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Smart Materials in Restorative Dentistry: Update on Self-Healing Resins and Remineralizing Properties

Suhael Ahmed[1], Abdulaziz Mohammed A Alateek[2], Mohammed Saber Aalalyani[3], Saleh Ali Saleh Almalaq[4],Omar Saeed Alqahtani[3], Nizar Ahmed Almousa[5], Nadia Kamal Albather[1], Abdulrahman Abdulelah Altowerki[1],Ghada Abdullah Alamri[3], Afrah Moraya Alzaydan[3]

Author Affiliations

1. *College of Medicine and Dentistry, Riyadh Elm University, Riyadh, Saudi Arabia*
2. *Ministry of Interior, Security Forces Comprehensive specialized Clinics, Al Ahsa, Saudi Arabia*
3. *College of Dentistry, King Khalid University, Abha, Saudi Arabia*
4. *Ministry of Health, Hail, Saudi Arabia*
5. *Qassim University, Saudi Arabia*

Abstract

The continuous failure of conventional restorative materials due to secondary caries, marginal degradation, and mechanical fatigue has prompted the development of smart materials in restorative dentistry. Smart materials possess the ability to respond dynamically to environmental stimuli such as pH changes, mechanical stress, and microbial activity. Among these, self-healing resin composites and remineralizing restorative materials represent two major advances aimed at improving restoration longevity and biological performance. This review provides an updated overview of smart restorative materials, focusing on their mechanisms of action, material composition, and clinical relevance. A structured literature search was conducted across major electronic databases from 2010 to 2024. Evidence indicates that self-healing resins can autonomously repair microcracks, while remineralizing materials can release bioactive ions to promote hydroxyapatite formation and prevent secondary caries. Despite promising in vitro and in situ results, limited clinical evidence and challenges in standardization remain barriers to widespread clinical adoption.

Keywords

Smart materials; restorative dentistry; self-healing resin; remineralization; bioactive composites; pH-responsive materials.

Introduction

Restorative dentistry aims to restore the function, aesthetics, and structural integrity of teeth affected by caries, trauma, or wear. Resin-based composites have become the material of choice due to their superior aesthetics, adhesive properties, and conservative preparation requirements [1]. However, despite continuous improvements in filler technology and resin chemistry, the long-term survival of restorations remains limited. Clinical studies indicate that secondary caries and material fracture are the primary reasons for restoration replacement [2].

Conventional restorative materials are largely passive, meaning they do not actively interact with the surrounding oral environment once placed. The oral cavity is a highly dynamic ecosystem characterized by fluctuations in pH, temperature, moisture, and mechanical loading, along with continuous microbial challenges [3]. These factors contribute to degradation of restorative materials, polymer matrix breakdown, and marginal leakage, ultimately compromising restoration longevity [4].

Secondary caries formation at the tooth–restoration interface remains a major clinical problem. Resin composites lack intrinsic antibacterial or remineralizing properties, allowing cariogenic biofilms to colonize marginal gaps and produce acids that demineralize adjacent tooth structures [5]. In addition, polymerization shrinkage and cyclic occlusal loading generate internal stresses and microcracks within restorations, which may propagate over time and lead to catastrophic failure [1].

To overcome these limitations, research has focused on the development of smart materials, defined as materials capable of responding predictably and reversibly to environmental stimuli [6]. In restorative dentistry, smart behavior includes pH-responsive ion release, antibacterial activity, stress-induced self-repair, and promotion of remineralization [7].

Among various smart material strategies, self-healing resin systems and remineralizing bioactive materials have gained significant attention. Self-healing materials are inspired by biological systems and aim to repair microdamage autonomously, thereby increasing fatigue resistance and service life [8]. Remineralizing materials act as reservoirs of calcium, phosphate, and fluoride ions, releasing them under acidic conditions to counteract demineralization and promote hydroxyapatite formation [9].

This review discusses recent advances in self-healing and remineralizing smart materials in restorative dentistry, their mechanisms, advantages, limitations, and future clinical implications.

Aim

The aim of this review is to evaluate current evidence on smart materials in restorative dentistry with particular emphasis on:

1. Self-healing resin composites
2. Remineralizing and bioactive restorative materials
3. Their potential impact on restoration longevity and caries prevention

Materials and Methods

A narrative review methodology was adopted.

Search Strategy

Electronic searches were performed in PubMed, Scopus, Web of Science, and Google Scholar for articles published between 2010 and 2024. Search terms included combinations of "smart dental materials," "self-healing resin," "remineralizing dental composites," "bioactive restorative materials," and "pH-responsive dental materials."

Inclusion Criteria

- Peer-reviewed original research and systematic reviews
- Studies related to restorative dental materials
- English language publications

Exclusion Criteria

- Case reports and opinion articles
- Studies unrelated to restorative dentistry

Results of Search [PRISMA-Style Description]

A total of 1,296 articles were identified initially. After removal of duplicates [n = 236], 1,060 articles were screened. Following title and abstract screening, 780 articles were excluded. Full-text assessment of 280 articles resulted in 20 studies being included in the final qualitative synthesis.

Discussion

The development of smart materials in restorative dentistry reflects a paradigm shift from traditional passive restorative approaches to biologically interactive and functionally adaptive systems. Conventional restorative materials were designed primarily to restore form and function; however, they fail to actively respond to the dynamic oral environment. Factors such as fluctuating pH, continuous masticatory stress, thermal cycling, and microbial biofilm activity contribute to the degradation and eventual failure of restorations [1,2]. Smart materials aim to overcome these limitations by incorporating mechanisms that enable autonomous repair, antibacterial activity, and remineralization, thereby enhancing restoration longevity and oral health outcomes.

