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Research Paper

LEADING-EDGE DEVELOPMENTS IN GUIDED ENDODONTICS: UTILIZING NEXT-GENERATION TOOLS

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Abstract: *Guided endodontics has revolutionized root canal therapy by integrating advanced technologies to improve precision, safety, and outcomes. This method combines imaging technologies like cone beam computed tomography (CBCT) with computer-assisted navigation systems to enhance the accuracy of root canal treatments. Key stages include initial diagnostic imaging, 3D virtual treatment planning, and the use of customized guides or templates during procedures. These guides help accurately identify canal orifices, reducing procedural errors and improving access to complex root structures. Benefits include better treatment predictability, reduced procedure time, and lower risk of complications. Recent advancements, such as high-resolution CBCT, advanced 3D printing for custom guides, and improved virtual planning, have enhanced the precision of access cavity preparations. Innovations like low-profile clinical templates address challenges with restricted mouth openings, while improved intraoral scanning and virtual planning streamline preparation processes. Despite higher costs and increased planning time, guided endodontics is increasingly seen as a standard method, offering substantial improvements in clinical practice and patient outcomes. This review consolidates these advancements, emphasizing their impact on precision, efficiency, and future research directions in endodontics.*

Keywords: *Guided endodontics, Pulp Canal Obliteration, Static guidance, Dynamic navigation, Virtual drill, CBCT Scan*

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I. Introduction:

The term "guided endodontics" combines the concept of "guided" with "endodontics." The word “guided" is derived from the verb "guide," meaning to direct or lead, and in this context, it refers to the use of specific techniques, tools, or technologies that assist in directing and improving the precision of the procedure. "Endodontics," on the other hand, comes from the Greek words "endo-" (meaning "inside") and "odontos" (meaning "tooth"), and it is the branch of dentistry that deals with the diagnosis and treatment of issues within the tooth, particularly the dental pulp and surrounding tissues. Thus, "guided endodontics" refers to endodontic procedures that are enhanced by guidance technologies or methods to achieve greater accuracy and improved outcomes in the treatment.[1] Conventional endodontics, also known as traditional endodontics, and guided endodontics are two distinct approaches to root canal treatment, differing in methodology, precision, and technology.[2] Conventional endodontics relies on manual techniques to locate and clean root canals using hand instruments and rotary files. Visualization is typically supported by magnification tools such as dental loupes or microscopes.[3] While this approach is effective, its success heavily depends on the dentist's skill and experience, with accuracy varying in complex cases, such as those involving calcified or curved canals.[4] Diagnosis and treatment planning usually involve basic X-rays, which may not capture the full complexity of the root canal system, potentially leading to missed canals or procedural errors.[5] In contrast, guided endodontics offers a state-of-the-art alternative, particularly for managing teeth with partial or complete canal obstruction.[6] This method utilizes advanced technologies, such as cone-beam computed tomography (CBCT) and digital surface scanning, to create detailed three-dimensional (3D) maps of the tooth and its root canal system.[7] These maps facilitate the design of custom 3D-printed guides or templates that direct preparation instruments with high precision.[8] Guided endodontics includes both static guidance, using pre-fabricated templates, and dynamic guidance, which involves real-time tracking and navigation. By integrating preoperative digital planning with real-time navigation, guided endodontics enhances accuracy, reduces variability, and improves the likelihood of successful canal negotiation.[9] It complements Minimally Invasive Endodontics by preserving healthy tooth structure and minimizing the loss typically associated with traditional methods. This technique generally leads to better outcomes, particularly in challenging cases such as calcified or curved canals, and often results in faster procedures with reduced chair time. Thus, while conventional endodontics relies on traditional methods with inherent variability, guided endodontics leverages advanced imaging and navigation technologies to achieve superior precision and improved clinical outcomes.[10] Guided endodontics is particularly effective for complex cases involving calcified canals and has gained popularity due to advances in 3D printing and tomographic imaging technologies. (**Figure 1**).[11]

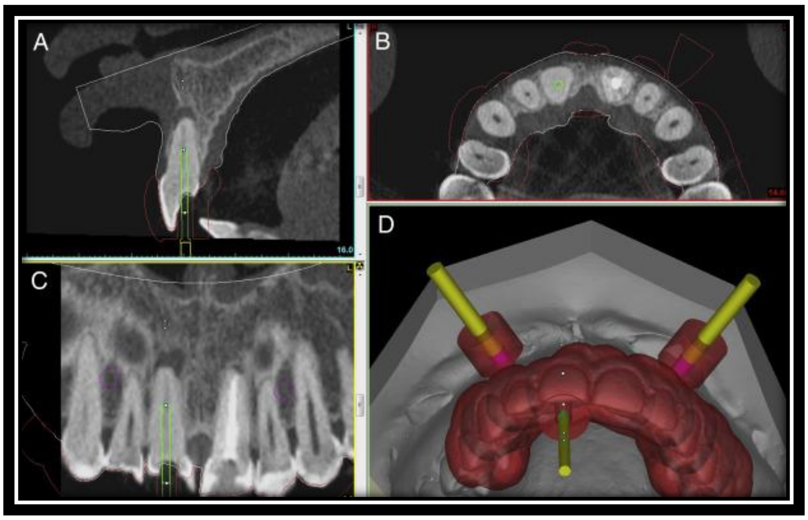

Figure 1: Guided endodontic access of calcified canal of maxillary anterior teeth

Courtesy: Tavares WLF, Viana ACD, Machado VC, Henriques LCF, Ribeiro Sobrinho AP. Guided endodontic access of calcified anterior teeth. J Endod. 2018; 44 (7):1195-1199.

