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Photoresponsive Materials for Root Canal Infection Control: Mechanisms, Applications, and Clinical Challenges

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Abstract. Root canal infection remains difficult to control because of the complex anatomy of the root canal system and the increased tolerance of microbial biofilms to conventional disinfection. Photoresponsive materials have therefore emerged as potential adjuncts that use photodynamic or photothermal mechanisms. This review summarizes the mechanisms and applications of conventional photosensitizers, photothermal agents, nanodelivery systems, and multimodal photoresponsive platforms. Photodynamic materials generate reactive oxygen species (ROS) that induce oxidative damage, whereas photothermal materials convert light energy into localized heat to inactivate microorganisms and disrupt biofilm structure. Their antibacterial effects and complementary roles alongside mechanical preparation and chemical irrigation are critically evaluated. Current evidence suggests that photodynamic therapy may provide additional reductions in microbial load, whereas photothermal and multifunctional nanomaterial systems remain supported mainly by preclinical studies. Major challenges include limited light penetration, uneven material distribution, insufficient oxygen supply, thermal injury, material residues, and inconsistent treatment parameters. Future studies should improve biocompatibility, delivery, and removal; standardize experimental protocols; and evaluate clinically meaningful outcomes, including periapical healing, infection recurrence, and tooth survival.

Keywords: photoresponsive materials, root canal infection, photodynamic therapy, photothermal therapy, biofilm

1. Introduction

Microbial infection is a principal biological cause of pulp necrosis, apical periodontitis, and persistent post-treatment apical periodontitis. Root canal treatment combines mechanical instrumentation, chemical irrigation, and obturation to reduce infected tissue, microorganisms, and their by-products and thereby create conditions favorable for periapical healing. However, the root canal system contains isthmuses, lateral canals, apical ramifications, and dentinal tubules that instruments cannot contact completely. Irrigant exchange and penetration may also be limited in apical and anatomically inaccessible regions. Consequently, microorganisms and infected tissue may remain after standardized chemomechanical preparation [1].

Microorganisms within root canals commonly persist as biofilms. The extracellular polymeric matrix, reduced metabolic activity, and interactions among community members can increase

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tolerance to disinfection [2]. Such biofilm tolerance should not be equated automatically with genetically mediated antimicrobial resistance; instead, it reflects the combined effects of root canal anatomy, microbial physiology, and treatment conditions. Residual biofilms may contribute to persistent or recurrent infection and have motivated the development of sonic, ultrasonic, laser-assisted, and light-activated adjuncts.

Photoresponsive materials provide mechanisms that differ from conventional chemical disinfection. Photodynamic therapy (PDT) activates a photosensitizer to generate reactive oxygen species (ROS), including singlet oxygen, whereas photothermal therapy (PTT) converts absorbed light into localized heat. Nanocarriers may improve the dispersion, delivery, and biofilm interaction of photosensitizers or photothermal agents and can support combined PDT-PTT platforms [3]. Nevertheless, efficacy depends on whether the material reaches the target and whether an effective light dose can be delivered throughout the root canal.

Systematic clinical evidence suggests that adding PDT to conventional chemomechanical preparation may further reduce the microbial load in primary or secondary root canal infections [4]. However, studies differ substantially in photosensitizers, wavelengths, energy doses, exposure times, and microbiological methods. Moreover, a reduction in microbial load is a surrogate outcome and does not by itself establish improved periapical healing or tooth survival. This review therefore examines the mechanisms, antibacterial applications, and translational limitations of photodynamic, photothermal, and multimodal photoresponsive materials, while positioning them as potential adjuncts rather than replacements for established root canal disinfection.

2. Root canal infection microenvironment and the basis of photoresponsive materials

Root canal infection can be viewed as a multispecies biofilm ecosystem within an anatomically constrained space. Although chemomechanical preparation is central to successful treatment, neither instrumentation nor irrigation can predictably render the entire root canal system sterile. Light-activated approaches are therefore being investigated as adjunctive strategies with externally triggered and partly controllable activity, rather than as methods that can reach every anatomical irregularity [5, 6]. Understanding their potential requires consideration of infection biology, material mechanisms, and the factors governing energy delivery.

