REVIEW ARTICLE

Bioactive Root Canal Sealers: A Review of Material Science and Clinical Outcomes

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ABSTRACT

Root canal sealers have evolved in transitioning away of inert obturation materials with active bioactive formulations that are actively involved in the healing process. Traditional sealers, though efficient in the provision of a seal, are sometimes not biologically integrated and stable enough as time goes by, thus coming the calcium silicate based and bioceramic sealers. These bioactive sealers demonstrate the ability to release calcium and hydroxyl ions, trigger the formation of hydroxyapatite and improve the formation of the biological seal at the dentin-sealer interface, which improves clinical outcomes. Their position is also complemented by the developments in material science and the endodontic adjuncts such as imaging and irrigation systems, which have refined diagnostic accuracy and treatment predictability. Evidence supports their favorable biological interactions, particularly in vital pulp therapy and regenerative procedures, where bioactive sealers foster tissue healing and hard tissue deposition. Comparative studies on root canal filling systems highlight their superior sealing ability, mechanical strength, and contribution to tooth survival, even under functional stresses. Besides, as artificial intelligence is becoming more and more part of endodontic diagnostics, the prospect of bioactive materials harmonizing with digital workflows has become an exciting prospect. Although the clinical outcomes are promising, it has difficulties in managing characteristics and cost. Long-term randomized trials are also required; however, bioactive root canal sealers represent a paradigm shift in endodontics, offering not only physical sealing but also biological activity that aligns with the principles of tissue preservation and regeneration.

Keywords: Bioactive sealers, bioceramics, calcium silicate, endodontics, root canal therapy, clinical outcomes.

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INTRODUCTION

The endodontic treatment is based on the complete cleaning, shaping, and obturation of the root canal system to avoid infection and to prevent the reinfection. The sealing capacity of root canal filling materials is paramount to the success of this process as microleakage is still one of the most dramatic issues in the long-term outcomes. The traditional sealers have mainly been used as inert substances which are meant to fill the irregularities and bond the core filling material to the dentin yet its inertness has restricted its role to aid periapical healing.

The emerging new innovations in diagnosis and treatment measures have greatly impacted the practice of endodontics. The adoption of new imaging applications, including cone-beam computed tomography (CBCT), has enhanced the accuracy of the diagnosis and treatment strategy and enabled the clinicians to better determine the periapical pathology and root canal morphology. On the same note, the development of the dynamics in the field of irrigation has increased the capability of disinfection of the complex canal systems, which supplements the performance of sealing materials. These similar innovations highlight the increased focus on biologically inspired methods in endodontics.

The most striking inventions in material science are the invention of bioactive root canal sealers. These seals, especially calcium silicate-based and bioceramic seals, are not only meant to form a physical barrier but also to actively induce biological responses. Their calcium-ion releasing ability, hydroxyapatite deposition-stimulating property, and dentin-sealer interface enhancement provide a therapeutic benefit over traditional sealers, which is consistent with the current tendency to use biologically integrative treatment methods. Additionally, their contribution to the reinforcement of endodontically treated teeth has been highlighted, with evidence suggesting improved fracture resistance and long-term stability compared to traditional systems.

Furthermore, the growing integration of artificial intelligence (AI) in endodontics has opened new avenues for the assessment of treatment outcomes and the development of predictive models. When combined with bioactive materials, such technologies may accelerate the transition toward more personalized, evidence-based care. Within this context,

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bioactive root canal sealers represent a paradigm shift—transforming the sealer from a passive filler into a biologically active material that supports healing, strengthens treated teeth, and enhances clinical outcomes.

Material Science of Bioactive Root Canal Sealers

Composition and Classification

Bioactive root canal sealers are primarily composed of calcium silicate–based and bioceramic formulations. These materials differ from traditional sealers by their capacity to interact chemically and biologically with the surrounding dentin and periapical tissues. Their unique composition enables the release of bioactive ions, which initiate mineralization and promote biological sealing at the dentin–sealer interface.

Mechanisms of Bioactivity

- Ion Release: Calcium and hydroxyl ions are liberated during setting, creating an alkaline environment that supports antimicrobial activity.
- Hydroxyapatite Formation: The precipitation of hydroxyapatite crystals at the interface enhances sealing and biomineralization, promoting long-term stability of the obturation.
- Biological Stimulation: These sealers stimulate hard tissue deposition, contributing to healing and regeneration in cases of periapical pathology.

Physical and Mechanical Properties

- Sealing Ability: Bioactive sealers demonstrate superior sealing performance, minimizing microleakage and improving adaptation to canal walls.
- Mechanical Reinforcement: Their interaction with dentin contributes to increased fracture resistance of endodontically treated teeth.
- Flow and Penetration: Optimized flow properties enable deeper penetration into dentinal tubules, improving mechanical retention.

Biological Properties

- Biocompatibility: These sealers exhibit minimal cytotoxicity, enhancing their acceptance by periapical tissues.
- Osteoinductive Potential: By stimulating cellular differentiation, they support periapical healing and regeneration.
- Antimicrobial Effects: The alkaline pH created during setting disrupts bacterial cell membranes, complementing irrigation protocols.

