JOURNAL OF INTERNATIONAL CRISIS AND RISK COMMUNICATION RESEARCH
ISSN: 2576-0017
2024, VOL 7, NO S10

Advances in Endodontic Microsurgery: Techniques, Materials, and Innovations for Enhanced Patient Outcomes

Ali Mohammed Falatah[1], Badr Omar Al – Ahmadi[1], Tariq Muteb Alharbi[1], Fayez Abdurrahman Aloufi[1], Suhail Abdulrahman Al – Amoudi[2], Hattan Saud Katib[1*]

1. Consultant endodontist, Specialized Dental Center, King Fahad Hospital, Almadinah - KSA
2. Specialist Endodontist, Specialized Dental Center, Ohud , Hospital ,Madin—KSA.

Email: hattan222333@gmail.com

ABSTRACT

Recent advancements in endodontic microsurgery have redefined the field, providing clinicians with more precise, minimally invasive techniques for managing complex root canal cases. This review highlights the critical role of enhanced magnification, specialized microsurgical instruments, and biocompatible materials in elevating the success rates and predictability of these procedures. Surgical operating microscopes and refined ultrasonic instruments now allow for improved visibility and precise manipulation in root-end surgeries, minimizing trauma and accelerating healing. Biocompatible filling materials, such as Mineral Trioxide Aggregate (MTA) and Biodentine, offer enhanced sealing and integration with periapical tissues, fostering superior healing outcomes. State-of-the-art imaging techniques, including cone beam computed tomography (CBCT) and emerging magnetic resonance imaging (MRI) applications, provide comprehensive, three-dimensional anatomical views that support meticulous preoperative planning and reduce surgical risk. Furthermore, CAD/CAM and 3D printing technologies enable customized surgical guides, improving precision and minimizing invasiveness. Nanotechnology has introduced novel materials with antimicrobial properties, enhancing canal disinfection, sealing, and regenerative potential, which is particularly beneficial for persistent infections. Instruments used in canal shaping have evolved from manual to advanced rotary and reciprocating systems, increasing efficiency and reducing operator fatigue and procedural complications. The integration of fluid dynamics-based systems, such as the GentleWave system, offers a non-instrumental approach for enhanced root canal disinfection, addressing biofilm presence within intricate canal anatomies. Laser-assisted endodontic disinfection (LAED) provides deeper bacterial elimination, leveraging the precise targeting and minimal thermal diffusion of lasers like Erbium and diode types. Pain management has also progressed with buffered anesthetics, computer-assisted delivery systems, and low-level laser therapy (LLLT), offering greater patient comfort and minimizing postoperative discomfort. Lastly, artificial intelligence (AI) has become an essential tool in endodontic diagnostics and treatment planning, enabling accurate identification of canal morphologies, prediction of treatment outcomes, and personalized care planning. These innovations in visualization, materials, instrumentation, and digital technologies collectively signal a transformative era in endodontic microsurgery, emphasizing precision, biocompatibility, and patient-centered care. As the field progresses, these advancements are poised to further improve procedural predictability, reduce treatment morbidity, and optimize patient outcomes, positioning endodontic microsurgery at the forefront of dental medicine.

KEYWORDS: Laser-assisted endodontic disinfection (LAED), low-level laser therapy (LLLT).

Introduction

Over the past few decades, endodontic microsurgery has evolved from a procedure of last resort to a minimally invasive and highly precise approach for managing complex dental cases. Traditionally constrained by limited visualization, rudimentary instruments, and high rates of procedural complications, endodontic surgery once frequently ended in tooth extraction rather than restoration (Setzer & Kratchman, 2022). However, recent advancements in technology, materials, and techniques have transformed endodontic microsurgery into a reliable and accurate alternative, achieving better long-term outcomes and minimizing patient discomfort (Strbac et al., 2017). A primary factor in this transformation is the enhanced ability to visualize and navigate intricate root canal systems. The introduction of surgical operating microscopes, capable of magnifications up to 31x, along with the adoption of focused lighting, has enabled clinicians to perform highly detailed incisions and identify accessory canals previously undetectable by conventional means (AlEid, 2019). Complementing this, advancements in imaging technologies, particularly cone beam computed tomography (CBCT), provide comprehensive three-dimensional views of root and periapical tissues, significantly improving the accuracy of preoperative assessments and surgical planning (Kruse et al., 2018). Innovations in radiation-free imaging, such as MRI, are also showing promise in endodontic diagnostics, particularly when managing cases involving sensitive structures (Reda et al., 2021). Instrumental advancements have paralleled these visual technologies. High-frequency ultrasonic tips and piezoelectric devices enable minimally invasive root-end preparations, effectively addressing apical lesions while preserving surrounding tissue. Such devices allow for more controlled removal of infected tissue and improved adaptability of retrograde filling materials, enhancing treatment success rates (Palma et al., 2020). Additionally, patient-specific surgical guides fabricated via CAD/CAM and 3D printing technologies have refined accuracy and reduced the invasiveness of procedures, underscoring the role of personalized care in modern endodontics (Nesic et al., 2020).

Biocompatible materials have also been a cornerstone of successful endodontic microsurgery. Traditional root-filling compounds have been enhanced with bioactive materials such as Mineral Trioxide Aggregate (MTA), Biodentine, and newer bioceramics, which exhibit excellent biocompatibility and sealing abilities. MTA, in particular, has become the gold standard for its capacity to create a durable, infection-resistant seal and encourage mineralization within the surrounding tissues, crucial for successful healing outcomes (Saxena et al., 2013; Brizuela & Daley, 2024). Innovations in nanotechnology have further advanced the efficacy of root canal fillings, with nanoparticles like nanosilica and silver nanoparticles enhancing the sealing, antibacterial properties, and longevity of endodontic restorations (Afkhami et al., 2023). Infection control remains a pivotal aspect of endodontic success, especially in complex canal anatomies. Novel irrigation and disinfection systems such as the GentleWave system and laser-assisted disinfection techniques have made strides in achieving comprehensive bacterial elimination. The GentleWave system, for instance, leverages advanced fluid dynamics to clean intricate canal spaces with minimal instrumentation, while lasers provide effective photothermal disinfection, reducing the need for extensive mechanical preparation (Coaguila-Llerena et al., 2022). Photoactivated disinfection (PAD) has also demonstrated impressive antibacterial efficacy, especially against resistant bacteria in challenging cases (Mohan et al., 2016). Furthermore, pain management in endodontics has been revolutionized by the introduction of buffered anesthetics, which reduce injection discomfort, and low-level laser therapy (LLLT), which minimizes postoperative pain and accelerates healing through photobiomodulation (Valiulla et al., 2023). These techniques cater to the growing emphasis on patient-centered care by enhancing comfort and minimizing recovery times. In recent years, artificial intelligence (AI) has emerged as a transformative tool in endodontics, particularly in diagnostics and treatment planning. AI algorithms, especially convolutional neural networks, offer rapid, precise image analysis, improving the identification of periapical lesions, root canal configurations, and other diagnostic markers (Alzaid et al., 2023; Karobari et al., 2023). Beyond diagnostics, AI's predictive modeling capabilities support personalized treatment planning, potentially anticipating treatment outcomes and complications (Asgary, 2024).

