Guided Endodontics: A Comprehensive Review of Techniques, Applications, and Future Directions

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***Abstract*:** Guided Endodontics represents a transformative advancement in root canal therapy, combining digital imaging, computer-aided design, and 3D printing technologies to enable precise, minimally invasive access to the root canal system. Particularly beneficial in cases of pulp canal obliteration (PCO), calcified canals, and anatomically complex teeth, guided approaches significantly improve treatment accuracy, reduce iatrogenic risks, and preserve tooth structure. This review explores the fundamental principles, technological components, clinical applications, and current evidence supporting static and dynamic guided endodontic techniques. The integration of guided endodontics into routine clinical practice has the potential to elevate endodontic success rates, especially in complex cases, provided practitioners receive adequate training and technology access.

Index Terms — Artificial Intelligence, Cone Beam computed tomography, Computer added Design

1. Introduction

Over recent decades, dentistry has undergone a significant transformation with the integration of digital technologies and minimally invasive techniques, enhancing diagnostics, treatment planning, and outcomes.[1] In endodontics, where precision and preservation of tooth structure are critical, these advancements are particularly impactful.[2] A major challenge in this field is Pulp Canal Obliteration (PCO), often caused by trauma, aging, or previous treatments, leading to calcification that complicates canal access.[3] Effective treatment requires precise canal location with minimal dentin loss.[4]

Guided Endodontics (GE), also known as Targeted Endodontic Treatment (TET), addresses this issue by combining CBCT, CAD/CAM, digital scanning, and 3D printing to create patient-specific guides for accurate and conservative access.[5,6]

2. 3D Printing in Endodontics

Three-dimensional (3D) printing, or additive manufacturing, has revolutionized dentistry by enabling the fabrication of precise, patient-specific tools across specialties, including endodontics.[7] By layering materials from digital files, it allows for rapid, cost-effective production tailored to individual anatomy.

In guided endodontics, 3D printing is crucial for producing access guides that direct instruments along pre-planned paths to locate calcified or complex canals.[8] Created using CBCT and intraoral scan data, these biocompatible guides support minimally invasive access, reducing perforation risk and preserving dentin.[9]

Additionally, 3D printing enables the fabrication of anatomical models from CBCT data, aiding in preoperative planning, simulation, and clinician training—especially in complex PCO or curved root cases.[10] These models enhance procedural accuracy and practitioner confidence.

Overall, 3D printing enhances the precision, predictability, and conservatism of guided endodontic treatment, while also advancing education and innovation in the field.

2.1 Types of 3D Printing Systems in Dentistry

Stereolithography (SLA) and Digital Light Processing (DLP) are most commonly used methods in dentistry for producing surgical and endodontic guides due to their high resolution and dimensional accuracy.[11] Both methods cure liquid photopolymer resin layer-by-layer—SLA using a laser, DLP using a digital projector—resulting in detailed, smooth, and anatomically precise components ideal for accurate intraoral fit.

In contrast, Fused Deposition Modeling (FDM), which extrudes thermoplastic filaments through a heated nozzle, is more affordable and accessible but offers lower resolution and a rougher finish, making it unsuitable for clinical-grade guides.[12] FDM is better suited for educational models or prototypes.

Thus, SLA and DLP remain the gold standards for clinical guide production in guided endodontics due to their superior accuracy, resolution, and reliability.

2.2 Workflow of 3D Printing in Guided Endodontics

After virtual planning, the finalized STL file of the endodontic guide is processed using slicing software like PreForm (Formlabs) or Chitubox (DLP/LCD printers), which defines printing parameters such as layer thickness, orientation, and support structures—factors crucial for accuracy and surface quality. The guide is then printed using SLA or DLP technology, followed by essential post-processing steps. These include washing in isopropyl alcohol (IPA) to remove uncured resin and UV light curing to ensure full polymerization, mechanical strength, dimensional stability, and biocompatibility.[13]

Appropriate Material selection is crucial for ensuring guide safety and accuracy. Biocompatible resins like NextDent Surgical Guide and Formlabs Dental SG—both ISO Class I certified—are widely used for their translucency, precision, and suitability for temporary intraoral use.[14] These properties make them ideal for endodontic and implant guides where accuracy and tissue compatibility are essential.