The use of 3D endodontic guides, or endo-guides, enhances the precision of identifying and examining root canal openings, as well as performing bone trephination and root end resections, ultimately improving outcomes in endodontic surgery.[12] Traumatic injuries can stimulate increased dentin production, resulting in narrowing of the pulp canal due to calcification.[13] This condition, known as calcific metamorphosis, involves a rapid build-up of hard tissue within the pulp area, which may obscure the pulp space on radiographs, although some pulp tissue might still be detectable upon histological examination.[14] Pulp canal obliteration is marked by the accumulation of calcified tissue within the root canal and can be caused by various factors, including carious lesions, coronal restorations, vital pulp therapy, dental trauma, and orthodontic treatments. It can also result from secondary dentin formation in older patients.[15] It is deemed a significant clinical complication by the American Association of Endodontists.[16] Managing severely calcified canals, especially in symptomatic teeth or those with radiographic signs of periapical disease, is challenging.[17] Variations in canal anatomy, constrictions, and curvatures can lead to procedural complications such as perforations, which may jeopardize treatment success by causing infections in inaccessible periapical tissues.[18] The use of dental loupes or microscopes can complicate access cavity preparation and canal orifice identification, potentially leading to excessive removal of dental tissue and a less favorable long-term prognosis.[19] CBCT provides considerable advantages in visualizing the entire root canal anatomy across multiple planes, making it a crucial tool for diagnosing and managing complex endodontic cases like pulp canal obliteration. It offers high-definition, submillimeter accuracy images, overcoming the limitations of traditional periapical radiographs. It is advisable to use CBCT with appropriate field-of-view settings and optimal parameters to ensure diagnostic accuracy while minimizing radiation exposure (**Figure 2**).[20]

Figure 2: CBCT scan of the left first maxillary molar showing the presence of second canal in mesiobuccal root in axial, coronal and sagittal plane

Courtesy: Mamede-Neto I., Bandeca M., Tonetto M., Borges A. H. The role of cone-beam computed tomography as an incremental tool in endodontic diagnoses.2016; 8(10):278-288.

Guided endodontics has emerged as an advanced method for addressing partially or fully obliterated root canals. This technique involves 3D planning and the creation of custom guides based on digital data from intraoral scans and CBCT.[21] These guides facilitate minimally invasive access to the root canal system, preserving healthy tooth structure and enhancing procedural efficiency.[22] Recent advancements in 3D printing have enabled the production of precise, patient-specific guides, improving the success of endodontic treatments.[23] Additionally, 3D-printed models of extracted teeth, made from materials that closely mimic natural dentin, are increasingly utilized for educational purposes and research.[24] Stereolithography (SLA) is a favored 3D printing technique in dental applications due to its cost-effectiveness, ability to produce detailed surface features, and compatibility with sterilization.[25] Despite its benefits, SLA has some limitations, such as reliance on light-curable resins and potential layer-by-layer production artifacts.[26] The accuracy of endodontic guides produced using CBCT images and 3D printing with SLA technology can vary depending on the materials used and the layer thicknesses.[27]Pulp obliteration can range from complete, where both the pulp chamber and root canals are indistinguishable, to partial, where the pulp chamber is visible but the root canals are notably constricted. Pulp inflammation reflects the tooth's reparative response, while pulp necrosis, often following trauma, can lead to additional complications. The connection between pulp obliteration and the risk of pulp necrosis remains an area of ongoing investigation. Guided endodontics addresses the challenges of interpreting CBCT images and executing precise procedures by integrating digital planning into endodontic therapy (**Figure 3**).[28]

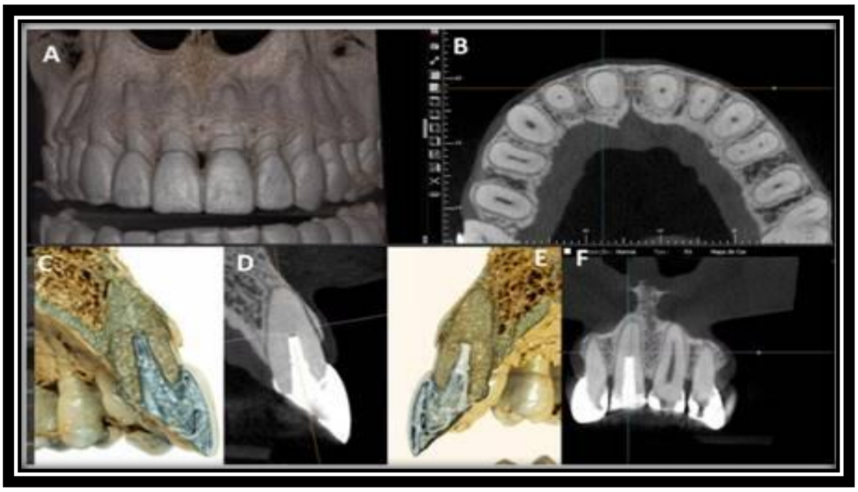

Figure 3: Digital planning in guided endodontics

Courtesy: Digital Planning on Guided Endodontics Technology. Braz Dent J. 2021; 32(5):23-33.