The aim of this review is to comprehensively examine recent advancements in endodontic microsurgery, focusing on innovative techniques, materials, and technologies that contribute to enhanced precision, efficiency, and patient outcomes. By evaluating developments in visualization tools, specialized instruments, biocompatible materials, advanced disinfection methods, and diagnostic technologies, this review seeks to highlight how these innovations collectively address challenges in complex root canal cases. Additionally, the review explores emerging trends such as artificial intelligence and patient-centered approaches in endodontic care, providing insights into the future trajectory of endodontic microsurgery.

1- Advances in Endodontic Microsurgery Techniques

Endodontic microsurgery refers to minimally invasive procedures conducted on the roots and surrounding tissues of a tooth under high magnification and illumination. The goal is to treat complex endodontic cases with enhanced precision, reducing trauma to surrounding structures, and improving healing outcomes. Advances in endodontic microsurgery address the challenges of anatomical complexity and residual infections in teeth that were historically challenging to treat using traditional methods. According to recent studies, the use of microscopic visualization, ultrasonics, and refined instruments has contributed to significant improvements in both success rates and patient recovery times (Setzer & Kratchman, 2022).

Historically, endodontic surgery was considered a last resort due to limited surgical tools, poor visibility, frequent complications, and a high failure rate, often resulting in tooth extraction. However, with advancements in microsurgery, including enhanced visualization tools, specialized instruments, and biocompatible materials, endodontic microsurgery has become a reliable and accurate option, offering a promising alternative to extraction (Strbac et al., 2017). Endodontic microsurgery relies on three key elements: magnification, illumination, and specialized instruments. The surgical operating microscope, with its magnification (4× to 31×) and bright illumination, has revolutionized the procedure, allowing for detailed visualization of apical anatomy and precise treatment. This enhanced visibility leads to smaller osteotomies, promoting better healing (Ananad et al., 2015). Microsurgical techniques encompass a variety of methods designed to improve the accuracy and efficacy of root canal treatments and apicoectomies. These techniques rely on specialized surgical microscopes and micro-instruments, allowing clinicians to visualize minute details of the root apex, detect accessory canals, and address lesions with greater precision. High-powered surgical microscopes, for instance, enhance visibility up to 20x magnification, which is crucial in locating narrow canals and cleaning complex root systems effectively (Ma & Fei, 2021). Studies have demonstrated that these techniques reduce procedural errors and postoperative complications, improving both short-term and long-term outcomes in endodontic surgeries. Advanced surgical microscopes also provide magnification and focused lighting essential for intricate procedures. It allows for accurate identification of pathological changes and enhances the surgeon's ability to remove infected tissue with minimal damage to surrounding areas. The microscope’s ability to distinguish between bone and root tips, especially when combined with methylene blue staining, ensures complete and exact tissue removal, improving surgical outcomes and reducing complications (AlEid, 2019). By enabling clinicians to view minute details in the surgical area, these microscopes support highly accurate incisions, reduce tissue trauma, and contribute to better postoperative comfort for patients.

In addition, working under magnification requires specialized instruments, such as reduced-size ultrasonic tips, curettes, pluggers, and mirrors, designed to fit into a narrow osteotomy (typically no larger than 5 mm). These tools enable effective access to the canals while maintaining minimal tissue disruption.

Ultrasonic tips and piezoelectric devices have been transformative in endodontic microsurgery, providing minimally invasive solutions for root-end preparation and retro-filling. Ultrasonic tips are another breakthrough, particularly in root-end surgeries like apicoectomies (Palma et al., 2020). They reduce the need for extensive bone removal, which was previously a limitation in traditional apicoectomy procedures. These instruments not only ensure better accessibility to apical areas but also result in smoother, cleaner cuts, which improve the adaptability of retro-filling materials and reduce microleakage (Salim et al., 2019). Piezoelectric surgery, which uses ultrasonic vibrations to selectively cut mineralized tissue while sparing soft tissue, has become increasingly popular (Prathap & Pradeep, 2021). It allows for precise root-end resection and root-end preparation with minimal collateral damage. This method provides a safer and more controlled approach, particularly in cases where the root apex is located near delicate structures, such as nerves or blood vessels. These high-frequency devices selectively remove hard tissues while sparing soft tissues, allowing for a minimally invasive approach that preserves natural anatomy and promotes healing (Besegato et al., 2022).

Endodontic microsurgery involves treating the root apex of infected teeth when conventional root canal therapy fails. This procedure typically requires removing the buccal bone to locate the root tip, then performing debridement and root-end resection. A 3 mm depth of root-end preparation is essential to seal accessory canals, and the site is then filled with Mineral Trioxide Aggregate (MTA) before suturing. In the past, initial localization relied on two-dimensional radiography, but advancements in cone beam computed tomography (CBCT) have brought precision to diagnosis and treatment planning. Advanced digital 3D imaging, especially Cone Beam Computed Tomography (CBCT), has transformed preoperative planning by providing detailed 3D views of tooth and bone structures (Kruse et al., 2018). This technology enhances procedural accuracy, allowing clinicians to locate lesions precisely and minimize invasiveness. CBCT allows for personalized and precise diagnoses, offering significant benefits in dental procedures. However, directly locating the root apex intra-orally is challenging, often requiring extensive bone removal and gingival flaps in freehand procedures (Kim et al., 2019). This prolongs surgery and increases risks of trauma and infection. Also, recent interest in radiation-free imaging, like MRI, suggests potential benefits by avoiding radiation exposure while providing detailed views of soft tissue, such as the alveolar nerve. This could further enhance 3D template accuracy and improve procedural outcomes. MRI may also further enhance accuracy, especially in cases where the apical lesion hasn't breached the buccal bone, complicating the identification of the root tip (Reda et al., 2021). Such challenges can risk damaging nearby structures, like the maxillary sinus or mandibular nerve. The integration of CAD/CAM and 3D printing now enables the production of patient-specific surgical templates, a breakthrough in endodontics. These templates improve the accuracy of implant placement, minimizing the risk of damaging adjacent structures and enhancing precision in root-end resection. Furthermore, CAD/CAM-generated templates allow for consistent results, reducing operator dependency and technical sensitivity (Nesic et al., 2020). Although these guides require sophisticated software, they represent an emerging standard in endodontics by offering precise, minimally invasive treatment options for complex cases, thus improving patient outcomes.

