth, and diameter. 3D-printed templates have been used earlier in guided endodontic procedures for minimally invasive and accurate access. This technique is fast becoming an aid in surgical endodontics.[23] Using this technique, the surgeon is able to make more precise incisions in the gingiva and bone, remove roots with greater accuracy, and facilitate more rapid healing following the operation. Less time is needed for this type of treatment compared to improvisational methods.[7,29]

For endodontic purposes, always a small field of view CBCT should be opted. If possible, depending upon the CBCT device, the image should be recorded in high-definition mode for better visualization of canals. Open-mouth CBCT is advised for guided treatments for better evaluation of anatomy and to avoid any superimpositions. Bite plates or cotton rolls can be used for this purpose.Stitching of the image volume could be carried out through a simple overlap (as the relative movement of patients between the scans is known exactly) or through automatic matching of the images using image registration.[30]

The guide should be printed using resin dedicated to surgical guides—a class IIa product that is sterilizable and safe to use in the oral cavity.[31] The entire workflow is presented in Figure 1.

Fig 1. Guided Endodontics - Workflow



Compared to conventional methods, guided endodontics significantly reduces the risks of procedural errors, such as perforation and excessive dentinal loss. By utilizing precise imaging and 3D-printed guides, this technique ensures better preservation of tooth structure, enhances procedural predictability and improves overall patient outcomes. The minimally invasive nature of guided endodonticscontributes to faster recovery and increased patient satisfaction.

While static guides are highly accurate and effective, their application is limited in posterior regions and curved canals due to spatial constraints and the rigidity of the guides. Additionally, creating static guides requires extensive preoperative planning and fabrication, which can increase treatment time and cost. Dynamic navigation, on the other hand, offers greater flexibility and real-time guidance but demands significant operator training and adaptation to monitor-based operation. The steep learning curve and high equipment costs may limit the widespread adoption of dynamic systems in routine clinical practice.

Clinical application, Benefits &Effectiveness

The navigation process in guided endodontics relies on a guide template, an approach similar to the implantology procedure. The initial steps involve a Cone Beam Computer Tomography (CBCT) scan, with the smallest necessary field of view and high resolution to detect calcified root canals. Following this, a digital surface scan is performed using either an intraoral scanner or by digitizing a plaster cast. Subsequently, the virtual position of the sleeve is planned, the template is fabricated using CAD/CAM technology or additive 3D printing. Studies utilizing 3D printed teeth have consistently demonstrated that GE preserves more tooth structure while maintaining high accuracy.[2]

Once the template is fabricated, it is inserted into the patient's mouth, along with the sleeve. The bur is guided through the sleeve, moving a few millimeters in depth at low pumping movements.[2] These computer aided techniques are less dependent on the operator's experience and are particularly beneficial for less experienced dentists.

Guided endodontics is primarily used for navigating calcified canals by identifying structure and anatomy through a computer-assisted approach. This precision reduces the risk of procedure errors such as perforation and iatrogenic errors.[32] Studies have shown that guided access leads to significantly less dentinal loss when locating and negotiating calcified canals. This approach not only preserves more tooth structure compared to traditional methods but also improves the long-term prognosis of treated teeth while reducing treatment time, benefiting both dentists and patients.[27]

Guided endodontics has proven useful in managing complex cases such as dens evaginate, removal of glass fiber posts, apical surgery, and removal of mineral trioxide aggregate (MTA) from the root canals.[28] A study successfully identified root canals in 50 single-rooted teeth and demonstrated their efficacy in narrow roots, such as lower incisors. Additionally, guided endodontics enables general practitioners to handle more complicated cases effectively. Multiple studies comparing GE to traditional freehand techniques for creating access cavities by using 3D printed teeth have shown that GE achieves similar success rates regardless of the practitioner's experience levels.[1]