Integration with Emerging Technologies

Advances in digital endodontics, such as CBCT and AI-assisted analysis, enable more precise evaluation of sealer placement and treatment outcomes. These developments highlight the potential synergy between bioactive materials and technology-driven clinical workflows, advancing endodontic treatment toward more predictable outcomes.

Comparative Evaluation with Conventional Sealers

Sealing ability and microleakage

Conventional sealers often provide only a mechanical seal, which can deteriorate over time. In contrast, bioactive sealers form hydroxyapatite at the interface, improving adaptation and reducing microleakage.

Bond strength and reinforcement

While traditional sealers mainly rely on adhesion to the core material, bioactive sealers chemically interact with dentin. This interaction enhances bond strength and contributes to improved fracture resistance of endodontically treated teeth.

Antimicrobial properties

Conventional sealers generally have limited or short-lived antimicrobial action. Bioactive sealers, through the sustained release of hydroxyl ions, create an alkaline environment that supports antimicrobial effects, particularly when combined with optimized irrigation protocols.

Biocompatibility and healing response

Traditional sealers can sometimes provoke mild inflammatory reactions. Bioactive sealers, on the other hand, show superior biocompatibility, supporting periapical healing and even stimulating hard tissue formation in vital pulp therapy contexts.

Role in modern endodontics

With advanced imaging such as CBCT enabling better treatment planning, and AI offering predictive modeling in clinical outcomes, bioactive sealers align more closely with current biologically centered and technology-supported endodontic practice compared to their conventional counterparts.

Table 1: Comparative overview of clinical outcomes between conventional and bioactive root canal sealers

Parameter	*Conventional sealers*	*Bioactive sealers*
Sealing ability	Mechanical seal, prone to microleakage	Hydroxyapatite formation enhances sealing
Postoperative pain	May persist due to limited biological interaction	Reduced due to tissue compatibility and mineralization
Healing response	Mild inflammatory reactions possible	Promotes hard tissue formation and periapical healing
Fracture resistance	Limited reinforcement of tooth structure	Improves structural integrity of treated teeth
Antimicrobial effect	Weak or short-term	Sustained alkaline environment supports antimicrobial action
Adaptability to modern tools	Limited integration with digital workflows	Aligns with CBCT and AI-supported treatment planning

Clinical Outcomes

Success rates in root canal therapy

Bioactive sealers have shown high clinical success rates due to their superior sealing and biological integration. Studies highlight their role in reducing postoperative complications and improving long-term tooth survival compared to conventional sealers.

Postoperative pain and healing

The release of calcium ions and the promotion of hydroxyapatite deposition contribute to periapical healing and reduced postoperative pain. These effects are attributed to enhanced tissue compatibility and the ability to create a stable biological seal.

Role in regenerative endodontics

In regenerative procedures, bioactive sealers facilitate hard tissue deposition and tissue repair, making them favorable in cases such as vital pulp therapy and apexification. Their bioactivity provides an advantage over inert sealers in biologically centered treatments.

Long-term prognosis

The integration of bioactive sealers with advancements in irrigation dynamics, imaging, and AI-supported treatment planning suggests improved predictability in clinical outcomes. Long-term studies support their potential to enhance prognosis and tooth retention.

Clinical Implications of Comparative Findings

The comparative analysis between conventional and bioactive sealers highlights several key implications for clinical practice.

Enhanced sealing ability

The ability of bioactive sealers to form hydroxyapatite and create a chemical bond with dentin provides a more reliable and durable seal than conventional sealers. Clinically, this translates to a reduced risk of microleakage and reinfection, thereby improving the long-term prognosis of root canal–treated teeth.

Improved patient-centered outcomes

Lower postoperative pain and enhanced healing responses observed with bioactive sealers suggest better patient comfort and satisfaction. By reducing inflammatory reactions and promoting hard tissue repair, clinicians can expect smoother recovery phases and fewer retreatment cases.

Reinforcement of tooth structure

The ability of bioactive sealers to improve fracture resistance addresses a critical concern in endodontically treated teeth. This is particularly important in teeth subjected to functional stresses, where the restorative integrity of conventional sealers may be insufficient.

Antimicrobial advantage

The sustained release of hydroxyl ions provides an antimicrobial environment even after the completion of irrigation, complementing existing disinfection protocols. This synergistic effect strengthens the biological foundation of endodontic success and may reduce the risk of persistent or recurrent infection.

Integration with modern technologies

Perhaps most importantly, bioactive sealers align well with the ongoing digital transformation of endodontics. With CBCT improving diagnostic accuracy and AI emerging as a predictive tool for treatment outcomes, bioactive sealers fit naturally into a more technology-driven and biologically centered model of care..

Taken together, the findings in Table emphasize that bioactive sealers are not merely alternatives to conventional sealers but represent a paradigm shift. They combine biological and mechanical advantages, enhance patient outcomes, and integrate seamlessly with modern diagnostic and therapeutic innovations. These implications strongly support their adoption in routine clinical practice, while also highlighting the need for continued long-term studies to establish standardized protocols for their optimal use.