Endodontic microsurgery involves a precise, minimally invasive approach to osteotomy and root-end resection, which can be complex to achieve in many cases. Emerging robotic systems add a new level of precision, performing intricate movements that reduce surgical error and fatigue (Liu et al., 2024). Altogether, these innovations in imaging, instrumentation, and automation enhance the accuracy, safety, and success of endodontic microsurgery, marking a new era of effectiveness and patient-centered care.

2- Materials in Endodontic Microsurgery – Biocompatible Filling Materials

Biocompatible filling materials are essential in endodontic microsurgery to ensure both effective sealing of the root canal system and promotion of periapical healing. Advances in material science have led to the development of new materials that possess improved biocompatibility, bioactivity, and sealing abilities compared to traditional materials. These materials are primarily used in retrograde fillings during apicoectomy procedures, apexification, root repair, and regeneration procedures. They must be able to integrate with the surrounding tissue, support healing, and prevent re-infection, as the quality of these materials directly impacts the success of the microsurgical procedure (Saxena et al., 2013).

Bioceramics, known for their excellent biocompatibility, are widely applied in dentistry, especially in endodontics. Mineral trioxide aggregate (MTA) is the most established bioceramic material, showing strong outcomes in treating endodontic issues. Although newer bioceramics like Biodentine and EndoSequence show promise, further rigorous clinical trials are needed to confirm their effectiveness in endodontic applications. Bioceramics are particularly valued for their biocompatibility, hydrophilicity, and ability to form a bond with surrounding dentin, creating a durable seal that reduces the risk of bacterial penetration (Dong & Xu, 2023). Bioceramics, including Biodentine and EndoSequence BC Sealer, are used in apical surgeries, root repairs, and regenerative endodontic procedures. Biodentine, for instance, has been shown to promote dentin bridge formation and pulp vitality, making it suitable for direct pulp capping as well as retrograde fillings (Brizuela & Daley, 2024). Research has shown that Biodentine exhibits lower cytotoxicity and higher bioactivity compared to MTA, which translates to faster and more complete healing of the periapical tissues. During dental trauma, early intervention is crucial to improve prognosis, especially in cases of coronal fractures with dentine exposure, where the primary goal is to seal dentinal tubules. When pulp exposure occurs due to trauma, immediate treatment focuses on managing the exposed pulp, with options including direct capping or partial pulpotomy using mineral trioxide aggregate (MTA) (Cervino et al., 2020). MTA is one of the most studied and widely used biocompatible materials in endodontic microsurgery. Initially developed in the 1990s, MTA consists of tricalcium silicate, tricalcium aluminate, and calcium sulfate, among other compounds (Tu et al., 2019). Its biocompatibility, sealing properties, and ability to promote hard tissue formation make it ideal for various endodontic applications, including root-end filling and perforation repair. One of the primary advantages of MTA is its ability to create a hermetic seal that effectively prevents microleakage, which is essential for successful endodontic treatment. MTA is known for its high pH, which provides an antimicrobial environment that inhibits bacterial growth and supports healing (Zarra et al., 2018). Additionally, the material's bioactivity encourages the formation of hydroxyapatite when in contact with tissue fluids, promoting mineralization and a favorable biological response.

3- Nanotechnology in Endodontics

Nanotechnology, which involves manipulating materials at the nanoscale (1 to 100 nanometers), has revolutionized various fields, including endodontics. In endodontics, the application of nanotechnology offers solutions for improved disinfection, enhanced material properties, and bioactivity in filling materials, as well as innovations in diagnostics and treatment monitoring. By using materials and particles on the nanoscale, endodontic therapies can achieve more targeted actions, improved sealing, and enhanced antimicrobial properties, addressing some of the key challenges in treating complex root canal infections (Cuppini et al., 2019).

Nanomaterials have become increasingly valuable in medical and dental fields due to their demonstrated effectiveness. In endodontics, they address challenges like accessing tooth roots, cleaning, and sealing root canals, thereby reducing risks of reinfection or adjacent tissue damage. Integrating biomaterials with nanotechnology has enhanced precision, comfort, and efficacy, significantly improving treatment quality. In endodontics, highly biocompatible nanomaterials are used in irrigation solutions, intracanal drug delivery, and root canal sealants. Nanoparticles also show promise in treating periodontal disease by enhancing antibacterial agents, penetrating biofilms, and delivering medications directly to infection sites. Additionally, their controlled release properties provide long-lasting antibacterial effects, reducing infection recurrence (Afkhami et al., 2023). Silver nanoparticles (AgNPs) are among the most widely studied nanoparticles for their potent antibacterial and antifungal effects. These nanoparticles release silver ions, which interact with bacterial cell membranes and DNA, causing cell death and effectively disrupting biofilms within the root canal system. Studies have shown that AgNPs, when incorporated into irrigants or sealers, significantly reduce microbial load within the canal and offer long-lasting antimicrobial action, making them particularly useful in cases of resistant infections (Bhandi et al., 2021). Chitosan nanoparticles, derived from natural sources, also demonstrate strong antimicrobial properties and are biocompatible with surrounding tissues. They disrupt biofilms by destabilizing cell walls and preventing bacterial adhesion, making them a valuable tool for disinfection protocols. Moreover, chitosan nanoparticles exhibit low cytotoxicity and are biodegradable, offering a safe and effective approach to bacterial elimination (Capuano et al., 2023). Nanotechnology has also enhanced the properties of endodontic sealers and fillers, which are critical for achieving a complete seal in the root canal system. Nanoparticles, such as nanosilica, can be incorporated into sealers to improve their mechanical strength, flowability, and adhesion to canal walls. Studies show that nanoparticles improve the sealing ability of root canal fillers by reducing porosity and enhancing dimensional stability, which reduces the risk of microleakage and increases the longevity of endodontic treatments (Tiffany et al., 2024).

Regenerative endodontics is an emerging field that focuses on the biological repair and regeneration of damaged pulp and periapical tissues. Nanotechnology plays a crucial role in this area, offering new materials that support the growth and differentiation of dental pulp cells and encourage tissue regeneration. Nanoparticles like calcium phosphate and bioactive glass nanoparticles are commonly used in regenerative endodontics because of their ability to promote mineralization and induce cellular responses conducive to tissue regeneration. For example, bioactive glass nanoparticles release ions that stimulate the proliferation of dental pulp stem cells and promote dentin formation, making them suitable for pulp capping and root repair applications (Corral Nunez et al., 2021). Calcium phosphate nanoparticles also provide an ideal scaffold for new tissue growth, supporting cellular attachment and differentiation, which is essential in regenerating lost or damaged pulp tissues (Moussa & Aparicio, 2019).