Fig 1. TRIOS Intraoral Scanner (3Shape, Copenhagen, Denmark)

2.3 Clinical Applications of 3D Printing in Endodontics

3D printing has significantly broadened clinical and educational applications in endodontics by enabling the fabrication of customized tools that enhance accuracy and outcomes. Key innovations include:

- Access guides for calcified canals in pulp canal obliteration cases, allowing minimally invasive entry with reduced risk of perforation or dentin loss.
- Templates for apical surgery to accurately localize and resect root apices, especially in complex anatomies or retreatment cases.
- Anatomical teaching models based on patient-specific CBCT data, offering realistic simulations for training and preclinical education.
- Templates for autotransplantation that guide precise recipient socket preparation, improving fit and success rates.

Studies confirm that 3D printing improves the predictability, safety, and efficiency of endodontic and surgical procedures while reducing iatrogenic risks in challenging cases.[15,16]

3. Guided Endodontic Surgery and Autotransplantation

3D-printed anatomical models play a vital role in endodontic surgical planning by allowing clinicians to simulate complex procedures—such as root-end resections, osteotomy planning, and autotransplantation socket preparation—prior to patient treatment. These anatomically accurate replicas help refine surgical techniques, reduce intraoperative errors, and minimize unnecessary trauma, leading to more conservative and effective outcomes.[17]

A key example is Krug et al., who used 3D-printed guides in guided apical surgery. Their study showed that these templates enabled precise osteotomies and root resections, resulting in predictable lesion access and favorable healing, while preserving critical anatomy.[18]

4. Static Guided Endodontics

Static Guided Endodontics (SGE) is a breakthrough technique for managing complex cases like pulp canal obliteration (PCO) or altered canal anatomy. It uses pre-fabricated, 3D-printed guides to facilitate minimally invasive and highly accurate access cavity preparation.[19]

The process begins with CBCT and surface scans, which are digitally merged to form a 3D model. This enables precise virtual planning of the drill path and depth, targeting the canal lumen while preserving healthy dentin.The guide, printed in high resolution, fits securely over the tooth and includes a metal or plastic sleeve to direct the bur along the planned trajectory. This improves accuracy, reduces chairside time, and minimizes iatrogenic errors like perforation or canal deviation.[20]

SGE promotes conservative preparation and has proven especially effective in cases where traditional access is risky or unreliable.

4.1 Indications for Static Guidance

Static Guided Endodontics (SGE) is highly effective in complex endodontic cases where conventional techniques may increase risks. Its precision and conservative nature make it ideal for the following indications:

- **Calcified anterior teeth**: In pulp canal obliteration from trauma or aging, SGE allows accurate canal access with minimal dentin loss and reduced perforation risk.[21]
- **Dens invaginatus**: SGE aids navigation through complex canal morphologies using preplanned paths, enhancing cleaning while minimizing complications.[22]
- **Re-treatment or failed access**: In cases with altered anatomy or scarring, SGE offers a predictable canal path, avoiding further structural damage.[23]
- **Apical surgery**: For conservative osteotomies, SGE ensures precise apex localization and minimal bone removal, leading to less trauma and better healing.[24]

These applications underscore SGE's value in both surgical and nonsurgical endodontics where accuracy and tissue preservation are critical.

4.2 Advantages of Static Guided Endodontics [26]

Static Guided Endodontics (SGE) provides several key advantages, especially in complex or high-risk cases:

- **High precision in canal localization**: Integration of CBCT and surface **scans** enables accurate planning and targeting of the canal, improving success rates in calcified or distorted anatomies.[25]
- **Reduced chair time**: Preplanned access allows for efficient, single-step preparation, minimizing procedure duration and patient discomfort.
- **Conservation of dentin**: The guided path avoids unnecessary removal of coronal and radicular dentin, preserving tooth strength and longevity.
- **Lower risk of perforation**: The precise trajectory reduces the chances of lateral or apical perforations, enhancing safety.
- **Increased clinical confidence**: Especially beneficial for less experienced clinicians, SGE offers a predictable workflow, improving outcomes and reducing stress.[26]

4.3 Steps of Static Guide Workflow

The clinical implementation of Static Guided Endodontics (SGE) follows a structured digital workflow that integrates imaging, design, and fabrication to create a patient-specific access guide.[27] Key steps include:

