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Review Article

Root canal disinfection strategies in persistent endodontic infection

Khaled Ahmed Bafail[1]*, Omar Musaad Alshammari[2], Faisal Sami Alsabhani[3], Ahmed Abdullah Althagafi[3], Turki Waheed Almuhayfith[4], Abdulrahman Mudaysh Bajawi[5], Rana Adel Reda[2], Ftoon Naser Alfrisy[6], Amal Musaad Alrashidi[7], Abdulaziz Mohammed Al Habshan[8], Aseelah Abdullah Alshahrani[9]

[1]Department of Endodontics, North Jeddah Specialist Dental Center, King Abdullah Medical Complex, Jeddah, Saudi Arabia
[2]Department of Dentistry, Ministry of Health, Hail, Saudi Arabia
[3]College of Dentistry, King Abdulaziz University, Jeddah, Saudi Arabia
[4]College of Dentistry, King Faisal University, Al-Ahsa, Saudi Arabia
[5]Department of Dentistry, Samtah General Hospital, Jazan, Saudi Arabia
[6]College of Dentistry, University Hail, Hail, Saudi Arabia
[7]Alkhozama Clinic, Ministry of Human Resources and Social Development, Hail, Saudi Arabia
[8]College of Dentistry, Prince Sattam bin Abdulaziz University, Riyadh, Saudi Arabia
[9]Department of Dentistry, Alslamah Medical Complex, Abha, Saudi Arabia

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***Correspondence:**
Dr. Khaled Ahmed Bafail,
E-mail: Khaledbafail@hotmail.com

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ABSTRACT

Persistent endodontic infections remain a significant challenge in root canal treatment, primarily due to the survival of microorganisms within complex anatomical structures and their ability to form resistant biofilms. Despite improvements in endodontic instruments, irrigation systems, and antimicrobial agents, complete elimination of microbial communities from infected root canals remains difficult. Biofilm-associated microorganisms exhibit increased tolerance to antimicrobial substances and unfavorable environmental conditions, allowing them to persist within dentinal tubules, lateral canals, isthmuses, and apical ramifications. Enterococcus faecalis has been frequently associated with persistent infections because of its ability to penetrate dentinal structures, withstand nutrient deprivation, and tolerate alkaline environments. Effective root canal disinfection involves mechanical instrumentation, chemical irrigation, and intracanal medication to reduce microbial populations and prevent reinfection. Sodium hypochlorite remains the most widely used irrigant because of its broad antimicrobial activity and tissue-dissolving properties, while chlorhexidine, ethylenediaminetetraacetic acid, and calcium hydroxide contribute to different stages of disinfection. However, conventional irrigation methods may provide insufficient antimicrobial penetration in anatomically inaccessible regions. Advanced techniques, including passive ultrasonic irrigation, sonic activation, laser-assisted irrigation, and antimicrobial photodynamic therapy, have demonstrated potential for improving irrigant distribution, disrupting biofilms, and enhancing microbial reduction. Disinfection efficacy is influenced by several factors, including root canal morphology, irrigant concentration, contact time, microbial composition, and the presence of organic debris. Clinical outcomes are closely associated with the extent of microbial elimination, preoperative periapical conditions, treatment quality, and the prevention of coronal leakage. Persistent microbial contamination may contribute to delayed periapical healing and unfavorable treatment outcomes, even following technically adequate procedures. Integrating effective chemical disinfection with appropriate mechanical preparation and irrigant activation may improve microbial control and support long-term treatment success. Further clinical investigations are necessary to establish standardized disinfection protocols and determine the long-term effectiveness of emerging antimicrobial technologies in persistent endodontic infections.

Keywords: Persistent endodontic infection, Root canal disinfection, Microbial biofilms, Intracanal irrigation, Apical periodontitis

INTRODUCTION

Root canal treatment is a fundamental procedure in endodontics aimed at eliminating microorganisms from the infected root canal system, preventing reinfection, and promoting the healing of periapical tissues. Despite advancements in instrumentation, irrigation techniques, and antimicrobial agents, persistent endodontic infections remain a significant challenge in clinical dentistry. These infections occur when microorganisms survive initial treatment or when new microorganisms enter the root canal system, potentially leading to persistent apical periodontitis and treatment failure. The complex anatomy of the root canal system, including lateral canals, isthmuses, apical ramifications, and dentinal tubules, creates areas where microorganisms can remain protected from conventional cleaning and disinfection procedures.[1]

