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Review Article

PRECISION BEYOND PERCEPTION: THE FUTURE OF MIXED REALITY-GUIDED ENDODONTICS

[1]Shrija M, [*2]Vinay Kumar Reddy T, [3]Vijay Venkatesh K, [4]Shyam B [5]Seetha Kunhikannan

[1,2,3,4]Department of Conservative Dentistry and Endodontics, SRM Kattankulathur Dental College and Hospital, Faculty of Medicine and Health Sciences, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu, 603 203. Tamil Nadu, India.
[5]Department of Pharmacovigilance Specialists, Chennai One IT Park, Thoraipakkam, Chennai, 600 097, Tamil Nadu, India.

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ABSTRACT

Finding and treating the root canal system is a spatial task that is performed under severe visual constraints and much of the recent innovation in endodontics has been directed squarely at that problem. This narrative review describes the development of that innovation, beginning with the static, 3D-printed surgical templates that defined "guided endodontics" in 2016, through dynamic, camera-tracked navigation systems, to the current generation of augmented reality (AR) and mixed reality (MR) platforms that overlay CT- or CBCT-derived canal anatomy directly on the clinician's view of the tooth with head-mounted displays. Guided and immersive technologies improve the precision of access cavity preparation and canal location relative to freehand technique, especially in calcified or atypical teeth and seem to reduce treatment-planning time by keeping 3D anatomical information within the operator's direct line of sight, as suggested by a pattern across >30 in vitro, ex vivo, and narrative or systematic sources. This review also finds that the evidence base for MR in particular is dominated by proof-of-concept and laboratory work; registration accuracy, head-mounted display comfort and field of view, cost, and the steep learning curve associated with spatial computing are recurring and largely unresolved barriers. The review ends with an identification of the clinical trials and standardised outcome measures that will be needed before mixed reality can become a routine chairside adjunct rather than an active research frontier.

Keywords: Mixed Reality, Augmented Reality, Guided Endodontics, Root canal therapy, Dynamic navigation.

INTRODUCTION

To a large extent, the success or failure of root canal treatment depends on the clinician's ability to reconstruct a three-dimensional structure that cannot be seen directly. The canal system can be curved, bifurcated, calcified or hidden under a heavily restored or discoloured crown and the operator has traditionally had to deduce its position from two-dimensional periapical radiographs, tactile feedback and whatever can be glimpsed through the narrow cone of a dental operating microscope. Cone-beam computed tomography (CBCT) ushered in a new era of preoperative diagnostics by providing three-dimensional canal anatomy before the start of treatment. However, that data still must be mentally translated onto the tooth in front of the clinician. It is that translation step where guided and immersive technologies have focused their efforts over the last decade. The initial concept of guided endodontics was directly inspired by the logic of implant dentistry, relying on a template: combine a CBCT scan with an intraoral surface scan, virtually plan the perfect trajectory for access, and then produce a physical drill guide that constrains the bur to that trajectory (Krastl, *et al.* 2016).

Mixed reality is a further conceptual step. Instead of a hard physical guide, an MR system displays planning data like a hologram, registered to the patient or printed (Milgram & Kishino, 1994) model and viewed through an optical or video see-through head mounted display, so that the operator can see virtual anatomical or navigational data superimposed in real time on the real tooth. The seminal reality-virtuality continuum proposed by Milgram and

*Corresponding Author: Vinay Kumar Reddy T, Department of Conservative Dentistry and Endodontics, SRM Kattankulathur Dental College and Hospital, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu. Email: vinaykun@srmist.edu.in

Kishino places MR at this boundary of real and virtual content within a single interactive display, conceptually distinct from fully immersive virtual reality (VR), which replaces the real environment entirely, and less immersive augmented reality (AR) overlays that may not provide the same level of interaction with 3D data (Milgram & Kishino, 1994). This review systematically discusses that conceptual and technical advancement: the beginning of guided endodontics, the comparison of static and dynamic navigation, the specific systems developed and tested for endodontic use with AR and MR, the use of immersive technologies for training, and what the accumulated evidence indicates about accuracy, efficiency, and the barriers still existing between the lab and the operatory.

