

International Studies
in the field of
endodontics

October 2026



EDITOR
Prof. Dr. Sadullah KAYA

İmtiyaz Sahibi / Yaşar Hız
Yayına Hazırlayan / Gece Kitaplığı

Birinci Basım / Ekim 2026 - Ankara
ISBN / 978-625-321-298-8

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CHAPTER 1

DENTAL OPERATING MICROSCOPE

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1. Introduction

Successful dental care rests on three pillars: a correct diagnosis, meticulous clinical execution, and the greatest possible conservation of biological tissue. Yet the small dimensions of the oral cavity, the intricate configuration of the root canal system, and poor lighting make these goals hard to reach, above all in endodontics, a field that demands exceptional precision. The limited resolving capacity of the human eye adds to the problem. Without optical aid, two points can be told apart only when they are at least about 0.2 mm apart, whereas the dental operating microscope (DOM) lowers this limit considerably and brings far finer anatomical details into view (Bud et al., 2023). For this reason, the DOM now ranks among the decisive determinants of clinical success, particularly in endodontic work, where details invisible to the naked eye often dictate the result.

By pairing strong magnification with coaxial lighting, the DOM delivers a sharp and brightly lit image of the working area without sacrificing the sense of depth. As a result, the clinician can recognize minor anatomical variations on the pulp chamber floor, find calcified canal entrances, spot crack lines, and notice iatrogenic mishaps sooner and with greater certainty (Bonsor, 2015). Structures that tend to escape detection with traditional methods, the second mesiobuccal canal (MB2) being a typical example, are located more consistently with microscopic assistance, which in turn benefits the treatment result. Figure 1 provides an overview of the main endodontic uses of the dental operating microscope and the clinical benefits it offers.

The value of the DOM in endodontics is not confined to diagnosis; it supports every phase of the treatment that follows. Demanding procedures such as finding and negotiating calcified canals, identifying perforations and sealing them with biocompatible materials, removing fractured instruments, and shaping the root canal system in a more controlled way all become safer and more predictable when performed under magnification (Connert et al., 2017). In this way, microscope use lowers the likelihood of iatrogenic mistakes and makes treatment results more reproducible.

Modern dentistry is moving steadily toward minimally invasive care, the aim of which is to keep as much sound tooth tissue as possible. Because it gives the operator better visual control, the DOM limits the needless removal of tooth structure and is therefore central to carrying out minimally invasive endodontic procedures (Bud et al., 2023). In recent years, linking the DOM with cone-beam computed tomography (CBCT), digital surface scanning, and guided endodontic systems has broadened its range of clinical uses even further. Used together, these tools allow access cavities to be prepared with high accuracy and minimal invasiveness, especially in teeth with calcified canals or complicated root canal anatomy (Connert et al., 2017).

To summarize, the dental operating microscope should not be viewed simply as a magnifying instrument; it is a core technology that has reshaped both diagnosis and treatment in contemporary dentistry. Thanks to its outstanding image quality, the precision it affords, and its support for minimally invasive concepts, the DOM has become a component of modern endodontic practice that is increasingly difficult to do without, and it is broadly accepted as an important contributor to better clinical results.



2. Structure and Technical Features of the Dental Operating Microscope

2.1. Optical System and Magnification Levels

The dental operating microscope (DOM) relies on a sophisticated optical arrangement intended to deliver high-resolution images. Its main elements are the objective lens, the eyepieces (oculars), a magnification changer, and a coaxial light source. Together, these parts generate an enlarged, bright, three-dimensional view of the treatment area in which depth perception is retained. This allows narrow and intricate anatomical regions to be assessed more accurately, which is especially relevant in endodontics (Bonsor, 2015). Figure 2 shows the main optical components of the dental operating microscope.

The overall magnification of the microscope results from the interplay of the objective lens, the eyepieces, and the magnification changer. Current dental microscopes use either a stepped changer with fixed settings or a continuous (zoom) system. Stepped changers usually offer three to five preset magnifications, while zoom systems permit seamless adjustment across a wider range. Higher magnification renders anatomical details more clearly, but at the cost of a smaller field of view and a shallower depth of field. Choosing the right magnification is therefore a prerequisite for good clinical performance.

Magnification in dental practice is generally divided into three ranges: low, medium, and high. Low magnification (roughly $3\times$ – $8\times$) gives a broad view and is favored for orientation, the early phase of access cavity preparation, and general inspection. Medium magnification ($8\times$ – $16\times$) suits the majority of endodontic procedures because it strikes the best compromise between detail and the size of the visible area. High magnification ($16\times$ – $30\times$) is reserved mainly for tasks that call for close scrutiny, such as finding calcified canal entrances, detecting microcracks, and examining delicate anatomical features (Bud et al., 2023).

A further key benefit of the optical system is that it compensates for the restricted resolving capacity of the human eye. The naked eye can separate details only when they lie about 0.2 mm apart, but the operating microscope raises resolution to the micrometer scale (Bud et al., 2023). Such improved vision makes it easier to locate canal orifices, find accessory canals, and recognize iatrogenic problems early, all of which help make endodontic treatment more accurate and predictable.

In short, the optical system of the dental operating microscope offers much more than enlargement. Through the combination of excellent image quality, retained depth perception, and efficient lighting, it acts as a basic element that shapes clinical performance directly. Matching the magnification to each phase of treatment improves outcomes and, at the same time, upholds the principles of minimally invasive dentistry.

2.2. Illumination Systems

How well the dental operating microscope (DOM) performs clinically depends not only on how much it magnifies but also on the quality of its lighting system (Bonsor, 2015). The advanced light sources built into current microscopes make the working field clearer and richer in detail, which supports both diagnostic accuracy and clinical precision. In the coaxial arrangement, light travels along the same axis as the line of sight, so the treatment area is lit evenly and without shadows (Bonsor, 2015). Because the light reaches the target directly, visibility improves markedly in narrow and deep regions.

During endodontic treatment, the joint effect of magnification and better lighting helps the clinician find canal orifices, notice additional anatomical structures, and assess calcified tissue. Stronger and more focused light makes minute details in the working field easier to see and thus raises diagnostic accuracy. The bright illumination of the microscope is of particular value in endodontic microsurgery, where it improves control over the surgical site and eases the use of minimally invasive methods. As a consequence, osteotomies can be kept smaller and the surrounding tissues are subjected to less trauma.

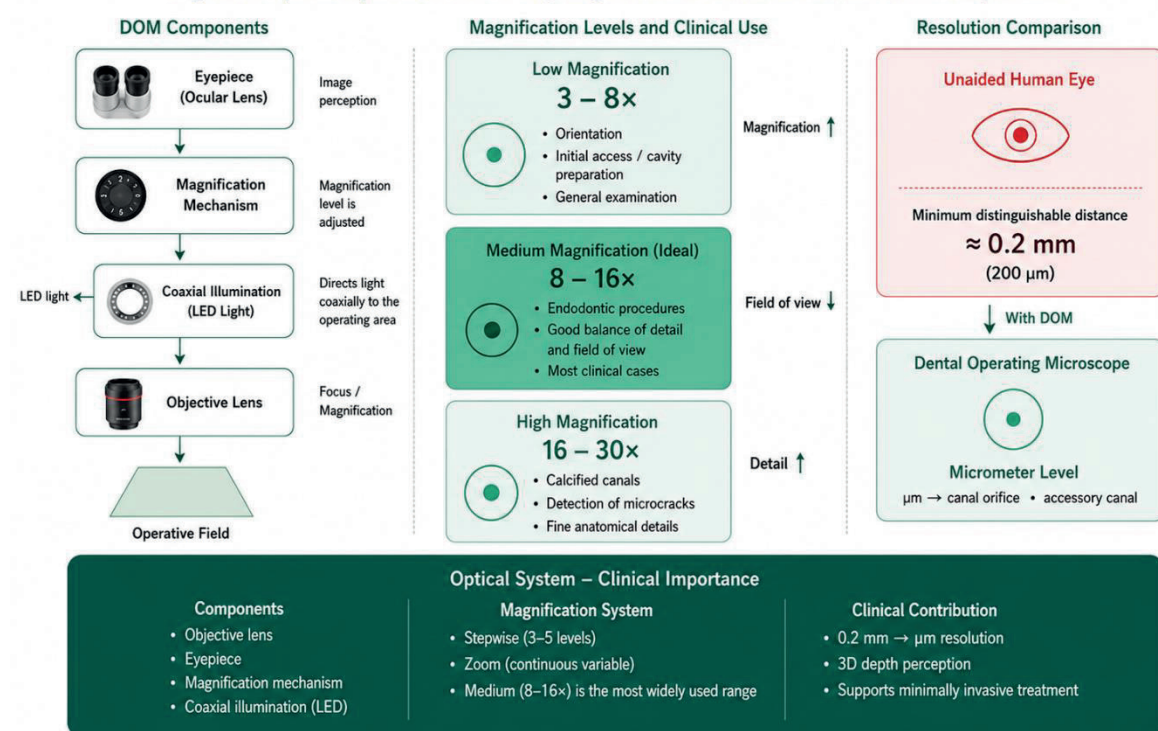
Microscope light sources have developed markedly over the years, moving from traditional halogen lamps toward more advanced technologies (Bud et al., 2023). At present, light-emitting diode (LED) and other high-output light sources are the common choice, since they give a steadier output and produce less heat (Bud et al., 2023). In combination with coaxial delivery, such high-output sources reproduce colors in the working field more faithfully, so that dentin, pulp tissue, and restorative materials can be told apart more reliably (Bud et al., 2023). This property matters greatly in minimally invasive dentistry, whose main aim is to retain sound tooth tissue. The lighting system of the DOM should therefore be seen as more than a way to see better; it is an essential element that sharpens diagnosis, increases treatment precision, and makes conservative treatment possible. Figure 3 depicts how the coaxial illumination system of the DOM works and what clinical benefits it brings.

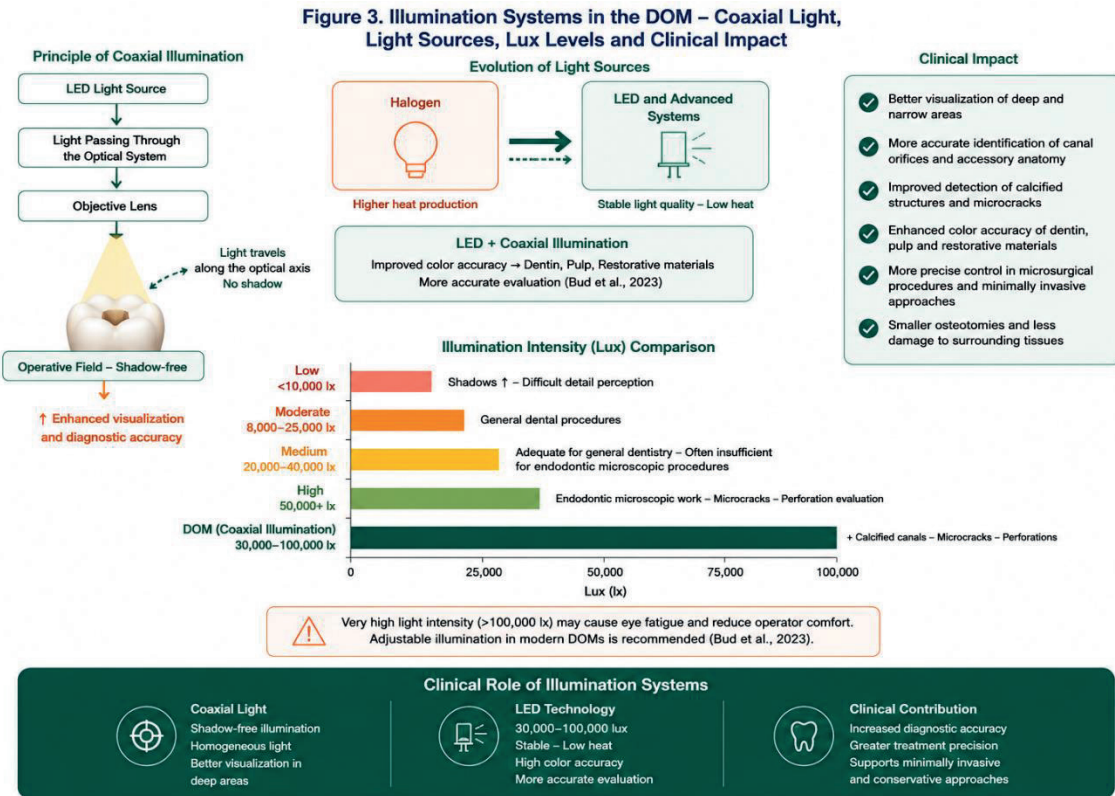
Illumination quality in the DOM is governed by the intensity of the light as well as by the kind of source. Intensity is measured in lux (lx), the quantity of light falling on a given unit of surface (Bud et al., 2023). A sufficient lux value is needed if fine anatomical features are to be seen correctly during treatment. Standard dental operatory lights usually deliver between 8,000 and 25,000 lux, whereas the coaxial lighting built into dental operating microscopes can reach far greater intensities, generally between 30,000 and 100,000 lux (Bonsor, 2015). This large gap

gives the microscope a clear clinical edge, notably in deep cavities and inside the root canal system, where light has difficulty penetrating.

When illumination is low (for example, <10,000 lux), shadows deepen and small anatomical features become harder to make out. Intermediate levels (20,000–40,000 lux) are usually sufficient for everyday dental work but may fall short for microscope-based endodontic treatment. High levels (>50,000 lux) are clearly beneficial for tasks that demand outstanding visual accuracy, including finding calcified canal entrances, identifying microcracks, and assessing perforations. On the other hand, long exposure to very intense light can tire the eyes and diminish operator comfort in extended sessions. For this reason, current dental operating microscopes allow the light intensity to be regulated, so that the clinician can tailor the illumination to the procedure and the working conditions (Bud et al., 2023).

Figure 2. Optical System of the DOM, Magnification Levels and Resolution Comparison





2.3. Ergonomics and Working Distance

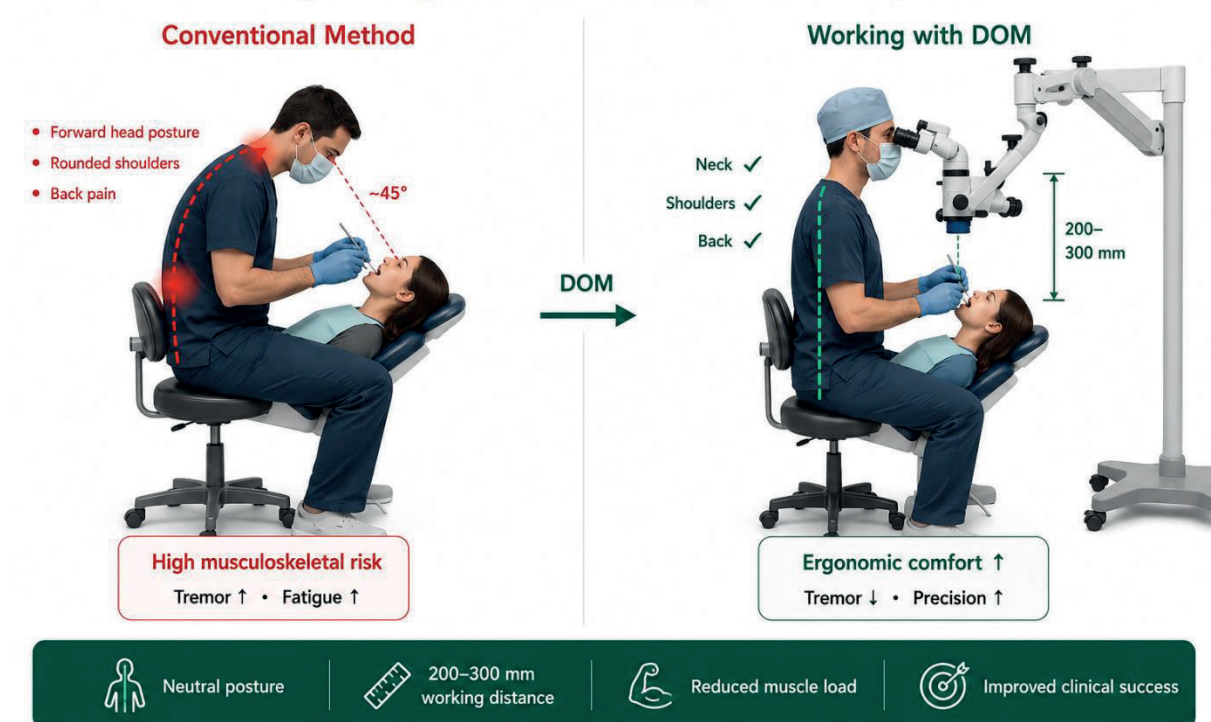
Besides offering excellent vision, the dental operating microscope (DOM) considerably improves the ergonomic conditions under which the clinician works (Bonsor, 2015). In traditional practice, dentists frequently have to bend forward, a position that can, in the long run, cause musculoskeletal complaints in the neck, shoulders, and back. Working with the DOM, by comparison, lets the clinician keep a straighter and more natural posture, which lowers these occupational hazards. Figure 4 contrasts the conventional working posture with the ergonomically advised posture adopted when the DOM is used (Bud et al., 2023).

Ergonomically, the head and trunk of the operator stay in a more balanced position during microscope work, and superfluous body movements are kept to a minimum. Muscle fatigue is thereby lessened, and clinical performance can be sustained throughout long procedures. Working under magnification has also been found to sharpen hand–eye coordination, so that procedures can be carried out with more control and accuracy.

The working distance is the space between the objective lens of the microscope and the treatment area, and it is a key variable for both ergonomic comfort and image quality (Bonsor, 2015). Objective lenses for dental microscopes typically offer working distances of 200 mm, 250 mm, and 300 mm, so the clinician can choose the setup that best fits their seating position and personal preference. A longer working distance encourages a more upright posture and greater comfort, while a shorter one can yield higher magnification and a better view of small anatomical features.

The ergonomic benefits of the microscope go beyond the comfort of the operator and influence the quality of treatment directly. A steadier posture dampens physiological tremor, allowing finer and more exact movements. This is especially relevant in endodontics, where treatment success depends on a high degree of accuracy. Overall, the dental operating microscope promotes sound ergonomic practice by easing the physical burden on the clinician, raising clinical efficiency, and helping to safeguard occupational health over the long term (Bud et al., 2023; Bonsor, 2015).

Figure 4. Ergonomics and Working Distance Comparison



2.4. Accessories and Auxiliary Equipment

The clinical value of the dental operating microscope (DOM) is not limited to its optics and lighting; a range of accessories and supplementary devices adds considerably to it (Bonsor, 2015). These add-ons increase the accuracy of clinical work and also bring clear benefits for teaching, record keeping, and ergonomics.

Among the most widely used add-ons in today's microscope systems are built-in cameras and image-capture units. They make it possible to record procedures in high resolution, which is useful for teaching, research, and explaining treatment to patients. Recorded images also create a lasting archive of the treatment, strengthening clinical records and giving the clinician extra protection in medico-legal matters.

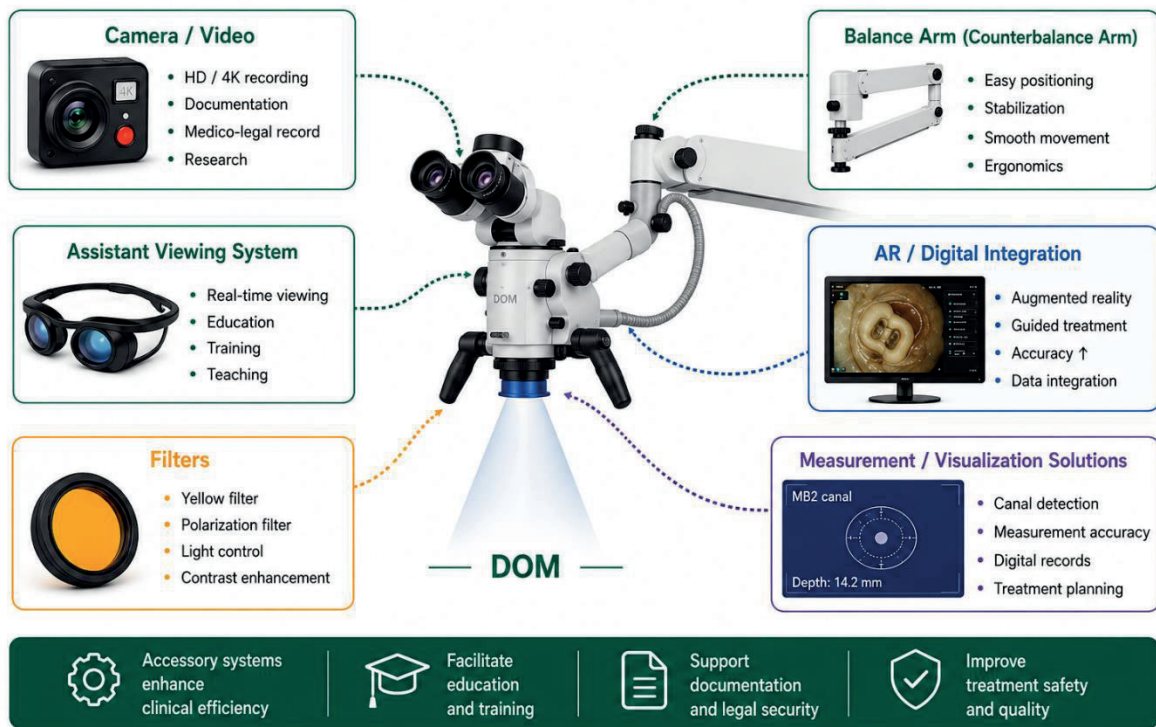
Co-observation systems, sometimes called assistant or secondary binocular tubes, let the operator and an assistant or student look at the same treatment area at the same moment (Bonsor, 2015). This is especially helpful in preclinical and clinical teaching, since instruction can be given in real time and students grasp the procedure more readily. Microscopes can also be fitted with optical filters, for instance yellow filters, which are employed during composite restorations to stop light-cured resins from setting too early. By altering the spectrum of the emitted light, these filters keep restorative materials workable for longer.

