REVIEW

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The Role and Clinical Applications of Bioceramic Materials in Modern Endodontic Practice: A Review of the Literature.

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Abstract
Bioceramic materials represent a significant paradigm shift in endodontics over the past three decades. This revolution, initiated by the development of mineral trioxide aggregate (MTA) in 1993, is attributed to the superior properties of these materials, such as excellent biocompatibility, bioactivity, sealing ability, and high alkalinity (pH ~12.5). This review summarizes the historical development, classification, physical, chemical, and biological properties, and current clinical applications of bioceramics. In clinical applications, calcium silicate-based materials such as MTA and Biodentine demonstrate success rates exceeding 90% in vital pulp therapy (pulp capping and pulpotomy) by promoting the formation of a dentin bridge. As root canal sealers, they have popularized the single-cone technique, achieving 90-99% clinical success rates by chemically bonding to dentin and providing a long-term seal. Furthermore, they have become the gold standard for apexification, perforation repair, management of resorption defects, and as a retrograde filling material in apical surgery. In regenerative endodontic procedures, they enhance long-term tooth survival by supporting continued root development. Nevertheless, certain limitations remain, including prolonged setting times, handling difficulties, the potential for tooth discoloration, and challenges associated with retreatment procedures. Despite these limitations, bioceramics have become an indispensable component of modern endodontics when applied with proper indications and techniques, significantly improving treatment outcomes and offering patients more biologically-oriented and conservative treatment options.

Keywords: Bioceramic materials, endodontics, treatment.

Introduction

Bioceramic materials represent one of the most significant paradigm shifts in endodontics over the past three decades. This revolution began in 1993 with the development of mineral trioxide aggregate (MTA), which overcame the limitations of traditional materials by combining excellent biocompatibility, bioactivity, and sealing ability [1,2]. Bioceramics are inorganic, non-metallic compounds specifically designed for tissue regeneration, repair, and replacement [3]. Today, bioceramics are widely applied in root canal sealers, obturation, and perforation repair, as well as in pulp capping, pulpotomy, resorption defect filling, apexification, and regenerative treatments. Their high alkalinity (pH ~12.5), hydroxyapatite-inducing capacity, antibacterial activity, and chemical bonding potential have significantly improved treatment success [1].

Historical Development of Bioceramic Materials

The origins of bioceramics trace back to 1824, when Joseph Aspdin patented Portland cement [4], and to 1878, when Dr. Witte first proposed its use as a root canal filling material in the *Deutsche Vierteljahrsschrift für Zahnheilkunde* [5].

The modern bioceramic era, however, began with the development of MTA by Dr. Mahmoud Torabinejad and colleagues at Loma Linda University in 1993 [6]. Composed of modified Portland cement and bismuth oxide, MTA was the first bioceramic to achieve clinical success [1,2]. ProRoot MTA received FDA approval in 1998 and was marketed in 1999 [1].

Since then, bioceramics have rapidly diversified. White MTA was introduced in 2002 to reduce discoloration [7], and the launch of Biodentine in 2009 provided a new generation with faster setting and improved mechanical properties [2,8]. During the 2010s, formulations such as the iRoot series, TheraCal LC, and EndoSequence BC Sealer were developed and adopted in clinical practice [1].

Classification of Bioceramic Materials

The classification of endodontic bioceramics is of critical importance for understanding their properties and ensuring appropriate selection in clinical practice. These materials may be categorized according to different criteria

[2,7,9-13]. The major categories are presented in Tables 1 and 2.

Physical and Chemical Properties

The physical properties of bioceramic materials are critical to their clinical success [1]. Porosity levels vary among materials; ProRoot MTA demonstrates the lowest porosity with 0%, whereas conventional MTA exhibits porosity rates of up to 28.44% [14]. In terms of compressive strength, TotalFill BC RRM provides the highest values at 87.21 MPa, while in push-out bond strength tests, Endoseal MTA achieved superior sealing ability with a void ratio of only 0.203% [15].

From a chemical perspective, calcium silicate constitutes the primary component, while zirconium oxide provides radiopacity, and calcium phosphate together with calcium hydroxide contribute to bioactivity [2,16]. The setting mechanism occurs through a hydration reaction with water, resulting in the formation of calcium silicate hydrate gel and calcium hydroxide [1].