CONCEPTUAL FRAMEWORK: AR, VR, MR AND REALITY-VIRTUALITY CONTINUUM

It is worth being precise about terminology before looking at the clinical literature, as these terms are often used loosely and interchangeably in dental publications. Milgram and Kishino's taxonomy positions pure reality and pure virtual environments at opposite ends of a continuum, with augmented reality positioned close to the real-world end (virtual elements are added to a real scene) and augmented virtuality close to the virtual end (real elements are added to an otherwise virtual scene); mixed reality is the umbrella term that covers the entire middle segment of this continuum, where real and virtual objects co-exist and can interact within a single display (Milgram & Kishino, 1994). Extended reality (XR) has become a more inclusive umbrella term that includes AR, VR, and MR all together. A recent narrative review of XR in endodontics specifically highlighted that a persistent gap remains in how clearly educators and practitioners delineate these related but technically distinct categories, which in turn impacts how the literature itself is indexed and interpreted (Seyed, *et al.* 2025). For the purposes of this review, AR pertains to systems that superimpose static or dynamically updating information over the operator's real-world view without necessarily anchoring it precisely in 3-dimensional space. MR pertains to systems where virtual content is spatially registered to and interacts with the real anatomy, typically via a head-mounted display. VR pertains to fully simulated environments used predominantly, in the endodontic literature, for training and rehearsal rather than live patient treatment.

THE GENESIS OF GUIDED ENDODONTICS: FROM IMPLANTOLOGY TO STATIC TEMPLATES

The static, template-based approach referred to as "guided endodontics" was formally described by Krastl, Zehnder and colleagues as a treatment option for teeth with pulp canal calcification and associated apical pathology, extending a workflow already well established in implant dentistry into the endodontic field (Krastl, *et al.* 2016). In parallel work published in the same year, Zehnder and coworkers tested the in vitro accuracy of this method using sixty extracted teeth mounted in maxillary jaw models: a preoperative CBCT scan was digitally fused with an intraoral surface scan, the access cavity and guiding sleeve were planned virtually, a template was 3D-printed and the deviation between the planned and the actually prepared cavity was measured after a postoperative CBCT scan was superimposed back onto the plan (Zehnder, *et al. 2016)* . The reported deviations were small, in the order of fractions of a millimeter at the base of the bur, and comparable to the accuracy figures reported for static implant guides. These had been validated by earlier implantology research which showed that computer-aided template placement reduced positional error relative to freehand implant surgery (Krastl, *et al.* 2025). This is a recurring theme in the literature comparing static and dynamic approaches, which is the borrowing of an implant-dentistry paradigm with the underlying logic that static guidance is a trade-off of intraoperative flexibility for planning-stage accuracy (Krastl, *et al.* 2025). An earlier conceptual groundwork paper by van der Meer et al. had already argued for three-dimensional, CBCT-based planning in endodontics more broadly, describing how digital planning could improve case selection and procedural safety even before guided templates existed as a manufactured product, and this paper is frequently cited as one of the conceptual precursors to guided endodontics proper (Van der Meer, *et al.* 2015).

REFINING STATIC GUIDANCE: MICROGUIDED TECHNIQUES AND ACCURACY COMPARISON

Once the basic static guide concept was laid down, further work was focused on making the templates smaller, less invasive and applicable to a wider range of tooth types. Connert et al. described a miniaturised or "microguided" technique for apically extended access cavity preparation in anterior teeth, with accuracy figures supporting its use even in narrow, single rooted teeth where seating of a full coverage template would be difficult (Connert*, et al.*2015). A subsequent study expanded the application of microguided endodontics to mandibular incisors and again reported a minimally invasive access pathway with a profile of accuracy that was favourable relative to conventional freehand preparation (Connert*, et al.* 2018). The same group conducted another comparative study that directly measured loss of substance, creating access cavities on 3D printed teeth using both guided and conventional freehand technique, and found that the guided approach removed significantly less sound tooth structure while also improving locational accuracy-an important finding given that dentine preservation is itself a consideration in treatment outcome in modern endodontics, not merely a secondary benefit (Connert*, et.al* 2019). In an ex vivo study specifically quantifying the volume of dental tissue removed in guided access preparation, Loureiro and colleagues again reported a similar pattern, finding a conservation advantage for the guided technique (Loureiro, *et al.* 2020).