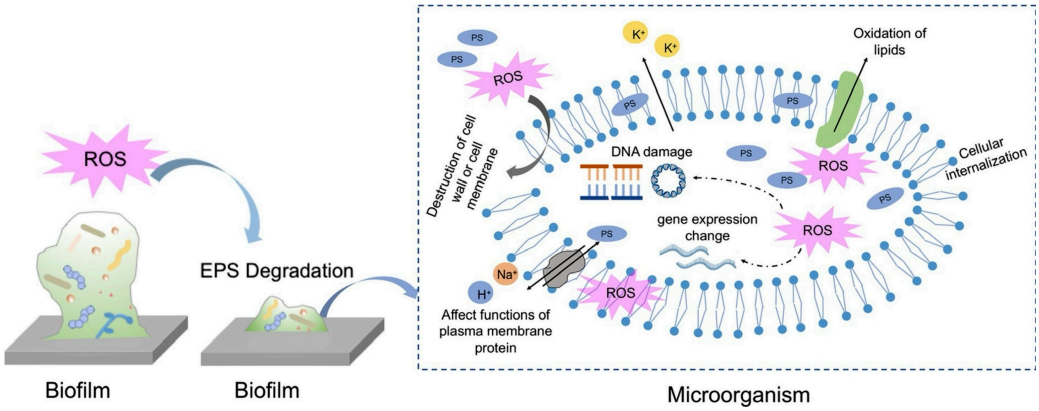


Figure 1. Proposed mechanisms of antimicrobial photodynamic therapy against biofilms and microbial cells [5]

Root canal infection is not simply an accumulation of planktonic bacteria. As shown in Figure 1, extracellular polymeric substances (EPS) surround microbial cells and form a physicochemical

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barrier that can impede the diffusion and activity of some disinfectants [5]. Nutrient limitation may also produce slowly metabolizing cells in deeper biofilm regions, reducing susceptibility to interventions that act preferentially on active cells. *Enterococcus faecalis* is frequently detected in persistent or secondary endodontic infections and can survive nutrient-limited conditions, invade dentinal tubules, and form biofilms with increased tolerance to common irrigants [6]. Interactions within multispecies communities further complicate disinfection.

Complex root canal anatomy creates an additional barrier to infection control. Instruments may leave parts of the canal wall untouched, particularly in isthmuses, fins, oval canals, and apical ramifications, while surface tension, contact time, and fluid dynamics limit irrigant penetration into dentinal tubules. The proportion of uninstrumented surface varies widely with tooth type, canal morphology, and preparation system, so a single percentage should not be generalized across all clinical situations [1]. These limitations provide a clinical rationale for adjunctive approaches but do not demonstrate that light-responsive materials can overcome every inaccessible region.

Photoresponsive systems can be classified by their dominant energy-conversion mechanism. In PDT, a photosensitizer is excited by light of a suitable wavelength and generates ROS through electron-transfer reactions (type I) or energy transfer to molecular oxygen (type II). These species can oxidize microbial membranes, proteins, and nucleic acids [5, 6]. In PTT, absorbed light is converted into heat that disrupts membranes and denatures proteins. Multimodal platforms combine these mechanisms, or add catalytic and gas-releasing functions, to reduce dependence on a single antibacterial pathway [7, 8]. Material-mediated phototherapy should also be distinguished from high-power laser disinfection, in which the laser itself produces the principal thermal, mechanical, or fluid-dynamic effect.

Antibacterial performance is governed by material distribution, spectral matching, light dose, and the local microenvironment. Photosensitizers or photothermal agents must disperse within the canal and contact the biofilm without leaving harmful residues [6, 9]. Near-infrared (NIR) light may improve penetration in some settings, but the optimal wavelength remains material- and device-specific. Irradiance, energy density, and exposure time determine ROS generation or thermal dose; inadequate settings may reduce efficacy, whereas excessive heating may injure periodontal tissues. Oxygen availability can also limit type II photodynamic reactions, and dentin, organic matter, and canal geometry can attenuate or scatter light. These constraints explain why promising antibacterial results under controlled conditions may not translate directly into predictable clinical benefit.

3. Application of photodynamic materials in root canal infection control

Among light-responsive approaches, PDT has the largest endodontic evidence base. After light absorption, the activated photosensitizer transfers electrons or energy to surrounding molecules and produces ROS that damage multiple microbial targets. This multitarget action may reduce the likelihood of selecting resistance through a single molecular pathway, although it does not eliminate biofilm tolerance or guarantee complete disinfection. Translation remains limited by the physicochemical properties of photosensitizers and by light and oxygen availability within the canal.