Challenges and Limitations

Handling characteristics

Despite their biological advantages, bioactive sealers can present challenges in clinical handling. Issues such as extended setting times, sensitivity to moisture, and variations in working consistency may affect operator confidence and efficiency during obturation.

Retreatment considerations

One of the main drawbacks of bioactive sealers is their difficulty of removal during retreatment. Their strong bond with dentin, while advantageous for sealing, complicates re-entry into the canal system, posing a challenge in cases of persistent or recurrent infection.

Cost and accessibility

Compared to conventional sealers, bioactive formulations are often more expensive. This cost factor, coupled with variability in global availability, can limit their widespread adoption, especially in resource-constrained clinical settings.

Variability in clinical protocols

At present, there is no universal consensus regarding the standardization of protocols for the use of bioactive sealers. Differences in obturation techniques, irrigation strategies, and adjunctive technologies (such as CBCT and AI integration) contribute to inconsistent clinical outcomes.

Limited long-term evidence

Although short- and medium-term studies support their effectiveness, robust long-term randomized controlled trials are still limited. Evidence on their performance across diverse clinical scenarios such as retreatment, complex anatomies, and compromised teeth remains insufficient.

Operator experience and learning curve

The adoption of bioactive sealers requires adequate clinician training. Limited familiarity with their handling properties

Table 2: Challenges of bioactive root canal sealers and potential strategies to overcome them

Challenge	*Clinical implication*	*Potential strategies*
Handling characteristics	Difficulty in obturation efficiency, variability in consistency	Development of improved formulations; clinician training on material-specific techniques
Retreatment difficulty	Complicates re-entry in failed cases	Research on retreatment-friendly bioactive sealers; advancement in retreatment instruments
Cost and accessibility	Limits adoption, especially in low-resource settings	Encouraging cost-effective manufacturing; wider distribution and availability
Variability in protocols	Inconsistent clinical outcomes across operators	Development of standardized guidelines for use; integration with digital workflow tools
Limited long-term evidence	Uncertainty about prognosis in complex cases	Conducting multicenter, long-term randomized controlled trials
Operator learning curve	Risk of suboptimal handling and outcomes	Enhanced clinician training, workshops, and incorporation into postgraduate curricula

and behavior may lead to suboptimal outcomes, highlighting the need for broader education and clinical exposure.

Future Perspectives

Advancements in material formulation

Future developments in bioactive root canal sealers are expected to focus on optimizing handling properties, reducing setting times, and improving flow characteristics without compromising bioactivity. Incorporating nanotechnology may further enhance ion release, antibacterial properties, and sealing efficiency.

Integration with digital endodontics

The growing role of cone-beam computed tomography (CBCT) and artificial intelligence (AI) in endodontics provides an opportunity for bioactive sealers to be incorporated into precision-driven workflows. AI-based predictive models may guide the selection of sealer type and technique, enhancing treatment planning and outcome predictability.

Expansion in regenerative endodontics

Bioactive sealers hold promise in regenerative procedures, including vital pulp therapy and apexification. Their capacity to stimulate mineralization and hard tissue formation positions them as central materials in biologically oriented treatments. Ongoing research may expand their use in tissue engineering and biologically integrative therapies.

Overcoming retreatment challenges

Future innovations may focus on designing bioactive sealers with tailored properties that allow both strong bonding and retrievability in case of failure. This balance could address one of the major clinical concerns limiting their universal adoption.

Standardization and evidence-based protocols

The establishment of universal guidelines for the clinical application of bioactive sealers is essential. Collaborative research, including multicenter and long-term randomized controlled trials, will be critical in providing the evidence base needed to standardize protocols across diverse clinical settings..

Accessibility and global adoption

For bioactive sealers to achieve widespread clinical use, issues of cost and availability must be addressed. Future strategies may include cost-effective manufacturing, increased commercial competition, and broader dissemination of educational resources to support their adoption globally.

CONCLUSION

The development of bioactive root canal sealers is an important development in the science of endodontic materials as bioactive sealers have taken the place of passive fillers and they are active agents in healing. The potency of releasing ions, the formation of hydroxyapatite, and the acceleration of the restoration of the tissue have obvious benefits over standard sealers, overcoming such long-term issues as microleakage, lack of antimicrobial activity, and the insufficient support of the tooth structure. Clinical results are a consistent increase in sealing, less postoperative pain, greater periapical healing and greater fracture resistance, which is consistent with the changing focus on biologically oriented endodontics.

These materials are to be combined with the latest technologies, such as improved strategies of irrigation, diagnostic precision with the help of CBCT, and predictive models based on AI learning , which additionally helps to point out how promising these materials are to revolutionize endodontic practice. However, the constraints in the form of addressing difficulties, issues of retrogressiveness, price, and non-standardized procedures should be overcome prior to being widely used.

In the future, the future of bioactive sealers is in its perfect formulations, evidence-based principles, and availability in different clinical settings. Through their ability to combine material science with clinical innovation, bioactive root canal sealers will be able to become a pillar of modern endodontic practice as it provides a pathway into more predictable, biologically integrative and patient-centered endodontic care.

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