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Review Article

Bioactive and self-healing smart materials in pulp therapy

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ABSTRACT

The efficiency of pulp therapy has been greatly impacted by the development of materials used in endodontic and restorative dentistry. Biologically based regenerative pulp treatment has entered a new era, specifically with the advent of smart materials, which are characterized by their capacity to react actively to environmental stimuli. Along with sealing and protecting the pulp, these materials' bioactivity and, in certain situations, self-healing properties enable them to aid in tissue repair, lower inflammation, and promote the regeneration of the dentin-pulp complex. Calcium silicate-based sealers, Mineral Trioxide Aggregate (MTA), and bioactive materials like biodentine encourage biomineralization and the formation of reparative dentin, while self-healing systems like microcapsule-based composites can independently restore structural integrity after microcracks. The third frontier in smart dental materials is represented by stimuli-responsive formulations, which release therapeutic agents under controlled conditions in response to variations in pH, moisture content, or bacterial activity. Through an analysis of their mechanisms of action, clinical results, advancements in material science, and potential applications, this review seeks to investigate the role of bioactive and self-healing smart materials in pulp therapy. To educate researchers and clinicians about the new technologies that are changing pulp preservation and regeneration techniques in minimally invasive dentistry, the objective is to present an up-to-date summary of available data.

Keywords: Pulp therapy, Smart materials, Self-healing systems, Bioactive materials, Reparative dentin, Stimuli-responsive formulations

INTRODUCTION

The art of pulp therapy has seen revolutionary change in recent decades, particularly in simple pulp treatments like pulpotomy, direct and indirect pulp capping, and regenerative endodontic therapy.[1,2] Pulp therapy was limited by the passive nature of the materials used, like zinc oxide, eugenol, and calcium hydroxide glass ionomers that essentially played a role to cover up the pulp and prevent further microbial invasion.[3,4] While the use of such materials gave symptomatic relief as well as trivial protective effects, the pulpal tissue healing and regeneration were not significantly supported by the bio-inert characteristics.[5,6]

Based on increased insight into pulp biology and tissue engineering, material formulation is shifting directions towards modalities compatible with the concept of regenerative medicine and to specific ones, which enhance the biological healing with host tissue integration.[7,8] Bioactive or self-repairing smart materials have been a promising advancement for this purpose. Smart materials can sense change, respond dynamically, and respond to the biological environment, something that makes them different from passive inert materials.[9,10] This thus translates to endodontic materials which can repair themselves, inducing pulp-dentin regeneration and releasing bioactive ions which modulate inflammation and respond to mechanical and chemical changes in the oral environment.[11,12] They are also able to seal microleakage by volumetric expansion.[13]

Mineral Trioxide Aggregate (MTA) and bio-dentine's cell differentiation-inducing ability help in dentin bridge formation and exhibit greater biocompatibility than agents used earlier, such as calcium hydroxide, which have drawn significant attention among bioactive materials.[14] Such chemicals release ions that induce crystallization of hydroxyapatite and create alkaline conditions that are inhibitory to pathogenic bacteria.[15] Their mechanical strength and seal ability also enable them to resist microleakage and structural fracture.[16,17] Meanwhile, a sophistication layer is formed by the technology of self-healing materials, particularly composites and sealers with microcapsules that release healing agents when cracks propagate.[18]

These formulations reduce the likelihood of repeated decay, prolong the life of restorations, and reduce the need for retreatment. Stimulus-sensitive materials constitute another innovation of this paradigm.[19] These materials are designed to modify their behavior when they come into contact with environmental stimuli such as temperature changes, pH drops, or bacterial metabolites to a better fit within cavity walls or pulp exposure sites.[20] They can alter rheological properties or release antibacterial compounds, for example. With advancing technology, there is more potential to reduce invasiveness while tailoring treatments to the individual needs of clinical conditions. Herein, the mechanisms, composition, clinical performance, and future outlook of bioactive and self-healing smart materials used in pulp therapy are outlined. Through enhanced long-term pulp preservation and biologically driven dentistry, this establishes the platform for material innovation towards future clinical integration.

METHODS

A narrative synthesis approach was used for this review, which was based on pertinent peer-reviewed literature published in English between 2012 and 2025. It was a non-systematic approach. ScienceDirect, PubMed, Scopus, ProQuest, and Google Scholar were among the data sources. "Smart dental materials", "pulp therapy", "bioactive materials", "self-healing composites", "bio ceramics in endodontics," and "stimuli-responsive dental materials" were among the keywords. Articles were chosen for inclusion based on their clinical applicability, scientific novelty, or fundamental theory about smart materials in regenerative endodontics or vital pulp therapy. Review papers, case series, in vitro and in vivo investigations, and randomized clinical trials were taken into consideration. Papers that were solely concerned with the orthodontic or restorative uses of smart materials and had no direct connection to pulp therapy were not included. Data regarding composition, material properties, biological responses, and laboratory or clinical results were examined in a few chosen articles. In keeping with a narrative review framework, no formal meta-analysis or evidence grading was done.