The adaptation of 3D-printed guides or splints from implantology to endodontics has demonstrated promising outcomes for accessing and treating root canals.[29] By combining guidance systems with CBCT imaging, this method improves the accuracy of surgical procedures, shortens treatment times, and enhances precision compared to traditional techniques.[30] Static guided endodontics involves scanning the maxillary or mandibular arch with CBCT and creating a template that overlay the target tooth for accurate drilling (**Figure 4**).[31]

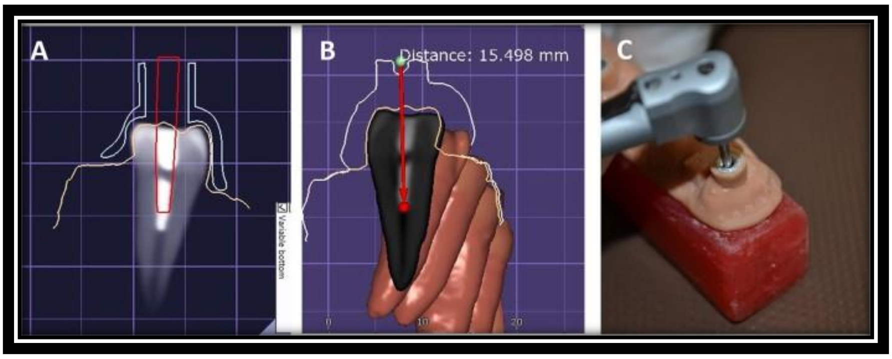

Figure 4: Effectiveness of the static-guided endodontic technique for accessing the root canal through MTA and its effect on fracture strength

Courtesy: Ali A, Arslan H. Effectiveness of the static-guided endodontic technique for accessing the root canal through MTA and its effect on fracture strength. Clin Oral Investig. 2020; 25(8):1989-95.

In contrast, Dynamic guided endodontics uses a stereo camera and an active navigation system to monitor and adjust the drilling process in real-time (**Figure 5**).[32]

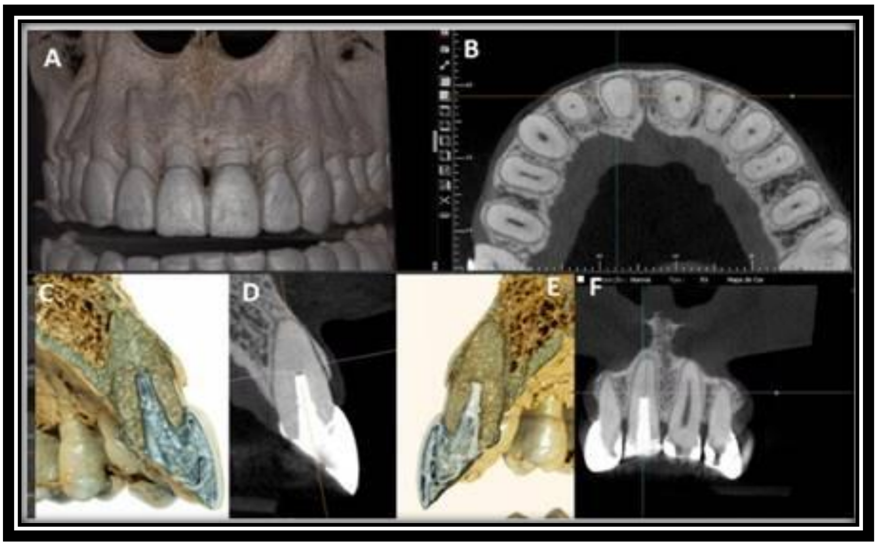

Figure 5: Dynamic surgical navigation for minimal endodontic access

Courtesy: X-NAV Technologies. X-Guide Dynamic Navigation receives FDA 510(k) clearance to aid in minimally invasive endodontic procedures [news release]. PR Newswire; 2022 Apr 26 [cited 2024 Sep 12].