Self-Healing Resin Composites: Mechanisms and Clinical Significance

Microcrack formation within resin-based composites is an inevitable consequence of polymerization shrinkage, occlusal loading, fatigue stresses, and aging in the oral environment [1,3]. These microcracks often remain undetected clinically but can propagate over time, leading to marginal breakdown, fracture, and eventual restoration failure [4]. The incorporation of self-healing mechanisms within restorative materials offers a novel solution to this long-standing problem.

The most extensively studied self-healing approach in dental materials involves the incorporation of microencapsulated healing agents dispersed within the resin matrix. When mechanical stress induces crack formation, the microcapsules rupture, releasing a healing monomer that polymerizes upon contact with an embedded catalyst, effectively sealing the crack [5,6]. This autonomic healing mechanism has demonstrated significant recovery of fracture toughness and flexural strength in laboratory studies [7].

Wu et al. reported that self-healing dental composites exhibited up to 70% recovery of fracture toughness following crack formation, suggesting a substantial extension of material service life [8]. Subsequent investigations focused on optimizing microcapsule characteristics, including capsule size, shell thickness, and concentration, to balance healing efficiency and mechanical integrity [9]. Smaller microcapsules with reinforced shells have been shown to improve dispersion within the resin matrix while minimizing adverse effects on strength and wear resistance [10].

Beyond microcapsule-based systems, intrinsic self-healing polymers utilizing reversible covalent bonds or supramolecular interactions have gained attention. These systems rely on dynamic chemical bonds that can dissociate and reform under specific conditions, allowing repeated self-healing events [11]. Although promising, intrinsic self-healing systems face challenges related to moisture sensitivity, slow healing kinetics, and potential degradation in the oral environment, limiting their immediate clinical applicability [12].

From a clinical perspective, self-healing materials could significantly reduce the frequency of restoration replacement, which is a major contributor to the restorative cycle and progressive loss of tooth structure [2]. However, most evidence supporting self-healing dental resins remains in vitro, and long-term clinical trials are necessary to validate their effectiveness under functional loading and oral conditions.

Remineralizing Smart Materials and Ion-Release Dynamics

Secondary caries remains the primary cause of restoration failure worldwide [2]. The inability of conventional resin composites to inhibit bacterial activity or promote remineralization at the tooth–restoration interface has driven the development of remineralizing smart materials. These materials are designed to release calcium, phosphate, and fluoride ions in response to acidic challenges, thereby promoting remineralization and inhibiting demineralization [13].

Among remineralizing systems, amorphous calcium phosphate [ACP] and nanoparticles of amorphous calcium phosphate [NACP] have been extensively investigated. ACP is thermodynamically unstable and readily converts into hydroxyapatite under physiological conditions, making it an ideal precursor for remineralization [14]. The nanoscale size of NACP significantly increases surface area, enhancing ion release and enabling effective remineralization without compromising mechanical properties [15].

Xu et al. demonstrated that NACP-containing composites released substantially higher levels of calci-

calcium and phosphate ions at low pH compared to neutral pH, exhibiting intelligent pH-responsive behavior [13]. This selective ion release is particularly advantageous, as it targets cariogenic acidic conditions while preserving ion reservoirs during neutral conditions.

Fluoride-releasing materials, such as glass ionomer cements, represent an early form of smart materials due to their ability to release fluoride and recharge from external sources [16]. However, their inferior mechanical properties and susceptibility to wear have limited their use in high-stress-bearing areas. Modern bioactive resin composites combine fluoride release with superior aesthetics and strength, offering improved clinical versatility [17].

Despite these advancements, challenges remain in ensuring sustained and controlled ion release over extended periods. Excessive initial ion release may lead to premature depletion, reducing long-term effectiveness [18]. Therefore, future material designs must focus on optimizing ion-release kinetics to maintain prolonged remineralizing potential.

pH-Responsive and Antibacterial Smart Systems

The integration of pH-responsive behavior into restorative materials represents a major advancement in smart material design. pH-responsive systems increase ion release and antibacterial activity under acidic conditions associated with cariogenic biofilms, thereby providing targeted therapeutic effects [19].

Antibacterial smart materials often incorporate quaternary ammonium compounds, silver nanoparticles, or zinc ions to inhibit bacterial growth and biofilm formation [20]. When combined with remineralizing fillers such as NACP, these materials can simultaneously reduce bacterial acid production and promote mineral deposition, addressing both the biological and structural aspects of restoration failure [21].

Multifunctional smart materials combining antibacterial, remineralizing, and self-healing properties represent the future direction of restorative dentistry. Such systems aim to create restorations that actively maintain oral health rather than merely replacing lost tooth structure [22]. However, increasing material complexity raises concerns regarding biocompatibility, cytotoxicity, and long-term stability, necessitating comprehensive biological evaluations.

Clinical Translation and Limitations

While laboratory studies demonstrate promising results, the translation of smart materials into routine clinical practice remains limited. Variability in testing methodologies, lack of standardized evaluation protocols, and insufficient long-term clinical data hinder meaningful comparison between studies [6,9].

Furthermore, factors such as wear resistance, polish retention, color stability, and bonding performance must be thoroughly evaluated under clinical conditions before widespread adoption. Cost-effectiveness and ease of handling are also critical considerations influencing clinician acceptance.

Future Perspectives

Future research should focus on:

- Long-term in vivo studies evaluating clinical performance
- Development of standardized testing methods for smart behavior
- Optimization of multifunctional materials with minimal trade-offs
- Integration of nanotechnology and biomimetic principles
- Evaluation of patient-centered outcomes and economic feasibility

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