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Review Article

Smart biomaterials in periodontology: a narrative review

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ABSTRACT

Periodontitis is a chronic inflammatory disease characterized by progressive destruction of the supporting structures of teeth, including gingiva, periodontal ligament, cementum and alveolar bone. Conventional periodontal therapies primarily focus on infection control and repair; however, complete regeneration of lost periodontal tissues remains a major clinical challenge. Recent advances in biomaterial science, nanotechnology, tissue engineering and regenerative medicine have led to the emergence of smart biomaterials, which possess the ability to respond dynamically to biological, chemical or physical stimuli within the periodontal microenvironment. These intelligent biomaterials can provide controlled drug delivery, antimicrobial action, immunomodulation, enhanced wound healing and targeted tissue regeneration. Smart biomaterials used in periodontology include stimuli-responsive hydrogels, nanoparticles, nanofibers, bioactive membranes, injectable scaffolds and stem cell-based matrices. These materials respond to various stimuli such as pH, temperature, enzymes, light, magnetic fields and inflammatory mediators, thereby improving therapeutic efficacy and minimizing adverse effects. In addition to periodontal regeneration, smart biomaterials have shown promising applications in guided tissue regeneration, peri-implantitis management, local drug delivery and bone tissue engineering. This narrative review discusses the concept, classification, mechanisms, applications, advantages, limitations and future perspectives of smart biomaterials in periodontology. The review also highlights emerging trends such as exosome-based therapy, 3D printing, nanotechnology, biosensor-integrated scaffolds and personalized regenerative approaches. Smart biomaterials represent a transformative advancement in modern periodontology and may significantly improve the predictability and success of regenerative periodontal therapy in the future.

Keywords: Guided tissue regeneration, Hydrogels, Nanoparticles, Periodontology, Periodontal regeneration, Regenerative dentistry, Smart biomaterials, Tissue engineering

INTRODUCTION

Periodontal disease is a chronic inflammatory disorder characterized by progressive destruction of gingiva, periodontal ligament, cementum and alveolar bone. Conventional periodontal therapies primarily focus on arresting disease progression and reducing microbial load; however, true regeneration of lost periodontal tissues remains a major clinical challenge. In recent years, advances in tissue engineering, nanotechnology, regenerative medicine and biomaterial science have led to the emergence of "smart biomaterials," which are considered one of the most promising developments in modern periodontology. Smart biomaterials differ from conventional passive materials because they can respond dynamically to environmental stimuli such as pH, temperature, enzymes, light, magnetic fields and inflammatory mediators, thereby producing controlled therapeutic effects.[1] The inflammatory periodontal environment exhibits altered pH, increased enzymatic activity, oxidative stress and elevated inflammatory cytokines. Smart biomaterials utilize these pathological changes to trigger targeted drug release, antimicrobial activity, tissue regeneration or immunomodulation. These materials include smart hydrogels, nanoparticles, nanofibers, injectable scaffolds, bioactive membranes and stem cell-loaded matrices.[2] Such intelligent systems have significantly enhanced the possibilities of periodontal regeneration and peri-implant tissue management. This narrative review aims to discuss the concept, classification, mechanism of action, applications, recent advances, limitations and future prospects of smart biomaterials in periodontology.

Concept of smart biomaterials

Smart biomaterials are defined as materials capable of sensing changes in their surrounding environment and responding in a controlled, predictable and reversible manner to achieve a desired biological effect.[3] Unlike traditional biomaterials that merely serve as passive scaffolds, smart biomaterials actively interact with host tissues and the disease microenvironment.

The concept of smart biomaterials originated from advances in biomimetic engineering and tissue engineering. These materials are designed to mimic the extracellular matrix and provide an ideal microenvironment for cellular adhesion, proliferation, differentiation and tissue regeneration. Their ability to deliver therapeutic agents in a site-specific and stimuli-responsive manner makes them particularly useful in periodontology, where localized inflammation and bacterial biofilms play a central role in disease pathogenesis.[4]

CLASSIFICATION OF SMART BIOMATERIALS

Smart biomaterials can be broadly classified according to the type of stimulus to which they respond.

pH-responsive biomaterials

Inflamed periodontal pockets usually exhibit acidic pH due to bacterial metabolism and inflammatory reactions. pH-responsive biomaterials are designed to release therapeutic agents selectively in acidic conditions. Chitosan-based nanoparticles and polymeric micelles are common examples used in periodontal therapy. These systems provide targeted antimicrobial activity while minimizing systemic side effects.[5] Recent studies have demonstrated that pH-sensitive hydrogels loaded with doxycycline or chlorhexidine exhibit prolonged antibacterial action against periodontal pathogens such as *Porphyromonas gingivalis* and *Aggregatibacter actinomycetemcomitans*.[6] Such biomaterials improve drug retention within periodontal pockets and reduce the frequency of drug administration.