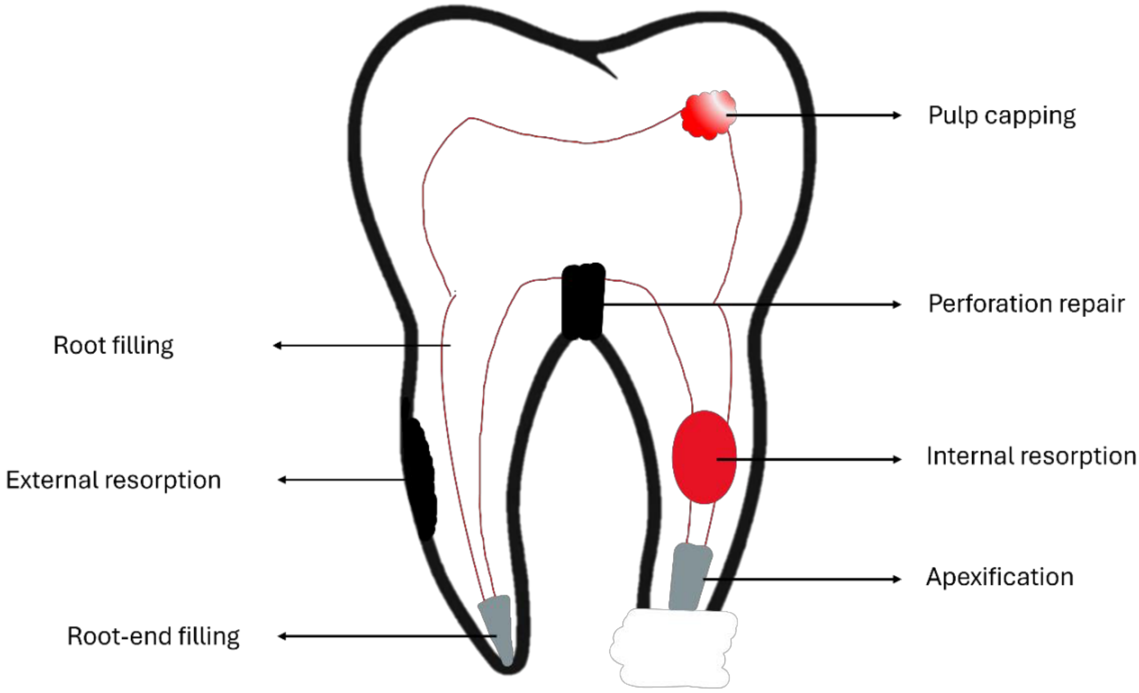

Figure 1. Clinical applications of bioceramic materials in endodontics.

Biological Properties

The most significant advantage of endodontic bioceramics is their excellent biocompatibility [2,12,13]. In cytotoxicity assays, EndoSequence BC Sealer demonstrated higher cell viability compared with AH Plus, whereas Bio-C Sealer supported 87% cell proliferation [17]. Their antibacterial activity is attributed to high alkalinity (pH > 12) and sustained calcium hydroxide release. Against *Enterococcus faecalis*, EndoSequence BC Sealer exhibited greater antimicrobial activity than AH Plus [18].

In terms of bioactivity, hydroxyapatite formation, osteoconductive properties, and osteoinductive capacity promote pulp tissue regeneration, dentin bridge formation, and healing of periradicular tissues [2,10,11].

Major Bioceramic Materials

MTA

MTA is considered the gold standard among endodontic bioceramic materials [1,2,7]. Its basic composition consists of Portland cement (75%), bismuth oxide (20%), and gypsum (5%), and it is available in two variants: Gray and White. MTA has wide clinical applications including apical barrier formation, retrograde filling, perforation repair, and vital pulp therapy [19,20].

Its advantages include hydroxyapatite formation, antibacterial properties, and zero shrinkage, whereas disadvantages involve a long setting time (2-6 h), difficult handling, high cost, and risk of tooth discoloration [9,21]. Reported clinical success rates include 80.5%

in direct pulp capping, >90% in pulpotomy, and 86.4-95.6% in apical surgery [1].

Table 1. Overview of bioceramic materials in dentistry, including their categories, representative products, composition, and main properties.

