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Management of strip perforations: A comprehensive review of marginal adaptation and fracture resistance

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Abstract
Strip perforations represent a critical endodontic mishap that compromises both tooth structure and periodontal integrity. They typically occur in roots with thin dentinal walls, especially in the mesial canals of mandibular molars, as a result of over-instrumentation or aggressive coronal flaring. Unlike apical or furcal perforations, strip perforations are elongated and irregular, making them difficult to seal and more prone to bacterial leakage. Their prognosis depends heavily on the immediate use of repair materials that provide a hermetic seal with dentin (marginal adaptation) and simultaneously reinforce the remaining root to resist functional stresses (fracture resistance). Mineral trioxide aggregate (MTA) has historically been the benchmark material for perforation repair due to its excellent sealing ability and bioactivity. However, its disadvantages, including prolonged setting time, challenging handling, and potential discoloration, have driven the search for alternatives. Biodentine, a calcium silicate-based cement with dentin-like elasticity and enhanced bioactivity, has demonstrated superior marginal adaptation and significantly greater reinforcement of structurally weakened teeth compared to MTA. More recent advancements, such as premixed bioceramic putties and sealers, show promise in combining ease of application with bioactive sealing, although their clinical evidence remains limited. Overall, available literature suggests that calcium silicate-based bioceramics, particularly Biodentine, provide the most favorable balance between sealing ability and reinforcement in strip perforation repair. Nevertheless, most supporting data originates from laboratory-based studies. Future research should focus on standardized methodologies and long-term clinical trials to establish evidence-based protocols and validate the superior outcomes suggested *in vitro*.

Keywords: Strip perforation repair, biodentine, MTA, calcium silicate bioceramics

1. Introduction
1.1 Root Perforations: Definition and Clinical Relevance
Root perforations are defined as pathological or iatrogenic communications between the root canal system and the supporting periodontal structures. They represent one of the most serious complications in endodontics, as they create a direct pathway for microbial contamination and inflammatory breakdown of periodontal tissues. If untreated, these defects lead to persistent infection, progressive alveolar bone loss, and ultimately tooth loss. The clinical significance of root perforations lies not only in their frequency, but also in the challenge of achieving predictable repair and long-term tooth survival [1-3].

1.2 Strip Perforations: A Unique Clinical Challenge
Among the different types of perforations, strip perforations are particularly problematic. They occur along the thin inner walls of curved roots, most commonly in the mesial roots of mandibular molars. strip perforations present with elongated defects and irregular margins, which make adaptation of repair materials more difficult and prognosis more uncertain [4-6].

1.3 Evolution of Repair Materials
Over the past three decades, a variety of materials have been evaluated for perforation repair. Mineral trioxide aggregate (MTA) has been considered the gold standard due to its excellent sealing ability, bioactivity, and capacity to induce cementum and bone regeneration. However, its limitations including extended setting time, difficult handling, and tooth discoloration have

restricted its universal acceptance [7, 8]. These shortcomings stimulated the development of newer calcium silicate-based cements, most notably Biodentine, which exhibits dentin-like mechanical properties, shorter setting time, and superior handling. Biodentine has demonstrated excellent marginal adaptation through micromechanical interlocking and mineral tag formation, as well as significantly enhanced reinforcement of structurally compromised roots [9-11]. Recently, bioceramic-based putties and premixed sealers have been introduced, offering simplified application and encouraging biological interactions, though their long-term clinical outcomes remain under investigation [12].

2. Etiology and Diagnosis of Strip Perforations

2.1 Etiology of Strip Perforations

Strip perforations are iatrogenic defects that arise primarily during the mechanical preparation of root canals. They occur most frequently in the danger zones of thin root walls, particularly the mesial roots of mandibular molars, where dentin thickness is limited and canal curvature is pronounced [13, 14]. Common causes include:

- Over-instrumentation with large or aggressive files in curved canals.
- Excessive coronal flaring, especially when Gates-Glidden drills or Peeso reamers are misused.
- Anatomic predispositions, such as deep concavities on the distal wall of mesial roots in mandibular molars and mesial concavities in maxillary premolars.
- Operator factors, including inadequate knowledge of root anatomy and improper tactile control during instrumentation [15].