Photosensitizer selection strongly influences antibacterial performance. Methylene blue (MB), toluidine blue O (TBO), and indocyanine green (ICG) have demonstrated activity against planktonic *E. faecalis* and experimental biofilms. MB and TBO absorb primarily in the visible red region, approximately 600-700 nm, whereas ICG absorbs near 780 nm and can support both photodynamic and photothermal effects. However, aggregation, photobleaching, limited penetration, dentin interactions, and potential tooth discoloration can reduce performance [6, 9]. Available models and treatment protocols are highly heterogeneous; therefore, PDT should not be declared universally

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inferior or superior to passive ultrasonic irrigation. Evidence that viable-cell counts decrease without a comparable reduction in total biofilm volume also indicates that physical biofilm removal continues to depend on irrigation and fluid movement [5].

Nanocarriers offer a strategy for improving photosensitizer solubility, stability, and contact with biofilms. Nanoparticles, liposomes, and polymeric carriers can reduce aggregation and may be engineered with surface properties that favor interaction with negatively charged biofilm components [9, 10]. Their penetration into mature biofilms and dentinal tubules, however, remains dependent on particle size, charge, composition, and experimental conditions. Functionalized systems can also combine mechanisms. As shown in Figure 2, a guanidinylated polymeric nanoparticle carrying chlorin e6 was designed to penetrate biofilms and release nitric oxide (NO) during antimicrobial PDT, producing synergistic activity in laboratory and animal models [8]. Such findings are promising but do not establish effectiveness in human root canal treatment.

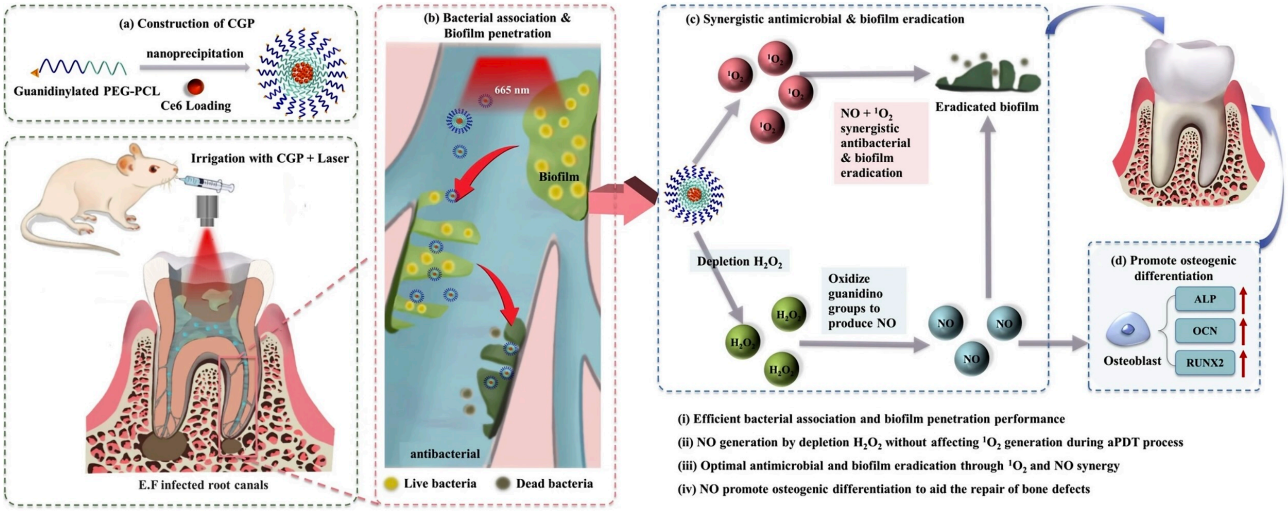


Figure 2. Preparation and antibacterial mechanism of the CGP nanoplatform. (a) Construction of chlorin e6-loaded guanidinylated poly(ethylene glycol)-poly(ε-caprolactone) nanoparticles and their application in laser-assisted root canal irrigation; (b) bacterial association and biofilm penetration of CGP under 665-nm irradiation; (c) synergistic biofilm eradication through antimicrobial photodynamic therapy-generated singlet oxygen (1O2) and hydrogen peroxide-triggered nitric oxide (NO) release; (d) NO-mediated promotion of osteogenic differentiation and periapical bone repair [8]

Most PDT studies report short-term microbiological outcomes. Reductions in colony-forming units (CFU) are often observed when PDT is added to sodium hypochlorite (NaOCl) irrigation, yet CFU reduction does not necessarily predict periapical healing, recurrence, or tooth survival. Although numerous *in vitro* and some *in vivo* studies support antibacterial activity, high-quality randomized controlled trials (RCTs) linking treatment protocols to long-term patient-centered outcomes remain limited. Existing reviews therefore support PDT as a possible adjunct while identifying protocol heterogeneity, indirect outcomes, and risk of bias as important sources of uncertainty [6, 10].