1. **CBCT Scanning**: High-resolution 3D imaging provides detailed visualization of root canal anatomy, including calcifications and periapical structures.
2. **Surface Scanning**: Intraoral or desktop scanners capture accurate dental arch topography for precise guide fit.
3. **Image Merging & Drill Path Planning**: CBCT (DICOM) and surface scan (STL) data are superimposed using software to plan a conservative, anatomically safe access path.
4. **Guide Design (CAD)**: The drill trajectory is integrated into a custom-fitted guide design using CAD software, including a drill sleeve and stable base.
5. **3D Printing & Post-Processing**: The guide is printed using SLA or DLP technology, followed by Isopropyl alcohol washing, UV curing, and sterilization to ensure accuracy and biocompatibility.
6. **Clinical Application**: The guide is seated intraorally, and a guided bur is used to follow the planned trajectory, ensuring precise, conservative canal access.[26]

4.4 Clinical Accuracy and Evidence

An increasing number of studies confirm the accuracy, efficacy, and clinical success of Static Guided Endodontics (SGE):

- **Zehnder et al. (2016)** reported angular deviations $<2°$ and linear deviations <0.5 mm in vitro, demonstrating high precision in canal localization—especially valuable in calcified or complex anatomies.[28]
- **Buchgreitz et al. (2019)** achieved a 100% success rate in locating canals of severely calcified maxillary incisors using SGE, highlighting its reliability over conventional techniques.[29]
- **Krug et al. (2020)** documented successful healing in a rare case of dentin dysplasia treated with SGE, showcasing its minimally invasive potential in managing atypical cases.[30]

4.5 Static Guided Endodontics in Posterior Teeth

While Static Guided Endodontics (SGE) is highly effective in anterior teeth, its use in posterior teeth poses challenges due to:

- Limited interocclusal space, restricting vertical access and guide placement.
- Angulated, multi-rooted anatomies, complicating drill path planning.
- Guide stabilization issues, stemming from the curved posterior arch and reduced support surface.

To address these, several innovations have emerged:

- **Open-sleeve designs** enhance drill access and allow greater flexibility in confined spaces.
- **Composite-based intracoronal guides**, as described by Buchgreitz et al. (2021), improve fit and stability by anchoring within the tooth cavity, making them suitable for posterior applications.[31]

5. Dynamic Navigation in Endodontics

Dynamic Navigation Endodontics (DNE) is an advanced, real-time, computer-assisted technique that guides access cavity preparation with live visual feedback. Unlike pre-fabricated static guides, DNE allows intraoperative flexibility, enabling clinicians to adapt in response to anatomical variations.

Adapted from stereotactic systems in neurosurgery, DNE was first applied in implantology and is now increasingly used in endodontics—particularly in cases of pulp canal obliteration, complex anatomy, or surgical interventions.[32]

The system tracks the bur's position in 3D relative to the patient's CBCT scan, offering augmented visualization for precise, real-time navigation—ideal for complex, high-stakes procedures requiring both accuracy and adaptability.[33]

5.1 Core Components of Dynamic Navigation Systems

Dynamic Navigation Endodontics (DNE) integrates advanced hardware and software to provide real-time, image-guided navigation during endodontic procedures. Key components include:

- **CBCT Imaging (DICOM)**: Serves as the anatomical reference, enabling 3D visualization of root canal and bone structures.
- **Stereoscopic Tracking Camera**: Monitors instrument and patient positions in 3D using dual-camera triangulation.
- **Reflective Tracking Arrays**: Infrared markers attached to the patient and handpiece enable precise spatial localization.
- **Navigation Software & Monitor**: Processes tracking data and overlays live drill position onto the CBCT scan, offering continuous visual guidance.

Popular systems like Navident (ClaroNav) and X-Guide (X-Nav Technologies) are increasingly adopted for their precision, adaptability, and effectiveness in managing complex cases such as calcified canals and apical surgeries.[34]

5.2 Workflow of Dynamic Navigation

The clinical workflow of Dynamic Navigation Endodontics (DNE) ensures precise and adaptable canal access through the following key steps:[35]

1. **CBCT Acquisition & Data Import**: A high-resolution CBCT scan is taken and imported into the navigation software (DICOM format), forming the basis for planning.
2. **Virtual Drill Path Planning**: The clinician defines the ideal bur trajectory—entry point, angulation, and depth—aligned with the canal anatomy.
3. **System Calibration**: Tracking arrays on the patient and handpiece are calibrated with the navigation camera to synchronize real-world positioning with the software.
4. **Live Navigation**: Access preparation is performed under real-time visual guidance, with the bur position displayed over the CBCT scan for on-the-fly adjustments.
5. **Postoperative Verification**: Radiographs or follow-up CBCT confirm accurate canal localization and procedural success.