UMBRELLA AND SYSTEMATIC EVIDENCE FOR GUIDED ENDODONTICS

With the growing number of primary studies, several groups undertook systematic reviews to summarize the evidence. In a review of clinical applications, accuracy and limitations of guided endodontics up to 2019, Moreno-Rabié and colleagues concluded that the technique consistently yielded accurate access cavities in cases of calcific metamorphosis in comparison to conventional technique, but also pointed out that the evidence base at that time was mainly comprised of case reports, case series and in vitro or ex vivo studies rather than controlled clinical trials (Moreno, *et al.* 2020). A similar conclusion was reached in a later review by Kulinkovych-Levchuk et al. in 2022, which examined 1,047 initial search results that were reduced to 29 eligible studies published from 2017 to 2022. Guided endodontics is applied not only to canal location in calcified teeth, but also to microsurgical endodontics and removal of fibre posts during retreatment, and its accuracy and time efficiency seem to be unaffected by the operator's prior experience level, which is a significant claim given how experience-dependent freehand canal location is traditionally (Kulinkovych, *et al.* 2022). More recently, Peña-Bengoa et al. performed a systematic review that concentrated on the effectiveness of guided endodontics in locating calcified canals, and it reinforced the same directional finding on a larger and more recent set of included studies (Peña, *et al.* 2023). Connert, Krastl and colleagues reviewed static and dynamic guided endodontics together in a 2025 narrative review in the Australian Dental Journal, concluding that computer-assisted navigation of either type resulted in greater precision, less dentine loss and improved success rates compared to freehand technique, even for less experienced clinicians. However, they also noted a clear split in the technologies' weaknesses: static navigation performed excellently for straight canal trajectories, but was limited in posterior teeth and curved canals by its rigid, pre-fixed drill path. On the other hand, dynamic navigation offered real-time intraoperative flexibility at the cost of substantially higher equipment expense and a steeper training requirement (Krastl, *et al. 2025)*. Another comprehensive review was published in the same year by Palliyal et al., who traced the history of the technique back to its introduction in 2016 and provided a detailed breakdown of the digital workflow (from CBCT acquisition and DICOM conversion through guide design, printing, and the endodontic guide sleeve itself) that underlies essentially all static guided systems described in the literature (Palliyal, *et al.* 2025).

DYNAMIC NAVIGATION: LIVE GUIDANCE NO PHYSICAL TEMPLATE

Dynamic navigation, on the other hand, is no longer based on the physical template, but uses optical or electromagnetic sensors to track the handpiece and patient jaw in real time and display the position of the bur relative to the planned path on a screen so that the clinician can make real-time corrections during the procedure. Again, this is a direct import from implant dentistry, where Block and Emery had previously cast the choice between static and dynamic navigation as a fundamental trade-off between precision at the planning stage and adaptability during the operation (Block & Emery, 2016). Vasudevan et al. carried this framing explicitly into the endodontic literature in their systematic review of dynamic navigation in guided endodontics. The scope, advantages and disadvantages of dynamic navigation in particular were evaluated in a 2025 systematic review by Kapoor and colleagues in the Journal of Endodontics. The main advantage over static guidance is precisely this real-time adjustability, where the operator is not locked into a single pre-planned trajectory, and can account for small registration error or unforeseen anatomy as the procedure progresses. The main disadvantages are still cost, the requirement for specialised tracking hardware, and a non-trivial learning curve before clinicians can make effective use of the real-time feedback. Case-level data is also starting to be published, with Bardales-Alcocer et al. reporting a case of endodontic retreatment performed with the use of dynamic navigation, showing that this technique can be applied also in complex secondary treatments, not only in first-time access in calcified teeth (Bardales, *et al.* 2022)