2.2 Clinical Signs and Symptoms

Recognition of strip perforations during endodontic therapy is crucial for early repair. Common intraoperative findings include:

- Sudden hemorrhage or profuse bleeding in the root canal during instrumentation.
- Unusual pain or sensitivity reported by the patient during cleaning and shaping.
- Failure to achieve dryness within the canal due to persistent exudation at the perforation site.

2.3 Radiographic and Imaging Diagnosis

Traditional radiographs can suggest a perforation if there is:

- An unusual radiolucent area along the lateral aspect of the root canal.
- Deviation of instruments toward the periodontal ligament space.

However, two-dimensional radiographs are limited in accuracy. Cone-beam computed tomography (CBCT) provides superior three-dimensional visualization, allowing precise localization and assessment of perforation extent, and has become the gold standard imaging modality for such defects [16, 17].

2.4 Other Diagnostic Methods

- **Paper point tracing:** Placement of a sterile paper point into the suspected canal, followed by radiographic evaluation of its exit path.
- **Operating microscope:** Magnification and illumination improve detection of unusual canal wall defects [18].

3. Materials for Management of Strip Perforations

3.1 General Requirements of Repair Materials

The long-term success of perforation management depends not only on timely diagnosis and adequate sealing technique but also on the material selected for repair. An ideal material should meet several biological and mechanical requirements.

From a biological perspective, the material must be biocompatible, inducing minimal inflammatory reaction in surrounding periodontal tissues while supporting repair of cementum and regeneration of the periodontal ligament [19, 20]. It should also promote hard tissue formation, such as cementogenesis and osteogenesis, which are critical for re-establishing the periodontal attachment apparatus [21]. Additionally, an antibacterial effect or the ability to resist microbial penetration is highly desirable, as microbial contamination is the main cause of treatment failure [22].

From a mechanical perspective, a suitable repair material must exhibit a hermetic seal to prevent microleakage between the root canal system and the periodontium [23]. Dimensional stability, insolubility in tissue fluids, radiopacity for radiographic detection, and adequate compressive strength to withstand occlusal forces are also required [24].

Handling characteristics are another important factor. Clinicians prefer materials that are easy to manipulate, have adequate working time, and can be delivered precisely into the perforation site without risk of extrusion [25]. Moisture tolerance is especially crucial, as perforations often communicate with periodontal tissues where hemostasis is difficult to achieve [26].

Historically, materials such as amalgam, zinc oxide-eugenol cements, and glass ionomer cements were used, but their limitations in biocompatibility, sealing, and long-term stability led to poor outcomes [17]. The advent of calcium silicate-based cements, starting with mineral trioxide aggregate (MTA), represented a breakthrough in perforation repair, offering improved sealing ability and bioactivity [27].

3.2 Mineral Trioxide Aggregate (MTA)

Mineral trioxide aggregate (MTA) was introduced in the early 1990s by Torabinejad and colleagues as a root-end filling and perforation repair material [25]. Since then, it has become the benchmark against which newer bioactive materials are compared.

A. Composition and Setting

MTA is primarily composed of tricalcium silicate, dicalcium silicate, tricalcium aluminate, calcium sulfate dihydrate (gypsum), and bismuth oxide as a radiopacifier [27]. When mixed with water, hydration reactions produce calcium silicate hydrate gel and calcium hydroxide, giving the material both its sealing and bioactive properties [26].

The material sets in the presence of moisture, which is a significant clinical advantage when dealing with perforations exposed to tissue fluids [28]. However, MTA has a relatively long setting time (approximately 2-4 hours), which may complicate single-visit treatments [29].

B. Biocompatibility and Bioactivity

MTA is considered highly biocompatible and capable of promoting hard tissue deposition. Calcium hydroxide released during hydration creates an alkaline environment that stimulates alkaline phosphatase activity and induces cementoblast and osteoblast differentiation [30, 31]. Histologic studies have shown new cementum deposition directly over MTA, facilitating periodontal regeneration [32].