Overall, PDT provides a controllable photochemical route for targeting microorganisms that remain after chemomechanical preparation. Its clinical adoption is nevertheless constrained by photosensitizer limitations, nonuniform light and oxygen distribution, incomplete biofilm removal, and uncertain long-term benefit. Future work should prioritize stable and removable photosensitizer

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systems, reproducible intracanal delivery, thermal and cytotoxicity testing, and clinical trials that evaluate healing and tooth retention rather than microbiological reduction alone.

4. Application of photothermal and multimodal materials in root canal infection control

PTT converts absorbed light into localized heat, which can disrupt microbial membranes, denature proteins, and inactivate cells. It is a broad-spectrum, non-antibiotic strategy with potential spatial and temporal control, but its activity depends on both temperature and exposure time. Excessive thermal dose may damage periodontal ligament, cementum, or surrounding bone. Achieving antibacterial temperatures without harmful heat transmission is therefore particularly important in narrow root canals that lie close to periradicular tissues. Unlike PDT, which acts primarily through photochemical oxidation, PTT relies mainly on thermal injury; the two mechanisms are distinct but potentially complementary.

Nanomaterials provide platforms for integrating photothermal and photodynamic functions. Metal-based materials, carbon nanomaterials, nanosheets, hydrogels, and multifunctional particles have been designed to combine heat with ROS-mediated oxidation. Copper sulfide (CuS) systems can generate heat under NIR irradiation and may be coupled with ROS-producing components. Molybdenum disulfide (MoS_2) and graphene oxide have likewise been incorporated into multimodal constructs. These examples demonstrate technical feasibility in general antibacterial models, but they should not be treated as direct clinical evidence for endodontic use. Intracanal delivery, light distribution, material removal, and tissue thermal safety require application-specific testing.

Combining PDT and PTT is intended to offset limitations of either modality alone. PTT may require a substantial thermal dose, whereas PDT depends on photosensitizer distribution, light delivery, and local oxygen and produces ROS with short lifetimes and limited diffusion distances. Incorporating both functions into one platform may strengthen antibacterial activity while reducing the dose required from either mechanism [7]. This rationale remains mechanistic, however, and synergistic effects demonstrated in simplified or nonendodontic infection models cannot be assumed to improve outcomes in the anatomically complex root canal system.

The evidence therefore follows a clear translational gradient. PDT has been evaluated in endodontic laboratory studies, clinical microbiological studies, and evidence syntheses and may provide supplementary disinfection after standard cleaning and shaping [6]. Nanoparticle-mediated PDT has also been reviewed, but evidence for superiority over conventional PDT remains low and inconsistent [9, 10]. By contrast, PTT and combined PDT-PTT platforms are supported mainly by material-development studies and preclinical infection models. At present, they are best regarded as investigational adjuncts. Standardized research must determine whether they improve periapical healing, reduce recurrence, or increase tooth survival without unacceptable thermal or material-related risks.

5. Conclusion

The complex anatomy of the root canal system and the tolerance of microbial biofilms remain major barriers to effective infection control. Photoresponsive materials offer potential adjuncts to conventional disinfection: photodynamic materials generate ROS, photothermal materials produce localized heat, and multimodal nanoplatforms combine complementary mechanisms while potentially improving material stability and biofilm interaction. Current evidence suggests that PDT may provide an additional reduction in microbial load when combined with chemomechanical preparation, whereas PTT and multifunctional nanomaterials remain predominantly preclinical.

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Limited light penetration, uneven material distribution, oxygen dependence, thermal injury, residual material, and inconsistent treatment parameters continue to restrict translation. Future studies should optimize biocompatibility, intracanal delivery, and material removal; standardize light and dose parameters; and use carefully designed clinical trials to assess periapical healing, infection recurrence, and tooth survival.

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