DISCUSSION

Contemporary pulp capping agents have tissue modulation and bioactive properties

Nowadays, the use of bioactive materials in pulp therapy has greatly progressed beyond conventional limitations to actively contribute to biological healing.[2] Mineral Trioxide Aggregate (MTA) is still the gold standard in vital pulp therapy due to its high biocompatibility, consistent dentinal bridge formation, and superior sealing ability.[21] Its constituents include Portland cement, tricalcium silicate, dicalcium silicate, and bismuth oxide.[22] When hydrated, a colloidal gel is formed, progressively solidifying and releasing calcium hydroxide as a byproduct.[23] Given that calcium ions are necessary for mineralization and hydroxyapatite formation, this release adds to its bioactivity.[24] Although biodentine and MTA have a similar calcium silicate chemistry, biodentine is frequently regarded as a next-generation substitute because it is easier to handle and sets faster.[25,26] In clinical settings, Biodentine has been demonstrated to produce dentin bridge formation and odontoblastic differentiation that are comparable, while posing fewer discoloration problems.[27] The formulation of Biodentine produces a denser microstructure than MTA, which could enhance its long-term mechanical behavior.[28,29] Additionally, it has been demonstrated that both materials increase growth factors that are essential for angiogenesis and pulp healing, such as vascular endothelial growth factor (VEGF) and bone morphogenetic protein-2 (BMP-2).[30] The regenerative advantages of calcium silicates are being combined with enhanced aesthetics and usability in the development of novel bioactive materials such as calcium phosphate cements and resin-modified bioactive materials.[31] To preserve the tooth's long-term durability under functional stress, these materials are increasingly being developed to resemble the inorganic phase of dentin and display mechanical characteristics that are similar to those of natural tooth structures.[32] Clinical research has demonstrated that the use of bioactive materials in direct pulp capping leads to improved patient outcomes, reduced rates of post-operative sensitivity, and higher success rates.[33,34] Their ongoing advancement is changing the paradigm from merely shielding exposed pulp tissue to actively encouraging dentin-pulp complex regeneration.[35]

Self-healing dental materials provide both structural repair and functional longevity

Even though bioactive materials enhance the biological response, they eventually have the potential to mechanically fail.[36] As a result, self-healing materials are gaining popularity to extend the useful life of interfaces and restorations involving pulp therapy. These materials incorporate autonomous repair concepts, which were initially researched in the domains of civil and aerospace engineering, into dental sealants and resins.[37] Microencapsulation is one of the most frequently investigated systems in dentistry.[38] Monomeric resins and catalysts are examples of healing agents that are encapsulated in tiny polymeric spheres.[39] The capsules burst and release their contents into the microcracks that are created by thermal cycling or masticatory stress.[40,41] Filling the micro gap and restoring structural integrity, the healing agent's polymerization may greatly increase the restoration's lifespan.[18,42] Root canal sealers that contain calcium silicate or hydroxyapatite nanoparticles control ion release and swelling behavior, which can reinforce the seal against bacterial reentry and self-seal voids.[43,44] Developments in polymer chemistry are driving the use of reversible cross-linking or dynamic covalent bonds, which enable the material matrix to change shape in response to stress without exclusively depending on released monomers. These developments are especially helpful in areas of high occlusal load and posterior restorations where marginal degradation is a significant concern.[45] Although there is a lack of clinical data, laboratory simulations employing thermocycling and load-fatigue tests indicate that self-healing materials can sustain their mechanical performance and sealing capacity for extended periods.[46] When incorporated into future pulp capping or liner materials, they may provide both mechanical longevity and biological support in a single application.

Smart stimulation for smart, eco-friendly treatments

Construction of stimulus-sensitive systems is one of the latest breakthroughs in intelligent material design. These materials possess great benefit in pulp treatment, where internal feedback mechanisms like bacterial activity, pH changes, and hydration are vital for clinical success.[47,48] They can change their behavior or release certain agents when environmental changes occur. PH-controlled antimicrobial release is one of the best-studied stimulus-sensitive processes in pulp treatment.[49,50] Bacterial metabolism leads to a dramatic reduction in local pH as caries progresses.[51] Materials can be engineered with encapsulated antimicrobial agents like silver nanoparticles, antimicrobial peptides, or chlorhexidine in such a way that these release their content only in this acidic environment.[52,53] This prevents the disruption of the balance of the normal oral microbiota and minimizes the possibility of creating resistant bacterial strains. Another area of research is injectable regenerative endodontic systems and temperature-sensitive hydrogels.[54,55] These types of materials include room temperature liquids that solidify when heated to body temperature and are therefore able to adhere to the intricate pulp chamber structure and eventually form a scaffold that can induce tissue regeneration as well as cell proliferation.[56,57] Some systems also utilize controlled release of growth factors and cell-adhesion peptides to guide stem cell differentiation in place.[58,59] Further still, recent literature has developed photo-sensitive systems in which resin materials incorporate photo-cleavable linkers which, upon actuation at designated wavelengths, liberate drugs or modify material stiffness.[60] All such developments hint at a day in the not-so-distant future where pulp therapy would become completely tailored as a procedure whereby material changes in a micro-instantaneous basis in conformity to pulp's requirements and microbiological profile, even as this is primarily still in its experimental stage.[61] By synergy, these stimulus-sensitive materials not only augment the outcome of treatment but also provide opportunities for biologically guided and minimally invasive endodontics. With ongoing development and clinical correlation, such materials could be integrated into standard pulp therapy and provide individually adjusted treatments with improved retention of tooth vitality and higher success.

CONCLUSION

Active bio-interactive systems that promote healing and regeneration have actively replaced passive materials as the indicator of pulp therapy's success. Smart materials have made it possible to control pulp exposure and damage in more biologically oriented manners, especially those with bioactive and self-healing characteristics. Bioactive materials that have proved to be effective in controlling inflammation and promoting tissue regeneration include MTA and Bio-dentine. While stimuli-responsive technologies provide pulp treatments with flexibility and accuracy, self-healing materials present a promising pathway toward restoration longevity improvement. For self-healing materials, more research needs to be conducted in evaluating their mechanism of action, in addition to establishing tests that assess their performance.

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