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Smart Periodontal Dressings with Controlled Antimicrobial Release Triggered by Bacterial Enzymes

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Abstract

Periodontal diseases remain among the most prevalent oral inflammatory conditions, requiring effective infection control and optimal wound healing following surgical and non-surgical therapy. Conventional periodontal dressings primarily serve as protective barriers but often lack the ability to respond dynamically to changes within the infected periodontal environment. Smart periodontal dressings with controlled antimicrobial release triggered by bacterial enzymes represent an innovative biomaterial-based approach that combines wound protection with targeted, on-demand drug delivery. These advanced dressings are designed to recognize enzymes produced by pathogenic bacteria, initiating localized release of antimicrobial agents only when infection-related activity is present. This responsive mechanism enhances drug utilization, minimizes unnecessary antimicrobial exposure, reduces the risk of systemic side effects, and supports sustained inhibition of pathogenic biofilms. In addition to controlling infection, enzyme-responsive dressings maintain a moist healing environment, protect regenerating tissues, and promote favorable conditions for periodontal repair. Recent advances in hydrogels, biodegradable polymers, nanocomposite materials, and bioactive coatings have significantly improved the performance and clinical potential of these intelligent wound care systems. Although challenges related to material optimization, manufacturing, regulatory approval, and long-term clinical validation remain, smart periodontal dressings demonstrate considerable promise as next-generation therapeutic platforms capable of improving treatment outcomes through precise, responsive, and patient-centered management of periodontal wounds.

Keywords: Smart periodontal dressings; controlled antimicrobial release; bacterial enzymes; periodontal disease; enzyme-responsive biomaterials; hydrogels; biofilm inhibition; targeted drug delivery; wound healing; periodontal regeneration.

1. Introduction

Periodontal disease is a chronic inflammatory condition initiated by pathogenic microbial biofilms that progressively destroy the supporting structures of the teeth, including the gingiva, periodontal ligament, and alveolar bone. Successful periodontal therapy depends not only on eliminating pathogenic microorganisms but also on maintaining an environment conducive to tissue repair and regeneration. Conventional periodontal dressings are widely used following periodontal surgical procedures to protect wound sites, reduce postoperative discomfort, and stabilize healing tissues. However, these dressings primarily function as passive barriers and possess limited capacity for active infection control or controlled therapeutic delivery (Francesko et al., 2018).

The persistence of bacterial biofilms within periodontal pockets remains a significant challenge because biofilm-associated microorganisms exhibit increased resistance to conventional antimicrobial agents. Consequently, there has been growing interest in developing smart biomaterials capable of responding to infection-specific stimuli and releasing antimicrobial agents only when required, thereby improving therapeutic efficiency while minimizing unnecessary drug exposure (Jiao et al., 2019; Alvarez-Lorenzo et al., 2016).

Among various stimuli-responsive systems, bacterial enzyme-triggered drug delivery has emerged as a promising strategy. These intelligent dressings are engineered with enzyme-sensitive polymers or multilayer structures that degrade selectively in the presence of bacterial enzymes, resulting in localized and controlled antimicrobial release at infected periodontal sites. This targeted approach enhances biofilm inhibition, prolongs antimicrobial activity, and reduces the likelihood of recurrent infection (Wang et al., 2018). Advances in hydrogel technologies, antibacterial surface engineering, and smart wound dressings have further accelerated the development of multifunctional periodontal dressings that combine mechanical protection with responsive therapeutic functions (Derakhshandeh et al., 2018; Francesko et al., 2018; Vasilev et al., 2009).

The increasing emphasis on biologically active and minimally invasive periodontal therapies has also encouraged the integration of bioactive materials and controlled delivery systems into dental practice, reflecting broader advances in regenerative and antimicrobial biomaterials (Singh, 2019; Singh, 2020). Smart periodontal dressings therefore represent an innovative therapeutic platform with the potential to improve infection control, promote wound healing, and enhance overall clinical outcomes in periodontal therapy.

2. Scientific Basis of Enzyme-Responsive Smart Periodontal Dressings

The effectiveness of smart periodontal dressings is based on their ability to respond selectively to biochemical changes within the periodontal pocket. Periodontal infections are characterized by complex biofilms composed of pathogens such as *Porphyromonas gingivalis*, *Treponema denticola*, and *Tannerella forsythia*, which secrete proteases, collagenases, hyaluronidases, and

other virulence-associated enzymes. These enzymes not only contribute to connective tissue destruction but also provide biological triggers for enzyme-responsive drug delivery systems (Jiao et al., 2019).