Main Category	*Subcategory / Generation*	*Representative Materials*	*Composition & pH*	*Key Properties / Clinical Notes*
Bioactive	Calcium Silicate–Based (1st Gen)	ProRoot MTA (Gray/White)	Portland cement (C_3S 50–70%, C_2S 10–30%, C_3A 1–5%, C_4AF 1–5%) + bismuth oxide; pH 12–13	Gold standard; biocompatible; high pH antibacterial; dentin bridge/HA formation; disadvantages: long setting time (2–6 h), handling difficulty, discoloration
	2nd Gen	Biodentine, BioAggregate	Tri-/di-calcium silicates + $CaCO_3$ + CaO; Biodentine liquid contains $CaCl_2$ accelerator; pH ~12	Faster setting (~12 min), no Al/metal inclusions, dentin-like mechanical properties, no discoloration
	3rd Gen	iRoot series, EndoSequence BC Sealer	Premixed Ca-silicate + Ca-phosphate + ZrO_2; injectable	Strong dentin bonding, easy handling, high flow; good sealing in moist canals
	4th Gen	Bio-C Sealer, TotalFill BC Sealer/Putty	Premixed Ca-silicate + additives (zirconia, CaOH)	Improved handling, premixed syringes/putty, expansion on setting, single-cone technique
	Bioactive Glasses	45S5 Bioglass, BioAggregate	SiO_2–Na_2O–CaO–P_2O_5; pH neutral	Osteoinductive, rapid HA formation, used in bone regeneration
	Calcium Phosphate–Based	MCPM, DCPD, OCP, HA, ACP, β-TCP	MCPM pH 0.5–3; DCPD pH 4–6; OCP pH 5.5–7; HA $Ca_{10}(PO_4)_6(OH)_2$ pH 7–9	Osteoconductive, chemical bonding with bone; ACP = precursor phase; HA stable, β-TCP resorbable
	Composite Materials	TheraCal LC, Bio-C Temp	Ca-silicate + resin; light/dual-cure	Immediate setting, controlled ion release, angiogenic stimulation; used as pulp capping/liner
Bioinert	Alumina	Al_2O_3	Inert oxide ceramic	High hardness, wear resistance; limited dental use
	Zirconia	ZrO_2	Stabilized zirconium oxide	Excellent mechanical properties, radiopacity; used in posts, restorations
	Titanium Oxide	TiO_2	Oxide ceramic	Corrosion resistance, radiopaque additive
Bioresorbable	β-tricalcium phosphate (β-TCP)	β-TCP scaffolds	$Ca_3(PO_4)_2$; resorbs in 6–24 months	Osteoconductive, scaffold for bone regeneration
	Calcium Sulfate	$CaSO_4$	$CaSO_4·2H_2O$	Rapid resorption (4–6 weeks); space maintainer, barrier
	Biodegradable Polymers	PLA, PGA	Poly-lactic acid, poly-glycolic acid	Controlled degradation; used as carriers/scaffolds

Table 2. Form, representative materials, clinical applications, and setting characteristics of bioceramic materials.

Form / Type	*Consistency / Mechanism*	*Representative Materials*	*Clinical Applications*	*Setting Time*
Repair Materials	Putty-like, moldable	EndoSequence BC RRM, Biodentine, MTA Repair HP	Retrograde filling, surgical endodontics, root-end closure	2.5–10 h (hydration)
Liners / Coatings	Thin layer, light-activated or dual-cure	TheraCal LC, Bio-C Pulpo, Lime-Lite	Dentin coverage, cavity liner, pulpal protection	~20 s (light cure)
Sealants / Cements	Paste-like, injectable, resin-free	BioRoot RCS, EndoSequence BC Sealer, AH Plus Bioceramic, MTA Fillapex	Root canal sealer, lateral/vertical condensation, single-cone technique	2.5–10 h (hydration) or manufacturer dependent (chemical cure)

Biodentine
Developed by Septodont, Biodentine was designed as a *"dentin substitute"* [3]. It is composed of a powder containing tricalcium silicate, zirconium oxide, calcium oxide, and calcium carbonate, and a liquid containing calcium chloride, hydrosoluble polymer, and water. Produced as high-purity tricalcium silicate powder, Biodentine is free of aluminum inclusions and trace metals commonly found in Portland cement–based cements [22]. Its major advantages include a short setting time (12 min), easy handling, absence of discoloration, and mechanical properties closely resembling dentin [19,22]. In pulpotomy, it has demonstrated a 99% success rate, with clinical outcomes comparable to MTA [19].

BioRoot RCS
Developed by Septodont, BioRoot RCS is a pure tricalcium silicate–based cement manufactured using Active Biosilicate Technology [23]. It is a resin-free, mineral-based sealer intended for root canal obturation. Its features include excellent flowability, strong adhesion to gutta-percha, and chemical bonding with dentin [1].

EndoSequence BC Sealer
Developed by Brasseler USA, EndoSequence BC Sealer is a nanoparticle premixed bioceramic containing calcium silicate, calcium phosphate, calcium hydroxide, and zirconium oxide [24]. Recent studies [25,26] using SEM and micro-CT demonstrated that this sealer exhibits low porosity, minimal solubility, and excellent apical sealing properties. These advantages support its reliable use in endodontic treatments.

iRoot SP
Produced by Innovative BioCeramix Inc., iRoot SP is a premixed, injectable bioceramic free of aluminum [27]. It provides effective flowability, a biomineralization-based mechanism, and osteogenic–angiogenic properties. In pulpotomy, iRoot SP has shown a 99% success rate, achieving clinical outcomes comparable to MTA [28].