Additionally, the high pH (≈12.5) contributes to an antibacterial effect, inhibiting growth of common endodontic pathogens such as Enterococcus faecalis [33].

C. Sealing Ability

MTA demonstrates excellent sealing ability, attributed to its expansion upon setting and ability to adapt closely to dentin walls [8]. Microleakage studies have consistently shown MTA to outperform earlier materials like amalgam, IRM, and glass ionomers in preventing bacterial penetration [34].

D. Mechanical Properties

While MTA offers superior sealing and bioactivity, its compressive strength is lower than dentin and may require reinforcement by coronal restoration to withstand occlusal forces [35]. Nonetheless, its dimensional stability and resistance to solubility in tissue fluids make it suitable for long-term repair [36].

E. Limitations

Despite its favorable properties, MTA has notable drawbacks:

- **Difficult handling:** Sandy consistency and limited flow [37].
- **Discoloration potential:** Due to bismuth oxide, especially problematic in anterior teeth [38].
- **Long setting time:** Which may increase risk of washout in areas with persistent bleeding [39].

These limitations prompted the development of newer calcium silicate-based materials, such as Biodentine, designed to overcome some of MTA's shortcomings.

3.3 Biodentine

Biodentine is a newer calcium silicate-based cement introduced as a "dentin substitute" with improved handling properties and shorter setting time compared to MTA [40]. It was specifically engineered to overcome MTA's drawbacks, particularly its difficult manipulation and potential for discoloration.

A. Composition and Setting

The powder mainly consists of tricalcium silicate, dicalcium silicate, calcium carbonate, and zirconium oxide as a radiopacifier, while the liquid contains calcium chloride (as a setting accelerator) and water-soluble polymer (as a plasticizer) [41]. The addition of calcium chloride significantly reduces the setting time to about 12-15 minutes, which is much shorter than MTA [42].

When hydrated, Biodentine undergoes a reaction similar to MTA, producing calcium silicate hydrate gel and calcium hydroxide [43]. The calcium hydroxide diffuses into surrounding tissues, creating an alkaline environment conducive to healing.

B. Biocompatibility and Bioactivity

Like MTA, Biodentine exhibits excellent biocompatibility. *in vitro* and *in vivo* studies have shown its ability to stimulate odontoblast-like cell differentiation and induce the formation of reparative dentin and mineralized tissue [44]. It also promotes secretion of growth factors such as TGF-β1 from dentin, enhancing the repair response [45].

Its bioactivity is attributed to the sustained release of calcium ions and the formation of apatite-like structures at the material-dentin interface [15]. This ability to form a "mineral infiltration zone" creates a strong micromechanical bond with dentin, improving sealing [46-48].

C. Sealing Ability

Biodentine demonstrates excellent sealing due to its micromechanical interlocking with dentin and slight expansion during setting [49]. Studies have shown it has lower microleakage values compared to MTA in perforation repairs [50].

D. Mechanical Properties

One of the main advantages of Biodentine is its superior mechanical profile compared to MTA. Its compressive strength (≈200 MPa) approaches that of natural dentin (≈300 MPa) after 1 month. It also exhibits high elasticity modulus and improved fracture resistance, making it a suitable dentin substitute [51].

E. Handling Advantages

Clinically, Biodentine is easier to mix and place than MTA due to its smoother, creamier consistency and shorter setting time [52]. It is less prone to washout and allows for placement of the permanent coronal restoration in a shorter time frame.

F. Limitations

Despite its many advantages, Biodentine has some limitations:

- Lower radiopacity compared to MTA, which may complicate radiographic interpretation [53].
- Cost: generally, more expensive than conventional MTA [54].
- Solubility concerns: though minimal, some studies report slight solubility in prolonged exposure to tissue fluids [55].

Nevertheless, its favorable combination of biocompatibility, bioactivity, sealing, and mechanical strength makes Biodentine a highly reliable alternative to MTA in perforation repair.