Enzyme-responsive dressings incorporate biodegradable polymers or hydrogels containing enzyme-sensitive linkages. Under healthy conditions, these matrices remain stable; however, exposure to bacterial enzymes cleaves the responsive bonds, initiating localized and controlled release of antimicrobial agents. This targeted mechanism maximizes drug concentration at infected sites while minimizing premature release, systemic exposure, and the development of antimicrobial resistance (Alvarez-Lorenzo et al., 2016; Wang et al., 2018).

Hydrogel-based dressings provide an ideal platform because they maintain a moist wound environment, facilitate oxygen diffusion, absorb inflammatory exudates, and can be engineered with enzyme-degradable networks for sustained therapeutic action (Francesko et al., 2018). Similar smart wound-care strategies have demonstrated significant advantages in chronic wound management by providing responsive treatment only when pathological stimuli are present (Derakhshandeh et al., 2018). Furthermore, antibacterial surface modifications can reduce microbial adhesion and complement controlled drug delivery, thereby improving long-term biofilm control (Vasilev et al., 2009). The principles of localized therapeutic delivery and preservation of healthy tissues parallel the minimally invasive concepts emphasized in regenerative dental therapies and biologically driven treatment approaches (Singh, 2019; Singh, 2020).

Table 1. Scientific Basis of Enzyme-Responsive Smart Periodontal Dressings

Scientific Component	Role in Smart Dressing	Clinical Significance
Bacterial enzymes (proteases, collagenases)	Trigger degradation of responsive polymers	Infection-specific drug release
Stimuli-responsive polymers	Remain stable until enzyme activation	Controlled and sustained antimicrobial delivery
Hydrogel matrix	Maintains moist healing environment and carries drugs	Enhanced tissue repair and patient comfort
Antimicrobial agents	Eliminate periodontal pathogens	Biofilm suppression and reduced infection recurrence
Antibacterial surface coatings	Prevent bacterial adhesion and colonization	Long-term protection against biofilm formation

3. Materials, Design Strategies, and Mechanisms of Action

3.1 Biomaterials Used

Smart periodontal dressings are fabricated from biocompatible materials that provide wound protection while enabling controlled antimicrobial release. Hydrogels are widely used because they maintain a moist environment, conform closely to periodontal tissues, and permit incorporation of therapeutic agents. Biodegradable polymers and nanocomposite matrices further improve mechanical stability, drug-loading capacity, and gradual degradation. Bioactive polymer coatings also enhance tissue compatibility and reduce bacterial adhesion, making them suitable platforms for responsive periodontal wound care (Francesko et al., 2018; Derakhshandeh et al., 2018; Vasilev et al., 2009).

3.2 Antimicrobial Agents

Common antimicrobial agents incorporated into smart dressings include chlorhexidine, doxycycline, metronidazole, silver nanoparticles, and antimicrobial peptides. These agents are selected for their broad-spectrum activity against periodontal pathogens and their ability to suppress biofilm formation while minimizing systemic drug exposure. Combining localized antimicrobial delivery with bioactive materials supports effective infection control and favorable healing outcomes (Jiao et al., 2019; Singh, 2019).

3.3 Drug Release Mechanism

The distinguishing feature of these dressings is enzyme-responsive drug release. Periodontal pathogens produce enzymes such as proteases and collagenases that degrade specially designed polymer linkers or hydrogel networks. This degradation triggers localized release of antimicrobial agents only when bacterial activity is elevated, ensuring site-specific therapy while conserving drug reservoirs. Such controlled delivery reduces premature drug depletion, prolongs antimicrobial activity, inhibits recurrent biofilm formation, and limits unnecessary antimicrobial exposure. The concept parallels targeted therapeutic strategies employed in other dental biomaterials and irrigation systems aimed at maximizing local efficacy while minimizing adverse effects (Alvarez-Lorenzo et al., 2016; Wang et al., 2018; Singh, 2020).