In addition, articulated arms and counterweight mechanisms allow the microscope to be moved smoothly and held firmly in place, which benefits ergonomics. With these systems, the microscope can be positioned accurately with little effort from the operator. Figure 5 presents the main accessories and supplementary devices used with dental operating microscopes. Stabilizing mechanisms are especially useful in long procedures, as they keep the image steady and limit operator fatigue.

Thanks to recent developments, certain premium microscope systems can now be connected to digital technologies and augmented reality (AR) platforms, which widens their clinical potential. Such innovations strengthen both treatment planning and its execution, notably in combination with guided treatment methods, and so make procedures more accurate and predictable.

All in all, the accessories and supplementary devices used with the dental operating microscope improve image quality, raise clinical efficiency, support teaching, strengthen documentation, and make procedures safer; they are therefore essential complements to present-day microscope systems (Bonsor, 2015).

Figure 5. Accessories and Auxiliary Equipment System of the DOM



3. Comparison of Magnification Systems

3.1. Comparison of Dental Loupes and the Operating Microscope

Both dental loupes and the dental operating microscope (DOM) serve to improve the clinician's view during treatment, but they differ markedly in magnification range, lighting, and ergonomic behavior (Bonsor, 2015). Loupes usually magnify between $2.5\times$ and $4.5\times$, whereas the DOM provides from $3\times$ up to $25\times$ or more, so that fine anatomical details can be seen far better (Bud et al., 2023). Figure 6 compares the main technical and clinical features of dental loupes and the DOM.

Regarding lighting, loupes usually depend on an external light source, which can light the field unevenly and cast shadows. The DOM, by contrast, has a coaxial lighting system that sends light along the optical axis and so produces even, shadow-free illumination of the treatment area (Bonsor, 2015). This gives the microscope a clear benefit, above all in deep and narrow regions.

Ergonomically, loupes are light, easy to carry, and simple to use in daily practice. During long procedures, however, they may not keep the head and neck in a neutral position, which can lead to operator fatigue. The DOM, on the other hand, encourages a straighter and ergonomically more favorable posture, lowering musculoskeletal load and increasing comfort during long treatments (Bud et al., 2023).

As for clinical performance, the higher magnification and better lighting of the microscope raise diagnostic accuracy and make results more predictable, especially in highly precise work such as endodontic treatment (Connert et al., 2017). Loupes, for their part, remain popular in routine practice because they are quicker to learn, easier to carry, and cheaper.

Taken together, loupes and the dental operating microscope are best regarded as magnification aids that complement, rather than compete with, one another. Loupes give enough magnification for many everyday procedures, while the DOM delivers the superior vision and precision needed in complicated cases that call for advanced microsurgical and endodontic techniques, which makes it an essential tool in present-day dentistry (Bonsor, 2015; Connert et al., 2017).

FIGURE 6. COMPARISON OF DENTAL LOUPES AND DENTAL OPERATING MICROSCOPE

FIGURE 6. COMPARISON OF DENTAL LOUPES AND DENTAL OPERATING MICROSCOPE			
DENTAL LOUPES (LOUPE)  2.5 – 4.5× MAGNIFICATION WIDER FIELD OF VIEW		VS	DENTAL OPERATING MICROSCOPE (DOM)  3 – 25× HIGHER LEVEL OF DETAIL AND DEPTH PERCEPTION
FEATURE	DENTAL LOUPES (LOUPE)	DENTAL OPERATING MICROSCOPE (DOM)	ADVANTAGE
 MAGNIFICATION capacity	2.5 – 4.5× Limited range	3 – 25× and above ★ Wide range – Adjustable	 DOM provides wider and adjustable magnification.
 ILLUMINATION system	External light source Risk of shadowing	Coaxial illumination ★ Shadow-free – Homogeneous	 DOM provides shadow-free and uniform illumination.
 ERGONOMICS posture impact	Limited support May lead to neck strain during long procedures	Neutral posture ★ Reduces muscle strain	 DOM offers better ergonomic posture and reduces strain.
 PORTABILITY and usability	High ★ Lightweight – Portable	Fixed system Clinic-based	 Loupes are more portable and practical.
 COST affordability	Low ★ More affordable	High Higher investment	 Loupes are more economical, DOM has higher cost.
 CLINICAL PERFORMANCE (endodontics)	Generally adequate Suitable for routine cases	Superior precision ★ Excellent for endodontics and microsurgical procedures	 DOM provides superior performance in high-precision procedures.
 DENTAL LOUPES AND DOM ARE COMPLEMENTARY, NOT ALTERNATIVE SYSTEMS. Loupes: suitable for general and routine dental procedures. DOM: superior performance in advanced and high-precision cases.			

3.2. Clinical Impact of Magnification Levels

The magnification setting of the dental operating microscope (DOM) is one of the most influential factors for the accuracy and precision of clinical work (Bonsor, 2015). Low settings

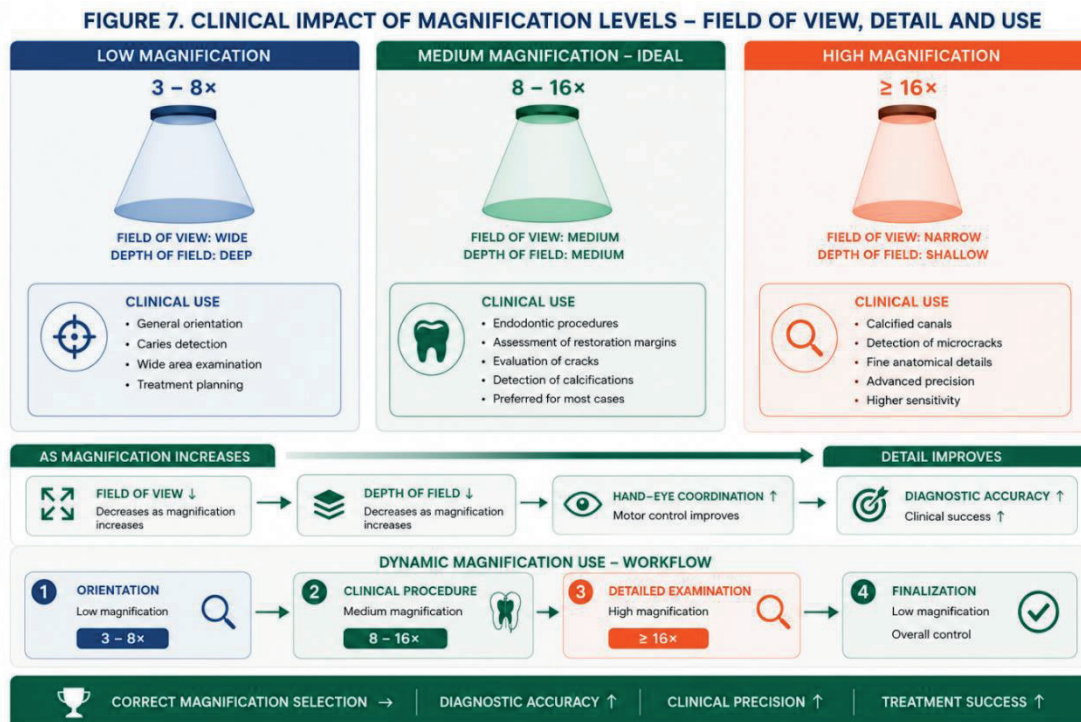
(roughly 3×–8×) are appropriate for orientation and for viewing a wide area, while medium settings (8×–16×) offer the best compromise between detail and field of view for most procedures (Bud et al., 2023). High settings ($\geq 16\times$) reveal microscopic anatomical features best, but they narrow the field of view and make the depth of field shallower. Figure 7 compares the different magnification ranges with respect to field of view, perception of detail, and clinical use.

Greater magnification renders the anatomical structures in the working field more visible and thus improves diagnostic accuracy. Endodontic studies indicate that stronger magnification helps in finding canal orifices, recognizing microcracks, and assessing calcified structures. Too much magnification, however, can make it difficult to grasp the field as a whole, so it is advisable to choose the magnification according to the stage of treatment.

Magnification affects not only what the clinician sees but also their manual skill. Working at higher magnification improves hand–eye coordination, so procedures can be done with more control and accuracy. This benefit is particularly valuable in minimally invasive treatment, whose chief goal is to keep healthy tooth tissue intact.

Changing the magnification as the procedure progresses is necessary to keep an overview while still obtaining detail when it is needed. Clinicians usually start at low magnification to orient themselves in the working field and move to higher settings as treatment advances and finer control is required (Bonsor, 2015). Working this way increases efficiency and lowers the chance of procedural mistakes.

In summary, using the magnification range of the dental operating microscope appropriately and deliberately markedly improves diagnostic accuracy and clinical precision and helps achieve more predictable, successful treatment results (Bud et al., 2023; Connert et al., 2017).



3.3. Image Quality and Depth Perception

With its high-resolution optics and stereoscopic (three-dimensional) viewing, the dental operating microscope (DOM) gives an excellent view of the treatment area (Bonsor, 2015). Its binocular design produces genuine three-dimensional vision, which strengthens depth perception and lets the clinician judge anatomical structures more accurately. Figure 8 illustrates the stereoscopic viewing system of the DOM together with the depth perception and visual benefits it provides.

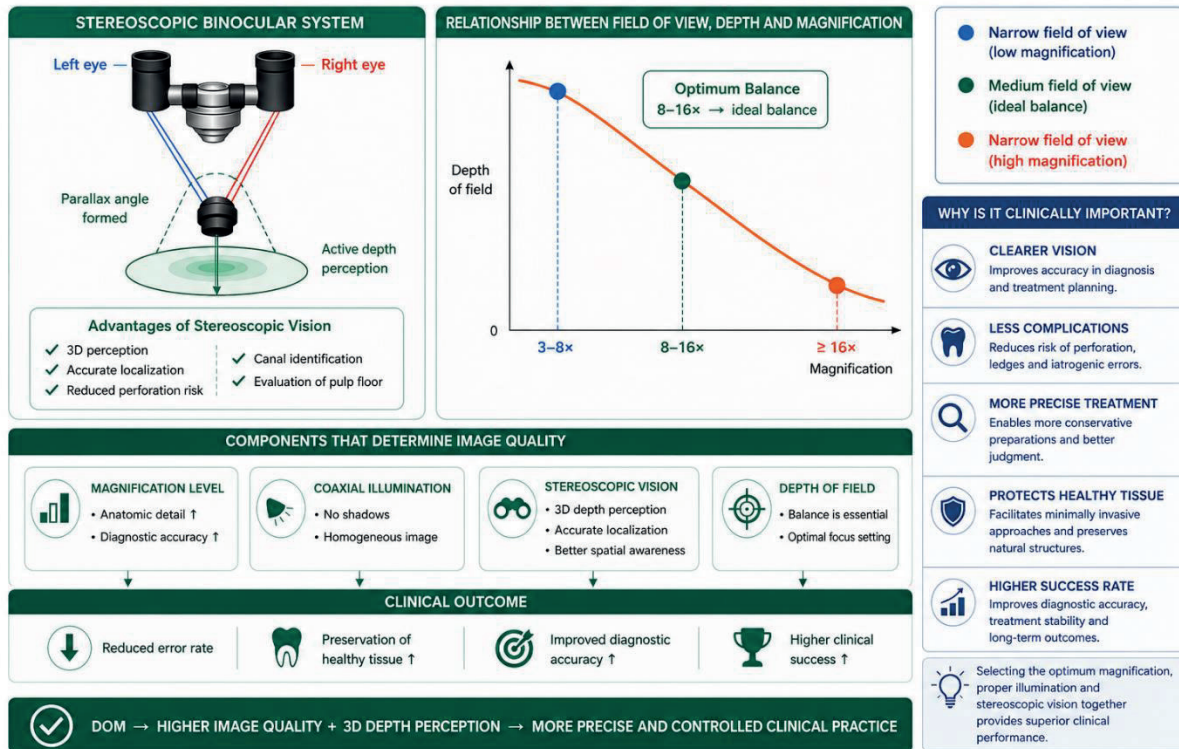
The quality of the image depends on magnification and illumination acting together. Coaxial lighting keeps shadows to a minimum and lights the whole working field evenly, which makes the image clearer (Bonsor, 2015). For this reason, the DOM has a clear advantage over loupes, particularly in deep and narrow regions.

Better depth perception ranks among the greatest strengths of the operating microscope. It helps the clinician judge the spatial relations between anatomical structures more correctly and so handle instruments precisely in the working field. In endodontics, this is especially useful for finding canal orifices, examining the pulp chamber floor, and lowering the risk of perforation while the access cavity is being prepared.

As magnification increases, however, the depth of field becomes shallower, and the focus may need to be readjusted more often during treatment. The clinician should therefore balance magnification against depth of field in line with the task at hand. By choosing appropriate magnification and focus settings, the clinician can obtain both a sufficient field of view and good depth perception (Bud et al., 2023).

Because of the better image quality of the operating microscope, fine anatomical details can be seen more distinctly, which increases diagnostic accuracy and makes procedural mistakes less likely. This benefit matters especially in minimally invasive dentistry, whose main goal is to keep healthy tooth tissue intact.

To conclude, by offering outstanding image quality and improved depth perception, the dental operating microscope has become an essential instrument in present-day dentistry. These features let clinicians work with more precision and control, which ultimately leads to better treatment results (Bonsor, 2015; Bud et al., 2023).

FIGURE 8. IMAGE QUALITY AND DEPTH PERCEPTION – STEREOSCOPIC SYSTEM AND CLINICAL IMPACT

4. Indications for the Use of the Dental Operating Microscope in Endodontics

4.1. Access Cavity Preparation

Working with the dental operating microscope (DOM) increases visual control while the access cavity is prepared, making the procedure more conservative and predictable (Bonsor, 2015). Magnification combined with coaxial lighting gives an excellent view of the working field, which helps keep healthy dentin intact and makes the procedure more accurate (Bud et al., 2023). Figure 9 shows how the DOM supports visual control, tissue-sparing management, and canal localization during access cavity preparation.

Today, the access cavity is expected to do more than open a path into the canal system; it should also keep the tooth structurally sound. Seen from this angle, the DOM helps preserve the pericervical dentin, which strengthens the tooth biomechanically and improves its long-term prognosis (Clark & Khademi, 2010). Better vision limits the needless removal of tooth tissue and makes minimally invasive access designs feasible.

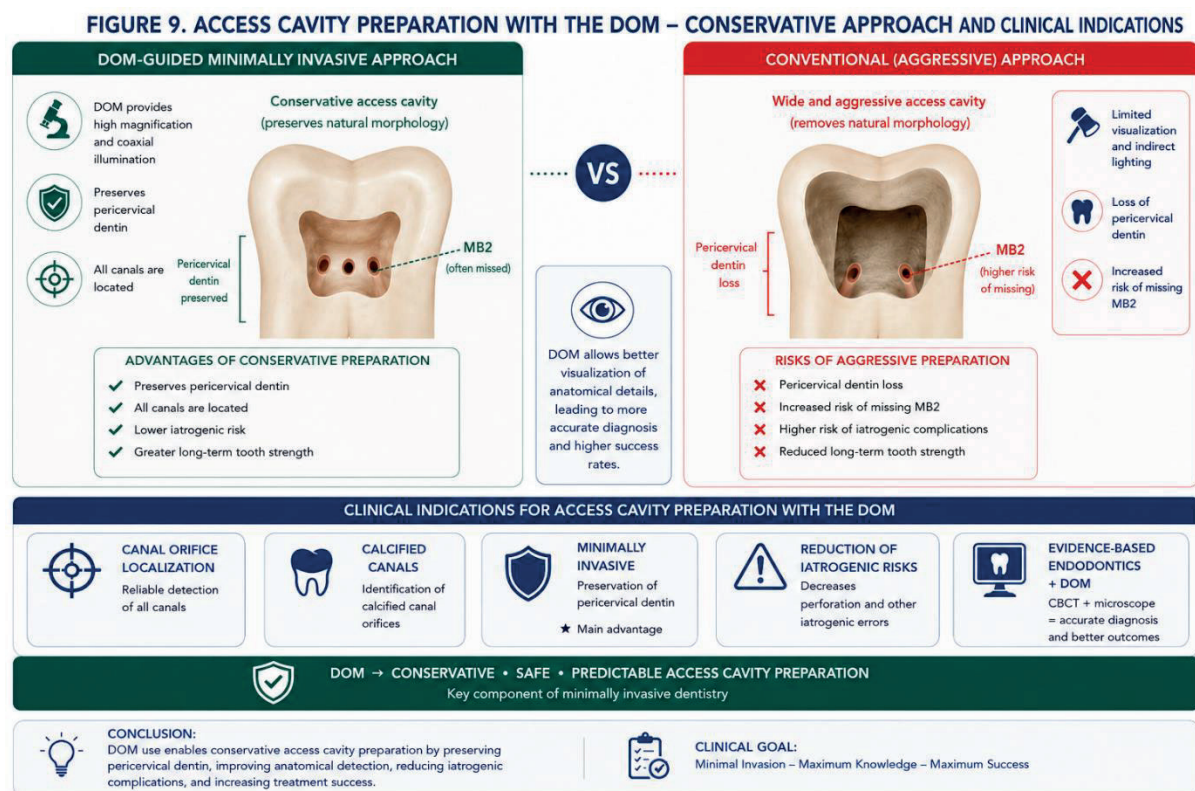
When the access cavity is prepared under the microscope, the anatomical limits of the pulp chamber can be identified more precisely, and the intricate floor anatomy, especially in molars, is easier to assess. Thanks to this clearer view, canal orifices are found more dependably and canals are less likely to be overlooked (Connert et al., 2017).

In teeth whose canals are calcified, the microscope is of great help because it makes slight changes in dentin color and the anatomical landmarks of the pulp chamber floor easier to see, which simplifies locating the canal orifices (Krasner & Rankow, 2004). The clinician can thus prepare a targeted access while avoiding unnecessary loss of tooth tissue.

Using the DOM during access preparation is also essential for avoiding iatrogenic complications. Clearer vision makes it possible to recognize and prevent problems such as perforation, excessive removal of dentin, and injury to the pulp chamber floor at an early stage. In addition, keeping the preparation on the correct axis allows the root canal system to be reached more directly and conservatively.

The growth of guided endodontic techniques in recent years has made the operating microscope even more important. Access cavities planned on the basis of cone-beam computed tomography (CBCT) data can be carried out more precisely under microscopic vision, which increases accuracy and limits dentin removal (Connert et al., 2019). Considerable clinical gains have been reported with this approach especially in teeth with pulp canal obliteration.

In summary, the dental operating microscope allows access cavities to be prepared more accurately, conservatively, and safely, improving treatment results and lowering the risk of iatrogenic complications. For this reason, microscope-assisted access preparation is generally considered a cornerstone of present-day minimally invasive endodontics.



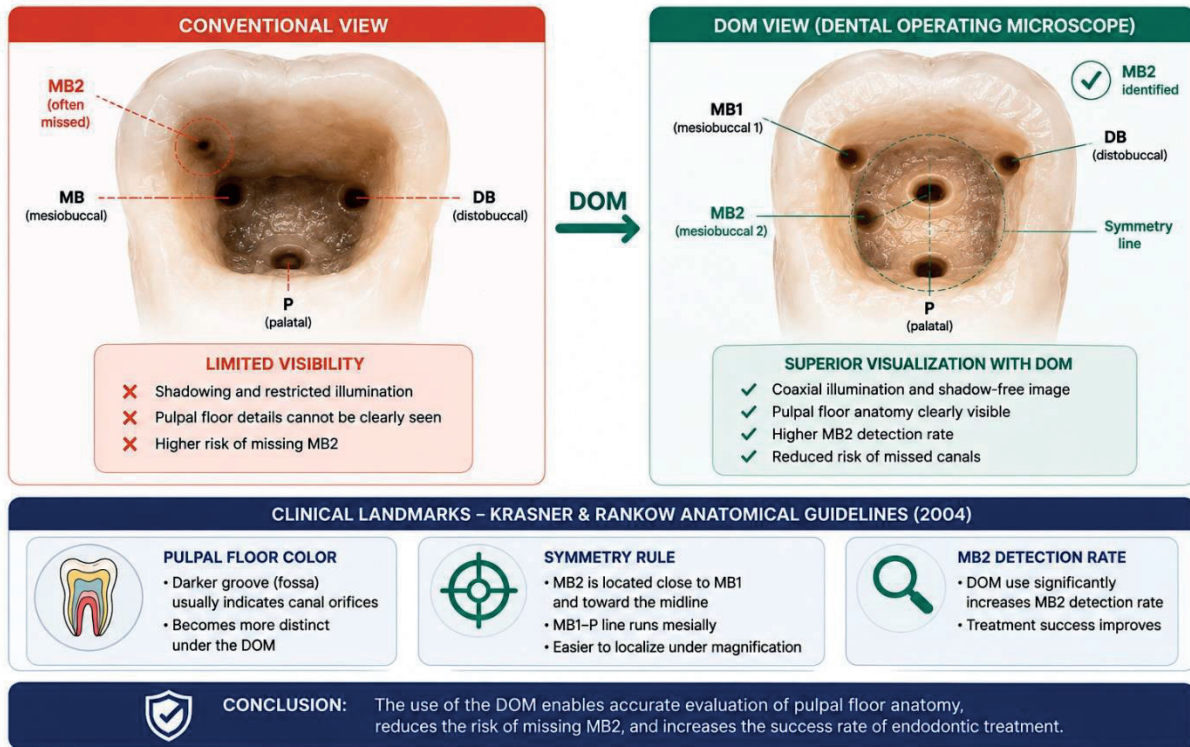
4.2. Identification of Root Canal Orifices

The dental operating microscope (DOM) increases visual accuracy when canal orifices are being located and thus contributes directly to better treatment results (Bonsor, 2015). The complicated floor anatomy of molars in particular can be judged more correctly with magnification and coaxial lighting, so canals are less likely to be missed (Connert et al., 2017).