Tooth structure conserving endodontic access cavity preparation and accurate root canal localization are the foundation for a successful root canal treatment. Challenges arise in complex cases, like finding obliterated second mesio-buccal root canals in maxillary molars, additional canals in mandibular canines or dealing with calcifications and pulp stones.[33] Treating such cases is time-consuming and often go hand in hand with higher substance loss and risk of perforation or missed canals. This leads to endodontic failure and reduced fracture resistance.[34] To address these challenges, static and dynamic guided endodontic systems utilizing treatment planning based on CBCT contribute to precise root canal orifice localization.[35] In the software, the bur's virtual placement at the orifice ensures direct access, minimizing substance loss even without direct sight.[36] Static navigation has been explored in numerous prior studies, primarily consisting of case reports or in vitro investigations utilizing either human or 3D-printed teeth.[37]For this method the CBCT-based planning is merged with a surface scan, and a template for guided drilling (**Figure 6**) is fabricated, either by subtractive or additive manufacturing.[38]

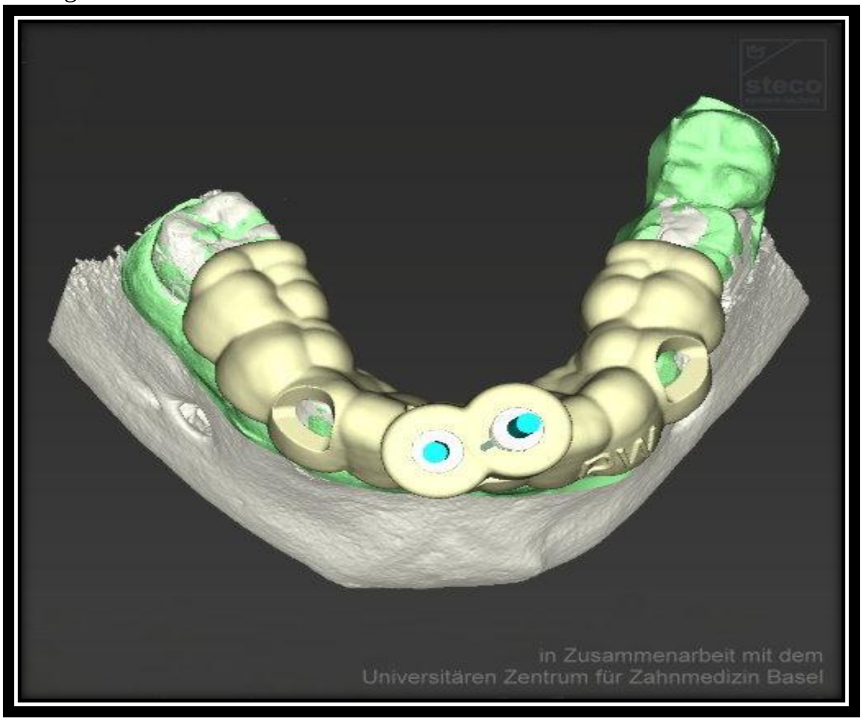

Figure 6: Guiding drill
Courtesy: https://steco.de/en/guided-endo/

On the contrary, dynamic navigation (**Figure 7**) is a relatively new area of modern digital dentistry, yet it is increasingly apparent in a vast spectrum of dental procedures, including endodontic treatments for obliterated root canals or endodontic surgery.[39]