In addition to its therapeutic applications, nanotechnology has improved diagnostic tools in endodontics. Nanoparticles are being explored for their potential in enhancing imaging contrast and enabling more precise identification of canal anatomy and periapical lesions. For instance, iron oxide nanoparticles can serve as contrast agents in magnetic resonance imaging (MRI), providing detailed visualization of the root canal system and aiding in the diagnosis of complex endodontic cases. These imaging advancements contribute to more accurate diagnoses and help endodontists plan more effective treatments (Rahman, 2023). Further, nanotechnology-based biosensors have been developed to detect biomarkers of endodontic infections, such as inflammatory cytokines or bacterial toxins, directly from the root canal environment. These biosensors offer real-time, non-invasive monitoring of the infection status and healing progress, allowing clinicians to make data-driven decisions on treatment adjustments. Such diagnostic innovations not only improve accuracy but also enhance patient care by minimizing invasive procedures (Hooshiar, et al., 2024).

4- Innovations in Endodontic Instrumentation

Root canal treatment is essential for saving teeth compromised by infection or necrosis. Advances in instrumentation have greatly improved the efficiency and outcomes of these procedures. Initially, manual instruments were used, but the shift to mechanical and rotary tools has made root canal treatments faster and more precise. Innovations like single-file systems enhance efficiency without sacrificing effectiveness, while nickel-titanium (NiTi) rotary files offer superior flexibility and reduce the risk of breakage and procedural errors (Arias & Peters, 2022). Reciprocating motion in engine-driven files also lowers the likelihood of microcracks and root fractures (Hariprasad et al., 2021). Additionally, digital imaging and navigation technologies are now enhancing precision and safety in endodontic treatments, allowing clinicians to improve patient comfort and increase treatment success rates. These developments mark a new era in endodontics, combining efficiency with accuracy for better patient care. Endodontic instrumentation has seen substantial advancements over the years, introducing innovative tools and techniques that have significantly improved the efficiency, safety, and outcomes of root canal treatments. These innovations aim to address challenges posed by complex root canal anatomies and to ensure thorough cleaning, shaping, and disinfection of the root canal system (Fagd, 2018). Traditional stainless steel files were often limited by their rigidity, increasing the risk of canal transportation and perforations, particularly in curved canals. Nickel-titanium (NiTi) rotary files, with their remarkable flexibility and superelasticity, allow clinicians to navigate and shape complex canal structures more effectively. NiTi files also exhibit a high resistance to cyclic fatigue, reducing the risk of instrument separation. Recent developments, such as heat-treated and controlled memory NiTi files, enhance their flexibility and durability even further (Srivastava, 2024).

Effective endodontic treatment depends on carefully prepared and disinfected canals, where infected dentin is removed while maintaining root strength. Reciprocating files excel in this regard, as their design minimizes dentin removal and reduces the risk of file breakage compared to continuous rotation files. Operating through a balanced force technique, these files alternate between clockwise and counterclockwise motions, with rotation degrees tailored to the material’s properties. This approach boosts file durability, making canal preparation both safer and more precise, ultimately enhancing the success of root canal treatments (Gavini et al., 2018). Reciprocating motion systems are designed to reduce instrument fatigue and the risk of breakage by moving the file back and forth rather than in continuous rotation. This motion mimics manual filing techniques but with the efficiency and power of rotary instrumentation. Studies show that reciprocating systems are effective in cleaning canals while lowering the risk of instrument separation, making them ideal for challenging cases (De Pedro-Muñoz et al., 2024).

Adaptive file systems adjust their motion in response to pressure, enabling safer and more effective instrumentation in irregular or curved canals. The GentleWave system is an innovative multi-sonic irrigation technology that uses fluid dynamics to clean and disinfect the entire root canal system. These technologies are designed to maximize debris removal, even in complex canal spaces, without aggressive mechanical instrumentation. (Velardi et al., 2022). A study on the GentleWave (GW) system for root canal treatment showed it to be highly effective. GW was not linked to irrigant extrusion, offered faster organic dissolution than conventional methods, and reduced bacterial DNA and biofilm more effectively than passive and continuous ultrasonic irrigation. It enhanced sodium hypochlorite penetration into dentinal tubules, removed more intracanal medication, and efficiently cleared pulp tissue, calcifications, hard-tissue debris, and smear layers. While its performance in removing obturation residues was similar or slightly lower than some methods, GW delivered high-quality obturation with a 97.3% clinical success rate and comparable short-term postoperative pain to conventional syringe irrigation (Coaguila-Llerena et al., 2022). The GentleWave System (GWS) enhances root canal cleaning and disinfection with minimal instrumentation by combining advanced fluid dynamics, acoustic energy, and tissue dissolution. This multi-sonic technology enables deep fluid penetration, thoroughly cleansing complex canal structures. Studies show GWS effectively removes biofilms (Choi et al., 2019), bacterial DNA (Zhang et al., 2019), calcium hydroxide, residual debris (Wang et al., 2019), separated instruments, and retreatment materials like gutta-percha (Wright et al., 2019).

5- Effectiveness of Laser-Assisted Endodontic Disinfection

The success of root canal treatment relies on thorough disinfection and preventing reinfection, but traditional disinfection methods, relying on chemical irrigation solutions and mechanical instrumentation, have limitations in effectively eliminating bacteria in the complex root canal anatomy, leading to treatment failure. Laser treatment, with its high energy and unique properties, has emerged as a promising alternative. Mechanism and Types of Lasers Used: LAED employs specific wavelengths to target and destroy microbial cells within the root canal system. Different laser types, including Cr, Nd, and Er lasers, have demonstrated effectiveness in endodontics. Er lasers, for instance, are particularly useful due to their ability to penetrate dentin and reach deep bacterial colonies, even within lateral canals and dentinal tubules. Evidence suggestes that lasers have effective bactericidal properties, aid in debris removal, and can reshape the root canal wall, enhancing treatment outcomes (Jurič & Anić, 2014). Lasers achieve this through photothermal and photomechanical effects, which heat and disrupt bacterial biofilms more effectively than conventional methods. Research has shown that diode lasers, for example, achieve higher reductions in E. faecalis and other resistant bacteria often found in endodontic infections (Amin et al., 2022).