Under the microscope, slight color differences on the pulp chamber floor and its anatomical landmarks are easier to recognize, which helps in finding orifices that are often missed, most notably that of the second mesiobuccal canal (MB2) (Krasner & Rankow, 2004). Figure 10 shows the anatomical landmarks of the pulp chamber floor and how canal orifices are located

under the dental operating microscope. Owing to the clearer view offered by the DOM, the clinician can work more conservatively while finding canals more accurately.

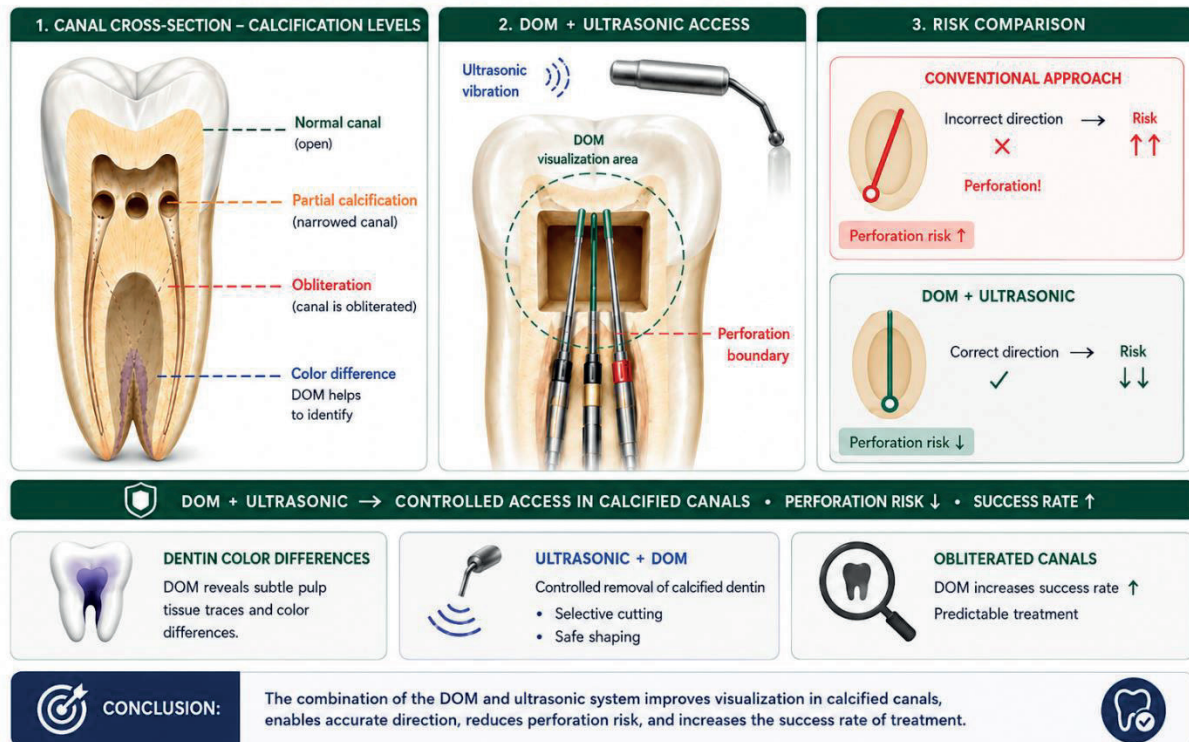
FIGURE 10. IDENTIFICATION OF ROOT CANAL ORIFICES – PULPAL FLOOR ANATOMY AND MB2 LOCALIZATION



4.3. Calcified Canals

Calcified canals are among the hardest situations an endodontist faces, and the dental operating microscope (DOM) is a major factor in raising the chance of success in such teeth. With magnification, small differences in dentin color and the remaining paths of pulp tissue can be seen more distinctly, so the canal orifice can be found conservatively without sacrificing sound tooth tissue (Bud et al., 2023). Figure 11 gives a schematic view of dentin color differences and the localization of calcified canals under the DOM.

Combining the microscope with ultrasonic instruments allows calcified dentin to be removed in a controlled way while keeping the risk of perforation low. Especially in obliterated canals, this offers a safer and more predictable strategy, since the canal can be negotiated precisely with little needless loss of sound dentin.

FIGURE 11. CALCIFIED CANALS – SAFE ACCESS WITH THE DOM AND ULTRASONIC SYSTEM

4.4. Retrieval of Separated Instruments

Instrument fracture is one of the most serious complications of root canal treatment, because the fragment can block the chemomechanical cleaning and shaping of the canal system and thereby endanger the result. In these cases, the dental operating microscope (DOM) is of considerable benefit, as it helps the clinician locate and deal with the fractured instrument.

Owing to its high magnification and coaxial lighting, the DOM shows the fragment in detail, along with how it relates to the surrounding dentin and how accessible its coronal end is. This clearer view lets the clinician take a focused, conservative approach and avoid removing sound dentin without need.

A frequently used retrieval technique consists of carefully removing the dentin around the fragment with ultrasonic tips while viewing it through the microscope. In this way, a staging platform is created around the coronal part of the fragment, which helps to loosen it and then take it out. Visual control through the DOM markedly lowers the risk of removing too much dentin or causing a perforation during this procedure. Figure 12 shows how a staging platform is prepared and how ultrasonic-assisted retrieval is carried out under the dental operating microscope.

Apart from ultrasonic methods, supplementary devices such as wire loops, microtube systems, and trephine burs can be used in certain cases. All of these, however, depend on good access to the coronal part of the fragment, so microscopic vision is indispensable. The better image quality of the DOM makes it possible to remove only the dentin around the fragment, which supports a more conservative approach.

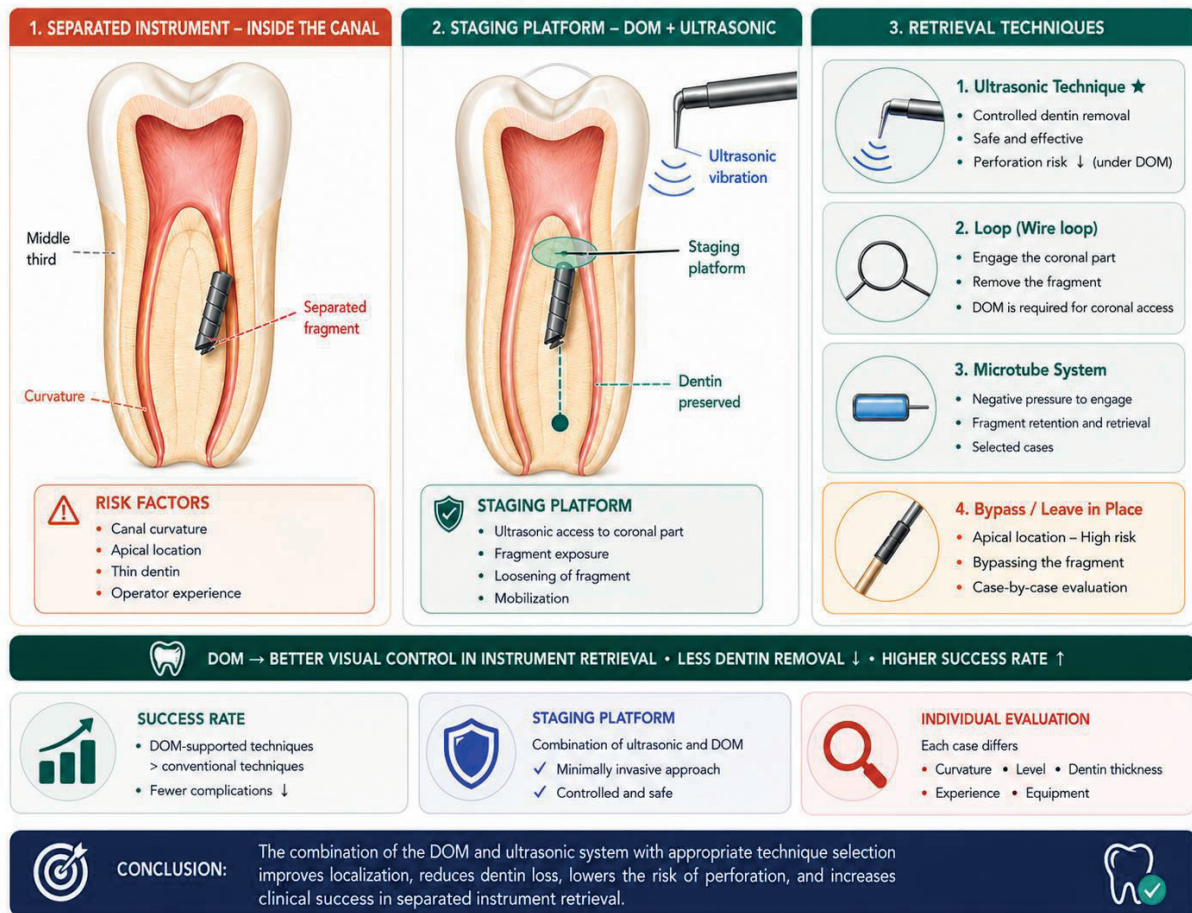
Even so, whether a fragment can be removed depends on several factors, such as where it lies in the canal, how curved the canal is, how much dentin remains, and how experienced the

clinician is. Removal is especially difficult when the fragment sits in the apical third of a strongly curved canal, since the danger of excessive dentin loss and perforation then rises sharply. The DOM makes such difficult cases easier to manage, but the clinician should accept that retrieval will not always be possible.

Published studies repeatedly report that removing fractured instruments with the help of the microscope succeeds more often and causes fewer complications than conventional methods. This gain is mainly explained by the better vision and greater precision that the operating microscope provides.

In conclusion, the dental operating microscope is a key tool for removing fractured instruments safely, in a controlled manner, and conservatively, and it contributes substantially to better treatment results. Each case should nevertheless be judged on its own merits, and other options, such as bypassing the fragment or leaving it in place where appropriate, should be weighed when removal is unlikely to offer a favorable balance of risk and benefit.

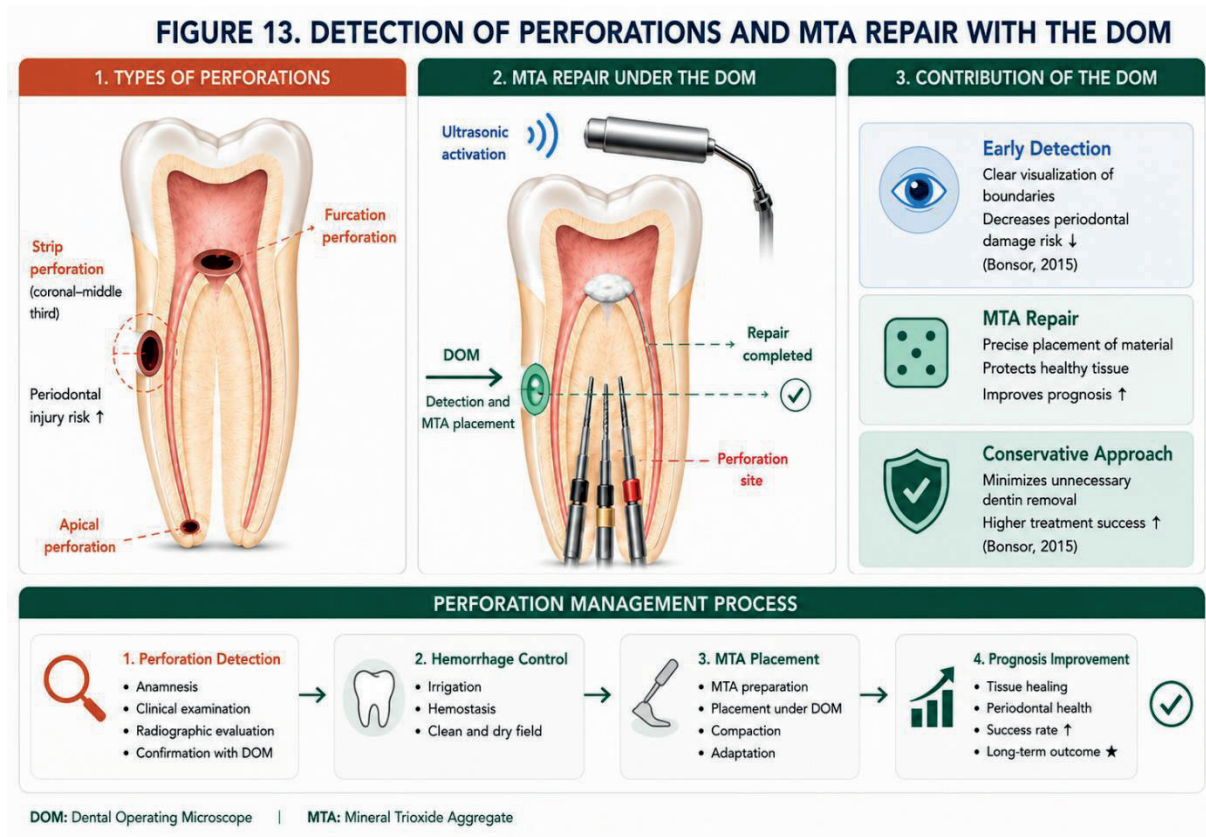
FIGURE 12. RETRIEVAL OF SEPARATED INSTRUMENTS WITH THE DOM – LOCALIZATION, STAGING PLATFORM, AND TECHNIQUES



4.5. Detection and Repair of Perforations

Perforations are grave procedural complications that can cause periodontal breakdown and treatment failure unless they are recognized and treated quickly. The dental operating microscope (DOM) helps detect perforations early and allows their position, size, and margins to be assessed accurately (Bonsor, 2015). Figure 13 schematically shows how a perforation is detected and then repaired under the DOM.

Examination under magnification lets the clinician seal the perforation more accurately with a suitable biocompatible material, for example mineral trioxide aggregate (MTA), once bleeding has been adequately controlled. The clearer view of the operating microscope also helps keep the surrounding healthy tissue intact during the repair, which improves the prognosis and makes the result more predictable.

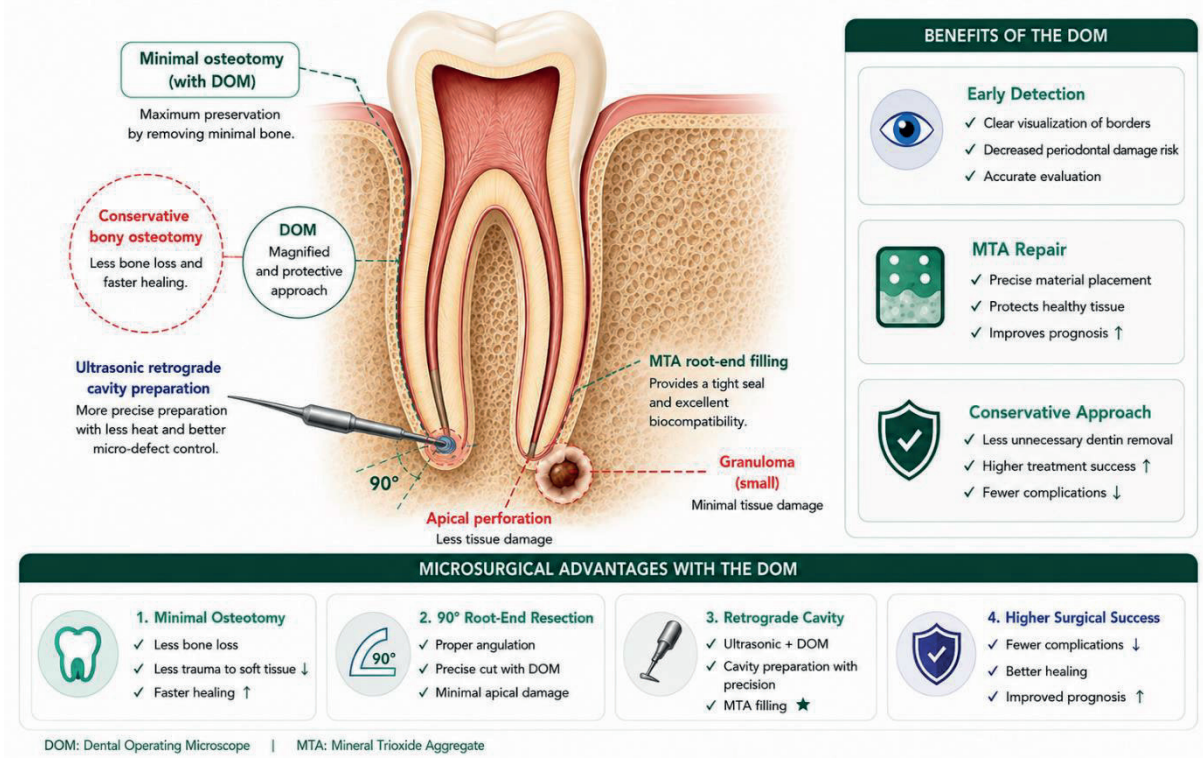


4.6. Endodontic Microsurgical Indications

In endodontic microsurgery, the dental operating microscope (DOM) increases precision by giving a much clearer view of the surgical site. Surgery performed with the microscope favors a minimally invasive approach, as osteotomies can be kept smaller and root-end resections can be performed in a more controlled way. Figure 14 presents the visual benefits and clinical uses of the DOM in endodontic microsurgery.

Higher magnification and coaxial lighting make retrograde cavity preparation and root-end filling more accurate, which increases surgical precision and the success rate of endodontic microsurgery. Microscope use also helps reduce surgical complications and supports better healing, so that surgically treated teeth have a better outlook over time.

FIGURE 14. ENDODONTIC MICROSURGERY – MINIMALLY INVASIVE APPROACH WITH THE DOM



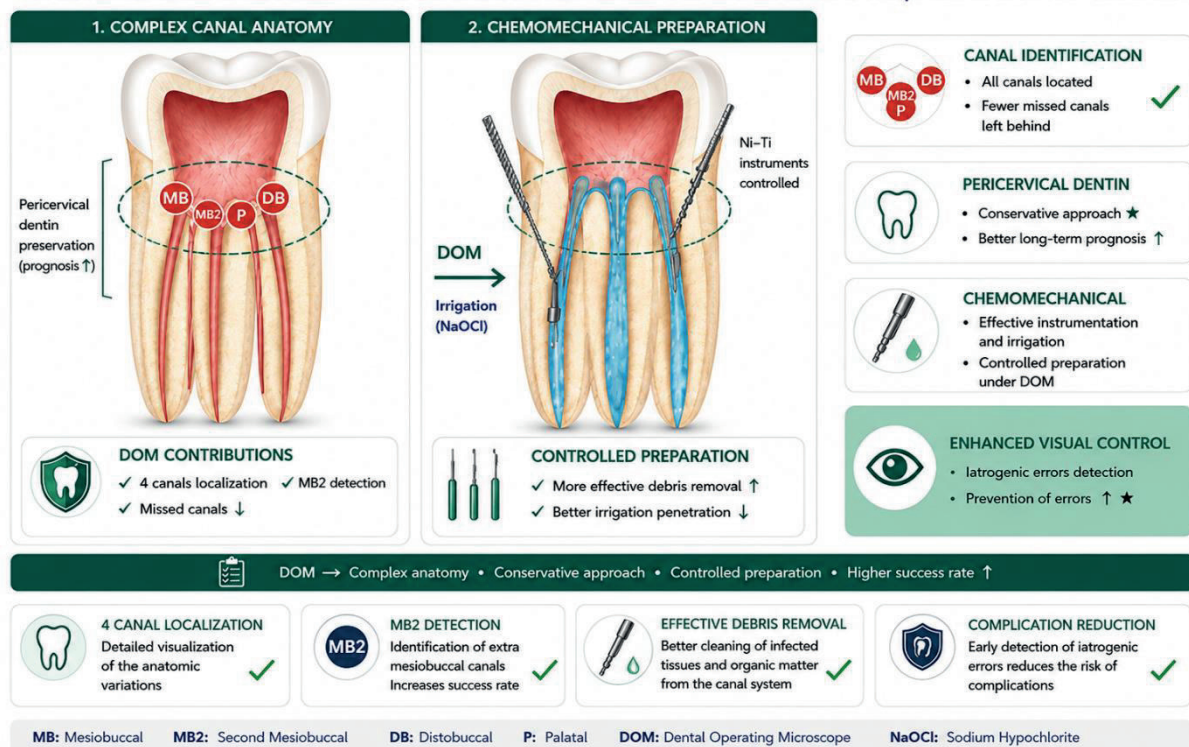
5. Clinical Applications of the Dental Operating Microscope

5.1. Endodontics

In nonsurgical root canal treatment, the dental operating microscope (DOM) improves results by allowing the root canal system to be examined in more detail (Connert et al., 2017). In teeth with complicated canal anatomy, magnification makes canal orifices easier to find and lowers the chance of missing a canal. Figure 15 illustrates how the dental operating microscope helps with canal localization, conservative access cavity preparation, and the avoidance of iatrogenic complications in nonsurgical endodontic treatment.