This workflow highlights DNE's precision, adaptability**,** and minimally invasive advantage, especially in complex endodontic scenarios.

5.3 Applications in Non-Surgical Endodontics

Dynamic Navigation Endodontics (DNE) offers significant clinical value in managing complex endodontic scenarios, thanks to its real-time guidance and intraoperative flexibility:

- **Calcified Anterior Canals**: DNE is highly effective for pulp canal obliteration in anterior teeth, where traditional methods risk perforation. Torres et al. (2021**)** reported a 93% success rate in canal localization using DNE—even by less experienced operators—demonstrating its accuracy and reduced learning curve.[36]
- **Anatomic Variations**: In cases involving sharp curvatures, deep canals, or atypical root morphology, DNE allows live adjustment of angulation and depth, unlike static guides. This adaptability is especially valuable in posterior teeth and surgical cases with limited access.

By improving precision, safety, and operator confidence, DNE elevates treatment outcomes in anatomically challenging or high-risk endodontic cases.

5.4 Applications in Surgical Endodontics

In addition to locating calcified canals, Dynamic Navigation Endodontics (DNE) is proving increasingly valuable in endodontic microsurgery and anatomically sensitive procedures due to its real-time visual guidance and precision:

- **Apicoectomy & Osteotomy**: In surgical root-end resections, DNE enhances control over angulation and depth. Dianat et al. (2021) reported that DNE significantly reduced angular and linear deviations compared to freehand techniques, improving bone preservation, operative efficiency, and healing predictability.[37]
- **Avoidance of Vital Structures**: Real-time trajectory tracking helps clinicians To avoid critical anatomy (e.g., maxillary sinus**,** inferior alveolar nerve**,** mental foramen), reducing the risk of neurovascular injury and complications.[38]

DNE thus supports safe, conservative**,** and accurate surgical interventions—even in anatomically demanding cases.

6. Clinical Applications and Evidence

Recent studies have demonstrated the broad clinical applicability of guided endodontics, particularly in complex scenarios. Both Static (SGE) and Dynamic (DNE) systems have shown superior precision and minimal invasiveness in cases where conventional methods are risky:

- Calcified canals**,** dens invaginatus, and Dilacerated roots benefit from improved visualization and targeted access.
- Guided systems also enable safe, conservative fiber post removal, minimizing dentin damage.
- In endodontic microsurgery (e.g., apicoectomy, osteotomy), navigation enhances apex localization and reduces iatrogenic trauma.

Overall, SGE and DNE outperform freehand techniques in accuracy**,** efficiency, and operator confidence, as supported by increasing clinical and in vitro evidence.[39]

6.1 Pulp Canal Obliteration (PCO)

The effectiveness of guided endodontic techniques has been well-supported by clinical and experimental studies, demonstrating high precision**,** reliability, and applicability across varying levels of clinical expertise—especially in managing calcified canals.

Static Guided Endodontics (SGE):

- **Zehnder et al. (2016)** reported mean angular and linear deviations of 1.81° and <0.5 mm, respectively, with 100% canal location in calcified teeth and no perforations, confirming high in vitro accuracy.[40]
- **Buchgreitz et al. (2019)** treated 50 severely calcified maxillary incisors using static guides and achieved 100% success in canal identification, with no procedural errors, validating SGE's clinical safety and efficacy.[41]

Dynamic Navigation Endodontics (DNE):

- **Torres et al. (2021)** evaluated DNE in operators of varying experience levels, achieving a 93% success rate in locating calcified canals. This emphasizes DNE’s ability to enhance accuracy and reduce technique sensitivity, making it valuable for clinicians at all skill levels.[42]

6.2 Endodontic Microsurgery

Further evidence highlights the utility of guided endodontics in surgical procedures, particularly in improving the precision and predictability of apicoectomy and osteotomy.