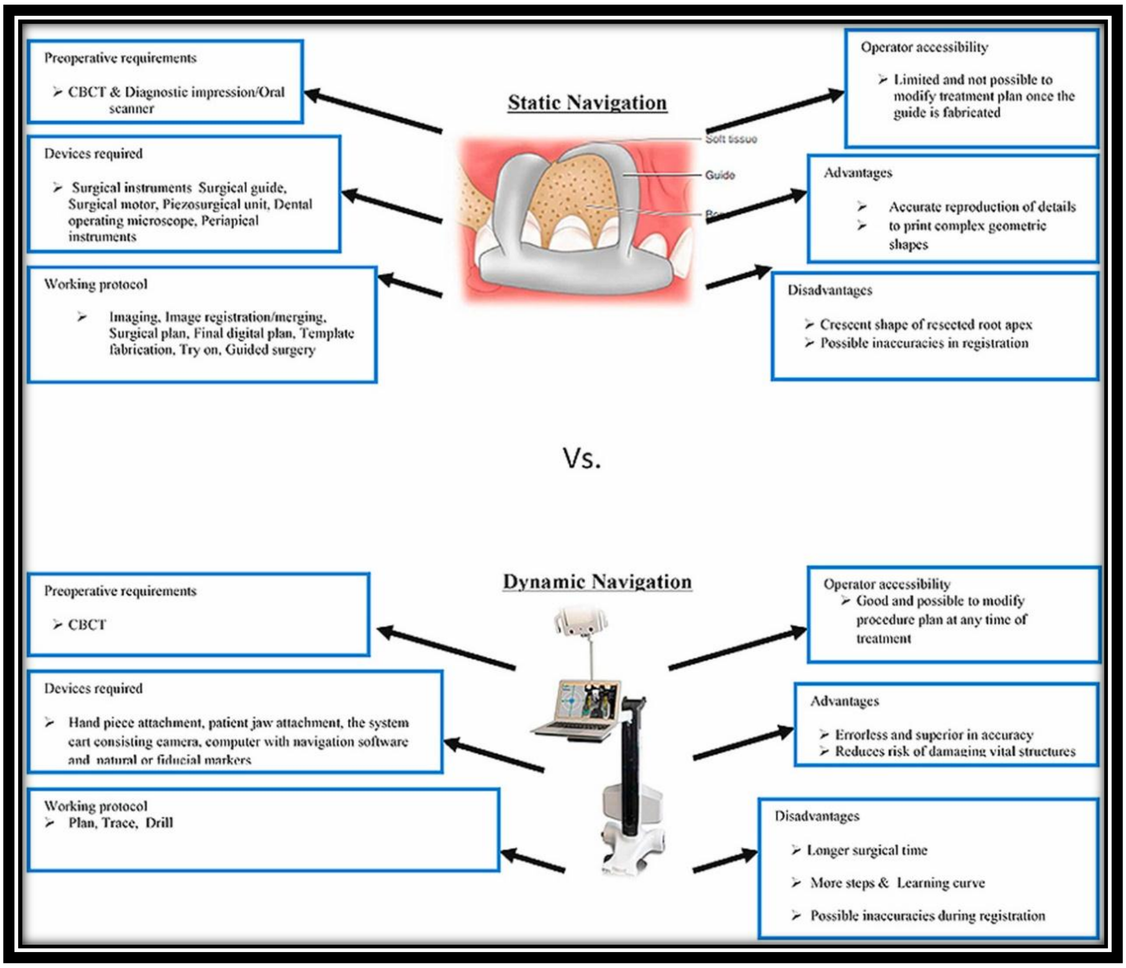

Figure 7: Static guidance vs dynamic navigation

Courtesy: Geo T. D., Saxena P., Gupta S. Static vs. dynamic navigation for endodontic microsurgery - A comparative review. J Oral Biol Craniofac Res. 2022; 12(4):410-412.

It integrates a visual marker during CBCT and operation, bypassing the need for surface scans. The marker is detected by an external camera, serving as a reference point for overlaying CBCT data, guiding real-time drill positioning as per the plan.[40] Dynamic navigation's key advantage lies in intra operative adjustments, in contrast to static guides, which may be required due to CBCT misinterpretation. Without physical templates, the procedure area remains visible, proper cooling is maintained, cavity rinse and rubber dam placement is possible, same-day treatment is viable, and even changes in planning are feasible.[41] A potential downside could be a steeper learning curve, as operators juggle display viewing and on-site drilling challenges. Static or dynamic guidance's advantages are evident in localizing calcified root canals. However, extending the research to the use of guided endodontics in complex root canal anatomies, such as clinicians are confronted with during treatment, is the aim of this review, thereby using 3D printed teeth (**Figure 8**).[42]

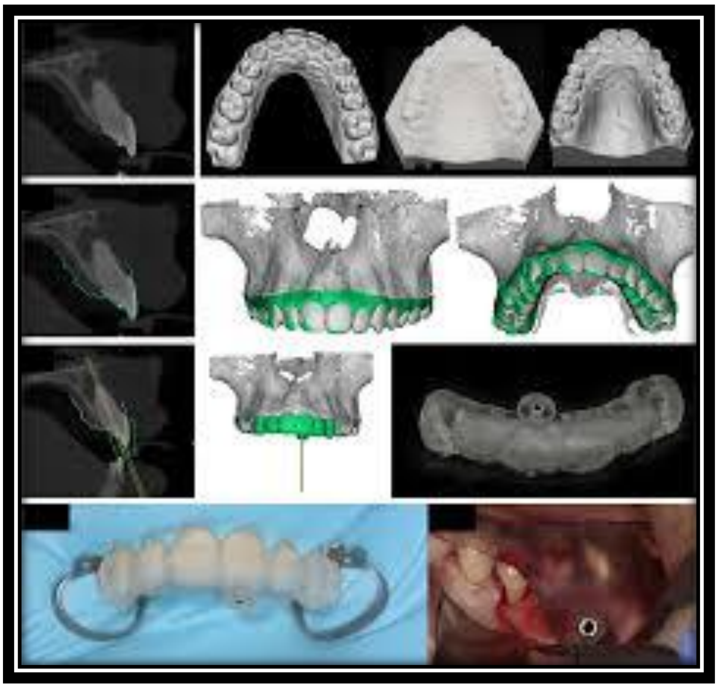

Figure 8: 3D printed teeth in guided endodontics

Courtesy: Moreno-Rabie C, Torres A, Lambrechts P, Jacobs R. Clinical applications, accuracy and limitations of guided endodontics: a systematic review. J Clin Endod. 2024; 50(3): 211-220.

As digital tools and guided techniques advance, a thorough literature review is necessary to evaluate their benefits, limitations, and potential uses in managing pulp obliteration. This review aims to define and assess guided surgical endodontics, highlighting recent advancements and their implications for endodontic practice.[43]

II. Discussion:

In endodontics, guided techniques are divided into static and dynamic methods. The static-guided approach involves pre-planning a virtual drill path by integrating optical impressions with CBCT scans before the clinical procedure begins.[44] On the other hand; dynamic guidance combines CBCT data with real-time recordings of drill movements. Both methods align CBCT and surface scans using radio graphically identifiable structures, such as the patient's teeth.[45] Specialized software then generates a virtual model of the commercially available bur, which is superimposed onto the visible portions of the calcified canal. Guided endodontics utilizes a sophisticated and technologically advanced approach to handle intricate endodontic cases.[46] The procedure begins with obtaining a high-resolution CBCT scan of the affected tooth to minimize patient movement and reduce artifact interference.[47] Subsequently, a detailed surface scan of the tooth and surrounding soft tissues is captured using an intraoral scanner or, alternatively, through a model created from an impression. (**Figure 9**) [48]