The microscope encourages a more conservative access preparation and so helps preserve pericervical dentin (Clark & Khademi, 2010). Keeping this vital part of the tooth intact is an important factor for the structural integrity and long-term prognosis of the tooth.

Chemomechanical preparation and irrigation can likewise be carried out more effectively and with better control under the microscope, so infected tissue is removed more efficiently. The clearer view of the DOM also helps the clinician notice and avoid iatrogenic complications early, making endodontic treatment safer and more predictable.

FIGURE 15. NON-SURGICAL ENDODONTICS WITH THE DOM – CANAL ANATOMY, PREPARATION AND IRRIGATION

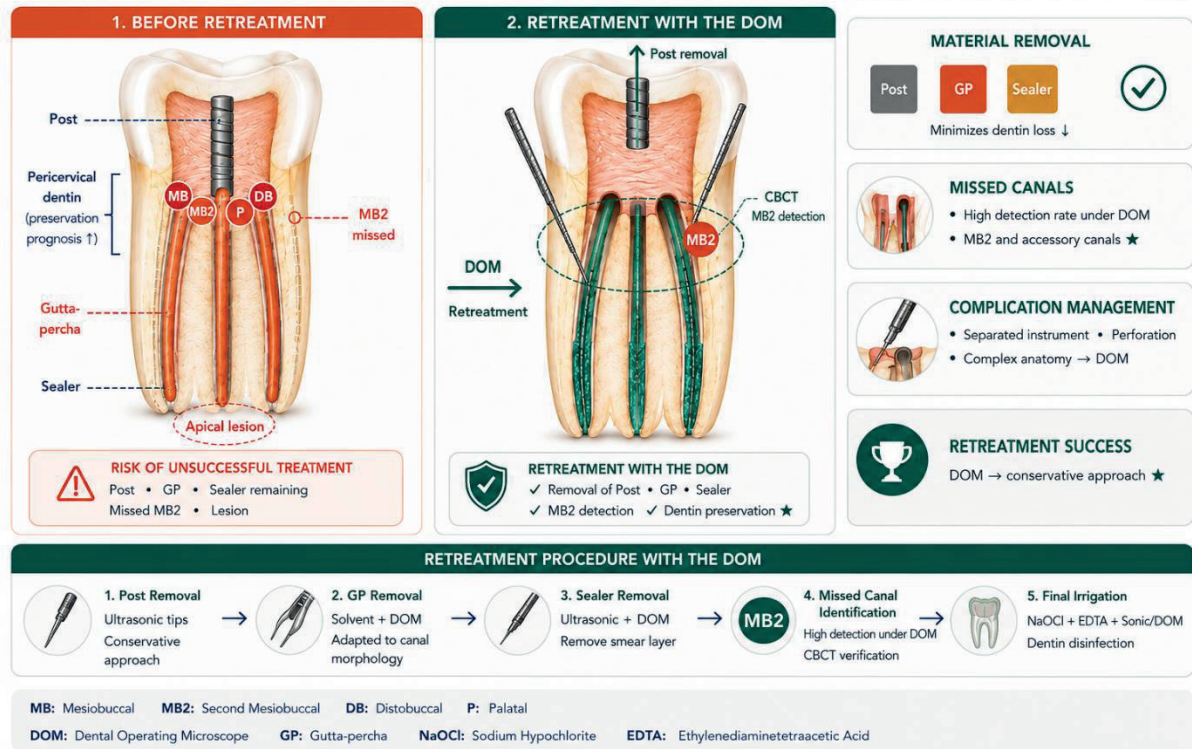
5.2. Retreatment Procedures

In nonsurgical endodontic retreatment, the dental operating microscope (DOM) is crucial, especially for removing the existing root filling and finding canals that were missed before. Canals left untreated in the first treatment can be found far more accurately at microscopic magnification, which raises the chance that retreatment will succeed (Connert et al., 2017). Figure 16 shows how the dental operating microscope supports removal of root filling material, detection of missed canals, and handling of procedural complications during retreatment.

When gutta-percha, sealer, and posts are being removed, the microscope gives better visual control, so sound dentin can be kept and needless loss of tooth tissue avoided. Such a conservative approach is particularly important in weakened teeth, in which keeping the remaining dentin is vital for the long-term integrity of the tooth.

Complications such as fractured instruments, perforations, and complex anatomical variations are also handled more predictably under the microscope. Greater magnification and better lighting raise precision and allow retreatment to be done more safely and efficiently. Accordingly, the dental operating microscope is widely accepted as one of the main factors behind better results and greater predictability in endodontic retreatment.

FIGURE 16. RETREATMENT PROCEDURES – MATERIAL REMOVAL AND COMPLICATION MANAGEMENT WITH THE DOM

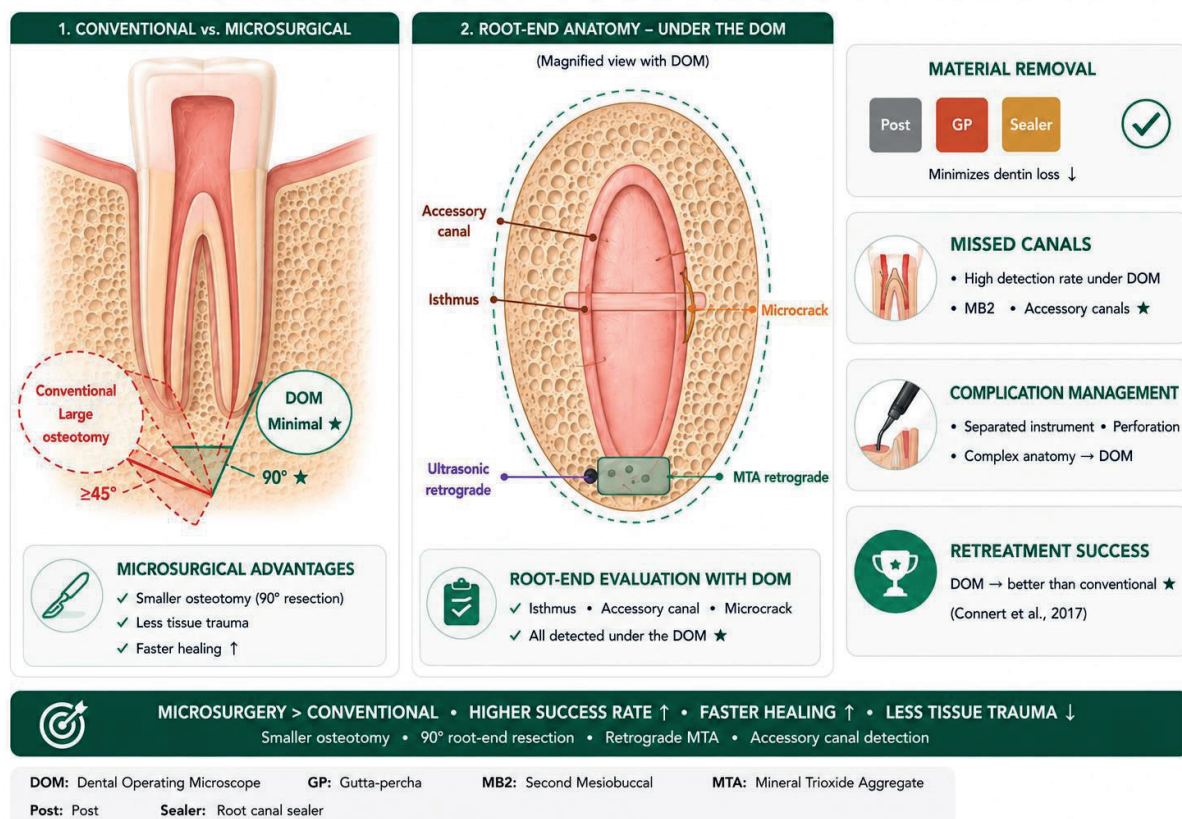


5.3. Apical Surgery

Endodontic microsurgery is one of the fields in which the dental operating microscope (DOM) offers the largest benefits. Operations done under the microscope are marked by smaller osteotomies, more exact resection of the root end, and retrograde cavities that are prepared with greater control. Figure 17 shows the conservative surgical benefits of the dental operating microscope in endodontic microsurgery.

Higher magnification and coaxial lighting allow the anatomy of the root end to be judged more accurately, so isthmuses, accessory canals, and microcracks are easier to find. This clearer view makes the retrograde cavity more exact and the root-end filling easier to place reliably, which ultimately raises the success of endodontic microsurgery.

Microsurgical methods have been reported to succeed more often and to allow faster healing after surgery than traditional surgical methods. Because microscope-assisted surgery is minimally invasive, it also traumatizes the tissues less, which lowers postoperative complications and supports better healing.

FIGURE 17. APICAL SURGERY – MINIMALLY INVASIVE MICROSURGICAL APPROACH WITH THE DOM

5.4. Use of the Dental Operating Microscope in Traumatic Dental Injuries

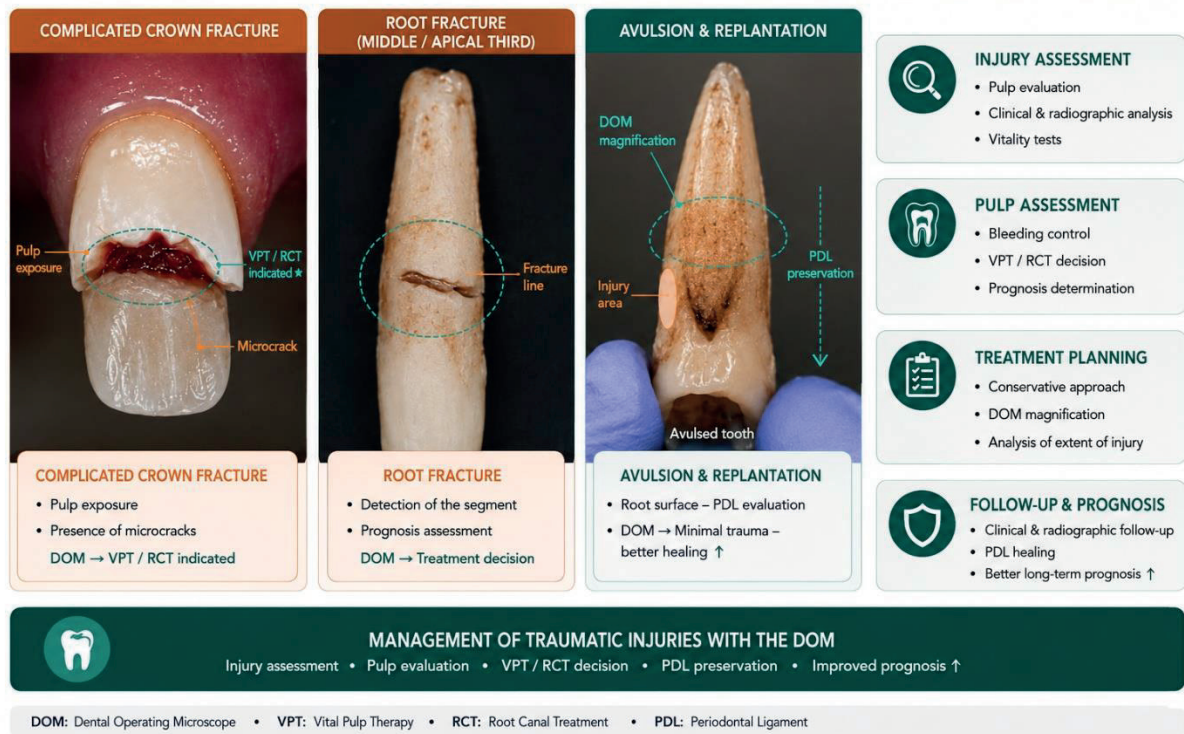
In traumatic dental injuries, the dental operating microscope (DOM) helps the clinician judge the extent of damage more accurately and draw up a suitable treatment plan. Magnification raises diagnostic accuracy considerably, especially in complicated crown fractures, root fractures, and pulp exposures. Figure 18 illustrates how the dental operating microscope supports diagnosis, treatment planning, and conservative management of traumatic dental injuries.

With the microscope, microcracks and the state of the pulp after trauma can be assessed in greater detail. Decisions between vital pulp therapy and root canal treatment can therefore rest on more reliable clinical findings.

Moreover, in avulsion and replantation cases, the root surface and the surrounding periodontal tissue can be inspected more closely at microscopic magnification. This clearer view supports more conservative procedures, as damage to neighboring tissue is minimized and healing is favored.

To sum up, the dental operating microscope is a useful aid in treating traumatic dental injuries: it raises diagnostic accuracy, refines treatment planning, and helps achieve more predictable and successful results.

FIGURE 18. USE OF THE DOM IN TRAUMATIC DENTAL INJURIES – DIAGNOSIS AND TREATMENT PLANNING



6. Minimally Invasive Endodontics with the Dental Operating Microscope

Minimally invasive endodontics is a modern treatment concept that seeks better long-term results by keeping the tooth biomechanically intact. Its central idea is to remove infected tissue effectively while retaining as much sound dentin as possible (Clark & Khademi, 2010). With its high magnification and coaxial lighting, the dental operating microscope (DOM) is central to putting these ideas into clinical practice (Bonsor, 2015).

Better visual control allows the clinician to intervene only where it is needed, which limits needless removal of tooth tissue and makes more targeted preparation possible (Connert et al., 2017). The DOM thus makes minimally invasive endodontic procedures more feasible helping the treatment work better while keeping the tooth structurally sound.

6.1. Dentin Preservation

How well a tooth resists fracture and how long it survives depend heavily on how much dentin is kept. Pericervical dentin in particular plays a key part in spreading occlusal loads along the root and so makes a major contribution to how strong the tooth is biomechanically (Clark & Khademi, 2010). Limiting dentin removal is therefore one of the main goals of minimally invasive endodontics.

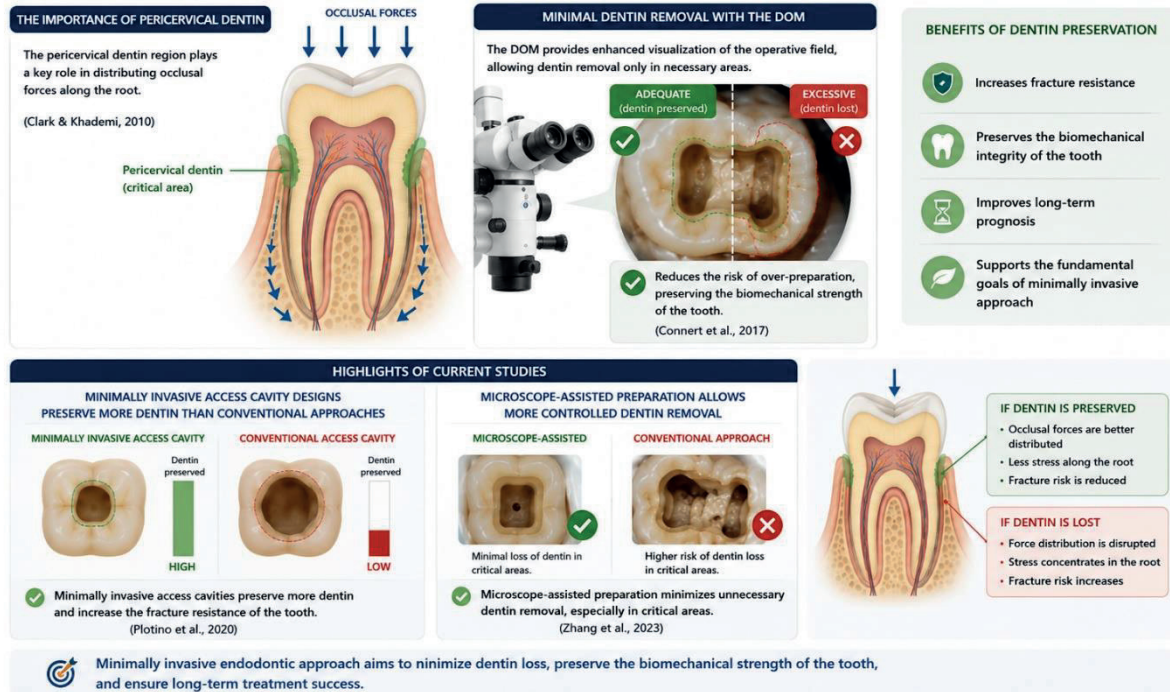
The dental operating microscope allows dentin to be removed selectively, since it shows the working field at high resolution. This clearer view lowers the risk of over-preparation and helps keep the tooth biomechanically intact (Connert et al., 2017).

Recent research has shown that minimally invasive access designs keep considerably more dentin than traditional access cavities and thereby raise the fracture resistance of root-filled teeth (Plotino et al., 2020). It has also been shown that preparing the cavity under the

microscope gives better control over dentin removal, especially in the critical areas around the pulp chamber, so that needless loss of sound tooth tissue is kept to a minimum (Zhang et al., 2023).

6.1. DENTIN PRESERVATION

Preservation of dentin is critical for the fracture resistance and long-term prognosis of the tooth.



6.2. Access Cavity Design

The minimally invasive concept favors access cavities that are more conservative and shaped by the anatomy. The older idea of making wide access openings in endodontics has slowly given way to smaller, more focused designs that keep sound tooth tissue (Clark & Khademi, 2010).

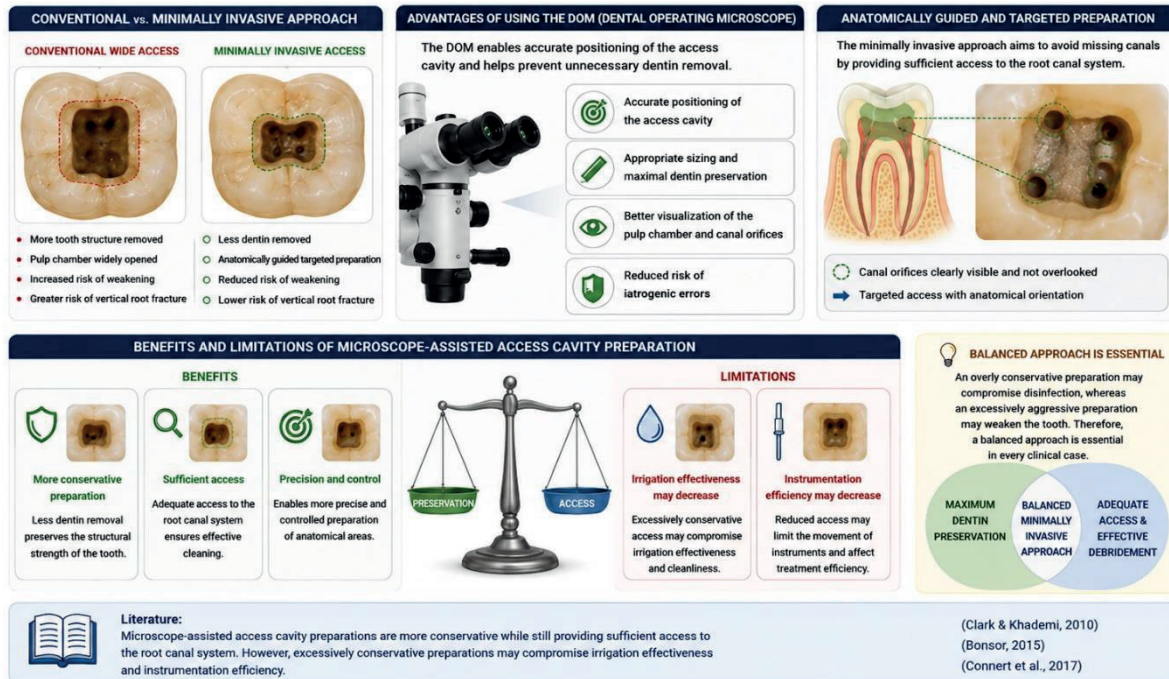
The dental operating microscope (DOM) helps place the access cavity correctly and keep it to the right size, so needless dentin removal is limited (Bonsor, 2015). Higher magnification and coaxial lighting show the pulp chamber and canal orifices more clearly and lower the risk of iatrogenic errors during preparation.

Published work shows that access cavities prepared under the microscope are more conservative yet still give enough access to the root canal system. Overly conservative designs, however, may impair irrigation and instrumentation. Authors have therefore stressed that minimally invasive principles should be applied with balance, so that access is sufficient for proper cleaning and shaping while sound tooth tissue is not sacrificed without need (Connert et al., 2017).

6.2. ACCESS CAVITY DESIGN

The minimally invasive approach prioritizes more conservative and anatomically guided access cavity designs.

Aim: To provide sufficient access while preserving the maximum amount of dentin.