A study reported that guided endodontics removed significantly less tooth material compared to conventional methods- averaging 10.5 cubic millimeters versus 29.7 cubic millimeters. Interestingly, while conventional techniques showed variability based on operator experience (19.9 cubic millimeters for experienced operators versus 39.4 cubic millimeters for less experienced ones), guided endodontics yielded consistent results across all experience levels, with both operators removing approximately 10.5 cubic millimeters of tooth structure. Despite these differences in material removal, both methods required roughly the same amount of time to complete about three minutes per tooth.[4]

Table 1:"Comparison of Material Removal and Operator Variability in Guided vs. Conventional Endodontics"

Technique	**Average Material Removed**	**Operator Variability**
Guided Endodontics	10.5 cubic mm	Consistent across experience levels
Conventional Method	29.7 cubic mm	Varies with operator skills

Guided endodontics also offers ergonomics advantages for dentists by enabling real time visual monitoring of procedures without causing physical strain.[4] It illustrates the superior performance in root canal identification and negotiation, achieving a success rate of 91.7%, compared to 41.7% with conventional methods.[4]An additional research study by Galino Buniag and colleagues highlights the potential of guided endodontics as a viable alternative for a surgical intervention particularly apicectomy and osteotomy.[28]

Guided endodontics has emerged as a transformative technique in modern dentistry, offering unparalleled precision, predictability, and efficiency in managing complex cases such as calcified canals and narrow roots. By significantly reducing procedural errors, preserving more tooth structure, and ensuring consistent results across varying skill levels, it bridges the gap between experienced and less experienced practitioners. Furthermore, its ergonomic advantages and ability to enhance long-term treatment outcomes make it a valuable tool for both clinicians and patients. As research continues to explore its applications, guided endodontics holds immense potential to redefine standards in endodontic care and expand its role in advanced dental procedures.

Challenges and limitations

Guided access is feasible only in the straight portions of the root canal and tends to lose precision in curved regions. Additionally, canals with extremely narrow diameters may not be visible in CBCT images due to the larger voxel sizes. Patients with restricted mouth opening may contraindicate the use of guided access, particularly for posterior teeth. Metallic restorations or fillings can create artifacts in radiographic images, further complicating the procedure. Lastly, the approach may not be economically viable for all patients.[2]

The static navigation (SN) guided technique presents several limitations. A key drawback is the necessity to isolate multiple teeth during the procedure to ensure the guide fits securely on the teeth, thereby maintaining stability. Additionally, the guide restricts visual access to the endodontic cavity, requiring removal for confirmation of the path during treatment. In posterior teeth, static guidance often necessitates the fabrication of multiple templates to achieve straight access to individual root canals, with the procedure's accuracy heavily reliant on the surgical template's design and manufacturing quality.[34]

Clinically, the SN technique is restricted to straight paths, making its application challenging in cases of limited mouth opening or reduced interocclusal space, particularly in posterior regions. To mitigate this, intracoronal guides have been suggested as alternatives. However, the use of larger diameter slow-speed drills may induce cracks in the tooth structure and generate excessive heat, potentially compromising the periodontal ligament. Furthermore, the lack of real-time 3D visualization prevents intraoperative adjustments to the drill trajectory, reducing procedural flexibility.[35]

Other notable limitations include its suitability primarily for straight root canals or the straight portions of curved canals. The technique requires extensive planning time and involves higher radiation exposure due to the mandatory CBCT imaging. Additionally, the associated costs for patients are elevated, owing to the need for CBCT imaging and template fabrication. Implementation in the posterior region remains particularly challenging due to spatial constraints.[1]

Dynamic navigation systems (DNS) present several disadvantages that limit their routine clinical application. A significant drawback is the high acquisition cost of the navigation system, which poses financial barriers to its widespread adoption. Additionally, unlike static guidance, dynamic navigation is highly operator-dependent and requires extensive training and practice to achieve precision in access cavity preparation. The technique necessitates adaptation to monitor-based operation, as the operator must focus on a screen rather than directly on the patient, which can be challenging [2,3].