Microbial persistence is considered one of the major factors contributing to unsuccessful endodontic treatment. Certain microorganisms can survive under unfavorable environmental conditions, including nutrient deprivation, limited oxygen availability, and exposure to antimicrobial agents. Among these, Enterococcus faecalis has been frequently associated with persistent and secondary endodontic infections due to its ability to penetrate dentinal tubules, tolerate alkaline environments, and form resistant biofilms. Furthermore, microorganisms organized within biofilm structures exhibit increased resistance to antimicrobial agents compared with their planktonic counterparts. The extracellular matrix surrounding these microbial communities provides additional protection, reducing the effectiveness of disinfection procedures and contributing to the persistence of infection within the root canal system.[2]

Effective root canal disinfection requires a combination of mechanical instrumentation, chemical irrigation, and, when indicated, intracanal medication. Mechanical preparation facilitates the removal of infected dentin and provides sufficient space for irrigants to penetrate the root canal system. Sodium hypochlorite remains the most widely used endodontic irrigant because of its broad antimicrobial activity and ability to dissolve organic tissues. Other solutions, including chlorhexidine and ethylenediaminetetraacetic acid (EDTA), are commonly used for their antimicrobial or smear layer removal properties. However, conventional irrigation methods have limitations, particularly in areas inaccessible to instruments or where biofilms are deeply established. Moreover, the antimicrobial effectiveness of irrigating solutions depends on several factors, including concentration, contact time, volume, and delivery technique.[3]

To overcome these limitations, several advanced disinfection strategies have been introduced to improve antimicrobial effectiveness and enhance irrigant penetration. These include passive ultrasonic irrigation, sonic activation, laser-assisted irrigation, and other approaches designed to improve fluid movement within complex root canal anatomy. Such techniques aim to increase the removal of debris, disrupt microbial biofilms, and improve contact between antimicrobial solutions and infected surfaces. Nevertheless, achieving complete disinfection remains challenging because of anatomical variations, microbial diversity, and the protective characteristics of established biofilms. The clinical effectiveness of different approaches may also vary according to the characteristics of the infection and treatment conditions.[4]

REVIEW

Persistent endodontic infections remain a major challenge in root canal treatment due to the ability of microorganisms to survive within the complex root canal anatomy. Bacterial biofilms play a significant role in microbial persistence by providing protection against antimicrobial agents and environmental changes. These biofilms can colonize inaccessible areas, including lateral canals, isthmuses, and dentinal tubules, reducing the effectiveness of conventional disinfection procedures. Ricucci and Siqueira highlighted the importance of biofilm organization in apical periodontitis, demonstrating that bacterial communities can persist within the root canal system and contribute to ongoing periapical inflammation.[5] Therefore, effective disinfection requires strategies capable of disrupting established biofilms rather than targeting only free-floating microorganisms.

The effectiveness of root canal disinfection also depends on the interaction between chemical irrigants, mechanical preparation, and anatomical complexity. Although sodium hypochlorite is widely used because of its antimicrobial and tissue-dissolving properties, conventional syringe irrigation may not adequately reach all infected areas. Advanced irrigation methods, including sonic and ultrasonic activation, have been developed to improve irrigant distribution, enhance biofilm removal, and increase cleaning efficiency. Boutsioukis and Arias-Moliz emphasized that irrigation effectiveness is influenced by fluid dynamics, canal anatomy, and the interaction between irrigants and microbial biofilms.[6] However, improved laboratory cleaning does not necessarily guarantee superior long-term clinical outcomes. Consequently, combining appropriate chemical

disinfection with effective irrigation techniques remains essential for reducing microbial persistence and improving endodontic treatment outcomes. The effectiveness of root canal disinfection is influenced by microbial biofilm formation, anatomical complexity, irrigant properties, and treatment techniques, which collectively affect clinical outcomes (Figure 1).