- **Ackerman et al. (2019)**, in a cadaver study, found that static guidance significantly improved the accuracy of osteotomy location and angulation compared to freehand techniques, allowing for more controlled apicoectomies and minimizing damage to adjacent structures.[43]

- **Dianat et al. (2021)** assessed Dynamic Navigation Endodontics (DNE) in root-end resections and observed enhanced surgical accuracy, shorter operative times, and fewer intraoperative complications, underscoring DNE's value in efficient and safe microsurgery.[44]

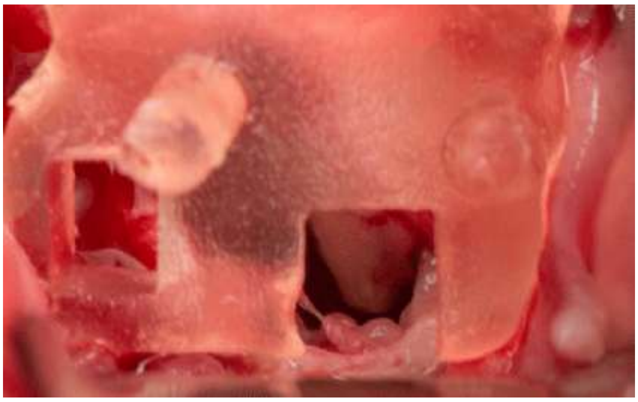

Fig.2: Location of Apices using Surgical Guide

7. Future Directions in Guided Endodontics

Guided endodontics is evolving rapidly, and future innovations promise to make procedures even more precise, biologically integrated, and accessible. The convergence of digital design, artificial intelligence (AI), virtual simulation, and regenerative strategies holds immense potential for expanding the boundaries of conservative and surgical endodontic therapy.

7.1 3D Bioprinting and Regenerative Endodontics

- The future of endodontics includes bioprinting of pulp–dentin complexes, scaffold-mediated tissue regeneration, and pulp stem cell integration into printed templates. Experimental studies have already demonstrated the feasibility of bioengineered pulp tissue constructs using hydrogel matrices and 3D-printed scaffolds.
- Though not yet clinically applied, these advances aim to restore vitality to immature or necrotic teeth, thereby moving from intervention to true tissue regeneration.

7.2 Artificial Intelligence (AI) in Endodontics

AI can be integrated into CBCT interpretation and guided planning software for:

- Automated canal identification and segmentation
- Path optimization using neural networks
- Real-time risk assessment for perforation or structural compromise

These systems will assist clinicians by reducing planning time and human error, especially in complex cases.

7.3 Haptic and Virtual Reality (VR) Simulation

VR-based simulators and haptic feedback systems are being used in dental education to train clinicians in guided procedures. These platforms allow:

- Simulated CBCT-based endodontic access planning
- Real-time feedback on angle, pressure, and trajectory
- Error tracking and performance metrics

They are particularly useful for preclinical training and skill refinement in postgraduate programs.

8. Limitations

Despite its high precision and minimally invasive nature, guided endodontics has several limitations. Static guided endodontics (SGE) lacks intraoperative flexibility, making it unsuitable for cases where canal anatomy varies or unexpected clinical findings arise. It also poses challenges in posterior teeth due to limited interocclusal space and difficulties in guide stabilization. Dynamic navigation, while more adaptable, requires expensive hardware, specialized training, and is sensitive to tracking errors from patient movement or visual obstruction. Both techniques face limitations in navigating curved canals, and their effectiveness can be compromised by poor CBCT quality, misalignment during data merging, or operator error. Additionally, the high cost, steep learning curve, and limited evidence for multi-canal applications restrict their routine use in general practice.

9. Conclusion

Guided Endodontics represents a significant advancement in conservative and surgical endodontic care. By merging CBCT, CAD/CAM, 3D printing, and digital navigation systems, clinicians are now equipped with tools that offer unparalleled precision in accessing obliterated, complex, or surgically challenging root canal systems.

Static Guided Endodontics (SGE) has proven especially effective in anterior teeth with calcified canals, while Dynamic Navigation Endodontics (DNE) offers enhanced intraoperative flexibility in posterior and surgical applications. The growing body of clinical evidence, including controlled studies and case reports, supports the safety, efficiency, and success of guided approaches in reducing iatrogenic errors and improving treatment outcomes.

However, limitations related to cost, anatomical access, and operator training remain important barriers to universal adoption. Future advancements in bioprinting, AI-driven planning, virtual simulation, augmented reality, and cloud-based collaboration promise to overcome many of these challenges and expand the scope of guided therapy.

With appropriate case selection, technical proficiency, and ethical considerations, guided endodontics will continue to transform how clinicians approach the most complex endodontic procedures—elevating the standard of care and patient outcomes in the years to come.

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