Figure 9: Intraoral scanner

Courtesy:https://dental-rotors.com/wp-content/uploads/2024/01/How-Intraoral-Scanners-Work-2.jpg

These scans are then integrated using specialized software to ensure accurate alignment. Designing the endodontic guide involves marking reference points on the scan files and using software to seamlessly merge the scans. This phase includes mapping calcified canals, developing a virtual drill path from the tooth's surface to the target pulp space, and choosing an appropriate virtual sleeve based on the drill's target, angle, and diameter.[49] During the clinical procedure, the fit of the guide template is verified on the patient, and the access preparation point is indicated with colored resin. Once the guide is removed, access is prepared with a high-speed bur, and drilling is performed with a micro-guided endodontic drill at 10,000 rpm, utilizing controlled and rhythmic movements to reach the apical third of the root.[50] The entire digital and clinical workflow involves scanning the root canal system with CBCT, obtaining a digital intraoral impression, importing Digital Imaging and Communications in Medicine (DICOM) and Stereo lithography (STL) files into planning software, and creating the endodontic guide through 3D printing (**Figure 10**) .[51]

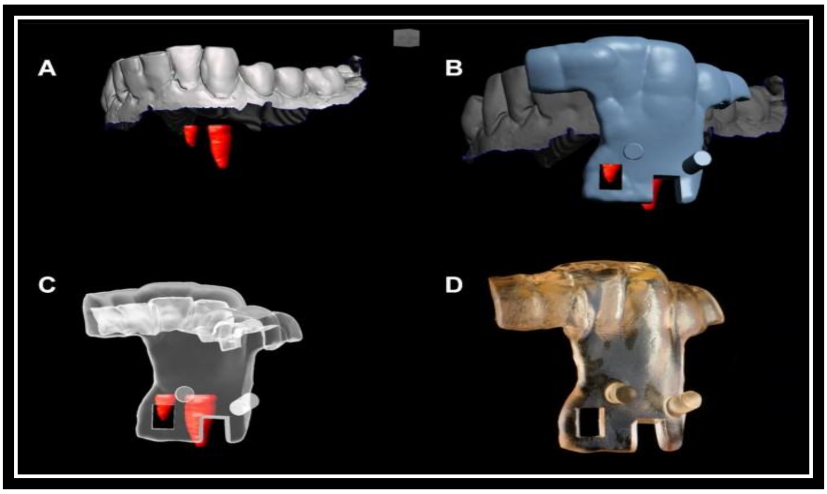

Figure 10: 3D printing for guided endodontics

Courtesy: 3D-printed guide for endodontic surgery. Clin Dent Rev. 2019 Jul 17; 3:13.

The guide's fit should be checked both before and after placing a rubber dam. An indicator should mark the access point on untreated teeth.[52] Enamel is removed until dentine is exposed, and the guide is placed on the teeth. Drilling is conducted through the guide, with the cavity rinsed and cleaned after the guide is removed.[53] An optical microscope is used to ensure proper endodontic access, followed by a radiographic examination to confirm accurate canal access and complete the root canal treatment.[54] While guided endodontics is an evolving technique that provides increasingly precise and cost-effective tools, enhancing clinician accessibility, it also has limitations and requires thorough evaluation before implementation.[55] Terms such as pulp canal obliteration, calcific metamorphosis, and pulp canal calcification refer to the increased formation of tertiary dentin within the root canal system.[56]This added dentin can decrease translucency and cause discoloration, complicating root canal treatment and heightening the risk of iatrogenic events.[57] Traditional root canal techniques demand excellent visualization and memorization of tooth structure to navigate canals effectively. Potential risks include access cavity overextension, missed canals, iatrogenic perforation, file separation, and deviation from the original canal course.[58] Guided endodontic access improves safety and predictability by enabling precise planning of the entrance point, bur direction, and depth, though careful planning is required to address the complex architecture of root canals and avoid issues like bending and overextension. CBCT scans that produce image artifacts can limit the virtual planning and accuracy of prototype guides.[59]

Advancements in Guided endodontics and Digital Integration: Guided endodontics represents a significant advancement in endodontic procedures, leveraging modern technologies to improve precision and treatment outcomes.[60] Recent studies highlight the integration of innovative software that enhances the accuracy of internal tooth anatomy reconstructions, effectively mitigating distortions and access errors.[61] Guided endodontics is reshaping the landscape of endodontic treatment through groundbreaking technological advancements. By integrating CBCT with digital surface scanning and 3D printing, Guided endodontics offers unprecedented accuracy and precision.[62] The use of CBCT provides a detailed, three-dimensional view of the tooth and its complex root canal system, which is essential for navigating challenging cases, such as those involving calcified canals. Complementing this, digital surface scanning captures the precise contours of the tooth, facilitating the design of custom endodontic guides, or "endo-guides," that direct drills with exceptional accuracy. This approach significantly reduces procedural errors and enhances treatment success by minimizing the removal of healthy tissue and preserving pericervical dentin (**Figure 11**). [63]