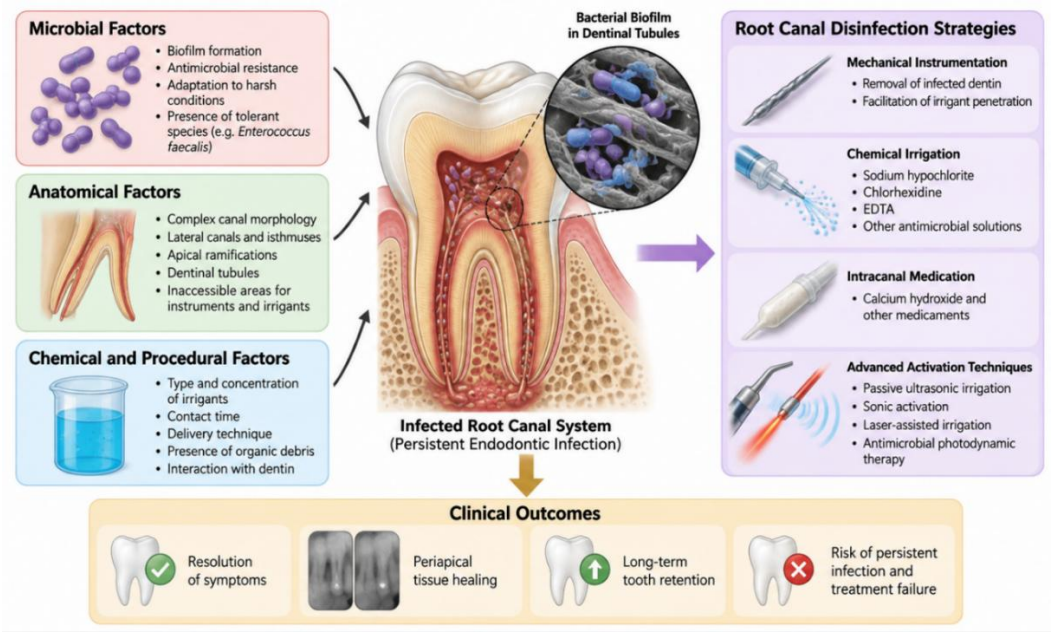


Figure 1: Schematic illustration of factors influencing persistent endodontic infection, root canal disinfection strategies, and associated clinical outcomes.

MICROBIAL PERSISTENCE AND BIOFILM FORMATION

The persistence of microorganisms within the root canal system is strongly associated with their ability to establish structured biofilm communities. Unlike planktonic bacteria, microorganisms within biofilms are embedded in an extracellular polymeric matrix composed of polysaccharides, proteins, and extracellular DNA. This arrangement promotes microbial adhesion, facilitates communication between bacterial cells, and creates localized environments with varying oxygen and nutrient availability. The biofilm matrix can also restrict antimicrobial penetration, while reduced metabolic activity and physiological adaptations allow certain bacterial populations to survive treatment. Costerton et al demonstrated that biofilm-associated microorganisms exhibit increased tolerance to antimicrobial agents and host defense mechanisms, contributing to the chronic nature of bacterial infections.[7]

Within infected root canals, biofilm development is influenced by the availability of nutrients, surface characteristics, and interactions between microbial species. Bacterial adhesion initially occurs along dentinal surfaces, followed by colonization and maturation into organized microbial communities. Svensäter and Bergenholtz described how the structural organization of endodontic biofilms contributes to bacterial survival under changing environmental conditions.[8] The irregular anatomy of the root canal system further supports microbial persistence, particularly within dentinal tubules, isthmuses, lateral canals, and apical ramifications, where mechanical instrumentation and chemical irrigants may have limited access.

Enterococcus faecalis has received considerable attention because of its association with persistent endodontic infections and its ability to survive harsh intracanal conditions. This microorganism can withstand prolonged nutrient deprivation, adhere to collagen-containing dentinal surfaces, and penetrate dentinal tubules. Its capacity to tolerate alkaline conditions may also reduce susceptibility to calcium hydroxide medication. Love explained that bacterial adhesion to dentinal collagen and subsequent invasion of dentinal tubules contribute to the survival of *E. faecalis* following endodontic treatment.[9] However, persistent infections are not exclusively associated with this species, as other facultative and obligate anaerobic microorganisms may also participate in complex microbial communities.

Antimicrobial resistance within biofilms involves several overlapping mechanisms, including restricted antimicrobial diffusion, altered bacterial metabolism, stress-response activation, and the presence of persister cells. These mechanisms can produce substantial differences in susceptibility between biofilm-associated and planktonic microorganisms. Stewart and Costerton emphasized that physiological heterogeneity within biofilms allows microbial subpopulations to withstand antimicrobial exposure even when the same agents demonstrate effectiveness against freely suspended bacteria.[10] In the root canal environment, these characteristics become particularly relevant when residual microorganisms remain within uninstrumented regions or deeply infected dentin. Biofilm maturation, microbial interactions, and variations in local environmental conditions may influence the response of these surviving populations to subsequent intracanal disinfection procedures.