Clinical Applications
Over the past 30 years, bioceramic materials have revolutionized endodontic treatment protocols and have become indispensable in nearly all areas of contemporary endodontics. Due to their superior biocompatibility, sealing ability, antimicrobial effect, and capacity to stimulate tissue regeneration, they have

emerged as the gold standard in a wide range of indications, including apexification, perforation repair, retrograde fillings, and root canal obturation [1,23]. Furthermore, in resorption therapy and regenerative endodontic procedures, these materials support root development and improve long-term tooth survival [29]. The different clinical application areas of bioceramic materials and the outcomes of related studies are summarized in Table 3.

Use of Bioceramics in Vital Pulp Therapy

Deep dentinal caries is a widespread problem that activates inflammatory and mineralization processes in the dentin–pulp complex, aiming to preserve pulp vitality and integrity. While traditional approaches required complete caries removal and root canal treatment in case of pulp exposure, current concepts emphasize minimally invasive techniques that preserve pulp vitality [30,31]. Thus, vital pulp therapies such as pulp capping and pulpotomy have become essential procedures in modern dentistry.

In practice, after rubber dam isolation, cavities are prepared with high-speed burs under water cooling, while hand instruments are used near the pulp. If healthy dentin remains after caries removal, indirect pulp capping can be performed [32]. In cases of pulp exposure, the tissue is rinsed with sterile saline, and hemostasis is achieved with a NaOCl-soaked pellet [33,34]. If bleeding persists, partial pulpotomy is performed with a tungsten carbide bur under copious water spray, followed by re-assessment of hemostasis [35]. Hemostatic agents such as ferric sulfate or lasers should be avoided, as bleeding response reliably indicates the degree of pulp inflammation [36].

Once hemostasis is achieved, a 2-3 mm layer of MTA or Biodentine is placed over the pulp and covered with composite. Cavity disinfection is also crucial; chlorhexidine, ozone, or sodium hypochlorite solutions may be used [35]. Bioceramics have gained prominence in vital pulp therapy due to dentin bridge induction, antibacterial activity, and sealing ability [37]. Calcium silicate-based materials provide an alkaline environment that prevents bacterial penetration and stimulates reparative dentinogenesis [38].

MTA has the longest clinical history with proven success in direct and indirect pulp capping as well as pulpotomy [38-40]. Advantages include tissue compatibility, low permeability, and bacterial inhibition, resulting in faster healing and more organized dentin bridges [39,40]. Limitations are difficult handling, long setting, and tooth discoloration [41]. To overcome these, Biodentine was developed, offering shorter setting (~12 min), easier handling, and no discoloration [32,42]. Studies [32,42,43] report that Biodentine accelerates pulp healing and induces greater dentin bridge formation, with randomized trials showing success rates of 90-100% for both Biodentine and MTA.

Other premixed bioceramics such as iRoot BP Plus also show promise. In a retrospective study, Rao et al. [28] reported success rates of 99% with iRoot BP Plus compared with 93% for calcium hydroxide after an ~18-month follow-up.

Clinically, vital pulp therapy, especially in deep caries and reversible pulpitis, depends on bleeding control, adequate removal of infected dentin, and well-sealed restorations [34]. Calcium silicate-based bioceramics both prevent bacterial invasion and stimulate reparative dentinogenesis, enhancing tooth resilience [31,33]. Even in irreversible pulpitis, partial or full pulpotomy with bioceramics has demonstrated success rates of 85-95% [44-47]. Figure 2 illustrates the clinical images of a full pulpotomy procedure performed on tooth 46, diagnosed with irreversible pulpitis. In this 6-year-old systemically healthy patient with a pronounced gag reflex, periapical radiographs could not be obtained. At the 6-month follow-up visit, the tooth demonstrated positive vitality responses, and clinical monitoring is ongoing.

In summary, bioceramic materials significantly contribute to the goals of vital pulp therapy by preserving natural pulp tissue and improving long-term restorative outcomes. Current literature confirms that MTA and Biodentine are reliable, biologically advantageous, and clinically effective when applied with proper indications and techniques, thereby enhancing long-term tooth survival and supporting conservative dentistry.