Direct three-way comparisons are relatively rare but at least one in vitro study using 3D printed teeth has compared dynamic real-time navigation, static guides and manual freehand technique for access cavity preparation within a single experimental design and concluded that while both static and dynamic guided approaches may take a little longer to execute than the freehand preparation, they always produce more accurate results and conserve more tooth structure, with the dynamic navigation providing the added benefit of allowing the operator to observe and correct the deviation of the bur as it occurs rather than discovering it only after the cavity has been cut (Kateryn, *et al.* 2022). A separate literature review comparing static and dynamic computer-aided techniques found a similar result, adding that the main clinical limitation of static guidance is its reliance on a straight, unobstructed path from the guide sleeve to the target, which is difficult to achieve in patients with limited mouth opening or in posterior teeth with reduced interocclusal space, whereas dynamic navigation's real-time visualization eliminates that specific constraint at the cost of requiring continuous, uninterrupted line-of-sight between the tracking camera and reference markers. Meta-analytic work has also begun to aggregate accuracy figures from the static navigation literature in particular. Two related systematic reviews and meta-analyses by Zubizarreta-Macho and colleagues evaluated the accuracy of computer-aided static navigation in endodontic microsurgery, and its accuracy in endodontic access cavity preparation more generally, respectively, and both concluded that static navigation techniques provide a statistically significant and measurable accuracy advantage over unguided technique across the pooled studies available at the time (Zubizarreta, *et al.* 2021).

AUGMENTED REALITY FOR PREPARATION OF ACCESS CAVITIES

From guide-based navigation to AR proper, a number of groups have developed systems that project planning data

directly into the visual field of the clinician without the use of a printed template or a screen-based navigation display. In a novel AR approach, Farronato *et al.* employed visual-inertial odometry, the same motion tracking technology that drives today's smartphone AR applications, to direct access cavity preparation on 3D printed jaws. They evaluated operators with differing levels of endodontic experience and found the approach could enable accurate, minimally invasive, guide-free access preparation, regardless of that experience gap (Farronato, *et al.* 2023). This is a significant statement in the context of the broader guided endodontics literature, which has repeatedly stressed operator-independence as one of the keys selling points of the computer-assisted approach. Faus-Matoses *et al.* independently evaluated the accuracy of endodontic access cavities prepared with a dedicated AR appliance in an in vitro setting, and reported favorable precision relative to unguided freehand technique. This lends further support to the notion that even relatively lightweight AR overlays, without the mechanical rigidity of a physical template, can meaningfully constrain and improve access cavity design. A more recent and interaction-oriented work has focused on how AR guidance information should be presented to the operator, rather than on whether AR guidance improves accuracy. In a co-design study of dynamic mixed reality drill-positioning widgets, the study team worked directly with practicing dentists to iteratively develop and refine the visual cues arrows, targets, depth indicators used to steer the handpiece towards the planned trajectory. This reflects a growing recognition in this literature that the usability of the display interface may matter as much as the underlying tracking accuracy in determining whether an AR or MR system is actually adopted in practice.