LAED is minimally invasive and biocompatible, minimizing thermal damage to surrounding tissues. Precise control over the laser's wavelength and intensity allows clinicians to target bacterial cells without causing damage to the surrounding dentin and pulp tissues. This precision is critical for preserving tooth structure and reducing post-operative discomfort. Rapp et al. (2023) studied femtosecond laser ablation on enamel and dentin using green (515 nm), infrared (1030 nm), and ultra-violet (343 nm) pulses to identify optimal conditions for precise tissue removal without damage. They tested ablation rates and efficiencies for each wavelength at room temperature, assessing the surfaces with microscopy, profilometry, and spectroscopy. Results showed 515 nm pulses offered the best ablation rate and efficiency, followed by infrared. Temperature changes in the pulp were within safe limits for infrared and green, peaking at 5.5 °C. However, ultra-violet caused excessive heat and structural damage, deeming it unsuitable for dental applications.

Beyond direct laser irradiation, photoactivated disinfection (PAD) is another laser-assisted technique. PAD uses photosensitizing agents activated by laser light to generate reactive oxygen species that kill bacteria within the root canal. This method has shown promising results in sterilizing even complex root canal anatomies and improving long-term treatment outcomes. A study compared photo-activated disinfection (PAD) with conventional endodontic treatment (CET) and their combination in reducing Enterococcus faecalis in infected root canals. Fifty-three maxillary incisors were divided into three groups: CET alone, PAD alone (using laser for 2 or 4 minutes), and a combination of CET and PAD. After inoculating the canals with E. faecalis, treatments were applied, and bacterial regrowth was assessed. Results showed that combining CET with PAD significantly reduced bacterial counts, achieving a 99.5% reduction at 4 minutes and 98.89% at 2 minutes, demonstrating the enhanced efficacy of combining PAD with CET (Mohan et al., 2016).

6- Advances in Endodontic Pain Management Techniques

Pain management in endodontics has evolved with the integration of pharmacological, technological, and procedural innovations, resulting in more predictable and effective strategies. Traditional methods of administering local anesthesia in endodontics can sometimes fail, especially in cases of acute pulpitis where achieving adequate anesthesia can be challenging. Newer improved local anesthetic techniques, such as the use of intraosseous (IO) injections, periodontal ligament (PDL) injections (Moore et al., 2011), and computer-assisted local anesthetic delivery systems (Kwak et al., 2016), allow for more targeted delivery of anesthesia directly to the pulp, leading to more effective and immediate pain relief for patients.

To ease dental treatment pain, local anesthesia is essential, yet many patients fear the injection itself more than the procedure. Anesthetic injections can cause discomfort due to mucosal penetration, solution pressure, temperature, low pH, and drug properties. These factors can still result in pain despite careful administration. Buffered anesthetics have become more popular in recent years due to their faster onset and higher efficacy in reducing pain. Buffering the anesthetic solution neutralizes the acidic pH of traditional anesthetic solutions, leading to faster drug absorption and reduced injection pain. This advancement has been particularly helpful for patients with inflamed tissues, as the buffering process enables better tissue penetration and more consistent results. A study evaluated 8.4% sodium bicarbonate-buffered versus conventional local anesthetics for bilateral maxillary orthodontic extractions, focusing on injection pain, onset, and duration of action. Buffered anesthetic reduced injection pain (VAS score 2.4 vs. 3.9), showed a quicker onset (62.3 seconds vs. 157.16 seconds), and provided a longer duration (225.65 minutes vs. 187 minutes) compared to the conventional anesthetic, demonstrating its superior efficacy across these measures (Valiulla et al., 2023).

Low-level laser therapy (LLLT) offers a unique, non-invasive approach in dentistry, prioritizing safety and patient comfort without relying on drugs or invasive methods. Using low-intensity lasers, LLLT promotes healing through photobiomodulation, affecting cellular behavior and enhancing metabolism and cell growth (Avci et al., 2013). Its antibacterial properties, stimulation of cell activity, tissue ablation, and fibroblast promotion make it effective across dental treatments. Additionally, LLLT aids hemostasis, boosts leukocyte chemotaxis, and encourages osteoblastic cell proliferation, differentiation, and calcification, which can effectively support endodontic lesion treatment by advancing cellular repair and regeneration. LLLT is a non-invasive technique that uses low-intensity lasers to reduce inflammation, promote healing, and decrease pain after endodontic treatment (Arslan et al., 2017). Clinical trials have demonstrated that LLLT can be effective for reducing post-operative pain, with minimal side effects. It stimulates cellular regeneration and decreases the production of inflammatory mediators, providing a soothing effect on treated tissues (Mankar et al., 2023). A study assessed low-level laser therapy's (LLLT) impact on postoperative pain following endodontic procedures, comparing it to mock laser therapy. Using the PICOS strategy, 12 randomized clinical trials were reviewed: six for primary root canal treatment, two for retreatments, and four for periapical surgeries. Most studies showed LLLT significantly reduced postoperative pain across various time points. Although evidence quality was limited, LLLT consistently demonstrated effectiveness in alleviating post-treatment discomfort (Guerreiro et al., 2021).

Low-level laser therapy (LLLT) combined with photobiomodulation therapy (PBMT) effectively reduces pain non-pharmacologically. Its pain-relief mechanisms include endorphin stimulation, anti-inflammatory effects, and neurological benefits, such as enhanced lymphocyte function, membrane stability, and neurotransmitter release (Artés-Ribas et al., 2013). LLLT also accelerates healing by promoting fibroblast activity and connective tissue repair. Previous studies confirm that LLLT and intracanal laser irradiation significantly alleviate post-endodontic discomfort, making it a valuable tool for postoperative pain management (Asnaashari et al., 2013).

7- Artificial Intelligence in Endodontics

AI models are transforming endodontics by offering precise analysis of root canal anatomy, early detection of periapical lesions, and accurate working-length measurement. They also assist in diagnosing dental conditions like caries, pulpal inflammation, and root fractures, while serving as a valuable second opinion in non-surgical treatments. AI, particularly convolutional neural networks (CNNs), has enhanced diagnostic accuracy and treatment planning by identifying complex root canal morphologies, predicting thrust force and torque, and detecting subtle pathologies in radiographs (Alzaid et al., 2023). Beyond diagnostics, AI-powered tools improve treatment planning by analyzing patient data to suggest personalized care strategies, reducing errors through real-time feedback during procedures, and alerting clinicians to potential complications. Early detection of endodontic issues through AI allows for timely intervention, potentially preventing disease progression. Research supporting AI integration in endodontics involves robust studies that validate AI diagnostic tools and algorithms with large clinical datasets, ensuring reliability and accuracy (Asgary, 2024). AI's strength lies in processing vast data quickly, making it invaluable in dental imaging interpretation. Its algorithms identify patterns and subtle anomalies, supporting dentists with precise and consistent diagnoses (Schwendicke et al., 2019). In detecting early conditions like dental caries and periodontal disease, AI effectively analyzes 2D and 3D radiographs to prevent overlooked details (Li et al., 2022). Additionally, it aids in treatment planning by drawing on insights from numerous cases. AI enhances diagnostics by mapping root canal configurations, segmenting pulp chambers, and detecting periapical lesions, improving accuracy and overall patient care (Sadr et al., 2023; Lin et al., 2021).