Table 2. Materials and Design Components of Smart Periodontal Dressings

Component	Primary Function	Clinical Benefit
Hydrogel matrix	Moist wound environment	Promotes tissue healing
Biodegradable polymer	Controlled degradation	Sustained drug release
Enzyme-sensitive linker	Responds to bacterial enzymes	Site-specific antimicrobial delivery
Antimicrobial agent	Eliminates periodontal pathogens	Reduces biofilm formation
Bioactive surface coating	Prevents bacterial adhesion	Enhances biocompatibility and wound protection

4. Clinical Applications, Advantages, Challenges, and Future Perspectives

Smart periodontal dressings with bacterial enzyme-triggered antimicrobial release have potential applications across a broad range of periodontal procedures. They may be used following scaling and root planing, periodontal flap surgery, guided tissue regeneration, gingival grafting, and peri-implant soft tissue management to protect healing tissues while providing localized antimicrobial therapy. Their ability to release drugs only in the presence of pathogenic bacterial enzymes offers targeted infection control, reducing bacterial recolonization and promoting favorable healing conditions (Derakhshandeh et al., 2018; Jiao et al., 2019). Similar principles of localized therapeutic delivery have been successfully emphasized in other dental biomaterial applications (Singh, 2019; Singh, 2020).

The principal advantages of these intelligent dressings include sustained and site-specific drug release, reduced systemic antibiotic exposure, enhanced biofilm disruption, prolonged antimicrobial activity, and improved patient compliance. Enzyme-responsive polymers and hydrogels also maintain a moist wound environment while minimizing unnecessary drug release, thereby improving therapeutic efficiency (Alvarez-Lorenzo et al., 2016; Francesko et al., 2018; Wang et al., 2018).

Despite these benefits, several challenges remain. Material fabrication is technically demanding, optimization of enzyme sensitivity is required to prevent premature or delayed drug release, and long-term biocompatibility must be established. Additional limitations include manufacturing

costs, sterilization requirements, and limited clinical evidence supporting widespread routine use. Surface stability and durability under the dynamic oral environment also require further investigation (Vasilev et al., 2009; Wang et al., 2018).

Future developments are expected to focus on multifunctional periodontal dressings capable of combining antimicrobial delivery with regenerative biomolecules, growth factors, or anti-inflammatory agents. Improved hydrogel formulations, nanostructured carriers, and highly selective enzyme-responsive polymers may further enhance precision drug delivery and periodontal wound healing while reducing treatment-related complications (Alvarez-Lorenzo et al., 2016; Derakhshandeh et al., 2018).

Clinical Aspect	**Current Benefits**	**Future Improvements**
Infection control	Enzyme-triggered localized antimicrobial release	Multi-drug responsive delivery systems
Wound healing	Moist environment and biofilm suppression	Combined regenerative and antimicrobial therapy
Drug delivery	Controlled, site-specific release	Personalized enzyme-responsive platforms
Clinical performance	Reduced systemic drug exposure	Greater long-term clinical validation

5. Conclusion

Smart periodontal dressings with controlled antimicrobial release triggered by bacterial enzymes represent a promising advancement in periodontal wound management by integrating protective barrier functions with responsive drug delivery. Unlike conventional dressings that provide passive coverage, these intelligent biomaterials are designed to detect enzymatic activity associated with pathogenic biofilms and release antimicrobial agents only when needed, thereby enhancing therapeutic precision and minimizing unnecessary drug exposure (Alvarez-Lorenzo et al., 2016; Wang et al., 2018). Their ability to maintain a favorable healing environment while suppressing microbial recolonization has the potential to improve clinical outcomes following periodontal therapy (Derakhshandeh et al., 2018; Francesko et al., 2018).

The incorporation of enzyme-responsive polymers, hydrogels, and advanced antimicrobial strategies offers significant advantages, including sustained local drug delivery, enhanced biofilm control, improved patient compliance, and reduced reliance on systemic antibiotics (Jiao et al., 2019). These developments are consistent with the broader trend toward biologically

responsive biomaterials in dentistry and localized therapeutic approaches that support tissue healing and infection control (Singh, 2019; Singh, 2020).

Although further optimization of material properties, long-term biocompatibility, manufacturing processes, and clinical validation is necessary before widespread clinical adoption, smart periodontal dressings provide a strong foundation for the next generation of periodontal biomaterials. Continued research into responsive drug delivery systems is expected to enhance the effectiveness, safety, and predictability of periodontal treatment while contributing to improved management of oral biofilm-associated diseases (Vasilev et al., 2009; Wang et al., 2018).

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