6.3. Integration with Guided Endodontics

Guided endodontics is a modern approach that joins digital imaging with three-dimensional planning to reach high precision, above all in treating calcified canals (Connert et al., 2017). In this method, cone-beam computed tomography (CBCT) data are combined with digital surface scans to design a targeted access path, which allows the access cavity to be prepared in a minimally invasive way.

When the dental operating microscope (DOM) is used together with guided endodontics, accuracy increases because the clinician gains both overall guidance and microscopic vision. The guided system sets the best path of access, and the DOM allows fine anatomical features in the working field to be examined closely.

According to published studies, combining these two technologies considerably reduces dentin loss and the risk of perforation, particularly in teeth with pulp canal obliteration. Microscope assistance also strengthens the clinician's visual control, adding to the safety and precision of guided endodontic treatment.

Seen this way, the DOM and guided endodontics form a complementary pairing of technologies that is likely to play a central part in the future of minimally invasive endodontics.

7. Ergonomics and Clinical Working Principles

Beyond its excellent optics, the dental operating microscope (DOM) is a valuable means of improving ergonomics in the clinic. In conventional endodontic work, clinicians often bend into awkward positions to see the treatment area properly. With the DOM, by contrast, the operator

can keep a more natural and balanced position (Bonsor, 2015). This ergonomic gain helps lower the load on the musculoskeletal system, notably in long procedures.

Because good magnification is combined with a suitable working distance, the clinician does not have to lean far toward the treatment area. The neck and lower back are thus clearly less strained (Porciuncula et al., 2022). The DOM should accordingly be seen not merely as a way to raise clinical performance but also as a significant means of protecting the long-term occupational health of dental practitioners.

7.1. Operator Position

Correct positioning of the operator at the microscope is necessary for both good image quality and ergonomic efficiency. Ideally, the back is kept straight, the head is held neutrally, and the shoulders are relaxed. The eyes should sit level with the binocular eyepieces, and the working distance should correspond to the focal length of the objective in use (Bonsor, 2015).

With the DOM, the clinician no longer needs to bend toward the treatment area, which creates a more balanced and ergonomic working setting. Earlier research has shown that microscope use clearly lowers neck flexion angles and may help prevent long-term musculoskeletal disorders in dentists (Porciuncula et al., 2022).

In addition, choosing a suitable magnification and setting up the microscope correctly spare the clinician needless changes of posture during treatment. This increases operator comfort and also benefits clinical performance and precision.

7.1. OPERATOR POSITION

Correct posture, clear vision, and long-term ergonomics are essential.

Correct posture, better vision
In the ideal working position, the operator should sit upright, with the head in a natural position and eyes parallel to the eyepieces. This ensures a clear view and helps prevent long-term musculoskeletal problems. (Bonsor, 2015)

Ergonomic working with the DOM
The DOM allows the operator to maintain an upright posture and reduces the need to lean forward, thereby lowering musculoskeletal load. (Porciuncula et al., 2022)

Correct posture, less fatigue
Proper posture selection and microscope adjustment help the operator maintain comfort during long procedures. This reduces fatigue, increases concentration, and improves overall performance.

INCORRECT POSTURE

Leaning forward, neck flexion increases; poor posture leads to higher risk of injury.

- ✗ Neck bent forward
- ✗ Rounded back
- ✗ Shoulders raised
- ✗ Eyes not parallel
- ✗ Working distance not suitable

POSSIBLE OUTCOMES

- Neck, shoulder and back pain
- Muscle fatigue and tension
- Increased risk of musculoskeletal problems
- Reduced concentration and performance

IDEAL POSTURE

Upright posture, natural shoulder position and proper adjustments ensure comfort and efficiency.

- ✓ Head in neutral position
- ✓ Upright back
- ✓ Shoulders relaxed
- ✓ Eyes parallel to eyepieces
- ✓ Working distance appropriate

BENEFITS

- Clear and high-quality vision
- Less muscle fatigue
- Less strain during long procedures
- Better clinical performance

MICROSCOPE AND WORKING AREA SETTINGS

1. MICROSCOPE HEIGHT

Adjust microscope height to your eye level.

2. ARM POSITION

Adjust arm position to bring the microscope closer and stabilize it.

3. WORKING DISTANCE

Adjust working distance according to the magnification level.

4. MAGNIFICATION LEVEL

Use the appropriate magnification for each procedure.

5. ILLUMINATION

Adjust light intensity and direction for optimal visibility.

TIP: Proper adjustment and regular control of the microscope and working area improve both clinical efficiency and comfort.

BENEFITS OF ERGONOMIC POSITIONING

- Reduces neck flexion
- Decreases spinal load
- Reduces muscle tension
- Improves comfort
- Supports longer working hours
- Enhances clinical performance



CONCLUSION: Correct posture and the use of the microscope provide maximum visual control, improve ergonomics, protect the operator's health, and increase treatment success.



7.2. Assistant Coordination

When video and monitor systems are integrated, the dental assistant can follow the treatment area live, which improves communication and teamwork among the clinical staff. Such closer

cooperation is especially helpful in complex procedures, where it shortens treatment time and makes procedural errors less likely.

7.3. Effects on the Musculoskeletal System

Musculoskeletal disorders are one of the most frequent occupational health problems in dentistry, affecting mainly the neck, shoulders, and lower back. Traditional working methods often force the clinician to lean forward for long periods, which contributes substantially to these disorders (Porciuncula et al., 2022).

The dental operating microscope (DOM) encourages a more ergonomic posture and thus lowers these occupational risks. Studies report that working with the microscope can relieve physical strain on the neck and back and lessen musculoskeletal stress in general.

Authors have also stressed, however, that the benefits of the microscope depend on following correct ergonomic rules. Poorly adjusted eyepieces, an unsuitable chair height, or wrong operator positioning can create new sources of strain and harm the musculoskeletal system.

In short, when it is used properly, the DOM effectively lowers musculoskeletal load and raises operator comfort. These gains, however, can only be realized if good ergonomic habits are adopted and the microscope is set up correctly.

8. Learning Curve and Training Process

Even though the dental operating microscope (DOM) improves clinical performance, working with it is regarded as an advanced skill that has to be learned deliberately. Treatment under the microscope requires the clinician to get used to stereoscopic vision, build hand–eye coordination, and master indirect viewing techniques (Bonsor, 2015). Good use of the microscope therefore calls for psychomotor skills as well as theoretical knowledge.

Published studies indicate that how quickly a clinician adapts to the microscope is closely linked to experience, training, and regular use in the clinic (Porciuncula et al., 2022). Starting microscope training early in dental education is therefore seen as key to shortening the learning period and improving later clinical performance.

8.1. Preclinical Training

Preclinical training is one of the most important phases for building the basic skills needed to use the operating microscope. In this phase, students learn how to work under magnification, acquire a correct ergonomic posture, and improve their hand–eye coordination (Bonsor, 2015).

Preclinical teaching with the microscope has been found to make basic endodontic steps, such as access cavity preparation and finding canal orifices, more accurate (Connert et al., 2017). Such training also helps students take up minimally invasive principles early on.

Recent studies have shown that adding microscope training to preclinical education boosts students' confidence and eases their move from the laboratory to the clinic. Incorporating operating microscope training into current dental curricula has therefore been strongly advised.

8.2. Adaptation Process

Getting used to the dental operating microscope is a demanding learning stage in which the clinician moves from traditional direct vision to working through the microscope. During this time, the operator slowly becomes accustomed to stereoscopic depth perception and refines fine motor skills under magnification.

At the start, procedures commonly take longer and visual coordination can be difficult. With regular practice, however, clinicians perform better and treatment times become steadily shorter (Porciuncula et al., 2022).

Ergonomic adjustment is also an important part of this learning phase. A correct posture, properly set eyepieces, and a suitable choice of magnification all help the clinician adapt more quickly and work more efficiently (Bonsor, 2015).

Published work stresses that skill with the operating microscope builds up step by step through regular clinical use. Training programs should therefore offer plenty of hands-on practice alongside theoretical teaching.

8.3. Effect on Operator Performance

How the dental operating microscope affects operator performance has been studied widely in recent years. The findings agree that the microscope brings clear benefits in accuracy, quality of work, and handling of complications (Connert et al., 2017).

Greater magnification and better lighting let clinicians work with more precision and control. These benefits are most obvious in critical steps such as access cavity preparation and finding canal orifices, for which higher success rates have been described.

Although microscope use may lengthen treatment at first, studies show that procedures become much shorter as the clinician gains experience, while overall performance improves markedly (Porciuncula et al., 2022).

Studies in education have also found that students taught with the operating microscope work more accurately and later perform better even when using freehand techniques. This suggests that training with the microscope improves not only immediate performance but also the transfer of skills to conventional procedures.

To conclude, given proper training and enough clinical experience, the dental operating microscope clearly raises operator performance and procedural accuracy and leads to better treatment results. These benefits, however, rely on structured training programs and on gradual adaptation.

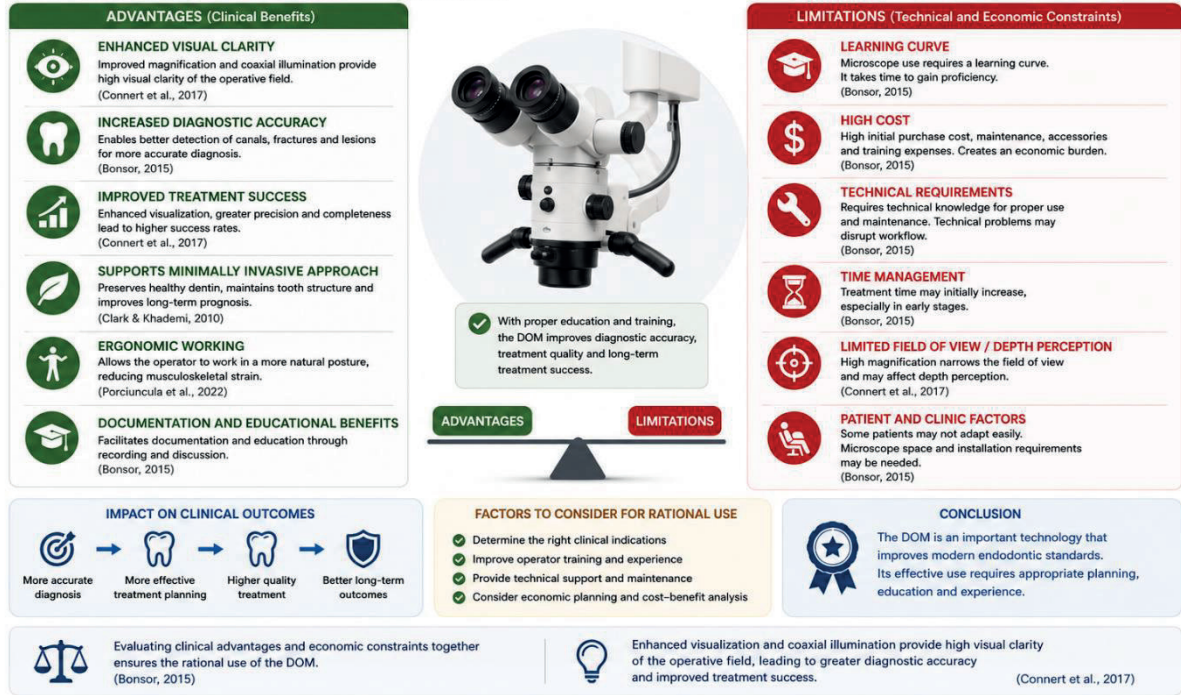
9. Advantages and Limitations

The dental operating microscope (DOM) is a key technology that sharpens diagnosis, raises treatment quality, and supports minimally invasive endodontics. For all its clinical benefits, though, the microscope also has some drawbacks. Weighing its clinical advantages against its technical and economic constraints is necessary if it is to be used sensibly in practice (Bonsor, 2015).

Owing to its greater magnification and coaxial lighting, the DOM shows the treatment area excellently, which improves both diagnosis and treatment results (Connert et al., 2017). Still, the learning period it requires, its high purchase price, and its technical demands are important drawbacks to bear in mind when introducing the microscope into daily practice.

9. ADVANTAGES AND LIMITATIONS

The DOM improves diagnostic accuracy, enhances treatment quality and supports minimally invasive approaches in endodontics. However, there are also some limitations to the use of a microscope. Clinical benefits must be evaluated together with technical and economic constraints for the rational use of this technology. (Bonsor, 2015)



9.1. Clinical Success and Visual Quality

A major strength of the dental operating microscope (DOM) is the outstanding image quality it delivers. Strong magnification together with coaxial lighting gives a clearer and more detailed picture of the treatment area (Bonsor, 2015). This is especially useful when assessing complex canal anatomy and finding canals that had previously gone unnoticed (Connert et al., 2017).

Published studies show that the microscope makes canal orifices easier to find and helps lower iatrogenic complications. Moreover, recognizing perforations, microcracks, and broken instruments earlier and more reliably has a direct favorable effect on treatment success.

It should be stressed, however, that how much the microscope contributes to clinical success depends closely on the operator's experience, and without sufficient training the hoped-for gains may not be fully realized (Porciuncula et al., 2022).

9.2. Time and Efficiency

How the DOM affects treatment time depends on how experienced the operator is. In the early learning period, work with the microscope may take longer because of the need for positioning, focusing, and coordination (Porciuncula et al., 2022).

With growing experience, though, working with the microscope becomes more efficient and treatment time may fall. Better visual control cuts down on procedural errors and complications, which in the end shortens overall treatment time.

The DOM also supports a more controlled and orderly workflow, which raises clinical efficiency (Connert et al., 2017). This benefit is most apparent in retreatment and in the management of complex cases.

9.3. Cost and Accessibility

A key drawback of the DOM is its high price. The cost of purchase, upkeep, and accessories is one of the main reasons the microscope is not more widely used (Bonsor, 2015).

Furthermore, using the microscope effectively demands extra training and clinical experience, which means further investment of both time and money.

In developing countries and in clinics with scarce resources, limited access to operating microscopes is still a major obstacle to their routine use. Even so, fewer complications and better treatment results may make microscope-assisted endodontics more cost-effective in the long run.

9.4. Technical Limitations

For all its strengths, the DOM has a number of technical drawbacks. A leading one is the narrower field of view and shallower depth of field at high magnification. As magnification rises, the visible area shrinks and the focus often has to be readjusted during treatment (Bonsor, 2015).

In addition, treatment with the microscope depends on indirect vision, which can be hard for inexperienced operators at first. This is one of the main reasons for the learning curve.

Reliance on equipment is a further technical drawback. Failure of the microscope or its lighting parts can halt treatment. Moreover, the positions of both the patient and the operator have to be adjusted precisely, which makes microscope-assisted treatment technically more demanding.

Overall, while the DOM offers considerable clinical benefits, it also has technical, financial, and educational limitations. Its use should therefore always be judged in light of suitable training, the operator's experience, and the clinical circumstances.

10. Current Technologies and Future Perspectives

The dental operating microscope is a basic technology for improving visual control in endodontics, and its recent combination with digital technologies has clearly increased clinical accuracy and the predictability of treatment. Progress in three-dimensional imaging, computer-aided planning, and navigation has turned the microscope into a key part of an integrated digital treatment workflow (Connert et al., 2017).

These advances back minimally invasive concepts by allowing treatment that is more precise, more controlled, and more focused on the patient. In addition, the digital transformation of

education and the growing role of data-based clinical decisions mark a significant change of paradigm for the future of endodontics.

10.1. Digital Integration

Digital integration has been achieved by linking the DOM with cone-beam computed tomography (CBCT), intraoral scanners, and CAD/CAM systems. This allows clinicians to plan treatment in three dimensions in advance and then carry out the plan more precisely in the clinic (Connert et al., 2017).

Using the DOM together with digital imaging increases the visual information available during treatment, so procedures can be done with more control and accuracy. Integrated cameras and recording systems are also of great value for documentation and teaching.

Recent progress in digital workflows has made every step, from diagnosis and planning through to the clinical procedure itself, more standardized. This lessens variation between operators and makes treatment more predictable.

10.2. Navigation Systems

Navigation systems are among the most significant technological steps toward greater precision in endodontics. Static (guided) and dynamic (real-time) navigation both achieve high accuracy, especially in calcified canals and in teeth with unusual or complicated anatomy (Connert et al., 2017).

In static navigation, the planned access route is carried over to the patient by means of three-dimensionally printed guides. This method keeps dentin removal to a minimum and clearly lowers the risk of perforation, above all in teeth with pulp canal obliteration.

Dynamic navigation gives real-time feedback, so the clinical experience resembles freehand work. Combined with the DOM, these systems offer both overall guidance and heightened visual precision, which makes treatment more accurate.

Published work suggests that navigation systems may also raise operator performance during training and speed up learning. Navigation technologies are therefore likely to become an important element of endodontic education in the future.

10.3. Artificial Intelligence Applications

Artificial intelligence (AI) is playing a growing part in how dentists diagnose and plan treatment. Within endodontics, AI has shown great promise for interpreting radiographs, assessing root canal morphology, and detecting pathological lesions.

AI algorithms can pick out fine details in CBCT data that the human eye may easily miss, which supports earlier and more accurate diagnosis. Treatment planning thereby becomes more objective and based on data.

Linking AI with the DOM could make future developments possible, such as live image analysis and immediate clinical decision support during treatment. Technologies of this kind may reduce procedural errors and improve clinical decisions.

AI-based teaching systems can also assess student performance and give personalized feedback, which improves learning. Such developments are expected to make endodontic education more objective and measurable.

11. Conclusion

By improving visual control, the dental operating microscope has become one of the basic technologies that make endodontic diagnosis more accurate, procedures more precise, and treatment more successful (Bonsor, 2015). With its strong magnification and coaxial lighting, the DOM gives an exceptional view of the treatment area and is crucial for assessing complex canal anatomy, finding missed canals, and avoiding iatrogenic complications (Connert et al., 2017).

In the context of minimally invasive endodontics, the DOM helps keep dentin intact, helps the tooth stay biomechanically sound, and improves its long-term outlook (Clark & Khademi, 2010). How effective microscope-assisted treatment is, however, depends directly on the operator's experience, proper training, and observance of ergonomic principles (Porciuncula et al., 2022).

Recent technological progress has widened the role of the DOM further by linking it with digital imaging, navigation technologies, and artificial intelligence. These developments have made endodontic treatment more predictable and more standardized. The pairing of the DOM with guided endodontics and dynamic navigation, in particular, supports minimally invasive concepts and raises clinical accuracy.

Although the DOM has drawbacks, among them a high price, a steep learning curve, and technical demands, the substantial clinical benefits it offers have made it one of the core elements of present-day endodontic practice.

In the end, when backed by proper training, clinical experience, and technological integration, effective use of the dental operating microscope clearly improves clinical results and stands out as a key technology that will shape the future of endodontic treatment.

11. CONCLUSION

The dental operating microscope (DOM) is one of the key technologies that enhances visual control in endodontic treatment, improves procedural accuracy, and increases clinical success.



ACCURATE DIAGNOSIS AND SUPERIOR VISUAL QUALITY
High magnification and coaxial illumination enable detailed evaluation of complex root canal anatomy, detection of missed canals, and prevention of iatrogenic complications.
(Connert et al., 2017)



PRESERVATION OF DENTIN AND MINIMALLY INVASIVE APPROACH
DOM supports minimally invasive endodontics by preserving dentin structure, maintaining biomechanics and improving the long-term prognosis.
(Clark & Khademi, 2010)



PROCEDURAL PRECISION AND CLINICAL SUCCESS
Clear visualization increases accuracy, reduces errors, facilitates early detection of clinical problems and directly enhances treatment success.
(Bonsor, 2015)



ERGONOMICS AND OPERATOR SAFETY
Natural posture reduces musculoskeletal strain, improves operator comfort, and increases clinical efficiency and safety.
(Porciuncula et al., 2022)



LONG-TERM PROGNOSIS
By preserving healthy tooth structure and preventing tissue loss, it improves long-term treatment outcomes.
(Clark & Khademi, 2010; Connert et al., 2017)



The effectiveness of the DOM is closely related to operator experience, appropriate training, ergonomics and technology integration.
(Porciuncula et al., 2022)

THE IMPACT OF DOM USE ON CLINICAL OUTCOMES



IN CONCLUSION: Effective use of the DOM, supported by appropriate training, experience and technological integration, enhances both the success of endodontic treatments and the future of modern endodontics.



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BETTER VISION
BETTER DIAGNOSIS



MORE PRECISE PROCEDURES
FEWER COMPLICATIONS



PRESERVATION OF TOOTH
STRUCTURE FOR BETTER
LONG-TERM OUTCOMES



THE ESSENTIAL COMPONENT
OF MODERN ENDODONTICS

TECHNOLOGICAL INTEGRATION AND FUTURE

Recent advancements enable the DOM to be integrated with other technologies, making endodontic treatment more predictable and standardized.



DIGITAL IMAGING
Provides clearer visualization, documentation and treatment monitoring.



NAVIGATION TECHNOLOGIES
Guided and dynamic 3D systems enhance precision and reduce complications.



ARTIFICIAL INTELLIGENCE APPLICATIONS
AI-based analysis helps in accurate diagnosis and supports clinical decision-making.



GUIDED ENDODONTICS AND DYNAMIC NAVIGATION
Minimally invasive, accurate and safe treatment through guidance and real-time navigation.

LIMITATIONS



LEARNING CURVE
Microscope use requires time and practice.



HIGH COST
Purchase price, maintenance, accessories and training expenses are high.