Some commercially available systems are bulky and less practical for everyday use, further limiting their utility. Moreover, maintaining the system display in view during the procedure is often difficult, adding to the complexity of the technique. The long learning curve required for effective operation underscores the importance of thorough operator training to prevent iatrogenic errors and ensure successful outcomes [36].

Augmented reality technology has been proposed as a potential solution, enabling the virtual image displayed by the DNS to be superimposed on the therapeutic area, thus enhancing visibility while reducing reliance on external monitors. However, the high initial investment in equipment and the necessity for advanced training remain significant barriers to implementation. Operators must exercise caution and adhere to preventive measures to mitigate potential complications and ensure safe and effective use of DNS.[37]

Average deviations of 0.46 mm were noted, leading to potential loss of healthy dentinal tissue. These deviations can result from the design of guides and are especially problematic for teeth with complex anatomy like C-shaped canals. Guided endodontics may be less suitable for anatomically complex cases. For example, challenges arise in treating heavily calcified canals or posterior teeth with restricted access.

High reliance on advanced imaging technologies, such as CBCT and navigation systems, increases costs and requires significant technical expertise, which limits accessibility. The use of dynamic and static navigation systems demands extensive training, which might not be feasible for all practitioners. The high cost of equipment and software limits its routine use in many clinical settings, particularly in resource-constrained environments. Errors during the design or manufacturing of static navigation templates may reduce precision. Dynamic navigation overcomes some of these issues but requires additional expertise and technology. Many studies lack adequate long-term follow-up, making it difficult to assess the durability and success of guided endodontic procedures over time. Variability in study designs, sample sizes, and evaluation methods across systematic reviews makes it challenging to draw standardized conclusions.[29]

Guided techniques may be impractical for patients with limited mouth opening or anatomical constraints that hinder the proper placement of navigation equipment. Despite the technological aids, the effectiveness of guided endodontics can still be influenced by operator skill and experience.[38]

Guided access cavity preparation faces several limitations, primarily related to CBCT imaging quality. Insufficient spatial resolution and variability in CBCT machines often hinder the visualization of calcified canals, especially when small-diameter files (size 06 or 08) are used. Reducing voxel size improves resolution but increases radiation exposure. The technique is also constrained to straight canals due to the rigidity of the drills, with severe curvatures often requiring alternative approaches like apical surgery. Factors such as limited mouth opening, thin root structure (e.g., mandibular incisors), and potential drill-induced cracks or heat damage further complicate its application.

Additionally, intraoral radiographs, often used for follow-up, may underestimate deviations or healing due to their 2D nature, while CBCT provides better accuracy at higher costs and radiation exposure. Preoperative planning is further challenged by radiopaque artifacts, which can distort digital planning when highly radiopaque materials are present. Proper cooling and thinner drills are essential to minimize risks and enhance precision.[39]

Henceforth Guided endodontics, both static and dynamic, face several challenges and limitations. CBCT imaging, integral to guided procedures, often lacks sufficient resolution for calcified canals and is prone to artifacts from metallic restorations, complicating planning. Static navigation systems demand the fabrication of precise templates, which limit flexibility and are unsuitable for curved canals or patients with restricted mouth openings. Dynamic systems, while more adaptable, involve steep learning curves, dependence on operator expertise, and challenges like focusing on monitors rather than the patient. Both approaches are resource-intensive, requiring significant costs for equipment and training. Additionally, deviations in drill trajectory can result in substance loss or perforation, particularly in anatomically complex cases. Limited clinical data and high costs further restrict their routine application, underscoring the need for advancements to improve accuracy, accessibility, and feasibility.[40]

While guided endodontics offers a transformative approach to endodontic care, its application is limited by significant challenges. The dependence on advanced imaging modalities, such as CBCT, introduces issues like insufficient resolution, high costs, and artifacts caused by restorations. Both static and dynamic navigation systems have their own constraints, including restricted applicability in curved canals, high equipment costs, and a steep learning curve for operators. Moreover, anatomical constraints, such as limited mouth opening and posterior access, further complicate its use in certain cases. These challenges underscore the need for continued advancements in imaging, navigation technologies, and training to enhance the precision, accessibility, and feasibility of guided endodontics, ensuring it becomes a routine tool in clinical practice.