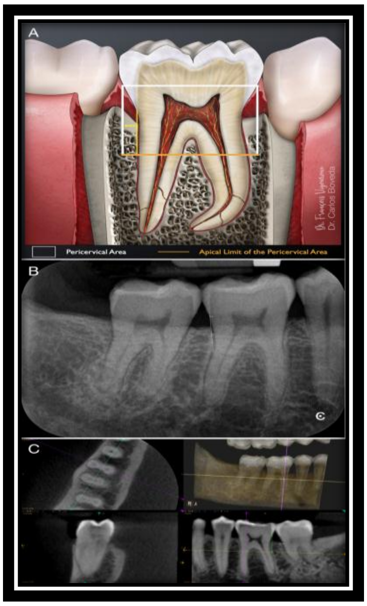

Figure 11: Pericervical dentin

Courtesy: Boveda C, Kishen A, Millan B, Camejo MV, Gomez-Sos JF. Pericervical dentin metrics in mandibular first molars determined with digital periapical radiography and cone-beam computed tomography. J Endod. 2024; 50 (5):637-43.

The advancement of guided endodontics from static to dynamic navigation systems further improves its effectiveness. Static navigation uses pre-fabricated guides based on virtual drill paths, while dynamic systems employ real-time tracking to adjust the drill's trajectory, offering superior control and flexibility.[64] These innovations not only streamline the procedure, reducing chair time and operational costs, but also deliver better outcomes in complex cases by overcoming the limitations of traditional methods.[65] Despite its benefits, including reduced procedural time and minimized risk of iatrogenic complications, guided endodontics faces challenges such as dependence on 3D-printed models(**Figure 12**) and issues with visibility in narrow or curved canals.[66] Ongoing research and technological advancements continue to refine these techniques, making guided endodontics a transformative and promising approach in modern dentistry. [67]

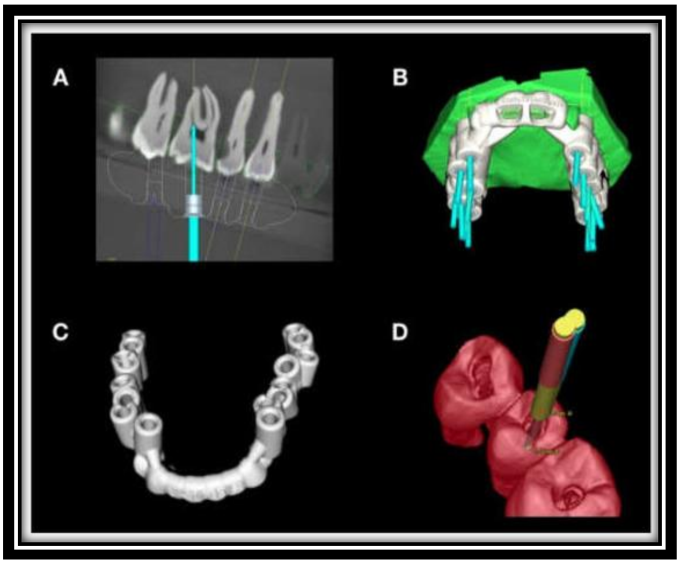

Figure 12: The image illustrating the digital workflow features a virtually designed straight-line access cavity, multiple planned access cavities for posterior teeth within a maxillary model, the created template, and a 3D rendered assessment highlighting the discrepancies between the planned and actual access cavity preparations.

Courtesy: Haarmann B, Leontiev W, Magni E, Kühl S, Dagassan-Berndt D, Weiger R, Connert T. Accuracy of Guided Endodontics in Posterior Teeth. Appl Sci. 2023; 13 (4):2321.