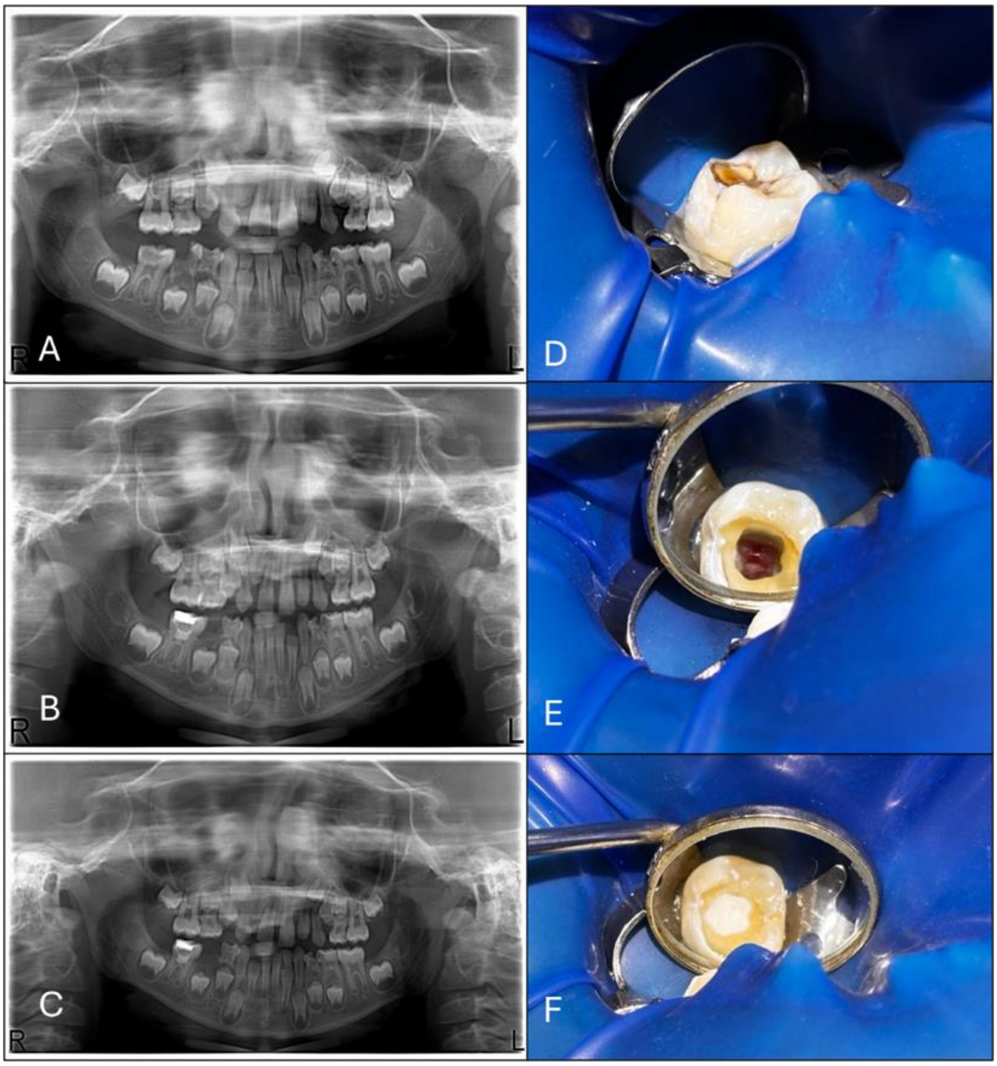

Figure 2. Clinical and radiographic follow-up of a full pulpotomy case in tooth 46 diagnosed with irreversible pulpitis. (A) Preoperative panoramic radiograph. (B) Three-month follow-up. (C) Six-month follow-up. (D) Clinical view prior to pulpotomy. (E) Pulp chamber following coronal pulp removal and hemostasis. (F) Final view after placement of MTA.

Use of Bioceramic Sealers in Root Canal Treatment

Bioceramic-based sealers have been introduced as alternatives to traditional root canal sealers and, particularly over the past decade, have become widely used. Calcium silicate-based sealers such as EndoSequence BC Sealer, BioRoot RCS, and TotalFill BC Sealer can chemically bond with dentin, reduce microleakage, and stimulate hard tissue formation [48]. Their ultrafine particle size enables penetration into dentinal tubules, while contact with tissue fluids leads to calcium hydroxide release and apatite-like crystal deposition, enhancing long-term sealing [49,50].

Their setting reaction depends on the presence of moisture; bond strength decreases in completely desiccated canals, while a moist environment promotes penetration and crystal formation [51,52]. Thus, excessive drying is not recommended. A key advantage is their favorable tissue tolerance even when extruded beyond the apex, as they may resorb or remain inert without inflammation, while exerting antimicrobial effects due to high alkalinity [50,53].

Bioceramic sealers have also facilitated the single-cone obturation technique. Unlike traditional lateral or vertical condensation, they expand slightly on setting and do not shrink, allowing obturation with one master cone and sealer [49,54]. In this approach, gutta-percha mainly generates hydraulic pressure to aid sealer penetration.

Table 3. Summary of clinical studies evaluating different treatment protocols using bioceramic materials compared with conventional materials or techniques.