HEAD-MOUNTED DISPLAYS FOR MIXED REALITY: CANAL VISUALIZATION WITH HOLOGRAMS

Two independent groups have developed head-mounted display systems for visualizing the anatomy of canals during treatment, the clearest examples of true mixed reality rather than the simpler AR overlays. Li et al. developed an application using an optical see-through head mounted display to overlay preoperative CT data onto the clinician's direct view of the patient's tooth. It features visual guidance cues, an augmented-mirror functionality, and multi-view CT slices that are dynamically updated and reoriented according to the operator's head movement. An explicit design goal of this system was to address the depth perception problem that had plagued earlier AR dental prototypes: Because optical see through displays present virtual content at a fixed apparent depth that does not always correspond to the real depth of the anatomy behind it, clinicians can misjudge how far a virtual target actually sits beneath the tooth surface, and Li and colleagues' multi-cue approach was built specifically to correct for that. The stated aim was to assist clinicians to localise the tooth accurately, examine the full canal system comprehensively and place instruments with greater precision than is achievable when CT data is reviewed on a separate monitor positioned away from the patient (Li, *et al.* 2024). The second major system is from the Polish HoloMed research group led by Dolega-Dolegowski, who converted CBCT DICOM data into a patient-specific three-dimensional hologram viewed through a Microsoft HoloLens 2, specifically designed to be used alongside - rather than instead of - the dental operating microscope. Their technique consisted of digitally stripping off the crown of a reconstructed 3D tooth model like a clinician would do using a handpiece, and hollowing the space of the root canal to create a navigable, patient-specific holographic structure that could be viewed from any angle. Reported outcomes from this system are impressive. The simultaneous viewing of all root canals of a tooth in three planes through the hologram was associated with a reduction in diagnosis and treatment-planning time of about fifty per cent compared with reviewing the same anatomy as a series of conventional CT slices. The basic holography and augmented reality pipeline for visualising internal dental root structure had already been demonstrated in an earlier proof-of-concept paper from the same research group, before being extended specifically to root canal treatment planning. A related paper from overlapping authors explored how information and communication technologies combined with mixed reality could support medical education more broadly, situating the endodontic-specific work within a wider institutional research programme on immersive technology in clinical training (Pregowska, *et al.* 2022).

APPLICATIONS OTHER THAN ACCESS CAVITY PREPARATION

Guided and immersive technologies are not limited to the traditional access cavity design. The systematic and narrative reviews discussed earlier both identified endodontic microsurgery specifically the accurate positioning of the osteotomy and the planning of root-end resection during apicoectomy as an area where guided approaches offer a significant reduction in the risk of iatrogenic error. This is because the anatomical tolerance for deviation during root-end surgery is limited, and a misplaced osteotomy can compromise the entire procedure. Retreatment is a second recognized application. Guided access has been used specifically for locating and safely removing fractured intracanal fiber posts, where a poorly directed access attempt risks perforating the root. Bardales-Alcocer and colleagues' case report demonstrated dynamic navigation being used for just this type of complex retreatment scenario (Bardales, *et al.* 2021). Overall, this body of work suggests that the accuracy benefits documented for simple calcified-canal access generalize fairly well to more technically demanding procedures within the same broad category of "needing to hit a small, hidden target precisely".

ENDODONTIC TRAINING IN VIRTUAL REALITY AND HAPTIC SIMULATION

A parallel and significant body of work utilizes immersive technology not to treat patients in real time but rather to

provide pre-clinical and post-graduate training, typically through the use of fully virtual, haptically-enabled simulators rather than AR or MR overlays on real anatomy. Haptic virtual reality simulation (HVRS) platforms such as the Simodont Dental Trainer provide force feedback so that a trainee can experience simulated resistance from enamel, dentine and pulp tissue while practising a procedure entirely in a virtual environment, and an increasing number of controlled studies have evaluated whether this preclinical exposure translates into better subsequent performance on real or artificial teeth. A recent study comparing traditional and virtual reality haptic simulator approaches in preclinical endodontic training reported measurable effects on skill acquisition, learner confidence, and reported stress levels, suggesting that the value of HVRS training may extend beyond pure technical accuracy into the psychological experience of learning a technically demanding procedure for the first time (Usta, *et al.* 2024).