3.4 Calcium Silicate-Based Materials (CSBM) Beyond MTA and Biodentine

The success of MTA and Biodentine paved the way for the development of newer calcium silicate-based biomaterials with the goal of improving handling, reducing setting time, enhancing bioactivity, and minimizing drawbacks like discoloration and washout [33]. These materials are often referred to as bioceramic cements or hydraulic calcium silicates and are increasingly applied in endodontic perforation repair, pulp capping, apexification, and root-end surgeries.

A. Composition and Mechanism of Action

Most CSBM formulations share a base of tricalcium silicate and dicalcium silicate, with additions such as radiopacifiers (zirconium oxide, tantalum oxide, or bismuth-free substitutes), and accelerators (like calcium chloride) to optimize handling [27].

The setting reaction involves hydration of calcium silicate particles to form calcium silicate hydrate (CSH) gel and calcium hydroxide [56]. The alkaline pH created favors antibacterial action and stimulates healing. Additionally, calcium hydroxide reacts with phosphate ions in body fluids, forming hydroxyapatite crystals at the material-dentin interface [15].

Examples of New CSBM

- **EndoSequence BC RRM (Brasseler USA):** A premixed, ready-to-use putty form with no mixing required. It has high biocompatibility, low solubility, and favorable sealing [57].

- **BioAggregate:** Composed of calcium silicates, calcium phosphate, and tantalum oxide, designed to eliminate bismuth oxide (a cause of discoloration in MTA) [58].
- **TheraCal LC:** A resin-modified, light-curable calcium silicate material with rapid setting and easy handling, though its resin content may compromise long-term bioactivity [27].
- **CEM Cement (Calcium Enriched Mixture):** A non-MTA-based material containing calcium oxide, calcium phosphate, and calcium carbonate, with promising sealing and regenerative potential [59].

B. Bioactivity and Sealing Properties

Like MTA and Biodentine, modern CSBM exhibit ion release and apatite precipitation, which improves sealing and supports periodontal and pulpal healing. Studies show that CSBM forms a mineral infiltration zone at the dentin interface, creating a micromechanical and chemical bond [60].

C. Handling and Clinical Advantages

Premixed calcium silicate pastes and putties (e.g., EndoSequence BC RRM) eliminate the variability of mixing and have extended working times, which make them user-friendly. Their shorter setting times also allow for quicker restoration placement compared to traditional MTA.

D. Limitations

Despite improvements, some limitations persist:[61]

- **Cost:** Often higher than MTA or Biodentine.
- **Limited long-term data:** Many of these newer materials lack extensive clinical trials.
- Resin modification (e.g., TheraCal LC) may reduce bioactivity compared to pure hydraulic calcium silicates.

Table 1: Comparative summary of MTA, Biodentine, and newer calcium silicate-based materials highlighting differences in composition, handling, bioactivity, sealing ability, and clinical limitations.

Feature	MTA	Biodentine	Newer CSBM (e.g., BC RRM, BioAggregate, CEM, TheraCal LC)
Composition	Tricalcium silicate, dicalcium silicate, bismuth oxide (radiopacifier), calcium sulfate	Tricalcium silicate, calcium carbonate, zirconium oxide, calcium chloride (accelerator)	Tricalcium silicate, dicalcium silicate, alternative radiopacifiers (zirconium/tantalum), sometimes resins
Setting Time	Long (≈2-4 hrs)	Shorter (≈12 min)	Variable - premixed putties: fast; resin-modified (TheraCal): immediate
Handling	Grainy, difficult to pack, requires mixing	Improved handling, smoother consistency	Excellent (premixed syringes/putties); some (TheraCal) are light-cured
Bioactivity	High - releases Ca^{2+}, promotes hydroxyapatite formation	High - stronger apatite deposition than MTA	High (ion release and apatite formation), varies with formulation
Sealing Ability	Excellent, gold standard	Comparable to or better than MTA	Strong sealing via mineral infiltration zone
Discoloration Risk	High (due to bismuth oxide)	Low	Very low (no bismuth oxide in most)
Biocompatibility	Excellent - promotes cementogenesis and PDL healing	Excellent - strong tissue compatibility	Excellent - promotes regeneration, reduced inflammatory response
Limitations	Long setting time, discoloration, difficult handling	Less strength than composite in long term	Higher cost, limited long-term clinical data, resin modification reduces bioactivity in some