Author(s) & Year	*Study Type*	*Treatment Type*	*Bioceramic Used*	*Comparison Material*	*Patient/Tooth Count*	*Follow-up Period*	*Success Rate (%)*	*Evaluation Criteria*
Hoseinifar et al. 2020 [8]	Randomized Controlled Trial	Direct pulp capping	MTA (Angelus), Biodentine (Septodont), CEM cement (Bionique Dent)	Control group (RMGI only)	38 teeth (9 MTA, 9 CEM, 10 Biodentine, 10 control)	6 weeks	Pulp vitality: 100% all groups; Dentin bridge formation: MTA 55.6%, CEM 66.7%, Biodentine 80%, Control 20%	Histological (inflammatory response, necrosis, dentin bridge formation, bridge thickness, inflammation type)
Rao et al. 2020 [28]	Retrospective	Pulpotomy	iRoot BP Plus	Calcium hydroxide	168 children aged 5.9-13 years	Mean 17.5±4.4 months (range 12-24 months)	iRoot: 99% total (100% clinical, 99% radiographic); CH: 93% total (94% clinical, 93% radiographic)	Clinical (pain, swelling, mobility, sinus tract, EPT) and Radiographic (resorption, periapical lesions, PDL widening)
Hilton et al. 2013 [40]	Randomized Controlled Trial (multicenter)	Direct pulp capping	ProRoot MTA	Calcium hydroxide	358 teeth (183 MTA, 175 CaOH)	Median: MTA 15.6 months, CaOH 12.1 months (up to 2 years)	MTA 80.3%, CaOH 68.5% (p=0.046)	Clinical (extraction/RCT recommendation) and Radiographic (radiolucency, resorption, calcification)
Brizuela et al. 2017 [41]	Randomized Controlled Trial (blind)	Direct pulp capping	ProRoot MTA (white), Biodentine (Septodont)	Calcium hydroxide	169 permanent molars (53 CH, 56 MTA, 60 Biodentine)	1 year	At 1 year: CH 94.3% (3 failures/53), MTA 94.6% (3 failures/56), Biodentine 100% (0 failures/60); p=0.127	Clinical (pain, sensitivity tests, percussion, edema, fistula) and Radiographic (resorption, periradicular disease, PDL width)
Parinyaprom et al. 2018 [43]	Randomized Controlled Trial (blind)	Direct pulp capping	Biodentine (Septodont)	ProRoot MTA (Dentsply)	55 permanent teeth (28 Biodentine, 27 MTA)	Mean 18.9±12.9 months	Overall 94.5%; Biodentine 96.4% (27/28), MTA 92.6% (25/27); p=0.61	Clinical (cold test, pain, swelling, fistula, mobility) and Radiographic (lamina dura, root formation, periapical lesions)
Pontoriero et al. 2023 [49]	Prospective Clinical Study	Root canal treatment (primary & retreatment)	CeraSeal, BioRoot RCS, AH Plus Bio, Bio-C Sealer ION+	Head-to-head comparison among four bioceramic sealers	210 teeth (168 patients); 98 primary RCT, 112 retreatments	Mean 19.7 months (minimum 18 months)	Overall 99% (73.3% healed, 25.7% healing, 0.95% failed); Primary RCT 100%, Retreatment 98.2%	Clinical (pain, swelling, sinus tract) and Radiographic (PAI score, lesion size changes)
Chybowski et al. 2018 [56]	Retrospective Clinical Study	Root canal treatment & retreatment (single-cone technique)	EndoSequence BC Sealer (Brasseler USA) + gutta-percha	None (no direct comparator)	307 patients / 307 teeth (72 retreatments, 235 initial)	Mean 30.1 ± 18.7 months	Overall 90.9% (83.1% healed, 7.8% healing, 9.1% not healed); Initial RCT 90.6%, Retreatment 91.7%	Clinical (pain, swelling, sinus tract, percussion/palpation, mobility, periodontal pocket) and Radiographic (periapical lesion size, healing vs