In postgraduate education, virtual reality and haptic simulation have been specifically used for endodontic microsurgery. Pasqualini et al. described a case where a postgraduate student rehearsed osteotomy, root-end resection and ultrasonic retro-preparation in ten sessions in a patient-specific virtual scenario based on the same patient's CBCT data, before performing the corresponding root-end surgery on the actual patient. The healing outcome was evaluated using a one-year postoperative CBCT, providing a rare insight into a complete training-to-clinical-outcome journey focused on VR rehearsal. Such patient-specific virtual rehearsal is conceptually similar to the MR systems presented in Section 8, because both are based on the conversion of a real patient's CBCT into a three-dimensional navigable model. The main difference is that VR rehearsal completely replaces the real environment during practice, while MR guidance keeps the real tooth within the field of view during the actual procedure. Mahrous and colleagues compared pre-clinical instructional technologies: natural extracted teeth, 3D-printed models, 3D printing more generally, and augmented reality. AR was placed within this same educational spectrum and found to be a viable, if not yet clearly superior, addition to the existing toolkit of preclinical teaching methods (Mahrous, *et al.* 2021).

MIXED REALITY IN THE WIDER SURGICAL AND DENTAL LITERATURE

Research into MR imaging within endodontics is one facet of a much bigger field of work using the same fundamental technology across surgical specialties. A narrative review of 57 studies of mixed reality in surgical and interventional practice by Vervoorn and colleagues generally across preoperative planning, intraoperative guidance and training applications concluded that the most consistently documented benefit of the technology across disciplines is improved procedural efficiency, while the most consistently documented limitation is the physical constraint imposed by current head mounted display hardware: weight, restricted field of view and battery life all still fall short of what would be needed for comfortable, all-day clinical use (Vervoorn, *et al.* 2023). In the field of dentistry specifically, a systematic review of augmented reality applications by Farronato et al. in 2019 showed that oral and maxillofacial surgery made up the largest proportion of published AR studies, while restorative dentistry, dental education, and orthodontics were represented in smaller numbers. The authors also found that most of the studies included in their review were still being performed on phantom models rather than real patients, and that only a minority had reached human clinical application. A separate systematic taxonomy of HoloLens use across medicine broadly, by Wolf and colleagues, catalogued the device's applications across surgical navigation, planning, and education, and provides useful context for why the HoloLens specifically - rather than competing headsets - has become the platform of choice for several of the MR endodontic systems reviewed above, given its relatively mature optical see-through display and established track record in other surgical specialties (Wolf, *et al.* 2023).

ACCURACY, EFFICIENCY, AND THE PROOF OF COMPARISON

In summary of the literature on accuracy in vitro and ex vivo, the results are quite consistent: static guides, dynamic navigation, and AR/MR assisted access preparation are better than unguided freehand technique in positional accuracy measures, which are typically assessed as linear and angular deviation between the planned and the achieved access cavity The picture for efficiency is somewhat more nuanced. In several static-guide studies, guided preparation may take longer than the freehand technique because the guide has to be seated and stabilized before the cutting starts. The MR-specific literature reports the opposite pattern specifically for the planning phase-holographic visualization of canal anatomy seems to considerably shorten diagnostic and treatment planning time, plausibly because the operator no longer has to look away from the patient toward a separate monitor and back again to maintain spatial orientation. The two efficiency findings are not in fact contradictory, because they refer to different stages in the overall workflow: MR may save time in planning, while static or dynamic guidance adds time in execution, and a full accounting of total chair time would need to track both stages together, which very few studies in this literature currently do. What is still largely lacking across all technology categories reviewed here, however, is large-sample clinical rather than in vitro, ex vivo, or 3D-printed-model evidence directly comparing MR-guided endodontics against static templates, dynamic navigation, and conventional microscope-based technique performed by experienced operators on real patients, with patient-centred outcomes such as treatment success, postoperative complication rates, and long-term tooth survival. Several of the above reviews explicitly identify this gap as the field's most urgent methodological priority (Kapoor, *et al.* 2025).