ROOT CANAL DISINFECTION STRATEGIES

Root canal disinfection relies on the combined effects of mechanical instrumentation, chemical irrigation, and intracanal medication to reduce microbial populations within infected dentinal structures. Mechanical preparation removes contaminated tissues and facilitates irrigant circulation, although instrumentation alone cannot adequately clean the entire canal system. Sodium hypochlorite (NaOCl) remains a widely used irrigating solution because of its antimicrobial activity and ability to dissolve organic tissue. Chlorhexidine (CHX) has also been investigated as an antimicrobial irrigant, particularly for its substantivity on dentinal surfaces. Siqueira et alcompared sodium hypochlorite and chlorhexidine during endodontic treatment and reported significant bacterial reductions with both solutions, although neither consistently eliminated microorganisms from infected canals.[11]

The effectiveness of chemical disinfection is influenced by irrigant concentration, exposure duration, temperature, and accessibility to infected surfaces. Ethylenediaminetetraacetic acid (EDTA) is commonly incorporated into irrigation protocols to remove the inorganic component of the smear layer, facilitating access to dentinal tubules. Intracanal medications may be used when disinfection is performed over multiple appointments. Calcium hydroxide remains a frequently employed medicament because of its high alkalinity and antimicrobial properties. Mohammadi and Dummer described its mechanisms of action, including damage to bacterial membranes, protein denaturation, and interference with microbial DNA.[12] However, dentin buffering, limited penetration, and the tolerance of certain microorganisms may reduce its effectiveness.

Irrigant activation techniques have been introduced to improve fluid movement and enhance cleaning in areas inaccessible to conventional syringe irrigation. Passive ultrasonic irrigation uses acoustic energy to generate fluid movement, promoting debris removal and irrigant exchange within complex canal configurations. Van der Sluis et al reviewed the effectiveness of ultrasonic irrigation and reported improvements in cleaning compared with conventional irrigation under several experimental conditions.[13] Its performance depends on canal preparation, instrument positioning, irrigant volume, and activation duration.

Laser-assisted irrigation, antimicrobial photodynamic therapy, and alternative mechanical activation systems have expanded the available approaches to intracanal disinfection. Laser-based techniques may enhance irrigant movement through rapid fluid expansion and cavitation effects, while photodynamic therapy involves activating a photosensitizing agent to generate reactive oxygen species capable of damaging microbial structures.

Plotino et al discussed emerging technologies for root canal disinfection, emphasizing their potential to improve antimicrobial activity within anatomical regions that remain difficult to access.[14] Differences in laser parameters, photosensitizer concentrations, activation protocols, and experimental models influence the antimicrobial effects reported across studies, particularly when evaluating mature biofilms and microorganisms located deep within dentinal tubules.

FACTORS AFFECTING DISINFECTION EFFICACY

The effectiveness of root canal disinfection is influenced by anatomical, microbiological, and chemical factors that determine the accessibility and antimicrobial activity of irrigating solutions. Root canal morphology presents considerable challenges because of variations in canal curvature, diameter, and the presence of isthmuses, lateral canals, and apical ramifications. These anatomical structures can retain microorganisms and organic debris despite mechanical instrumentation. Peters et al demonstrated that nickel-titanium instrumentation techniques leave portions of root canal walls untouched, highlighting the limitations of mechanical preparation in achieving complete cleanliness.[15] Narrow and curved canals may also restrict irrigant circulation, reducing direct contact between antimicrobial solutions and contaminated dentinal surfaces.

Irrigant delivery plays a substantial role in determining disinfection efficiency, particularly within the apical third of the root canal. Needle design, insertion depth, irrigation pressure, and canal enlargement influence the distribution and replacement of irrigating solutions. The formation of an apical vapor lock, caused by air entrapment in closed-ended canal systems, can further restrict irrigant penetration. Tay et al investigated this phenomenon and demonstrated that vapor lock formation interferes with effective irrigant delivery and debris removal during positive-pressure irrigation.[16] Such limitations are particularly relevant in narrow apical regions, where insufficient fluid exchange may allow residual bacteria and organic material to remain following treatment.