MTA remains the historical gold standard for perforation repair because of its proven bioactivity and sealing capacity, but its long setting time and handling difficulties limit single-visit convenience. Biodentine was developed to overcome those limitations: it sets rapidly, has improved handling and a mechanical profile closer to dentin, and shows excellent marginal adaptation and reinforcement in laboratory studies. Newer premixed bioceramic cements and sealers combine ease of use with comparable bioactivity and sealing; they are particularly convenient for monoblock obturation strategies. Clinically, a hybrid approach (local bioceramic plug for the defect + bioceramic sealer/monoblock obturation) combines biological sealing and system-wide reinforcement, though long-term randomized clinical trials comparing techniques remain limited.

4. Management of Strip Perforations: Techniques of Repair

4.1 Sandwich Technique

The Sandwich Technique is a multilayered approach in which different biomaterials are strategically placed to maximize sealing ability, biocompatibility, and fracture resistance. The core principle is to combine the biological sealing capacity of calcium silicate-based materials with the mechanical reinforcement provided by resin-based sealers or composite overlays.

4.1.1 Procedure

- The perforation site is first sealed with a bioceramic material (commonly MTA or Biodentine). This acts as a biological barrier, preventing microbial leakage and promoting periradicular healing [62].
- Over this, a layer of resin-modified glass ionomer or flowable composite may be placed to reinforce the area.
- Finally, the obturation is completed using gutta-percha and sealer in the coronal and apical segments.

4.1.2 Advantages

- Provides a dual seal: bioceramic barrier for biological healing and resin-based reinforcement for strength [63].
- Minimize microleakage and bacterial infiltration.
- Increases the fracture resistance of the repaired root.

4.1.3 Limitations

- Technique-sensitive due to multiple steps.
- Potential polymerization shrinkage of resin layer if not carefully applied [25].

4.2 Monoblock Technique

The Monoblock Technique aims to create a single bonded unit by integrating the root canal filling material with the dentin walls. In the context of perforation repair, this technique attempts to eliminate interfacial gaps and provide a seamless interface.

4.2.1 Procedure
- Calcium silicate-based sealers (e.g., premixed bioceramic sealers, BioRoot RCS) are placed directly into the canal along with gutta-percha or bioceramic-coated cones.
- The sealer penetrates dentinal tubules, forming a mechanical interlocking bond as well as a chemical bond through hydroxyapatite formation [26].
- In some protocols, only bioceramic-based filling material is used, producing a true monoblock structure.

4.2.2 Advantages
- Enhanced adaptation to canal walls.
- Reduced microleakage compared with conventional obturation [64].
- Promotes biological repair due to bioactivity of calcium silicate cements.

4.2.3 Limitations
- Debonding may occur in the long term due to differences in modulus of elasticity between dentin and sealer.
- Incomplete polymerization or dimensional changes may compromise seal [65].
- Limited clinical long-term data compared to Sandwich Technique.

4.4 Comparative Overview
- The Sandwich Technique is favored where mechanical reinforcement and layered sealing are desired, particularly in structurally compromised roots.
- The Monoblock Technique emphasizes biological sealing and chemical integration, potentially offering superior adaptation but with concerns about long-term durability.
- Current evidence suggests that both approaches provide clinically acceptable outcomes, but further long-term studies are needed to determine superiority [66].

5. Prognosis of Strip Perforation Management
The prognosis of strip perforations is multifactorial and depends on variables such as the location of the perforation, size and extent of the defect, time elapsed before repair, the material used for sealing, degree of microbial contamination, and the clinician's experience [2, 67]. Early diagnosis and immediate sealing of the perforation are key determinants of success because delay increases the risk of periodontal breakdown, persistent infection, and epithelial proliferation into the defect [3].