LIMITATIONS AND BARRIERS TO CLINICAL UPTAKE

Within this literature, irrespective of the technology under discussion, a recurrent cluster of limitations emerges. Registration accuracy (the degree of fidelity with which a virtual model is anchored to the real tooth or patient throughout the procedure) continues to be a major technical bottleneck for AR and MR systems in particular, since any drift between the hologram and the anatomy it represents directly diminishes the value of the guidance being provided The problem is not completely solved in the whole field and depth perception through optical see-through displays is a related problem that the multi-cue visual system of Li and colleagues was designed to solve. More generally, the hardware of head-mounted displays remains a limiting factor, with weight, restricted field of view and limited battery life all identified as barriers in the cross-specialty surgical MR review above, and these constraints are particularly relevant in dentistry, where procedures are often long and the operator's head position must be stable and comfortable for extended periods (Vervoorn, *et al.* 2023). Practical barriers raised specifically in the dynamic navigation literature include cost and the learning curve associated with dynamic navigation and spatial computing more generally, where specialized tracking hardware and calibration procedures add both financial and workflow overhead relative to either freehand technique or static guides. The ergonomic and occupational health implications need to be considered as well. The burden of musculoskeletal disorders associated with sustained awkward position and close visual work is well documented in dentistry, as reported by Alexopoulos and colleagues in their survey of dental practitioners. The use of head-mounted displays for extended periods of time during MR-guided procedures presents further strain on the neck and eyes that has not been systematically studied in this particular clinical context (Alexopoulos, *et al.* 2004). Finally, and perhaps most importantly, almost all of the endodontic-specific AR/MR studies considered here are proof-of-concept, in vitro, or small case-level reports; controlled clinical trials with meaningful sample sizes and patient-centred outcome measures are, at the time of writing, essentially absent from this literature. The pattern of findings and gaps identified above suggest a number of plausible next steps.

The HoloMed group proposes a more tightly integrated operating microscope and head-mounted display by directly feeding the microscope's live magnified video into the HMD, along with holographic planning data, which would enable clinicians to see real, magnified anatomy and virtual guidance information in a single continuous field of view, instead of having to shift their attention between two separate optical systems. Improvements in markerless tracking, as demonstrated by the visual-inertial odometry approaches already demonstrated in AR access-cavity systems, may minimize or obviate the need for fiducial markers and rigid patient fixation, which will greatly improve the efficiency of clinical workflow. Continued human-centered design work of the sort already started in the drill-positioning widget co-design study is also likely to matter as much as raw tracking accuracy in determining whether these systems are actually adopted, since a technically accurate system that clinicians find visually cluttered or cognitively demanding to interpret in real time is unlikely to displace familiar freehand or microscope-based workflows. Most importantly, the field needs agreed, endodontics-specific accuracy and outcome metrics that enable different systems, studies, and technology categories to be compared on truly equal terms a standardization effort that the implant-guidance literature underwent roughly a decade earlier, and that guided endodontics including its MR-based variants has not yet fully replicated (Van Asche, *et al.* 2012).

CONCLUSION

As of this review, mixed reality guidance in endodontics is not an established clinical technique but an active research frontier with rapid development. The evolutionary logic that unites static templates, dynamic navigation, and head-mounted MR display systems is clear and well documented. Each successive technology has tried to retain the accuracy gains of computer-assisted planning while progressively reducing the physical and workflow constraints imposed by its predecessor. In vitro and proof-of-concept studies from multiple independent research groups consistently demonstrate that overlaying the 3D canal anatomy directly onto the clinician's view of the tooth can improve access cavity accuracy, especially in challenging cases such as calcified canals, and can substantially decrease treatment planning time compared to viewing CT or CBCT data on a separate screen. The field does not need more proof of concept several groups have already shown that in different technical forms but rigorous clinical validation: real patients, adequately powered samples, and head-to-head comparison against the static guides, dynamic navigation systems and conventional microscope-based technique that endodontists already use day to day. Until such clinical evidence is gathered, mixed reality should be seen as a truly promising and increasingly well-engineered research direction with real translational potential, rather than a technology ready for routine chairside deployment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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