TECHNICAL REQUIREMENTS
Requires technical knowledge and regular maintenance. Technical failures may disrupt clinical workflow.



TIME MANAGEMENT
Treatment time may increase during the learning phase.



LIMITED FIELD OF VIEW / DEPTH
High magnification reduces the field of view and depth of field.

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CHAPTER 2

ASSESSMENT OF PULP VITALITY IN ENDODONTICS: CONVENTIONAL AND CURRENT DIAGNOSTIC METHODS

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1. Introduction

Accurate assessment of pulpal status is central to endodontic diagnosis and treatment planning. In a patient presenting with deep caries, trauma, an extensive restoration, a crack, orthodontic movement, or spontaneous pain, determining whether the pulp is vital and establishing the clinical significance of any existing inflammation affects the choice among vital pulp therapy, root canal treatment, monitoring, or another treatment option. However, the pulp is enclosed within rigid dentinal walls, cannot be directly observed, and does not always reflect inflammatory changes in a linear manner through clinical findings. Pulpal diagnosis is therefore too complex to be reduced to the result of a single test (Donnermeyer et al., 2023; Duncan et al., 2023).

In everyday clinical practice, cold, heat, and electric pulp testing are often called “vitality tests.” However, these methods measure the excitability of sensory nerves rather than blood supply, the primary indicator of pulp vitality; they are therefore more accurately classified as pulp sensibility tests. Laser Doppler flowmetry and pulse oximetry, by contrast, are considered true vitality tests because they provide data on pulpal circulation. This conceptual distinction is particularly important in traumatized teeth, teeth with open apices, recently transplanted teeth, or teeth subjected to orthodontic forces. In such teeth, circulation may persist while neural responses are temporarily absent (Chen and Abbott, 2009; Gopikrishna et al., 2009).

The purpose of diagnostic testing is not simply to classify the pulp dichotomously as vital or necrotic. The patient’s pain history, the nature of the sensibility response, the condition of the periapical tissues, radiographic findings, and changes over time are considered together to determine the treatment need for pulpal disease. Current systematic reviews show that evidence for clinically determining the true histopathological status of the pulp is limited; the most appropriate approach is a “diagnostic package” composed of symptoms and multiple tests (Mejäre et al., 2012; Donnermeyer et al., 2023). This chapter addresses the biological foundations of pulp sensibility and vitality, conventional and circulation-based tests, emerging technologies, special clinical situations, and an evidence-based approach to decision-making.

2. Conceptual and Biological Foundations of Pulp Diagnosis

Three distinct concepts should be differentiated in pulp diagnosis: vitality, sensibility, and pulpal health. Vitality is the presence of sustainable blood circulation in the tissue. Sensibility is the perception of an externally applied thermal or electrical stimulus by pulpal

nerve fibers. Pulpal health extends beyond circulatory and neural responses to include the extent of inflammation, microbial burden, healing capacity, and treatment prognosis. A vital pulp may be normal or inflamed; likewise, a positive sensibility response does not indicate that the pulp is histologically healthy (Chen and Abbott, 2009; Donnermeyer et al., 2023).

Pulp tissue has a rich microcirculation consisting of arterioles, venules, lymphatic structures, and nerve bundles entering through the apical foramen. Rigid dentinal walls limit the tissue's capacity to expand during inflammation. Vasodilation, increased vascular permeability, and edema may elevate intrapulpal pressure; however, the limited collateral circulation of the pulp makes the clinical course of inflammation different from that in other connective tissues. Changes in blood flow are associated with pain, neural excitability, and healing capacity; nevertheless, a test that merely demonstrates the presence of circulation cannot by itself determine the reversibility of inflammation.

Myelinated A-delta fibers in the dental pulp are concentrated predominantly at the pulp–dentin border and are associated with brief, sharp, well-localized pain. Unmyelinated C fibers are located in more central regions of the pulp; they have a higher stimulation threshold and contribute to prolonged, dull, or throbbing pain. Responses to thermal and electrical tests are influenced by the anatomical distribution of the fibers, dentin thickness, root development, inflammation, age, trauma, and application technique. The sensation elicited by a stimulus is therefore an indirect indicator of the tissue's circulatory status.

An important limitation of pulp testing is the absence of a reliable and practical reference standard. Although histological examination is theoretically ideal, it requires extraction or pulpectomy; moreover, a histological section may not represent the entire pulp. Bleeding observed during access cavity preparation may confirm vital tissue, but the absence of bleeding can be influenced by technical or local factors. Differences among the criteria used as references in clinical studies—such as extraction, bleeding during access, the presence of root canal filling, or periapical radiolucency—are among the principal reasons for heterogeneity in reported diagnostic accuracy values (Mainkar and Kim, 2018; Patro et al., 2022).

3. Clinical Examination and Ancillary Diagnostic Findings

Pulp assessment should begin with a detailed medical and dental history. The onset of pain; whether it is spontaneous or stimulus-induced; its duration, intensity, localization, effect on sleep, relationship with heat and cold, change with chewing, and response to analgesics should be questioned. Allowing the patient to describe the complaint in their own words

reduces bias that may be introduced by leading questions. Brief thermal sensitivity and pain that persists after removal of the stimulus may have different clinical meanings; however, no universal, histologically validated time threshold for pain duration exists (Donnermeyer et al., 2023).

Visual examination assesses caries, restoration margins, cracks, fractured cusps, discoloration, sinus tracts, swelling, and signs of trauma. Periodontal probing, mobility, percussion, and palpation complement pulp testing. Percussion and palpation primarily provide information about apical periodontal tissues; a positive result does not directly indicate whether the pulp is vital or necrotic. An isolated deep periodontal pocket may increase suspicion of a crack or vertical root fracture. Transillumination and magnification support clinical examination, particularly when a cracked tooth is suspected.

Periapical radiographs are evaluated for the proximity of caries and restorations to the pulp, canal-space width, calcification, root development, periodontal ligament space, and periapical bone changes. A normal radiographic appearance does not exclude pulpal disease; early inflammation and necrosis may be present without causing bone changes. Cone-beam computed tomography does not demonstrate pulpal circulation and is not a routine vitality test. It should be considered only for selected three-dimensional questions that conventional imaging cannot answer and whose result would change the treatment decision.

Appropriate control teeth should be selected before diagnostic testing. A sound adjacent tooth in the same arch and, if possible, the homologous tooth in the opposing arch are tested to teach the patient the expected sensation and establish the individual response threshold. Teeth with extensive restorations, trauma, caries, calcification, or recently applied orthodontic forces should be excluded when selecting controls. Recording the response of the control tooth before testing the suspect tooth improves reliability, especially in children and individuals with high anxiety.

4. Pulp Sensibility Tests

4.1. General Principles of Application

Sensibility tests should, whenever possible, be performed without local anesthesia after the tooth has been isolated and dried and the purpose of the test has been explained to the patient. The patient should be instructed to use a simple stop signal, such as raising a hand, as soon as the sensation is felt. Testing should proceed from control teeth to the suspect tooth, and the pulp should be allowed to return to baseline between repetitions of the same

stimulus. The result should be recorded not merely as positive or negative, but according to the onset, intensity, duration, and difference from the control-tooth response.

Test results can be influenced by the operator's expectation and the patient's psychological state. Whenever possible, the patient should not see which tooth is being tested; application pressure, duration, and the amount of agent should be standardized. When a test is negative, the possibility of technical error should be checked and the finding should be verified using a different method. Particularly before an irreversible treatment decision, at least two independent findings should point in the same direction. In an assessment of 656 patients in a clinical setting, accuracies of 0.904 for cold testing and 0.75 for EPT were reported, showing that although conventional tests are valuable, they are affected by clinical and technical variables (Jespersen et al., 2014).

4.2. Cold Test

The cold test is the most common and practical pulp sensibility test in clinical practice. Sudden cooling of the tooth surface with a refrigerant causes outward movement of fluid in the dentinal tubules and stimulation of A-delta fibers through the hydrodynamic mechanism. In healthy pulps, this generally produces a sharp sensation that begins with the stimulus and disappears shortly after the stimulus is removed. Pain that persists after the stimulus or reproduces the patient's clinical complaint increases suspicion of pulpal inflammation; however, a specific time limit does not establish a histological diagnosis.

Carbon dioxide snow, refrigerant sprays, and ice may be used for cold testing. Modern refrigerant sprays provide a practical and strong thermal stimulus. The agent is applied to a small cotton pellet; without contacting the cervical gingiva or adjacent teeth, the pellet is placed on the most intact facial surface possible. In teeth with extensive restorations, application to the remaining tooth structure rather than the restoration is preferred. Because melted ice can flow onto adjacent tissues and impair stimulus localization, ice may be less controlled than spray (Jafarzadeh and Abbott, 2010a).

False-negative results may arise from transient nerve injury after trauma, an open apex, age-related dentin thickening, canal calcification, a very thick restoration or crown, inadequate cooling, or inability of the patient to respond. False-positive results may occur when the stimulus is transmitted to an adjacent tooth or the gingiva, when the patient reports prematurely because of expectation, or when vital tissue remains in only some canals of a multirrooted tooth. Thus, a cold response does not show that the entire root canal system is in the same biological condition.

In the meta-analysis by Mainkar and Kim (2018), pooled sensitivity, specificity, and adjusted accuracy for the cold test were reported as 0.87, 0.84, and 0.84, respectively. These values indicate that the cold test is a strong initial test among conventional methods, but is not perfect on its own. Weisleder et al. (2009) showed that using cold tests together with EPT improves reliability in determining pulpal status.

4.3. Heat Test

The heat test is not used as frequently as the cold test for routine screening; it is particularly valuable when pain initiated or aggravated by hot beverages is the patient's chief complaint. A controlled increase in temperature may produce pain through intrapulpal fluid movement, vascular response, and neural stimulation. In some teeth with advanced inflammation, pain aggravated by heat and temporarily relieved by cold may be a typical history; however, this finding is not present in every case.

Heated gutta-percha, warmed materials, or controlled warm water may be used. The tooth surface should be protected with petroleum jelly, the heated material should not be overheated, and contact with soft tissues should be avoided. The use of warm water under rubber dam isolation may help stimulate the entire surface in a controlled manner, particularly in a crowned tooth. The aim is not to cause tissue damage but to safely reproduce the pain described by the patient.

The heat test is difficult to standardize and, in a meta-analytic evaluation, had the lowest performance of the five tests, with pooled sensitivity of 0.78, specificity of 0.67, and adjusted accuracy of 0.72 (Mainkar and Kim, 2018). It should therefore be considered a complementary test guided by the history, rather than a method automatically used in place of a negative cold test.

4.4. Electric Pulp Test

EPT assesses the excitability of myelinated sensory fibers in the pulp by delivering a gradually increasing electrical current from the tooth surface. The number displayed on the device does not measure pulp blood flow, degree of vitality, or severity of inflammation; it represents only the patient's sensation threshold with the device and electrode position used. Therefore, rather than comparing absolute values among different teeth and patients, relative comparison with control teeth in the same patient should be made (Jafarzadeh and Abbott, 2010b).

After the tooth has been isolated and dried, the conductive medium recommended by the manufacturer is placed between the electrode and the tooth. The electrode is applied to

sound enamel without contacting the gingiva or a metal restoration. To complete the circuit, the patient may hold the metal part of the device or a lip clip may be used. Starting at a low level, the current is increased slowly and stopped as soon as the patient reports tingling or warmth. Unnecessary repetitions on the same tooth may create adaptation and expectation effects.

Moisture, leakage to the gingiva, transmission to an adjacent tooth through a metal restoration, and premature reporting by the patient may produce false-positive results. Trauma, an open apex, calcification, recently applied orthodontic force, local anesthesia, or incorrect electrode placement may cause a false-negative or high-threshold response. Although the risk of contemporary devices in patients with pacemakers has been suggested to be low, the device manufacturer's warnings and the patient's medical condition should be considered.

In the meta-analysis, EPT had a sensitivity of 0.72 and specificity of 0.93; in other words, its ability to confirm an appropriate response in vital pulps is high, whereas its performance in identifying necrotic pulp solely through the absence of a response is more limited (Mainkar and Kim, 2018). This feature supports using EPT as a complement to cold testing.

4.5. Other Conventional Adjunctive Methods

The test cavity is based on evaluating whether the patient experiences dentinal sensation during preparation of a small cavity without local anesthesia. Because it is invasive, causes loss of sound tooth structure, and a negative result does not establish necrosis, it should be considered a last resort only in the very limited situations in which other methods cannot be used. Selective anesthesia may help localize the source of pain when it cannot be distinguished between the maxilla and mandible or among adjacent teeth; it does not directly measure pulp vitality.

Transillumination, dyes, magnification, and bite tests are valuable adjunctive methods when a cracked tooth is suspected. A positive finding with these methods does not demonstrate pulpal circulation; however, it may explain the etiology of an unexpected response on pulp tests. The biological structure assessed by each test should be clearly distinguished in the diagnostic approach.

5. Pulp Vitality Tests: Blood Flow–Based Methods

5.1. Laser Doppler Flowmetry

LDF is based on directing coherent laser light into tissue and analyzing the backscattered light. While the frequency of light scattered from stationary tissue remains unchanged, light interacting with moving erythrocytes undergoes a Doppler shift. The device produces a relative perfusion signal related to the number and velocity of erythrocytes. It can thus provide information about pulpal circulation without requiring a subjective response from the patient.

During measurement, the probe must be kept fixed in the same position on the tooth surface. Patient- or tooth-specific splints improve repeatability. Because blood-flow signals from the gingiva and periodontal tissues may contaminate the signal, a rubber dam, an opaque isolation material, or appropriate probe geometry may be used. Patient movement, probe angle, enamel–dentin thickness, tooth type, optical properties, and device settings affect measurement. These factors make it difficult to establish a common threshold value across studies.

The most important clinical advantage of LDF is its ability to assess vitality during periods when neural responses cannot be obtained despite ongoing circulation in traumatized or incompletely developed teeth. Nevertheless, device cost, time requirements, motion artifacts, and signal contamination from surrounding tissues limit routine use. A systematic review emphasized that LDF has the potential for high accuracy in differentiating normal pulp from necrosis, but that the number of included studies was small and the risk of bias was high (Alghaithy and Qualtrough, 2019).

5.2. Pulse Oximetry

Pulse oximetry exploits the different absorption of red and infrared light by oxygenated and deoxygenated hemoglobin. Medical pulse oximeters calculate oxygen saturation by analyzing the pulsatile arterial component. In dental applications, the transmitter and receiver are placed on opposing surfaces of the tooth so that light passes through the coronal pulp tissue. The method is painless, noninvasive, and independent of the patient's response.

A sensor design appropriate for the tooth is a fundamental requirement of the method. Standard probes produced for the finger do not fully adapt to tooth curvature and size. Nonparallel alignment of the transmitter and receiver, ambient light, patient movement, tooth color, enamel–dentin thickness, restorations, crowns, and signals from surrounding tissues

may distort measurement. Pulpal saturation may be expected to be lower than finger saturation; medical thresholds should therefore not be applied directly to the tooth. Measurements should be recorded together with control teeth and the systemic SpO₂ value.

Patro et al. (2022) reported that pulse oximetry showed higher diagnostic performance than EPT, cold, and heat tests; however, none of the studies included in the meta-analysis reached a good level in the quality assessment. More recent reviews likewise support the potential of pulse oximetry but continue to show heterogeneity in sensor design, thresholds, and study design (Sabharwal et al., 2025; Hosseinzadehfard et al., 2026). The method should therefore be presented not as one that definitively replaces conventional tests, but as a tool that provides additional objective information in selected cases.

Pulse oximetry is particularly promising in traumatized and immature teeth. In the clinical study by Dindaroğlu and Güngör (2024), a high correlation was found between pulse oximetry and EPT and cold-test responses in immature and mature permanent incisors; oxygen saturation measured in immature teeth was reported to be higher than in mature teeth. This finding demonstrates the need for reference ranges specific to tooth type and developmental stage.

6. New and Emerging Vitality-Assessment Methods

Laser speckle contrast imaging (LSCI) analyzes temporal changes in the speckle pattern resulting from interaction of coherent laser light with moving erythrocytes. Whereas LDF measures at a single point, LSCI has the potential to rapidly generate a perfusion map over a wider area without contact. However, motion artifacts, the optical properties of the tooth, surface geometry, surrounding tissues, and the lack of clinical thresholds keep its dental use at the research stage (Heeman et al., 2019).

Dual-wavelength spectrophotometry aims to provide information about pulpal circulation by using the absorption of oxygenated and deoxygenated hemoglobin at different wavelengths. Photoplethysmography records the effect of pulsatile changes in blood volume on light transmission or reflection. In these methods, which are based on optical principles similar to pulse oximetry, the light transmission of enamel and dentin, sensor geometry, and signal-to-noise ratio are the main technical challenges.

Ultrasound Doppler flowmetry uses changes in the frequency of ultrasound waves reflected from moving blood cells. Its advantages are the absence of ionizing radiation and the provision of data related to blood flow. However, the small size of the tooth, probe stabilization, and contamination of the signal by gingival blood flow limit clinical

applicability. Thermography and measurement of tooth-surface temperature aim to indirectly assess thermal changes produced by pulpal blood flow; standardization is difficult because of ambient temperature, air flow, and surface moisture.

Methods such as optical coherence tomography and magnetic resonance imaging also have the potential to assess the pulp–dentin complex noninvasively. At present, however, clinical evidence for their use in determining vitality is limited, equipment requirements are high, and protocols are not standardized. Artificial intelligence does not measure vitality on its own; in the future, it may enable decision-support models that combine history, thermal response curves, EPT, optical perfusion, and imaging data. Such use requires multicenter data, external validation, explainability, and a framework for clinical responsibility.

7. Pulp Tests in Special Clinical Situations

7.1. Traumatized Teeth

After trauma, stretching or disruption of the neurovascular bundle may cause neural conduction to recover at a different rate from circulation. Particularly in luxation injuries, the absence of a response to cold and EPT at the initial examination is common and does not, by itself, establish a diagnosis of necrosis. Baseline tests should be recorded for future comparison; serial follow-up should be performed together with assessment of color, mobility, percussion, root development, periapical changes, and signs of resorption (Bourguignon et al., 2020).

In traumatized teeth, circulation-based methods such as LDF, pulse oximetry, and ultrasound Doppler may provide objective information earlier than sensibility tests. A comparative study in recently traumatized teeth supported the advantage of pulse oximetry over electrical and thermal tests in directly assessing circulation (Gopikrishna et al., 2007). Nevertheless, although findings in a systematic review of trauma cases were promising, a high risk of bias in research designs was reported and superiority could not be established conclusively (Lima et al., 2019). Therefore, a single positive vitality measurement, no less than an initial negative sensibility response, should not be interpreted independently of clinical follow-up.

7.2. Immature Permanent Teeth

In teeth with incomplete root development, the plexus of Raschkow and the nerve network at the dentin–pulp border are not yet mature; thermal and electrical responses may therefore be weak or variable. Failure of a vital tooth with an open apex to respond to EPT

may lead to a false-negative result. Using age-appropriate control teeth, radiographically monitoring root development, and adding blood-flow-based tests when possible improve diagnostic reliability.

A false diagnosis of necrosis in an immature tooth may result in loss of the pulp's capacity to continue root development and in unnecessary regenerative or apexification procedures. Symptoms, sensibility, circulation, and follow-up findings should therefore be assessed together. Repeated, standardized records are more valuable than a single negative test.

7.3. Multirooted, Crowned, Restored, and Calcified Teeth

In multirooted teeth, different canals may have different pulpal statuses. Vital tissue in one canal may produce a positive thermal or electrical response despite necrosis in other canals. The surface and cusp to which the stimulus is applied may influence the result. Findings should be interpreted at the canal level together with the distribution of caries/restorations, periodontal probing, and periapical images.

Full crowns alter the transmission of thermal and electrical stimuli. Almutairi et al. (2021) found sensitivity and accuracy of 87% for cold testing in crowned teeth and accuracy of 67% for EPT using a bridging technique. Both methods are useful adjuncts, but a negative response should be interpreted cautiously because of crown material and application technique. In metal restorations, transmission of EPT to the gingiva or an adjacent tooth may lead to a false-positive result.

Age- or trauma-related calcification in the pulp chamber and canals makes it more difficult for a stimulus to reach neural tissue. Discoloration and radiographic narrowing are not synonymous with necrosis. In a calcified tooth, absence of symptoms, periapical health, and serial radiographs may have greater clinical value than a one-time sensibility test.

7.4. Children, Older Adults, and Patients Receiving Orthodontic Treatment

In children, understanding test instructions, fear, and expectation responses affect the result. The test should first be demonstrated on a sound control tooth, a simple stop signal should be used, and unnecessary repetition should be avoided. In older adults, secondary dentin deposition, reduced pulp volume, and changes in the number of nerve fibers may raise the sensibility threshold. Absolute EPT values should therefore not be compared across age groups.

Orthodontic forces may cause temporary changes in pulpal blood flow and neural response. A systematic review and meta-analysis reported an increased EPT threshold and a

higher likelihood of nonresponse during active orthodontic movement (Golež et al., 2023). A negative EPT result in a tooth undergoing orthodontic treatment should not be interpreted as necrosis in the absence of trauma, caries, symptoms, and radiographic findings.