Benjamin Haarmann et al.'s ex vivo proof-of-principle investigation demonstrates that guided endodontics facilitates precise and dependable access cavity preparation in posterior teeth.[68] Other ex vivo studies corroborate that guided endodontics is a highly effective, efficient, and accurate method for creating endodontic access cavities in anterior teeth.[69] Clinical case reports also confirm its practicality for treating the maxillary second and third molars, as well as the first mandibular molar.[70] Evidence indicates that guied endodontics is less dependent on operator skill, allowing even novice practitioners to successfully access calcified root canals.[71] Haarmann's study records an average angular deviation of 1.39 degrees for all access cavities, consistent with earlier research findings.[72] The quantity of main root canals per tooth notably influenced both angular and spatial deviations at the bur tip in the bucco-lingual direction.[73] Access cavity preparation was less precise in teeth with a single main root canal compared to those with multiple canals. This discrepancy might be attributed to the absence of severe calcification in the teeth studied and the potentially larger, oval lumen of single-canal teeth, which could have facilitated the bur's central positioning in rounder canals once the orifice was located.[74] However, inaccuracies may also result from operator-related factors, such as manual adjustments during specific steps, and semi-automatic alignment of CBCT and surface scan data, which could introduce local deviations.[75] Guided endodontics does have its drawbacks, especially in posterior regions where limited mouth opening may hinder the use of guided endodontics templates. Nonetheless, clinical templates can be designed with lower profiles to mitigate this issue.[76] Furthermore, guided necessitates that the root canal orifice be reachable by a straight, rigid bur, making severe root curvature a contraindication if the orifice is situated far apically.[77] Despite the complexities of canal morphologies, guided could be beneficial for detecting calcified root structures or variations, such as radix entomolaris or a middle mesial canal. While guided endodontics planning phase is more demanding, it might reduce overall treatment time and enhance patient comfort by eliminating prolonged searches for the pulp chamber.[78] CBCT has become essential for preoperative planning, aiding in the detection of resorptions, calcifications, and intricate canal morphologies.[79] However, it entails higher radiation doses compared to conventional radiography, necessitating careful consideration. The American Association of Endodontists and the American Academy of Oral and Maxillofacial Radiology recommend using a limited field-of-view to identify and locate calcified canals and complex canal structures.[80]A limitation of this study is that none of the treated teeth were severely calcified, which could impact the accuracy of virtual access cavity planning. Severely calcified, caries-free, and restoration-free extracted teeth are challenging to obtain. Recent developments include the use of 3D-printed teeth in endodontic research and education, which allows for the digital creation of root canal calcifications, though these models may not entirely replicate the properties of human dentin.[81] Guided endodontics also requires additional time for CBCT, intraoral scanning, virtual planning, and guide template fabrication. Future research should compare traditional freehand techniques with guided endodontics in posterior teeth, focusing on factors such as time, operator experience, costs, and the amount of tooth substance loss associated with each technique.[82]

Future Directions in Leading-Edge Guided Endodontics: Utilizing Next-Generation Tools: Guided endodontics is poised for significant advancements aimed at improving clinical outcomes and patient safety. Key future directions include integrating Artificial Intelligence (AI) to enhance diagnostic accuracy and treatment planning by analyzing CBCT scans and patient data. AI can aid in predicting canal anatomy and optimizing real-time navigation.[83] Enhanced real-time navigation systems with advanced sensors will offer precise feedback on drill positioning, reducing human error. Innovations in 3D printing are expected to make the production of biocompatible, customized endodontic guides more efficient and cost-effective. Augmented Reality (AR) (**Figure 13**) may provide better visualization of canal systems, making procedures more intuitive.[84]

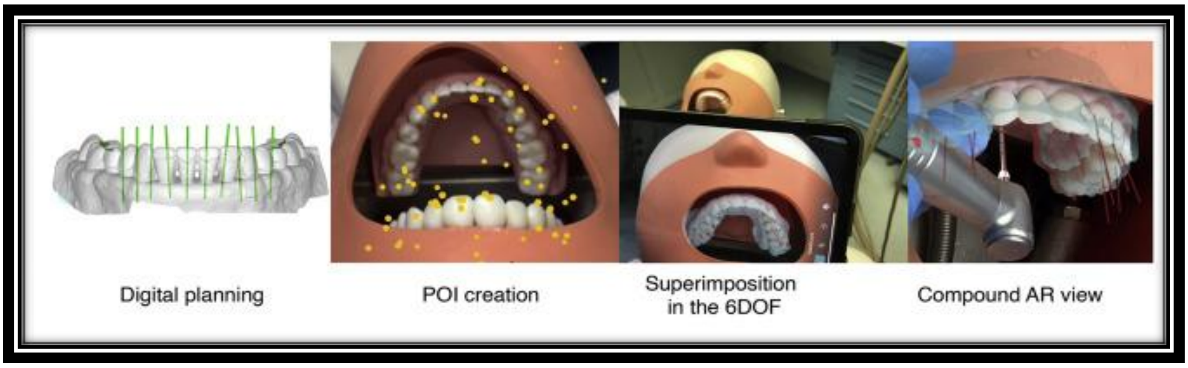

Figure 13: Augmented reality in guided endodontics

Courtesy: Farronato M, Torres A, Pedano MS, Jacobs R. Novel method for augmented reality guided endodontics: An in vitro study. J Dent. 2023; 132:104476.

Further advancements in imaging technologies are likely to improve guide accuracy and treatment planning. Efforts to refine minimally invasive techniques will focus on preserving tooth structure and improving access guides.[85] Personalized endodontic tools tailored to individual anatomy could enhance treatment outcomes. Long-term research will be crucial for refining techniques, while virtual simulations and AI-driven training will improve practitioner proficiency. Increased interdisciplinary collaboration will drive further innovation. These directions promise to advance guided rndodontics, offering greater precision, safety, and efficacy in root canal therapy.[86]

III. Conclusion:

Next-generation tools in guided endodontics are transforming root canal therapy by enhancing precision and reducing invasiveness. The integration of AI, real-time navigation systems, and advanced 3D printing methods is making procedures more accurate. Augmented Reality (AR) and improved imaging technologies refine visualization and planning, while personalized tools and minimally invasive techniques further optimize treatment. Continued innovation and research, supported by virtual training and interdisciplinary collaboration, will drive advancements in endodontic care, leading to better patient outcomes and a higher standard of care.

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