Thermo-responsive biomaterials

Thermo-responsive biomaterials undergo phase transformation in response to temperature changes. These materials remain in liquid form at room temperature but convert into gel at body temperature, making them suitable for injectable periodontal applications. Poloxamer-based hydrogels are among the most extensively studied thermo-responsive systems in regenerative periodontology.[7]

Injectable thermo-sensitive hydrogels possess several advantages including minimally invasive delivery, easy adaptation to irregular periodontal defects and sustained release of drugs or growth factors. Recent investigations have shown favorable regenerative outcomes when thermo-responsive hydrogels are combined with platelet-rich fibrin or stem cells.[8]

Enzyme-responsive biomaterials

Periodontitis is associated with elevated levels of enzymes such as matrix metalloproteinases (MMPs), collagenases and bacterial proteases. Enzyme-responsive biomaterials are engineered to degrade or release therapeutic agents in response to these enzymes. This targeted approach ensures drug delivery specifically at diseased sites.[9] Researchers have developed MMP-sensitive scaffolds capable of releasing anti-inflammatory agents in periodontal pockets. These systems not only suppress inflammation but also enhance wound healing and tissue regeneration.[10]

Light-responsive biomaterials

Light-responsive biomaterials react to laser or light irradiation and are frequently utilized in photodynamic therapy. These materials contain photosensitizers that generate reactive oxygen species upon activation, leading to destruction of periodontal pathogens.[11]

Photodynamic therapy using smart nanoparticles has shown significant antimicrobial efficacy against anaerobic biofilms without causing antibiotic resistance. In addition, low-level laser-responsive biomaterials have demonstrated enhanced angiogenesis and fibroblast proliferation.[12]

Magnetic and electrical responsive biomaterials

Magnetic nanoparticles and electrically conductive scaffolds represent another important category of smart biomaterials. These materials stimulate cellular proliferation, osteogenic differentiation and angiogenesis through external magnetic or electrical stimulation.[13] Magnetic nanoparticles loaded with antibiotics have been investigated for targeted drug delivery into deep periodontal pockets. Similarly, conductive scaffolds containing graphene or carbon nanotubes have shown promising effects on bone regeneration and stem cell differentiation.[14]

Smart hydrogels in periodontology

Hydrogels are three-dimensional hydrophilic polymeric networks capable of retaining large amounts of water. Smart hydrogels are among the most extensively researched biomaterials in periodontology because they mimic the extracellular matrix and provide an ideal environment for tissue regeneration.[15]

These hydrogels can respond to pH, temperature, enzymes or inflammatory mediators. Injectable hydrogels have gained particular attention because of their minimally invasive application and excellent adaptability to periodontal defects. Drug-loaded hydrogels provide sustained release of antibiotics, anti-inflammatory agents and growth factors over prolonged periods.[16] Recent advances include multifunctional hydrogels incorporating stem cells, antimicrobial peptides and angiogenic growth factors. Such systems have demonstrated enhanced periodontal ligament regeneration, new cementum formation and alveolar bone regeneration in animal models.[17]

Nanoparticles in periodontology

Nanotechnology has revolutionized regenerative periodontology through the development of nanoparticles capable of targeted drug delivery and biofilm disruption. Nanoparticles possess high surface area, enhanced penetration and improved bioavailability.[18]

Silver nanoparticles are widely known for their potent antimicrobial properties against periodontal pathogens. Gold nanoparticles promote osteogenic differentiation and tissue regeneration through modulation of cellular signalling pathways.[19] Mesoporous silica nanoparticles have been used for controlled release of antimicrobial and osteogenic agents within periodontal defects. Polymeric nanoparticles loaded with chlorhexidine, doxycycline or metronidazole have shown prolonged antibacterial effects and improved periodontal healing compared to conventional local drug delivery systems.[20]

Smart scaffolds and tissue engineering

Scaffolds play a crucial role in periodontal tissue engineering by providing structural support for cell attachment and tissue formation. An ideal scaffold should be biocompatible, biodegradable, porous, mechanically stable and bioactive.[21] Modern smart scaffolds incorporate growth factors, stem cells, nanofibers and antimicrobial agents to create multifunctional regenerative systems. Three-dimensional printed scaffolds have enabled the fabrication of patient-specific constructs tailored to periodontal defects.[22] Multiphasic scaffolds capable of simultaneously regenerating cementum, periodontal ligament and alveolar bone have shown highly promising regenerative outcomes. Such biomimetic scaffolds mimic the natural hierarchical architecture of periodontal tissues.[23]