Future directions static/template-guided endodontics.

1.Guiding by means of a template and sleeve is already relatively technically mature.

2.A wider range of commercially available drills in diameter and length would be desirable, as this would enable a patient-oriented approach. Particularly in the posterior region, a drilling system graduated in length could compensate for the limited space available.

3.Magnet resonance imaging (MRI) may also gain importance in dentistry in the future. This would lead to the avoidance of ionizing radiation, which would be desirable especially in children as their tissues and organs are more sensitive to radiation.[40]

4.Leontiev et al. (2021)[26] showed in a proof-of-principle study that similarly precise access cavities based on MRI can be prepared in a laboratory environment. The (indirect) visualization of the tooth structure was achieved by using a splint with a hydrous gel, which enabled the successful superimposition of the MRI data with the surface scan. Thus, successful visualization of root canals was achieved in 91 out of 100 cases with a mean angular deviation of 1.82°.

5.However, these results still need to be confirmed clinically, and at present MRI equipment is not available to dentists. Nevertheless, depending on technical progress, this is desirable and conceivable for the future.

6.Otherwise, high-quality, prospective clinical studies are still needed to increase the evidence for guided endodontics

7.Artificial intelligence (AI) can play a crucial role in automating the design of templates and sleeves, enabling faster and more precise customization based on individual patient anatomy. AI could also assist in identifying optimal drill paths and predicting potential complications."

8.Advances in 3D printing materials, such as biocompatible and heat-resistant resins, are expected to improve the durability, accuracy, and safety of surgical guides. These materials could further streamline intraoral applications and enhance patient outcomes.

By addressing the current limitations and exploring innovative integrations, static/template-guided endodontics has the potential to revolutionize endodontic care. Continuous advancements in imaging, materials, and software technologies will likely expand its scope and accessibility, ultimately improving clinical outcomes and patient care.

Future directions of dynamic navigation.

1.For the future, it would be desirable if the systems were further reduced insize to improve handling on the patient. In addition, all systems should have thepossibility to digitally plan the required markers in order to avoid having to perform another CBCT scan if a scan (without markers) is already available. Of course, it would be even better if no markers were needed at all and the system could orient itself to the existing anatomical structures.

2.Augmented reality (AR) navigation might be the next step towards simplification and improving the operator experience with dynamic navigation. The AR approach overlays images, such as radiographic images and navigation paths, with a view of the operative field in a wearable head-up display or a dedicated microscope. Thus, the operator can simultaneously visualize the operative field and 3D navigation images without having to look up at a display. Whilst such approaches have been used in neurosurgery [40] clinical implementation in endodontics has only been proposed but has not yet been implemented in a clinical setup (Song et al., 2018).[32][41]

Guided endodontics using static or dynamic navigation appears to be a safe and minimally invasive method for negotiating calcified root canals [42,43] enabling both chemo-mechanical debridement and conservation of tooth structure. Larger population studies with longer follow-up periods are required, as well as standardize experimental studies with similar sample size, aim and standardize measuring method.[44]

Conclusion

Guided endodontics using static or dynamic navigation appears to be a safe and minimally invasive method for detecting calcified root canals. Dynamic navigation in particular still has great potential for further development. Guided endodontics has transformed the field of endodontics, offering improved accuracy, efficiency and outcomes. Also advancement in CBCT technology has improved resolution and reduced radiation dose. While limitations exist, ongoing advancements will continue to expand its applications and accessibility.

However, further high-quality clinical studies on both static and dynamic navigation are needed.

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