Chemical interactions within the root canal environment can modify the antimicrobial performance of irrigants and intracanal medications. Dentin, organic tissue remnants, and microbial byproducts may interfere with the activity of disinfecting agents, reducing their effectiveness under clinical conditions. Haapasalo et al demonstrated that dentin can inhibit the antimicrobial activity of several intracanal medicaments, emphasizing the influence of surrounding dental tissues on disinfection outcomes.[17] The buffering capacity of dentin may also reduce the alkalinity associated with calcium hydroxide, limiting antimicrobial activity in regions where microbial penetration extends deeply into dentinal tubules.

Irrigant concentration and exposure duration directly affect antimicrobial effectiveness, particularly against microorganisms organized within mature biofilms. Higher concentrations of sodium hypochlorite generally demonstrate stronger antimicrobial and tissue-dissolving activity, although increased concentrations may also increase cytotoxicity and the risk of tissue damage following extrusion.

Retamozo et al investigated the minimum contact time and concentration required for sodium hypochlorite to act against *Enterococcus faecalis* biofilms and infected dentinal tubules, demonstrating that antimicrobial effectiveness varies according to these parameters.[18] Biofilm thickness, microbial density, and physiological adaptation can further modify susceptibility, while the presence of residual organic material increases the chemical demand placed on irrigating solutions during treatment.

CLINICAL OUTCOMES

Clinical outcomes following root canal disinfection are primarily assessed through the resolution of symptoms, periapical tissue healing, and long-term tooth retention. Successful treatment is associated with sufficient microbial reduction, prevention of reinfection, and restoration of normal periapical conditions. However, persistent microorganisms within the root canal system may compromise healing even when treatment appears technically satisfactory.

Sjögren et al investigated the influence of residual infection at the time of root canal obturation and demonstrated that teeth with negative bacterial cultures exhibited more favorable healing outcomes than those with detectable microorganisms.[19] These findings established a relationship between microbial status before obturation and the prognosis of endodontic treatment.

The presence of preoperative apical periodontitis can influence treatment outcomes because established periapical lesions reflect microbial infection and associated inflammatory tissue responses. Healing may require prolonged observation, particularly in teeth presenting with extensive periapical radiolucencies. De Chevigny et al evaluated outcomes following initial nonsurgical root canal treatment and identified preoperative periapical status as a relevant prognostic factor.[20] Radiographic evidence of healing does not always develop immediately after treatment, and the persistence of radiolucency during early follow-up may reflect incomplete tissue repair rather than active infection.

Clinical management becomes more complicated when persistent infection necessitates nonsurgical retreatment. Previous root canal fillings, untreated anatomy, procedural complications, and established intraradicular microbial communities may restrict effective disinfection. During retreatment, removal of existing filling materials and renewed canal preparation aim to improve access to contaminated surfaces. De Chevigny et al examined the outcomes of orthograde retreatment and reported that healing was influenced by preoperative conditions and treatment-related factors.[21] Persistent periapical lesions may respond differently depending on the extent of microbial infection, accessibility of the canal system, and the presence of structural damage.

Long-term clinical assessment also requires distinguishing periapical healing from functional tooth survival. A tooth may remain functional despite persistent radiographic changes, whereas technically successful endodontic treatment may eventually be followed by extraction because of fracture or restorative complications. Ng et al evaluated tooth survival following primary root canal treatment and demonstrated the influence of restorative and tooth-related factors on retention.[22] These findings indicate that clinical outcomes cannot be attributed solely to antimicrobial effectiveness. The quality of coronal restoration, remaining tooth structure, periodontal support, and occlusal loading may affect prognosis independently of intracanal disinfection, while radiographic interpretation and follow-up duration influence how treatment outcomes are classified.

CONCLUSION

Persistent endodontic infections remain a major challenge due to microbial biofilm formation, complex root canal anatomy, and resistance to antimicrobial agents. Effective disinfection requires the integration of mechanical instrumentation, chemical irrigation, and advanced activation techniques to improve microbial elimination. The success of these strategies depends on irrigant properties, treatment protocols, and the accessibility of infected areas within the root canal system. Further clinical research is needed to optimize disinfection protocols, minimize microbial persistence, and improve long-term endodontic treatment outcomes.

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