Traditional radiographic diagnostics in endodontics rely on visual inspection and clinician experience, often leading to variability in interpreting complex images like periapical radiographs or cone-beam computed tomography (CBCT). AI, particularly DL algorithms, have demonstrated high accuracy in identifying periapical lesions, root fractures, and canal morphology. Studies show that AI systems trained on thousands of radiographs can detect these conditions with accuracy levels comparable to experienced clinicians, helping standardize diagnostic quality across practitioners (Karobari et al., 2023). AI has been employed to assess factors influencing endodontic treatment success and predict outcomes with greater precision. By analyzing clinical and demographic data, ML models can identify patterns that correlate with higher treatment success rates, guiding clinicians in tailoring treatments based on patient-specific risk factors like tooth anatomy, infection severity, and procedural techniques used. This predictive ability aids in recommending whether to proceed with a root canal treatment or extraction, ultimately improving long-term patient outcomes (Asgary, 2024).EnhanceIncorporating AI in endodontic practices can streamline workflows by automating routine tasks such as radiographic image analysis, patient record review, and even scheduling follow-ups based on predictive analytics. This integration leads to more consistent treatment standards and allows endodontists to focus on complex decision-making aspects of care, ultimately enhancing patient satisfaction (Lisican, 2014). AI-driven software can help personalize treatment plans by integrating data from various sources, such as clinical history, imaging, and genetic factors. This level of personalization, combined with predictive analytics, can help tailor endodontic treatments to each patient's unique profile, increasing the likelihood of success. Moreover, AI-based visualizations and simulations can be used to educate patients about their conditions and expected treatment outcomes, improving patient understanding and compliance (Johnson et al., 2021).

Conclusion

The continuous advancements in endodontic microsurgery have transformed it into a reliable, precise, and minimally invasive option for treating complex cases. The combination of enhanced magnification, specialized tools, and biocompatible materials has led to improved success rates and patient outcomes. Future innovations, including robotics and artificial intelligence, are poised to further refine procedural accuracy, reduce operator dependency, and enhance patient satisfaction. As the field progresses, endodontic microsurgery will likely become increasingly patient-centered, with continued improvements in healing outcomes and procedural efficacy.

References

Afkhami, F., Forghan, P., Gutmann, J.L. and Kishen, A., 2023. Silver nanoparticles and their therapeutic applications in endodontics: A narrative review. Pharmaceutics, 15(3), p.715.

AlEid, A.A.A.R., 2019. Magnification aids in endodontics: A review. Egyptian Dental Journal, 65(2-April (Fixed Prosthodontics, Dental Materials, Conservative Dentistry & Endodontics)), pp.1477-1485.

AlEid, A.A.A.R., 2019. Magnification aids in endodontics: A review. Egyptian Dental Journal, 65(2-April (Fixed Prosthodontics, Dental Materials, Conservative Dentistry & Endodontics)), pp.1477-1485.

Alzaid, N., Ghulam, O., Albani, M., Alharbi, R., Othman, M., Taher, H., Albaradie, S. and Ahmed, S., 2023. Revolutionizing Dental Care: A Comprehensive Review of Artificial Intelligence Applications Among Various Dental Specialties. Cureus, 15(10).

Amin, W.O., Mohamed, M.A.E.M. and Barakat, I.F., 2022. Antibacterial Effect of Chitosan and Low-Level Diode Laser Against Enterococcus faecalis in Infected Root Canals in Primary Molars. Al-Azhar Journal of Dental Science, 25(3), pp.347-352.

Ananad, S., Soujanya, E., Raju, A. and Swathi, A., 2015. Endodontic microsurgery: An overview. Dentistry and Medical Research, 3(2), pp.31-37.

Arias, A. and Peters, O.A., 2022. Present status and future directions: Canal shaping. International Endodontic Journal, 55, pp.637-655.

Arslan, H., Güven, Y., Karataş, E. and Doğanay, E., 2017. Effect of the simultaneous working length control during root canal preparation on postoperative pain. Journal of endodontics, 43(9), pp.1422-1427.

Artés-Ribas, M., Arnabat-Dominguez, J. and Puigdollers, A., 2013. Analgesic effect of a low-level laser therapy (830 nm) in early orthodontic treatment. Lasers in medical science, 28, pp.335-341.

Asgary, S., 2024. Artificial Intelligence in Endodontics: A Scoping Review. Iranian Endodontic Journal, 19(2), p.85.

Asgary, S., 2024. Artificial Intelligence in Endodontics: A Scoping Review. Iranian Endodontic Journal, 19(2), p.85.

Asnaashari, M. and Safavi, N., 2013. Application of low level lasers in dentistry (endodontic). Journal of lasers in medical sciences, 4(2), p.57.

Avci, P., Gupta, A., Sadasivam, M., Vecchio, D., Pam, Z., Pam, N. and Hamblin, M.R., 2013, March. Low-level laser (light) therapy (LLLT) in skin: stimulating, healing, restoring. In Seminars in cutaneous medicine and surgery (Vol. 32, No. 1, p. 41). NIH Public Access.

Besegato, J.F., Melo, P.B.G.D., Bernardi, A.C.D.A., Bagnato, V.S. and Rastelli, A.N.D.S., 2022. Ultrasound device as a minimally invasive approach for caries dentin removal.

Brazilian dental journal, 33(1), pp.57-67.

Bhandi, S., Mehta, D., Mashyakhy, M., Chohan, H., Testarelli, L., Thomas, J., Dhillon, H., Raj, A.T., Madapusi Balaji, T., Varadarajan, S. and Patil, S., 2021. Antimicrobial efficacy of silver nanoparticles as root canal irrigant's: a systematic review. Journal of Clinical Medicine, 10(6), p.1152.

Brizuela, M. and Daley, J., 2024. Dental Materials: Biodentine, a Calcium Silicate Bioactive. StatPearls.

Capuano, N., Amato, A., Dell'Annunziata, F., Giordano, F., Folliero, V., Di Spirito, F., More, P.R., De Filippis, A., Martina, S., Amato, M. and Galdiero, M., 2023. Nanoparticles and Their Antibacterial Application in Endodontics. Antibiotics, 12(12), p.1690.