8. Factors Affecting Test Results and Diagnostic Errors

A false-positive result is the interpretation of a test as showing a response in a necrotic tooth or a tooth that does not have the target condition. The patient signaling early because of expectation, transmission of EPT current to the gingiva or an adjacent tooth, spread of the cold stimulus to adjacent tissues, and residual vital tissue in a multirrooted tooth are the main causes. A false-negative result is the classification of a vital pulp as nonresponsive; trauma, an open apex, calcification, advanced age, a thick restoration, local anesthesia, inadequate stimulus, and problems in patient communication may lead to this situation.

Patient-related variables include age, anxiety, pain threshold, systemic neurological diseases, use of analgesics or sedatives, and communication difficulties. Tooth-related variables include tooth type, root development, restorations, crowns, dentin thickness, calcification, trauma, orthodontic movement, and partial necrosis. Operator-related variables include failure to use a control tooth, inadequate isolation, a nonstandard amount of agent, incorrect electrode/probe position, and recording only a binary outcome.

For standardization, the clinical record should specify the test agent and device, application surface, control tooth, nature and duration of the patient's response, EPT threshold value, and clinical conditions that may affect the test. During follow-up, the same method and a similar application point should be used whenever possible. It should be remembered that diagnostic-accuracy measures are affected by disease prevalence and the definition of "positive"; sensitivity and specificity values should not be generalized directly to every clinic.

9. Diagnostic Performance and Limitations of the Evidence

In the meta-analysis by Mainkar and Kim (2018), which included 28 studies, sensitivity values for cold testing, EPT, heat testing, LDF, and pulse oximetry were calculated as 0.87, 0.72, 0.78, 0.98, and 0.97, respectively; specificity values were 0.84, 0.93, 0.67, 0.95, and 0.95. LDF and pulse oximetry showed the highest adjusted accuracy, whereas the heat test showed the lowest. Nevertheless, differences in the number of studies, reference standards, and quality among methods limit the establishment of a clinical hierarchy based solely on these figures.

Patro et al. (2022) reported that pulse oximetry had a higher diagnostic likelihood ratio than the other methods, but did not rate any study as good in terms of quality. In addition,

some recent meta-analyses have wide confidence intervals and mutually inconsistent sensitivity–specificity estimates (Sabharwal et al., 2025). Thus, an “objective” measurement does not automatically mean high-quality, generalizable evidence.

Although most pulp tests focus on differentiating vital from necrotic pulp, clinical decision-making often requires distinction among normal pulp, mild inflammation, severe inflammation, and healing capacity. A current ESE-supported systematic review emphasizes that existing clinical tests have low effectiveness in determining the true status of pulpitis and that future diagnostic packages combining symptoms, clinical tests, circulation, and biomarkers are needed (Donnermeyer et al., 2023).

10. Clinical Decision-Making and Diagnostic Algorithm

The first step of the clinical approach is to obtain a pain and trauma history; the second is visual, periodontal, and periapical assessment. In the third step, sound control teeth are selected and the cold test is performed first. If the cold response is clearly different from that of the control tooth or if no response is obtained, a complementary assessment with EPT is performed. A controlled heat test may be added if the patient’s principal complaint is related to heat. When the results are consistent with radiographic and apical findings, pulpal and apical diagnoses are recorded together.

If tests are contradictory, technical causes are investigated before irreversible treatment is initiated: isolation, stimulus intensity, restorations, crowns, calcification, trauma, an open apex, and orthodontic movement are reviewed. Tests are repeated at an appropriate interval and another control tooth is used. When available, pulse oximetry or LDF may provide additional information about circulation. In trauma cases without acute infection, progressive resorption, or clear apical pathology, serial follow-up is safer than relying on a single negative sensibility test.

In the first example scenario, a mature molar with deep caries shows a severe and prolonged response to cold, responds differently to EPT than the control tooth, and may be negative to percussion. This pattern suggests a vital but inflamed pulp; the tests assess treatment need in clinical context rather than necrosis alone. In the second scenario, an immature incisor with a recent luxation injury may not respond to cold or EPT; if radiography is normal and a circulation-based measurement is positive, follow-up takes priority. In the third scenario, failure of a crowned, calcified, asymptomatic tooth to respond to cold does not by itself indicate root canal treatment if periapical health is preserved.

The clinical record should not consist only of the words “vital” or “nonvital.” The history, test type, control tooth, nature of the response, apical diagnosis, imaging, and uncertainty should be clearly documented. This approach provides comparable data during follow-up and makes visible the findings on which the diagnostic decision is based.

11. Future Perspective

The most important future need is the development of circulation-based devices with standardized, small, and repeatable sensors for dental use. It is not safe to apply a single SpO₂ or perfusion threshold to all teeth before reference ranges are established for tooth type, age, root development, and restorative status. Multicenter, prospective diagnostic-accuracy studies with appropriate reference standards are needed.

Biomarkers may enable assessment not only of the presence of pulpal inflammation but also of its biological severity and healing potential. Measurement of dentinal fluid, pulpal bleeding, and inflammatory mediators, when combined with thermal and circulation tests, may provide a more precise classification. However, the invasiveness of sampling methods, threshold values, and clinical applicability remain issues to be resolved.

Artificial intelligence–supported decision systems have the potential to integrate multidimensional data from different tests. However, model performance cannot replace clinician responsibility. Automated diagnostic recommendations should not become the basis of routine care until representation bias in datasets, lack of external validation, and explainability problems are resolved. The most realistic near-term goal is decision support that facilitates standardized data collection by the clinician and makes conflicting findings visible.

12. Conclusion

Assessment of pulp vitality is not limited to the positive or negative response produced by a single device. Cold, heat, and EPT assess neural excitability, whereas LDF and pulse oximetry assess circulation-related parameters. Each method has a different biological target, application technique, and source of error. The cold test remains the most useful first-line method in daily practice; EPT is complementary, and the heat test is used in selected cases guided by the history. Circulation-based tests hold important potential, particularly in traumatized and immature teeth, but device and evidence standardization still lag behind routine use.

The most reliable clinical approach combines a detailed history, clinical and radiographic assessment, appropriate control teeth, multiple tests, and monitoring over time

when necessary. It should be remembered that a test result is not the same as the histological status of the pulp, that blood flow alone does not determine the degree of inflammation, and that a negative sensibility response does not always mean necrosis. Such a holistic approach both reduces unnecessary endodontic treatment and contributes to the correct selection of cases in which vital pulp can be preserved.

Table 1. Comparison of pulp sensibility and vitality tests

Method	Biological target	Main advantage	Main limitation
Cold test	Neural response	Practical, inexpensive, and a strong first-line test	Does not measure blood flow; false negatives in trauma, open apices, and calcification
Heat test	Neural response	May reproduce a complaint triggered by heat	Standardization and diagnostic accuracy are lower
EPT	Electrical neural excitability	Complementary to cold testing and provides a quantitative threshold record	The numerical value does not indicate pulp health; current leakage
LDF	Erythrocyte movement/perfusion	Circulation measurement independent of subjective response	Motion and gingival signal; cost and standardization
Pulse oximetry	Oxygen saturation	Noninvasive; potential in trauma and immature teeth	Lack of dental sensors and reference ranges
LSCI	Area-based perfusion	Potential for rapid, contact-free perfusion mapping	Insufficient dental clinical validation and threshold values

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CHAPTER 3

GUIDED ENDODONTICS: STATIC GUIDES AND DYNAMIC NAVIGATION

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1. Introduction and Historical Background

Preparing the access cavity is the opening move of every root canal treatment, and much of what follows depends on it. A well-made access gives a straight path to every canal orifice while sacrificing as little of the pericervical dentine as possible, because that dentine largely determines how well the tooth will resist fracture in the long run (Zehnder et al., 2016; Ribeiro et al., 2022). In most teeth this balance is routine. When the pulp space has been narrowed or closed by hard tissue deposition, however, it can test even the most experienced clinician.

Pulp canal obliteration (PCO) is above all a late consequence of dental trauma, reported in 15–40% of teeth after luxation injuries (Connert et al., 2022). Because ongoing dentine deposition implies that the pulp is still alive, root canal treatment is not indicated unless clinical or radiographic signs of disease appear. Over long observation periods, though, up to about 27% of obliterated teeth go on to develop apical periodontitis (Connert et al., 2022). The clinician must then search for a canal that cannot be seen while managing the risks of perforation, deviation from the root axis, instrument fracture and excessive dentine removal. A classic retrospective study, summarised by Connert et al. (2022), found technical failures in one third of totally obliterated incisors, with a clear drop in healing as a result. The American Association of Endodontists accordingly classifies these teeth as high-difficulty cases (Connert et al., 2017; Lara-Mendes et al., 2018).

Operating microscopes, ultrasonic tips and CBCT have made such cases easier to manage, yet locating the canal has remained dependent on the operator's spatial reasoning and manual skill (van der Meer et al., 2016). Guided endodontics was developed to reduce that dependence. Its central idea is borrowed from computer-assisted implant surgery: the route to the canal is first designed virtually and then reproduced in the mouth, either with a template or with a real-time navigation system that keeps the operator on the planned path (Connert et al., 2022; Wei et al., 2023).

The first systematic descriptions appeared almost simultaneously in 2016. Buchgreitz et al. (2016) merged CBCT data with an optical surface scan to build a guide rail and tested its accuracy *ex vivo*, while Zehnder et al. (2016) showed that access cavities drilled through 3D-printed templates deviated from the plan by only a few tenths of a millimetre and reached every canal. The term “guided endodontics” became established through the work of the Basel and Würzburg groups in this period (Connert et al., 2022). In the same year, van der Meer et al. (2016) reported the clinical use of digitally designed, rapidly prototyped directional guides in severely obliterated anterior teeth. Guides had in fact been used even earlier to locate the entry point and angle into the invagination of dens invaginatus (Wei et al., 2023).

The technique diversified quickly. Smaller burs and sleeves led to “microguided endodontics” for narrow mandibular incisors (Connert et al., 2017, 2018), and intracoronar guide techniques were described for molars where mouth opening is limited (Buchgreitz et al., 2019). From 2019, dynamic navigation systems originally built for implantology entered endodontics, and the field split into a static and a dynamic branch (Wei et al., 2023; Hegde et al., 2024). Today, guided approaches are used not only for calcified canals but also for developmental anomalies, removal

of fibre posts and mineral trioxide aggregate (MTA), management of separated instruments, endodontic microsurgery and tooth autotransplantation (Wei et al., 2023; Ren et al., 2025).

The chapter first covers the underlying technology and the indications, then walks through the static and dynamic workflows. After reviewing the evidence on accuracy and clinical outcome, it closes with the limitations of the method and its likely future.

2. Core Concepts and Technology

Guided endodontics rests on four elements that depend on one another: CBCT to show the canal anatomy in three dimensions, a surface scan that records the teeth and gingiva in high resolution, software that superimposes the two data sets for virtual planning, and a guidance tool that carries the plan into the mouth (Connert et al., 2022; Wei et al., 2023).

2.1. Terminology

The literature uses several names for the same ideas. In **static guided endodontics** (also called static navigation or template-guided endodontics), a template designed on the computer and produced by 3D printing or milling holds the bur at a predetermined angle and depth. **Microguided endodontics** is a version of this approach adapted to narrow roots with thinner burs and sleeves (Connert et al., 2017). **Dynamic navigation** (dynamic or real-time guided endodontics) replaces the template with optical tracking, so that the position, angle and depth of the bur are displayed live on the CBCT images (Hegde et al., 2024; Hildebrand et al., 2025). Wei et al. (2023) grouped all of these, including targeted endodontic microsurgery performed with surgical templates, under the umbrella term “digital guided therapy”.

2.2. Cone-beam computed tomography

CBCT is the indispensable data source for guided treatment. Two-dimensional periapical radiographs can disagree considerably with CBCT about the number of canals and about the presence and size of periapical lesions, particularly in maxillary molars (Cheung et al., 2013). In an obliterated tooth, only cross-sectional imaging can show the level at which the canal becomes visible again.

The smallest suitable field of view (FOV) and the highest practical resolution should be chosen; for endodontic diagnosis and treatment an FOV below 80 mm is usually enough (Connert et al., 2022; Wei et al., 2023). Placing cotton rolls or gauze between the arches during the scan prevents artefacts caused by opposing teeth touching. Scatter from metallic restorations can compromise planning accuracy, and in such cases a scanning appliance carrying radiopaque fiducial markers may help (Wei et al., 2023). If the canal cannot be seen at all on CBCT, the root apex is taken as the apical target for the bur (Connert et al., 2022).

The decision to take a CBCT scan should follow national and international guidance. Horner et al. (2015) found that the methodological quality of dental CBCT guidelines was often low, but that the guidelines broadly agreed on clinical use, and they stressed that the justification principle of radiation protection is especially important because CBCT delivers a higher dose than conventional dental radiography. In guided endodontics the additional exposure may be warranted because iatrogenic damage becomes less likely (Moreno-Rabié et al., 2020).

2.3. Surface scanning

CBCT does not depict the tooth and soft-tissue surfaces on which a template will sit with enough precision. Static guidance therefore requires a surface scan in almost every case, obtained either directly with an intraoral scanner or indirectly by digitising an impression-based cast in a laboratory scanner (Connert et al., 2022; Wei et al., 2023). The scanned area should include enough teeth to keep the template stable. Because dynamic navigation uses no template, a surface scan is not mandatory there (Wei et al., 2023).

2.4. Planning software and data registration

The CBCT data are imported in DICOM format and the surface scan in STL format, and the two are aligned on shared anatomical landmarks. Software written specifically for endodontics is still scarce, so implant planning programs are used in most published cases (Wei et al., 2023). Successful use has been reported with coDiagnostix (Zehnder et al., 2016; Krug et al., 2020), Blue Sky Plan (Hegde et al., 2019; Perez et al., 2021) and Simplant (Lara-Mendes et al., 2019). A true-to-scale virtual copy of the chosen bur is placed in the aligned data set so that its tip reaches the point where the canal becomes visible. In the static workflow a virtual sleeve and template are then designed; in the dynamic workflow the planned path is passed to the navigation system.

2.5. Manufacturing

Static templates can be produced additively by 3D printing or subtractively by CAD/CAM milling (Connert et al., 2022). Templates printed in clear resin let the clinician confirm visually that the template is fully seated (Hegde et al., 2019; Buchgreitz et al., 2019). The sleeve is usually metal, and the clearance between bur and sleeve directly affects accuracy; the high accuracy of the microguided technique has been attributed largely to optimising this fit (Connert et al., 2017, 2022).

3. Indications

The main indication is a tooth that needs root canal treatment but whose canal orifice is unlikely to be found safely by conventional means. Pulp canal obliteration sits at the centre of this group, while developmental anomalies, teeth needing retreatment and surgical endodontics are increasingly managed with guidance as well (Moreno-Rabié et al., 2020; Wei et al., 2023).

3.1. Pulp canal obliteration

PCO, also described as calcific metamorphosis, pulp canal calcification or reduced pulpal lumen, is the partial or complete closure of the canal space by hard tissue laid down along its walls (Fonseca Tavares et al., 2018; Hegde et al., 2019). Luxation injury is the most common cause, but caries, deep restorations, vital pulp therapy, orthodontic forces, regenerative endodontic procedures and the age-related build-up of secondary dentine can also lead to it (Ishak et al., 2020; Connert et al., 2022). Reported figures include an incidence of 22% in traumatised permanent teeth, pulp necrosis in 1–16.5% of obliterated teeth, and apical periodontitis in 7.3–24% within four years of the injury (Fonseca Tavares et al., 2018). The commonest clinical sign is a yellowish discolouration, seen in roughly 70–80% of affected

teeth, and the response to sensibility testing is often reduced or absent (Llaquet Pujol et al., 2021).

Obliteration alone is not a reason to treat. Treatment becomes relevant when there are symptoms, signs of apical periodontitis, or discolouration that calls for internal bleaching combined with root canal treatment (Llaquet Pujol et al., 2021; Connert et al., 2022). In these situations even an experienced specialist working under the microscope may need up to an hour to negotiate the canal, and a successful negotiation can still remove a substantial amount of dentine, particularly in the cervical region (Connert et al., 2022).

Wei et al. (2023) recommend that guidance for PCO be considered first in anterior teeth with a single straight root and clear signs of apical periodontitis, and they note that a template can efficiently direct the bur through the calcified segment when the canal is visible on CBCT in the apical third. For narrow-rooted teeth such as mandibular incisors, the microguided technique is preferred (Connert et al., 2018; MahjourianQomi et al., 2024). Successful cases have also been published in premolars and molars (Lara-Mendes et al., 2018; Shi et al., 2018; Buchgreitz et al., 2019), but whether guidance is suitable in the posterior region remains debated because of limited interocclusal space and root curvature (Wei et al., 2023).

3.2. Developmental anomalies

Dens invaginatus produces an irregular canal system and has a prevalence of about 9% in adults examined with CBCT (Wei et al., 2023). Ali and Arslan (2019) used a guided approach to reach both the invaginations and the main canal in two maxillary lateral incisors with multiple invaginations, and they reported that the technique shortened chair time and lowered the risk of iatrogenic damage. Stereolithographic splints have also allowed conservative access in dens evaginatus (Mena-Álvarez et al., 2017). Hereditary dentine disorders such as dentine dysplasia can cause widespread obliteration across the dentition. Krug et al. (2020) described a patient with radicular dentine dysplasia in whom the first molar, treated conventionally, suffered two perforations; after switching to a guided technique for the remaining six teeth, every canal was located quickly, and clear apical healing was seen at one year.

3.3. Retreatment

Guidance is also used to remove intracanal obstructions. Adhesively cemented fibre posts are difficult to remove without perforation or deviation from the root axis. Despite CBCT artefacts from composite materials, Perez et al. (2021) achieved mean deviations of 0.39 mm coronally and 0.40 mm apically when removing fibre posts with a microguided technique. Abella Sans et al. (2024) showed that, compared with freehand removal using ultrasonic tips, static navigation reached the gutta-percha more often and more quickly, produced fewer perforations, and gave similar results for experienced and inexperienced operators. Comparable benefits have been described clinically (Maia et al., 2022). When an MTA barrier placed during regenerative treatment had to be removed, static guidance was faster, free of mishaps and better at preserving fracture resistance than unguided removal (Ali & Arslan, 2021). Templates that guide a trephine to a separated instrument have been described (Bordone et al., 2022), but a systematic review

of in vitro studies warns that, for this particular indication, guided techniques may cause more iatrogenic errors and take longer than freehand work (Samiei et al., 2025).

3.4. Surgical endodontics and other applications

In endodontic microsurgery, locating the root apex precisely and controlling the length of the resection are difficult when the buccal cortical plate is thick or when the mental foramen or maxillary sinus is close by. Targeted endodontic microsurgery, in which a surgical template and a trephine bur of fixed diameter remove the bone and cut the root end together in one pass, was developed for these situations. According to data summarised by Wei et al. (2023), 24 cases treated in this way showed a success rate of 91.7% at one year or later, and 11 teeth treated with dynamic navigation showed 90%. Guidance is also used in tooth autotransplantation to prepare the recipient site and to shorten the time the donor tooth spends outside the mouth (Wei et al., 2023).

3.5. Case selection

When deciding whether a guided approach suits a given tooth, the following points should be considered together:

- Whether the root is straight, or straight up to the target point; static guidance cannot be carried beyond a curvature (Moreno-Rabié et al., 2020; Connert et al., 2022).
- The level at which the canal becomes visible on CBCT and the bur length this implies.
- Whether mouth opening and interocclusal space can accommodate the template, the bur and the handpiece head together (Buchgreitz et al., 2019).
- Whether neighbouring teeth can support the template securely and whether metal artefacts obscure the CBCT image (Wei et al., 2023).
- Whether the extra radiation dose and cost are justified by the expected clinical benefit.

4. Static Guided Endodontics

The static workflow borrows its principles from template-guided implant surgery and is, technically speaking, the more mature of the two approaches (Connert et al., 2022). The steps below summarise the procedures described in the literature and in expert consensus (Connert et al., 2022; Wei et al., 2023).

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Figure 1 shows where the two approaches share a starting point and where they diverge: the static route depends on a surface scan and a manufactured template, whereas the dynamic route relies on registration and calibration carried out at the time of treatment (Connert et al., 2022; Wei et al., 2023).

4.1. Diagnosis and pre-treatment assessment

The diagnosis is established from the clinical examination and a periapical radiograph. The patient is told about the benefits of the method as well as its drawbacks, including the additional

radiation dose and cost, before informed consent is obtained (Wei et al., 2023). CBCT is then used to judge how far the obliteration extends, how curved the root is and what the periapical status is.

4.2. Data acquisition and virtual planning

A high-resolution, small-FOV CBCT scan and an intraoral surface scan are acquired and superimposed in the planning software. A virtual copy of the chosen bur is placed along the long axis of the root so that its tip reaches the point at which the canal becomes visible again. If no canal can be seen on CBCT at all, the root apex serves as the target (Connert et al., 2022). In anterior teeth the entry point deserves particular thought, because many published cases have sacrificed the incisal edge, entering through or very close to it in order to obtain a straight path (Wei et al., 2023). Fonseca Tavares et al. (2018) showed that the incisal edge can be preserved when the plan is built around a conventional palatal access. The virtual sleeve is then positioned, the template is designed, and the design is exported as an STL file.

4.3. Template fabrication and verification

The template is 3D printed or milled, and a metal sleeve is fitted into it. Some clinicians test the template and the bur angulation on a tooth model printed in transparent resin before using it in the patient (Hegde et al., 2019). At the chairside, the template must be confirmed to sit completely and without tension.