								non-healing, sealer extrusion resorption)
Alsulaimani 2016 [66]	Randomized Controlled Trial	Root canal obturation in mature teeth with chronic apical abscess	White ProRoot MTA (Dentsply)	Gutta-percha + Tubliseal Xpress sealer	32 teeth (16 MTA, 16 GP+sealer; mix of primary and secondary RCT)	Mean 3.6 years (range 2.5–5 years)	Complete periapical healing: MTA 87.5% (14/16), GP+sealer 75% (12/16), p=0.69; Survival: MTA 100%, GP+sealer 83.3% at 5 years	Clinical (symptoms, survival, function) and Radiographic (periapical healing, obturation length, extrusion resorption)
Bonte et al. 2015 [71]	Randomized Controlled Trial	Apexification of non-vital immature permanent teeth	ProRoot MTA (Dentsply)	Calcium hydroxide (Ca(OH)$_2$)	30 teeth (15 MTA, 15 CH)	12 months	Functional survival: MTA 100% vs CH 73.3%; Apical barrier formation: MTA 76.5% vs CH 50%; Radiographic healing (PAI <2): MTA 82.4% vs CH 75%	Clinical (pain, tenderness, swelling, sinus tract, mobility, tooth survival) and Radiographic (apical barrier closure, PAI score, periapical radiolucency)
Caleza-Jiménez et al. 2022 [73]	Retrospective Comparative Clinical Study	Apexification vs Revascularization in immature necrotic incisors and molars	ProRoot MTA (Dentsply)	Revascularization protocol (triple antibiotic paste + blood clot + MTA coronal plug)	18 teeth (9 MTA apexification, 9 RET)	Mean 22 ± 19 months (range 6–66 months)	Periapical healing: both groups successful, no sig. difference (P>0.05); Root development: RET superior (length $\uparrow$12.8% vs 0.3%; dentin wall $\uparrow$34.6% vs −3.4% at 6 months)	Clinical (tooth function, symptoms) and Radiographic (PAI score, root length/dentin wall thickness, apical healing)
Lin et al. 2017 [76]	Prospective Randomized Controlled Trial	Apexification vs Regenerative Endodontic Treatment in immature necrotic permanent teeth with apical periodontitis	White ProRoot MTA (Dentsply) used as coronal plug in RET	Calcium hydroxide (Vitapex) for apexification	118 teeth recruited (80 RET, 38 apexification); final analysis 103 teeth (69 RET, 34 apexification)	12 months	Both groups 100% survival & asymptomatic; Radiographic healing 100% both; Root development: RET superior (length $\uparrow$81.2%, thickness $\uparrow$82.6%, apex closure 65.2%) vs Apexification (length $\uparrow$26.5%, thickness 0%, apex closure 82.4%)	Clinical (pain, swelling, sinus tract, mobility, discoloration, complications) and Radiographic/CBCT (root length, root thickness, apical foramen size, periapical healing)
Pontius et al. 2013 [100]	Retrospective Multicenter Clinical Study	Perforation repair (nonsurgical and surgical)	Mineral Trioxide Aggregate (MTA; multiple brands)	Other materials (Geristore, Gutta-percha, OptiBond/Tetric Flow + $CaSO_4$, Biomed)	70 perforations in 69 patients; 50 teeth recalled	Mean 37 months (range 6–116 months)	90% overall success (47/50 functional, asymptomatic teeth); Failures 10% (5/50)	Clinical (symptoms, function, probing, sinus tract, mobility) and Radiographic (PAI, Root Perforation Index, coronal seal, root filling length/homogeneity)

Huang et al. 2020 [118]	Retrospective Cohort Study (long-term recall and survival analysis)	Endodontic microsurgery (apical resection + retrograde filling)	ProRoot MTA (Dentsply)	Intermediate Restorative Material (IRM)	191 teeth initially; 92 teeth included for healed rate analysis	1–2 years (short-term) and 5–9 years (long-term); Kaplan–Meier 9-year survival	Healed: 78.3% (72/92); 9-year survival 83% (all causes) and 95.2% (excluding non-endodontic failures)	Clinical (symptoms, function) and Radiographic (Rud classification: complete/scar/uncertain/unsatisfactory healing); Prognostic analysis (REF material: IRM HR 5.95× non-healing vs MTA)
von Arx et al. 2019 [119]	Prospective longitudinal cohort (single surgeon, university clinic)	Apical surgery with root-end resection and retrograde filling	ProRoot MTA (gray until 2003, then white)	None (all cases filled with MTA)	195 teeth (195 patients) initially; 119 teeth evaluated at 10 years	1 year, 5 years, 10 years	Healed: 91.6% at 1 year; 91.4% at 5 years; 81.5% at 10 years	Clinical (symptoms, mobility, probing, fistula/swelling) and Radiographic (Rud & Molven classification: complete, incomplete, uncertain, unsatisfactory healing; worst root outcome per tooth)

Clinical studies [49,55,56] show success rates of 90-99%, comparable to warm vertical compaction. A prospective study of 210 cases reported 99% overall success, with 100% in primary and 98% in retreatments, regardless of preoperative lesion status [49]. Another retrospective study of 307 cases found 90.9% success at a ~30-month follow-up, with smaller lesions healing more predictably; sealer extrusion, observed in nearly half the cases, did not affect outcomes [56].
Advantages include dentin bonding and reduced microleakage, mechanical interlocking, long-term sealing through apatite deposition [9], antimicrobial activity [21], and good tissue tolerance [53]. Limitations are the difficulty of removal during retreatment once fully set, as conventional solvents are ineffective and ultrasonic or mechanical methods are required [57,58]. Nevertheless, retreatment is possible and working length can be regained when proper techniques are used [59]. Setting time and solubility vary among products: BioRoot RCS sets in <4 h and promotes HA formation [60], whereas AH Plus Bioceramic sets faster but has higher solubility, potentially compromising obturation quality [15]. Low viscosity may also complicate manipulation [60]. Despite these limitations, bioceramic sealers are now the most widely used sealer type among endodontic specialists due to their biocompatibility and consistently high success rates.