5.1 Influence of Location and Size
Perforations located coronally or in the cervical third generally carry a poorer prognosis due to proximity to the gingival sulcus and higher risk of bacterial contamination, compared with those in the middle or apical third [1]. The size of the perforation is also critical; smaller defects sealed promptly have significantly higher healing potential than wide perforations that compromise root dentin integrity [5].

5.2 Time of Repair and Microbial Contamination
The timing of repair strongly affects outcome. Perforations sealed immediately with biocompatible materials demonstrate higher rates of periodontal healing than those repaired after microbial colonization has occurred [6]. Studies have shown that the success rate of MTA or Biodentine repair exceeds 80-90% when the perforation is addressed early, whereas delayed treatment is often associated with persistent inflammation and reduced healing [68].

5.3 Role of Repair Materials
The choice of repair material plays a decisive role in prognosis. MTA has been consistently associated with favorable long-term outcomes due to its sealing ability and biocompatibility [29]. Similarly, Biodentine and newer calcium silicate-based materials have shown comparable success rates, with advantages such as faster setting and reduced discoloration [69]. Materials with poor sealing capacity, such as amalgam or intermediate restorative material (IRM), have been correlated with increased failure due to leakage and lack of bioactivity [70].

Table 2: Comparative Studies on Materials for Strip Perforation Repair

Author/Year	Material(s) Compared	Study Type	Key Findings	Outcome/Success
Pitt Ford *et al*., 1995 [7]	MTA vs Amalgam	Animal study	MTA induced cementogenesis and periodontal ligament regeneration; amalgam showed inflammation	MTA superior
Alhadainy, 1994 [70]	Amalgam, Cavit, GIC, IRM	In vitro	Amalgam and Cavit leaked significantly; IRM and GIC performed slightly better but not ideal	Poor to moderate
Holland *et al*., 2001 [71]	MTA vs Calcium hydroxide	Dog model	MTA provided better sealing and cementum deposition	MTA superior
Main *et al*., 2004 [72]	MTA (clinical cases)	Case series	Perforation repair with MTA showed healing in 16/16 teeth	100% success
Modaresi *et al*., 2023 [19]	Cold ceramic vs MTA	Clinical report	Cold ceramic showed comparable sealing and healing	Comparable
Kabtoleh *et al*., 2023 [20]	Biodentine, MTA, EndoSequence BC RRM	In vitro fracture resistance	Biodentine and BC RRM enhanced fracture resistance more than MTA	Biodentine/BC RRM superior

A number of studies have evaluated different repair materials for strip perforation management, focusing on sealing ability, marginal adaptation, biocompatibility, and long-term clinical outcomes. A tabular summary of key findings is presented below.

6. Future Directions in Strip Perforation Management
Advances in biomaterials and digital technologies are shaping the next generation of strategies for managing strip perforations. Current trends indicate a transition from conventional sealing approaches toward biologically oriented and technology-assisted repair.

6.1 Nanotechnology in Bioceramics
Incorporating nanoparticles into calcium silicate-based cements enhance their hydration, bioactivity, and sealing ability, offering the potential for faster setting and improved clinical stability [73].

6.2 Regenerative and Scaffold-Based Therapies

Bioengineered scaffolds and hybrid constructs designed to support stem-cell migration and mineral deposition may promote functional tissue regeneration rather than mere defect closure [74].

6.3 Bioactive Molecules and Biologics

Adjunctive use of growth factors or platelet derivatives can stimulate angiogenesis, cell differentiation, and repair processes, complementing conventional repair materials [73].

6.4 Guided Endodontics

CBCT-based static and dynamic navigation improves detection and management of perforations, reducing operator error and increasing treatment predictability [75].

7. Conclusion

Strip perforation remains a challenging endodontic complication, with prognosis influenced by early detection, sealing technique, and material selection. The advent of calcium silicate-based biomaterials, particularly MTA and Biodentine, has significantly improved outcomes due to their sealing ability, bioactivity, and biocompatibility. While current evidence supports their clinical effectiveness, future progress will depend on innovations in biomaterials, regenerative strategies, and digital technologies, alongside robust clinical trials to establish standardized treatment protocols.

Conflict of Interest
Not available

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Not available

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