Cervino, G., Laino, L., D'Amico, C., Russo, D., Nucci, L., Amoroso, G., Gorassini, F., Tepedino, M., Terranova, A., Gambino, D. and Mastroieni, R., 2020. Mineral trioxide aggregate applications in endodontics: A review. European journal of dentistry, 14(04), pp.683-691.

Choi, H.W., Park, S.Y., Kang, M.K. and Shon, W.J., 2019. Comparative analysis of biofilm removal efficacy by multisonic ultracleaning system and passive ultrasonic activation. Materials, 12(21), p.3492.

Coaguila-Llerena, H., Gaeta, E. and Faria, G., 2022. Outcomes of the GentleWave system on root canal treatment: a narrative review. Restorative dentistry & endodontics, 47(1).

Corral Nunez, C., Altamirano Gaete, D., Maureira, M., Martin, J. and Covarrubias, C., 2021. Nanoparticles of bioactive glass enhance biodentine bioactivity on dental pulp stem cells. Materials, 14(10), p.2684.

Cuppini, M., Zatta, K.C., Mestieri, L.B., Grecca, F.S., Leitune, V.C.B., Guterres, S.S. and Collares, F.M., 2019. Antimicrobial and anti-inflammatory drug-delivery systems at endodontic reparative material: synthesis and characterization. Dental Materials, 35(3), pp.457-467.

De Pedro-Muñoz, A., Rico-Romano, C., Sánchez-Llobet, P., Montiel-Company, J.M. and Mena-Alvarez, J., 2024. Cyclic Fatigue Resistance of Rotary versus Reciprocating Endodontic Files: A Systematic Review and Meta-Analysis. Journal of Clinical Medicine, 13(3), p.882.

Dong, X. and Xu, X., 2023. Bioceramics in endodontics: updates and future perspectives. Bioengineering, 10(3), p.354.

Fagd, R. V. P. D. (2018, April 11). Innovations in Endodontic Cleaning and Disinfection. Decisions in Dentistry. https://decisionsindentistry.com/article/innovations-endodontic-cleaning-disinfection/

Gavini, G., Santos, M.D., Caldeira, C.L., Machado, M.E.D.L., Freire, L.G., Iglecias, E.F., Peters, O.A. and Candeiro, G.T.D.M., 2018. Nickel–titanium instruments in endodontics: a concise review of the state of the art. Brazilian oral research, 32, p.e67.

Guerreiro, M.Y.R., Monteiro, L.P.B., de Castro, R.F., Magno, M.B., Maia, L.C. and da Silva Brandão, J.M., 2021. Effect of low-level laser therapy on postoperative endodontic pain: An updated systematic review. Complementary therapies in medicine, 57, p.102638.

Hariprasad, R., Anoop, V.N., Raj, P.R., Obulareddy, V.T., Kunjumon, R.M. and Sadula, K.K., 2021. Evaluation of Crack Propagation after Root Canal Preparation with Continuous and Reciprocating Files and Final Finishing with XP Endo Finisher–An In vitro Study. Journal of Pharmacy and Bioallied Sciences, 13(Suppl 2), pp.S1700-S1704.

Hooshiar, M.H., Moghaddam, M.A., Kiarashi, M., Al-Hijazi, A.Y., Hussein, A.F., A. Alrikabi, H., Salari, S., Esmaelian, S., Mesgari, H. and Yasamineh, S., 2024. Recent advances in nanomaterial-based biosensor for periodontitis detection. Journal of biological engineering, 18(1), p.28.

Johnson, K.B., Wei, W.Q., Weeraratne, D., Frisse, M.E., Misulis, K., Rhee, K., Zhao, J. and Snowdon, J.L., 2021. Precision medicine, AI, and the future of personalized health care. Clinical and translational science, 14(1), pp.86-93.

Jurič, I.B. and Anić, I., 2014. The use of lasers in disinfection and cleanliness of root canals: a review. Acta Stomatologica Croatica, 48(1), p.6.

Karobari, M.I., Adil, A.H., Basheer, S.N., Murugesan, S., Savadamoorthi, K.S., Mustafa, M., Abdulwahed, A. and Almokhatieb, A.A., 2023. Evaluation of the diagnostic and prognostic accuracy of artificial intelligence in endodontic dentistry: A comprehensive review of literature. Computational and Mathematical Methods in Medicine, 2023(1), p.7049360.

Kim, J.E., Shim, J.S. and Shin, Y., 2019. A new minimally invasive guided endodontic microsurgery by cone beam computed tomography and 3-dimensional printing technology. Restorative dentistry & endodontics, 44(3).

Kruse, C., Spin-Neto, R., Wenzel, A., Vaeth, M. and Kirkevang, L.L., 2018. Impact of cone beam computed tomography on periapical assessment and treatment planning five to eleven years after surgical endodontic retreatment. International endodontic journal, 51(7), pp.729-737.

Kruse, C., Spin-Neto, R., Wenzel, A., Vaeth, M. and Kirkevang, L.L., 2018. Impact of cone beam computed tomography on periapical assessment and treatment planning five to eleven years after surgical endodontic retreatment. International endodontic journal, 51(7), pp.729-737.

Kwak, E.J., Pang, N.S., Cho, J.H., Jung, B.Y., Kim, K.D. and Park, W., 2016. Computer-controlled local anesthetic delivery for painless anesthesia: a literature review. Journal of dental anesthesia and pain medicine, 16(2), pp.81-88.

Li, S., Liu, J., Zhou, Z., Zhou, Z., Wu, X., Li, Y. et al. (2022) Artificial intelligence for caries and periapical periodontitis detection. Journal of Dentistry, 122, 104107.

Lin, X., Fu, Y., Ren, G., Yang, X., Duan, W., Chen, Y. et al. (2021) Micro- computed tomography- guided artificial intelligence for pulp cavity and tooth segmentation on cone-beam computed tomography. Journal of Endodontics, 47(12), 1933–1941.

Lisican, E. (2024, April 3). Enhancing Endodontic Practice with Artificial Intelligence: A Vision for the Future. American Association of Endodontists. https://www.aae.org/specialty/enhancing-endodontic-practice-with-artificial-intelligence-a-vision-for-the-future/

Liu, C., Liu, X., Wang, X., Liu, Y., Bai, Y., Bai, S. and Zhao, Y., 2024. Endodontic microsurgery with an autonomous robotic system: a clinical report. Journal of Endodontics, 50(6), pp.859-864.

Ma, L. and Fei, B., 2021. Comprehensive review of surgical microscopes: technology development and medical applications. Journal of biomedical optics, 26(1), pp.010901-010901.

Mankar, N., Burde, K., Agrawal, P., Chandak, M., Ikhar, A. and Patel, A., 2023. Application of Low-Level Laser Therapy in Endodontics: A Narrative Review. Cureus, 15(10).