4.4. Clinical procedure

With the template in place, the enamel is marked through the sleeve and then removed with a high-speed diamond bur until dentine is exposed; in retreatment cases this step may not be needed (Wei et al., 2023). The guide bur is next advanced a few millimetres at a time at low speed, using a pumping motion. Published bur diameters range from 0.8 to 1.5 mm and rotational speeds from 350 to 10,000 rpm (Wei et al., 2023). For example, Torres et al. (2019) used a round carbide bur with a 0.8 mm head, while Llaquet Pujol et al. (2021) used a purpose-made cylindrical bur 1 mm in diameter. To avoid overheating, the cavity should be flushed generously about every 2 mm (Wei et al., 2023). After each advance the operator probes for the canal with a hand file; if it has not yet been reached, the bur is cleaned of debris and drilling continues. This cycle is repeated until the bur meets the mechanical stop of the sleeve, which corresponds to the planned apical target (Connert et al., 2022). Some clinicians also take a periapical radiograph after every 3 mm of progress (Hegde et al., 2019).

The rubber dam is placed at the outset if it does not interfere with seating the template; otherwise it is applied once the canal has been found (Ishak et al., 2020; Wei et al., 2023). When the target has been reached, the tooth is inspected under the operating microscope, and once the canal is located, treatment continues in the usual way with shaping, irrigation, medication, obturation and restoration.

4.5. Technical modifications

- **Microguided endodontics:** reducing the diameter of the bur and sleeve makes a minimally invasive access into the apical third possible even in narrow roots such as those of mandibular incisors (Connert et al., 2017, 2018; Torres et al., 2019).
- **Intracoronar guide:** in molars, the limited occlusal space may not allow the template, bur and handpiece to fit together. Buchgreitz et al. (2019) overcame this by using the template to create a guide channel inside composite placed within the crown.
- **Sleeveless design:** here the handpiece head is steered between guide rails on either side of the tooth. No special bur is required and access in the posterior region is intended to be easier, although accuracy data are still scarce (Connert et al., 2022).
- **Multiple templates:** separate templates for enamel and dentine can allow a palatal entry, but at the cost of greater expense and procedural complexity (Wei et al., 2023).

4.6. Advantages

The chief strength of static guidance is that its results depend very little on the operator's experience. In a study in which three operators with different levels of experience treated 3D-printed calcified incisors, Connert et al. (2019) found that the canal was located in 41.7% of attempts with the conventional technique and in 91.7% with the guided technique. Mean substance loss was 49.9 mm³ with conventional access and 9.8 mm³ with guided access, and treatment took 21.8 and 11.3 minutes, respectively. Operator experience had no influence on the guided results. Lara-Mendes et al. (2019) likewise pointed out that the method can be used by less experienced clinicians and does not require an operating microscope. It should be noted, however, that most of these time comparisons leave out the extra time needed to produce the template (Wei et al., 2023).

5. Dynamic Navigation

In dynamic navigation the planned bur path is executed with the help of an optical tracking system rather than a physical template. The system follows the position of the bur and of the patient's jaw in real time and displays both on screen over the CBCT data, which is why it is often likened to a GPS (Hegde et al., 2024). The technique was first developed for implant dentistry and has been applied in endodontics since 2019 (Connert et al., 2022; Wei et al., 2023).

5.1. System components

The systems reported most often in the endodontic literature are Navident (ClaroNav), X-Guide (X-Nav Technologies) and DENACAM, a miniaturised system (Wei et al., 2023; Hegde et al., 2024). In general, a system consists of the following parts (Hegde et al., 2024):

- a computer and monitor running the planning and tracking software;
- a stereoscopic camera that follows optical markers;
- trackers carrying optical markers, fixed to the patient's jaw or head (jaw or head tracker);

- a tracer tool used to calibrate the system and register it to the patient's anatomy;
- a drill tag attached to the handpiece, which allows the axis and tip of the bur to be followed.

5.2. Workflow

Because no template is fabricated, a surface scan is not essential in dynamic navigation (Wei et al., 2023). In the classic workflow, a registration appliance containing radiopaque fiducial markers is fixed to teeth on the side opposite the treatment site, and the CBCT is taken with the appliance in the mouth. With newer systems the fiducials can be planned digitally and 3D printed, so an existing CBCT acquired without an appliance may also be used (Connert et al., 2022). Hegde et al. (2024) describe the workflow in three stages:

1. **Plan:** the CBCT data are loaded into the system, and the bur path is planned virtually on the axial, bucco-lingual and mesio-distal views of the software.
2. **Trace:** the tracker is attached to the patient, visible anatomical points or fiducials are touched with the tracer tool to register the CBCT data to the patient's actual position, and an accuracy check confirms that the on-screen position matches the real teeth.
3. **Place:** the drill tag is fitted to the handpiece and the bur axis and tip are calibrated. Throughout the procedure, the clinician watches the virtual bur on screen and corrects its position, angle and depth in real time.

Once the canal orifice has been reached, the remaining steps are carried out conventionally, exactly as in the static approach.

5.3. Advantages

Compared with static guidance, dynamic navigation offers the following main benefits (Connert et al., 2022; Wei et al., 2023; Hegde et al., 2024):

- With no template to manufacture, the interval between diagnosis and treatment is shorter, and patients in severe pain can be treated on the same day.
- The bur path can be seen during the procedure and altered if necessary; the plan is not fixed.
- Without a template and sleeve, space is less of a problem in patients with limited mouth opening and in the posterior region.
- In anterior teeth, a conventional palatal access can be used if the enamel is removed appropriately beforehand, although drilling may be less stable without the mechanical support a template provides (Wei et al., 2023).

5.4. Learning curve and operator effect

Unlike the static approach, dynamic navigation is not independent of the operator. Working while looking at a monitor rather than at the patient calls for unfamiliar hand–eye coordination, so adequate practice on models is recommended before clinical use (Connert et al., 2022; Wei

et al., 2023). More experienced operators have been reported to remove less tooth structure (Wei et al., 2023), and in molars the camera may have difficulty detecting the drill tag (Connert et al., 2022; Wei et al., 2023).

At the same time, dynamic navigation is also regarded as a tool that can narrow the gap between experienced and less experienced clinicians. In 72 extracted calcified teeth, Hildebrand et al. (2025) found that a general dentist without specialist training located 34 of 36 canals using real-time guided endodontics, while an endodontist using the conventional technique located 32 of 36. Navigation removed less tooth structure (95% CI 9–14.3 mm³ versus 15–24.2 mm³) but took considerably longer (95% CI 11.6–17.8 min versus 1.4–2.5 min). The authors concluded that the method may be a safe option for non-specialists.

5.5. Disadvantages

The purchase cost of these systems is high, and some commercial units are bulky and cumbersome to use in the clinic (Connert et al., 2022). The need for training and the set-up time are also listed among the factors that keep the technology from becoming routine in everyday practice (Hegde et al., 2024; Ren et al., 2025).

5.6. Static and dynamic approaches compared

Feature	Static guided endodontics	Dynamic navigation
Guiding device	3D-printed or milled template with sleeve	Stereo camera, trackers, drill tag
Data required	CBCT and surface scan	CBCT (surface scan optional)
Time from diagnosis to treatment	Template must be produced	Same-day treatment possible
Changes during the procedure	Not possible	Real-time correction
Dependence on operator experience	Low	High, with a learning curve
Posterior teeth and limited opening	Difficult	Relatively easier; tracking problems possible in molars
Cost	Template cost for every case	High initial investment
Level of evidence	Case reports, case series, one RCT	Mostly in vitro studies and case reports

Sources: Connert et al. (2022), Ribeiro et al. (2022), Wei et al. (2023), Hegde et al. (2024), Li et al. (2025).

6. Accuracy and Clinical Outcomes

Laboratory studies agree that both static and dynamic guided access cavities deviate from the planned path by, as a rule, less than half a millimetre and by only a few degrees. Clinical evidence still comes largely from case reports and case series, but the results of the first randomised controlled trial are now available.

6.1. How is accuracy measured?

In most accuracy studies, a post-operative CBCT or surface scan is superimposed on the virtual plan. Linear deviation is then calculated in millimetres at the bur's entry point (coronal, or "base") and at its tip (apical), and the deviation of the bur axis is calculated in degrees (Zehnder et al., 2016; Connert et al., 2017). A threshold has also been proposed to give these numbers clinical meaning. Buchgreitz et al. (2016) added the radius of the bur (0.6 mm) to the radius of a canal that is only just visible radiographically (0.1 mm) to arrive at a risk threshold of 0.7 mm, and showed that the mean deviation they measured lay well below it (95% CI 0.31–0.49 mm). Other studies, such as Hildebrand et al. (2025), assess performance directly in terms of canal detection rate, substance loss and treatment time.

6.2. Laboratory studies

The findings of representative studies are summarised in the table below.

Study	Model	Method	Linear deviation	Angular deviation	Main finding
Zehnder et al., 2016	60 extracted teeth in maxillary models	Static	Base 0.16–0.21 mm; tip 0.17–0.47 mm	1.81°	All canals reached; no difference between operators
Buchgreitz et al., 2016	48 teeth in acrylic blocks	Static (guide rail)	Mean < 0.7 mm (95% CI — 0.31–0.49)	—	Deviation below the risk threshold
Connert et al., 2017	60 mandibular anterior teeth	Microguided static	Base 0.12–0.13 mm; tip 0.12–0.34 mm	1.59°	High accuracy in narrow roots
Connert et al., 2019	48 printed calcified incisors	Static vs freehand	—	—	Canals found in 91.7% vs 41.7%; substance loss 9.8 vs 49.9 mm ³
Perez et al., 2021	40 posterior teeth with fibre posts	Microguided static	Coronal 0.39 mm; apical 0.40 mm	—	Accurate post removal despite CBCT artefacts

Huth et al., 2024	144 printed teeth, 4 tooth types	Static, dynamic, freehand	No significant difference between methods	1.12°, 2.82° and 9.53°	Least substance loss with dynamic; shortest time freehand
Hildebrand et al., 2025	72 calcified extracted teeth	Dynamic (general dentist) vs freehand (endodontist)	—	—	Canals found 34/36 vs 32/36; less substance loss but longer time with navigation

In comparative studies, both guided methods outperformed the freehand technique. Huth et al. (2024) reported that the method was the strongest determinant of angular deviation (partial eta squared 0.524), followed by tooth type (0.364) and operator (0.08). Early work on dynamic navigation produced similar values. As summarised by Connert et al. (2022), printed teeth with simulated obliteration showed a mean angular deviation of 1.7° and a three-dimensional deviation of 1.3 mm, and in one of the first studies on extracted teeth the canals were found in 26 of 29 cases; all three failures were maxillary molars, and in two of them the drill tag could not be tracked reliably.

Accuracy also differs by tooth type. In a study cited by Wei et al. (2023), static guidance produced tip deviations of 0.28 mm in anterior teeth, 0.40 mm in premolars and 0.64 mm in molars, with angular deviations of 1.73°, 2.23° and 4.00°, respectively. The larger error in molars was attributed to the opposing teeth obstructing the bur and pushing it away from its planned entry point.

6.3. Systematic reviews and meta-analyses

Moreno-Rabié et al. (2020) assessed 22 articles, comprising 15 case reports, six preclinical studies and one observational study. They concluded that guided access cavities and guided surgery are accurate and successful compared with the planned path, but that the evidence is of low level and the methods are heterogeneous. In the meta-analysis by Zubizarreta-Macho et al. (2021), the pooled success rate for locating canals with computer-aided navigation was 98.1% (95% CI 95.7–100). There was no significant difference between static (98.5%) and dynamic (94.5%) techniques, and the odds ratio for success with navigation compared with conventional access was 13.1. Based on a small number of studies, Langaliya et al. (2024) found that dynamic navigation preserves more dentine than the freehand technique, and they called for studies comparing it directly with static guides. An umbrella review by Puri et al. (2024) also concluded that guided endodontics is more precise and gives better results than conventional procedures. Focusing on retreatment, Samiei et al. (2025) pointed out that every included study was conducted in vitro and that clinical evidence is lacking.

6.4. Clinical studies

In a case series of 50 patients with PCO in single-rooted teeth, the canal was located and treatment was completed in every case. Accuracy scores for the bur path were higher in mandibular than in maxillary teeth, and better in teeth in which a previous attempt to find the canal had been made (Connert et al., 2022; Wei et al., 2023).

The strongest evidence to date comes from the randomised controlled trial published by Li et al. (2025). Eighty patients with PCO were randomly allocated to freehand or static guided treatment. In the guided group, the mean deviation was 0.14 ± 0.08 mm at the coronal entry point and 0.35 ± 0.16 mm at the apical point, with an angular deviation of $1.75^\circ \pm 0.30^\circ$, all significantly lower than in the freehand group. Pain during treatment and clinical outcomes at one year, however, did not differ between the groups. This suggests that the main contribution of the guided technique is to make the procedure predictable, less invasive and safer, rather than to raise the healing rate.

Case reports describe consistently favourable results as well. Examples include complete apical healing after six months in a maxillary lateral incisor (Torres et al., 2019), clear shrinkage of lesions in maxillary molars at one-year review (Lara-Mendes et al., 2018), apical healing in all teeth after one year in a patient with dentine dysplasia (Krug et al., 2020), and periapical healing at 12 months in a maxillary central incisor (Ghosh et al., 2024). The possibility of publication bias in case reports should nonetheless be borne in mind.

7. Limitations, Complications and Radiation Safety

Used in the right case, guided endodontics is a powerful tool. It is not, however, suitable for every obliterated tooth, and it carries risks of its own. Clinicians need to understand these limitations both to select cases well and to inform patients properly.

7.1. Anatomical and technical limitations

- **Root curvature:** because a rigid bur cuts a straight path, static guidance can only be used in straight roots or in the straight segment of a curved root, and the bur must not be taken past the start of the curve (Moreno-Rabié et al., 2020; Connert et al., 2022). The risk of perforation in curved canals is high, and the technique still needs refinement in this respect (Wei et al., 2023).
- **Posterior region and mouth opening:** the template, the bur and the handpiece head all have to fit at once, which makes treatment of posterior teeth difficult (Buchgreitz et al., 2019; Connert et al., 2022). With dynamic navigation, tracking the drill tag in molars can be problematic (Wei et al., 2023).
- **Chain of accuracy:** the final accuracy is the sum of the errors introduced at each successive step, including CBCT resolution, data superimposition, template manufacture, the tolerance between bur and sleeve, and the seating of the template in the mouth. Artefacts from metal restorations can distort planning (Perez et al., 2021; Wei et al., 2023). The spatial resolution of CBCT is limited, and reducing the voxel size raises the dose (Moreno-Rabié et al., 2020).

- **Loss of the incisal edge and visibility:** a straight guided access in anterior teeth often means removing part of the incisal edge (Fonseca Tavares et al., 2018). Narrow, deep guided cavities also make it harder to see and debride the pulp chamber (Wei et al., 2023).
- **Flexibility:** a static template gives no real-time image and cannot be adjusted during the procedure (Wei et al., 2023).

7.2. Possible complications

Guided access lowers the risk of perforation but does not remove it. Faulty planning, incomplete seating of the template or advancing the bur beyond a curvature can all lead to root perforation. Connert et al. (2022) drew attention to a case in which a perforation created during guided access was managed by apical resection and the tooth was retained. In surgical applications, mishaps such as sinus perforation and incomplete root-end resection have been reported with both static and dynamic methods, attributed respectively to incorrect positioning of the template and to the lack of direct vision of the surgical field (Wei et al., 2023). For some retreatment indications, such as removal of separated instruments, guided techniques may produce more iatrogenic errors (Samiei et al., 2025). Intermittent advancement and generous irrigation are important so that heat generated during drilling does not harm the periodontal tissues (Wei et al., 2023). In teeth that have already suffered an iatrogenic deviation, a guide can be used to regain the original canal, but whether this further weakens the tooth must be weighed carefully (Wei et al., 2023).

7.3. Time and cost

The static method requires extra time for planning and template production; chairside time may fall, but laboratory time is frequently left out of the calculation (Wei et al., 2023). The CBCT and the template add to the patient's costs (Connert et al., 2022). For dynamic systems, the high purchase price and the need for training are the main barriers to wider adoption (Hegde et al., 2024; Ren et al., 2025). On the other hand, van der Meer et al. (2016) emphasised that an endodontic guide can make difficult treatments easier at little extra cost.

7.4. Radiation safety

Guided endodontics depends on a pre-operative CBCT, which increases the dose the patient receives (Connert et al., 2022; Wei et al., 2023). Imaging should therefore be justified for each individual case (Horner et al., 2015), the smallest field of view suitable for the endodontic question should be chosen, and a new scan should not be taken if an adequate diagnostic CBCT already exists. In dynamic navigation, systems that allow the fiducial markers to be planned digitally avoid the need for a second CBCT with markers in place (Connert et al., 2022). These principles matter even more in children and young patients, whose tissues and organs are more sensitive to radiation (Connert et al., 2022). The extra dose and cost may be justified by the reduced risk of iatrogenic error (Moreno-Rabié et al., 2020). During follow-up, healing is mostly assessed on two-dimensional radiographs, which is a further limitation when interpreting outcomes (Cheung et al., 2013; Moreno-Rabié et al., 2020).

7.5. Level of evidence

Most publications on guided endodontics are case reports and laboratory studies, and systematic reviews rate the level of evidence as low (Moreno-Rabié et al., 2020; Connert et al., 2022). Evidence on which of the static and dynamic methods is better suited to clinical practice remains very limited (Wei et al., 2023). The method should therefore be regarded not as a standard that replaces conventional techniques, but as a complementary, risk-reducing tool for selected difficult cases.

8. Future Perspectives

The future of guided endodontics is developing along three lines: adapting current techniques to posterior teeth and to a wider range of patients, reducing the reliance on ionising radiation, and bringing navigation into the clinician's field of view.

8.1. Refining the static method

Connert et al. (2022) stress the need for commercially available burs in a wider range of diameters and lengths for static guidance, and in particular for a bur system graded by length to compensate for the limited space in the posterior region. Sleeveless templates and intracoronaral guides are steps in this direction (Buchgreitz et al., 2019; Connert et al., 2022). Planning software designed specifically for endodontics would also reduce the dependence on implant software (Wei et al., 2023).

8.2. Magnetic resonance imaging

The arrival of magnetic resonance imaging (MRI) in dentistry could make it possible to avoid ionising radiation, especially in children, who are more sensitive to it. In a proof-of-concept study cited by Connert et al. (2022), access cavities planned on MRI data reached 91 of 100 canals under laboratory conditions, with a mean angular deviation of 1.82°. These results still need clinical confirmation, and MRI units are not currently available to most dentists.

8.3. Smaller and markerless dynamic systems

The developments expected in dynamic navigation are smaller systems, the ability to plan fiducial markers digitally on existing scans with every system, and eventually systems that orient themselves on anatomical structures without markers at all (Connert et al., 2022). Early studies with miniaturised systems indicate that the gap between inexperienced and experienced operators can be narrowed (Connert et al., 2022; Hildebrand et al., 2025).

8.4. Augmented reality

Augmented reality (AR) aims to project radiographic images and the planned bur path directly onto the operating field through wearable glasses or a microscope, so that the clinician no longer has to look at a monitor (Connert et al., 2022). Using a markerless AR system to prepare access cavities in 3D-printed jaws, Farronato et al. (2023) reported deviations of 0.51 mm at the coronal entry point, 0.77 mm at a depth of 4 mm, and 8.5° in angulation. These figures are

encouraging, but they lag behind those of static and dynamic methods, and the technology needs further development before clinical use.

8.5. Strengthening the evidence

Whatever technological progress is made, the field's most basic need is high-quality prospective clinical research (Moreno-Rabié et al., 2020; Connert et al., 2022). The first randomised controlled trial of static guidance (Li et al., 2025) and ongoing randomised trials comparing dynamic navigation with freehand endodontic microsurgery (Wei et al., 2023) are important steps forward. Future studies should also assess patient-centred outcomes such as long-term tooth survival, fracture resistance, patient comfort and cost-effectiveness.

9. Conclusions and Clinical Recommendations

Guided endodontics makes root canal treatment more predictable, less invasive and less dependent on operator experience in teeth whose canals cannot be reached safely by conventional means. Laboratory studies and the first randomised clinical trial show that static guides can achieve linear deviations below half a millimetre and angular deviations of about two degrees. Dynamic navigation reaches similar levels of accuracy but differs in its learning curve and cost profile.

The following recommendations stand out for clinical practice:

1. Obliteration on its own is not an indication for treatment; a guided approach should be considered only once root canal treatment is clearly indicated.
2. The ideal case is an anterior tooth with a straight root, a canal that can be followed on CBCT into the apical third, and neighbouring teeth that give the template stable support.
3. CBCT should be taken with a small field of view and justified for the individual patient, and suitable existing images should be reused.
4. The bur path should be planned so that it does not extend beyond any root curvature and, where possible, preserves the incisal edge.
5. In the clinic, seating of the template should be confirmed, the bur advanced in steps with generous irrigation, and the canal checked with a file at every step.
6. Dynamic navigation may be an option for posterior teeth, limited mouth opening and emergency cases, provided enough practice on models has been completed before clinical use.
7. Patients should be informed about the additional radiation dose, cost, possible complications and alternative treatments.

Guided endodontics does not replace the operating microscope or clinical experience; it complements them. As the level of evidence rises and the technology is adapted to posterior teeth, the method can be expected to become one of the standard options for managing difficult endodontic cases in the years ahead.

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