Stem cell-based smart biomaterials

Stem cell therapy combined with smart biomaterials represents one of the most advanced approaches in regenerative periodontology. Periodontal ligament stem cells (PDLSCs), gingival mesenchymal stem cells and bone marrow-derived mesenchymal stem cells have demonstrated remarkable regenerative potential.[24]

Smart scaffolds provide an appropriate microenvironment for stem cell survival, proliferation and differentiation. Injectable hydrogels loaded with stem cells and growth factors have shown enhanced periodontal regeneration in preclinical studies.[25] Exosome-loaded biomaterials have recently emerged as a novel cell-free regenerative strategy. Exosomes derived from mesenchymal stem cells possess anti-inflammatory and regenerative properties and can be incorporated into hydrogels or scaffolds for targeted periodontal therapy.[26]

Smart biomaterials in guided tissue regeneration

Guided tissue regeneration (GTR) membranes have evolved significantly with the incorporation of smart technologies. Conventional membranes primarily act as passive barriers, whereas modern smart membranes possess antimicrobial, osteogenic and immunomodulatory properties.[27]

Electrospun nanofiber membranes loaded with antibiotics or growth factors provide controlled drug release while promoting cellular proliferation and angiogenesis. Antimicrobial membranes containing silver nanoparticles or antimicrobial peptides reduce bacterial colonization and improve regenerative outcomes.[28]

Bioactive membranes capable of selective cellular recruitment have further enhanced the predictability of periodontal regeneration.

Smart biomaterials in peri-implantitis

Peri-implantitis is a major complication associated with dental implants and is characterized by inflammatory destruction of peri-implant tissues. Smart biomaterials have shown promising applications in implant surface modification and peri-implant tissue regeneration.[29]

Titanium implants coated with antimicrobial peptides, bioactive nanotubes or drug-eluting hydrogels can prevent bacterial adhesion and promote osseointegration. Smart implant coatings capable of releasing antibiotics or anti-inflammatory agents in response to infection are currently being investigated.[30] Nanostructured implant surfaces have demonstrated enhanced osteoblastic activity and improved soft tissue integration.

ADVANTAGES OF SMART BIOMATERIALS

Smart biomaterials offer several advantages over conventional periodontal regenerative materials. Their ability to provide site-specific and controlled drug delivery minimizes systemic adverse effects and improves therapeutic efficacy. These materials enhance tissue regeneration, promote angiogenesis, reduce bacterial colonization and support stem cell differentiation.[31]

Injectable systems reduce surgical trauma and improve patient comfort. Multifunctional smart biomaterials capable of combining antimicrobial, anti-inflammatory and regenerative properties have significantly improved treatment outcomes in experimental studies.

Limitations and challenges

Despite encouraging results, smart biomaterials still face several challenges before routine clinical application. Complex fabrication techniques, high production costs, limited long-term human studies and regulatory concerns remain significant barriers.[32]

Nanoparticles may exhibit cytotoxicity at higher concentrations and some biomaterials demonstrate unpredictable degradation rates. Furthermore, achieving simultaneous regeneration of cementum, periodontal ligament and alveolar bone remains difficult due to the complex structure of periodontal tissues.[33]

Standardization of clinical protocols and large-scale randomized controlled trials are required to establish the long-term efficacy and safety of these materials.

CONCLUSION

Smart biomaterials represent a transformative advancement in modern periodontology. Their stimuli-responsive behavior, controlled therapeutic release, antimicrobial activity and regenerative potential provide significant advantages over conventional biomaterials. Smart hydrogels, nanoparticles, bioactive membranes, injectable scaffolds and stem cell-based systems have demonstrated promising outcomes in periodontal regeneration and peri-implant tissue management.

Although current evidence is highly encouraging, further long-term clinical studies are necessary to validate their routine clinical application. The future of periodontology is likely to be strongly influenced by intelligent biomaterials capable of personalized, minimally invasive and highly predictable regenerative therapy.

Future perspectives

Future developments in smart biomaterials are expected to focus on personalized and precision periodontal therapy. Advances in artificial intelligence, biosensors, 4D bioprinting, gene therapy and CRISPR technology may further revolutionize regenerative periodontology.[34]

Self-healing biomaterials capable of autonomously repairing tissue damage and biosensor-integrated scaffolds capable of real-time monitoring of inflammation represent exciting future possibilities. Exosome-based biomaterials and immunomodulatory scaffolds are also expected to play major roles in next-generation periodontal regeneration.[35]

The integration of nanotechnology, stem cell biology, digital dentistry and tissue engineering may ultimately lead to predictable and complete periodontal regeneration.

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