Mohan, D., Maruthingal, S., Indira, R., Divakar, D.D., Al Kheraif, A.A., Ramakrishnaiah, R., Durgesh, B.H., Basavarajappa, S. and John, J., 2016. Photoactivated disinfection (PAD) of dental root canal system–An ex-vivo study. Saudi journal of biological sciences, 23(1), pp.122-127.

Moore, P.A., Cuddy, M.A., Cooke, M.R. and Sokolowski, C.J., 2011. Periodontal ligament and intraosseous anesthetic injection techniques: alternatives to mandibular nerve blocks. The Journal of the American Dental Association, 142, pp.13S-18S.

Moussa, D.G. and Aparicio, C., 2019. Present and future of tissue engineering scaffolds for dentin-pulp complex regeneration. Journal of tissue engineering and regenerative medicine, 13(1), pp.58-75.

Nesic, D., Schaefer, B.M., Sun, Y., Saulacic, N. and Sailer, I., 2020. 3D printing approach in dentistry: the future for personalized oral soft tissue regeneration. Journal of clinical medicine, 9(7), p.2238.

Palma, P.J., Marques, J.A., Casau, M., Santos, A., Caramelo, F., Falacho, R.I. and Santos, J.M., 2020. Evaluation of root-end preparation with two different endodontic microsurgery ultrasonic tips. Biomedicines, 8(10), p.383.

Prathap, M.S. and Pradeep, R., 2021. Endodontic Microsurgical Instruments--A Review. Journal of Evolution of Medical and Dental Sciences, 10(20), pp.1532-1539.

Rahman, M., 2023. Magnetic resonance imaging and iron-oxide nanoparticles in the era of personalized medicine. Nanotheranostics, 7(4), p.424.

Rapp, L., Madden, S., Brand, J., Maximova, K., Walsh, L.J., Spallek, H., Zuaiter, O., Habeb, A., Hirst, T.R. and Rode, A.V., 2023. Investigation of laser wavelength effect on the ablation of enamel and dentin using femtosecond laser pulses. Scientific Reports, 13(1), p.20156.

Reda, R., Zanza, A., Mazzoni, A., Cicconetti, A., Testarelli, L. and Di Nardo, D., 2021. An update of the possible applications of magnetic resonance imaging (MRI) in dentistry: a literature review. Journal of imaging, 7(5), p.75.

Reda, R., Zanza, A., Mazzoni, A., Cicconetti, A., Testarelli, L. and Di Nardo, D., 2021. An update of the possible applications of magnetic resonance imaging (MRI) in dentistry: a literature review. Journal of imaging, 7(5), p.75.

Sadr, S., Mohammad- Rahimi, H., Motamedian, S.R., Zahedrozegar, S., Motie, P., Vinayahalingam, S. et al. (2023) Deep learning for detection of periapical radiolucent lesions: a systematic review and meta- analysis of diagnostic test accuracy. Journal of Endodontics, 49(3), 248–261.e3.

Salim, S., Feroze Raheem, D., Kumar, G.A., Ch, T., Mustafa, M. and Vajpayee, A., 2019. Ultrasonic in endodontics. Saudi J Oral Dent Res, 4(6), pp.421-7.

Saxena, P., Gupta, S.K. and Newaskar, V., 2013. Biocompatibility of root-end filling materials: recent update. Restorative dentistry & endodontics, 38(3), pp.119-127.

Schwendicke, F., Golla, T., Dreher, M. & Krois, J. (2019) Convolutional neural networks for dental image diagnostics: a scoping review. Journal of Dentistry, 91, 103226.

Setzer, F.C. and Kratchman, S.I., 2022. Present status and future directions: Surgical endodontics. International endodontic journal, 55, pp.1020-1058.

Setzer, F.C. and Kratchman, S.I., 2022. Present status and future directions: Surgical endodontics. International endodontic journal, 55, pp.1020-1058.

Srivastava, S., 2024. Root Canal Instrumentation: Current Trends and Future Perspectives. Cureus, 16(4).

Strbac, G.D., Schnappauf, A., Giannis, K., Moritz, A. and Ulm, C., 2017. Guided modern endodontic surgery: a novel approach for guided osteotomy and root resection. Journal of Endodontics, 43(3), pp.496-501.

Strbac, G.D., Schnappauf, A., Giannis, K., Moritz, A. and Ulm, C., 2017. Guided modern endodontic surgery: a novel approach for guided osteotomy and root resection. Journal of Endodontics, 43(3), pp.496-501.

Tiffany, S.A., Abidin, T. and Prasetia, W., 2024. Nanotechnology Implementation as Root Canal Sealer. Dentika: Dental Journal, 27(1), pp.64-72.

Tu, M.G., Sun, K.T., Wang, T.H., He, Y.Z., Hsia, S.M., Tsai, B.H., Shih, Y.H. and Shieh, T.M., 2019. Effects of mineral trioxide aggregate and bioceramics on macrophage differentiation and polarization in vitro. Journal of the Formosan Medical Association, 118(10), pp.1458-1465.

Valiulla, M.U.E., Halli, R., Khandelwal, S., Mittal, A., Singh, A. and Bhindora, K., 2023. Efficacy of sodium bicarbonate-buffered local anesthetic solution in cases requiring bilateral maxillary premolar orthodontic extraction: a comparative split-mouth study. Cureus, 15(4).

Velardi, J.P., Alquria, T.A., Alfirdous, R.A., Griffin, I.L., Tordik, P.A. and Martinho, F.C., 2022. Efficacy of GentleWave system and passive ultrasonic irrigation with minimally invasive and conventional instrumentation technique against Enterococcus faecalis lipoteichoic acid in infected root canals. Journal of Endodontics, 48(6), pp.768-774.

Wang, Z., Shen, Y. and Haapasalo, M., 2018. Root canal wall dentin structure in uninstrumented but cleaned human premolars: a scanning electron microscopic study. Journal of Endodontics, 44(5), pp.842-848.

Wright, C.R., Glickman, G.N., Jalali, P. and Umorin, M., 2019. Effectiveness of gutta-percha/sealer removal during retreatment of extracted human molars using the GentleWave system. Journal of Endodontics, 45(6), pp.808-812.

Zarra, T., Lambrianidis, T., Vasiliadis, L. and Gogos, C., 2018. Effect of curing conditions on physical and chemical properties of MTA+. International Endodontic Journal, 51(11), pp.1279-1291.

Zhang, D., Shen, Y., de la Fuente-Núñez, C. & Haapasalo, M. In vitro evaluation by quantitative real-time PCR and culturing of the effectiveness of disinfection of multispecies biofilms in root canals by two irrigation systems. Clin. Oral Investig. 23, 913–920 (2019).