Use of Bioceramic Materials as Sole Root Canal Filling

In certain cases where conventional obturation with gutta-percha and sealer is not feasible, or where retreatment is unlikely, bioceramic materials alone have been suggested as an effective alternative for root canal filling [21]. Studies on calcium silicate–based materials such as MTA and Biodentine have shown that they can be used as full-length root filling materials without gutta-percha, providing success rates comparable to traditional techniques [50,61,62]. Both MTA and Biodentine exhibit slight expansion upon setting, ensuring tight adaptation to dentinal walls and creating a leak-proof seal [61]. Acting as a monoblock, these materials integrate with dentin and may reinforce structurally compromised teeth, unlike gutta-percha, which does not bond to dentin [61,63].
In a comparative study, Al-Hezaimi et al. [64] reported that canals filled exclusively with Gray or White ProRoot MTA achieved superior sealing compared with conventional gutta-

percha–sealer combinations. Similarly, Mousavi et al. [65] demonstrated that Biodentine, ProRoot MTA, and Ortho MTA exhibited comparable microleakage performance. In addition, single-visit MTA obturations in cases of apical periodontitis were associated with lower postoperative pain compared with conventional gutta-percha obturations [66]. Ortho MTA (BioMTA, Seoul, South Korea) has been proposed as a newer material specifically for orthograde root filling [67]. Structurally similar to ProRoot MTA but with lower heavy metal content, Ortho MTA is claimed by the manufacturer to form a hydroxyapatite-based interface with dentin, reducing microleakage, while releasing calcium ions that neutralize apical pH and promote periodontal regeneration [67].

This gutta-percha–free obturation concept, however, carries certain limitations: MTA is difficult to manipulate, has a long setting time, and poses discoloration risk due to bismuth oxide [68]. Furthermore, fully set MTA and Biodentine are significantly more difficult to remove than gutta-percha, complicating retreatment. High-quality long-term clinical trials are also still limited [62].

Role of Bioceramic Materials in Apexification and Regenerative Endodontic Treatment

Apexification is used in necrotic immature teeth with open apices to create a hard tissue barrier, enabling root canal treatment. Traditionally, long-term calcium hydroxide protocols were employed; however, in the past decade, single-visit apexification with MTA or Biodentine has become common [69]. Placement of a 3-5 mm apical plug in a moist environment provides rapid barrier formation, eliminating months of calcium hydroxide applications [70]. Compared with calcium hydroxide, MTA apexification offers greater success and practicality, with reported rates of 81-100% [71-73]. A randomized trial confirmed comparable periapical healing to calcium hydroxide but with fewer visits [69]. Importantly, trauma-related necrotic teeth treated with MTA apexification show longer survival than those treated with calcium hydroxide [74].

In recent years, regenerative endodontic treatments (RETs) have emerged as alternatives, aiming to continue root development. Both RET and apexification provide high short- and mid-term success, but RET yields greater increases in root length and wall thickness [75,76]. Thus, RET is preferred in teeth with wide apices, while MTA apexification remains reliable in more advanced roots [70].

RET seeks to restore pulp-dentin complex function in necrotic immature teeth [77], particularly in young patients where continued root development is crucial [78]. Conventional treatment is challenging due to open apices and thin walls, halting root growth and predisposing to fracture; calcium hydroxide-treated teeth show cervical fracture rates of 28-77% [79]. RET, also called revascularization, follows a disinfection protocol with minimal instrumentation, NaOCl/EDTA irrigation, and temporary medicament, followed by induction of apical bleeding and sealing of the blood clot with a bioceramic material. EDTA additionally releases dentin growth factors that enhance stem cell attachment [80,81].

Bioceramics play a critical role in RET due to their excellent bioactive behavior, antibacterial action, and sealing capacity [80,82]. Among them, MTA remains the most frequently applied material, being reported in over 85% of RET studies [84]. It offers chemical stability, mechanical durability, and reliable dentin bridge induction; however, limitations include a prolonged setting period, challenging manipulation, and the risk of discoloration associated with bismuth oxide [50,85]. Biodentine shows outcomes similar to MTA [86,87]. Meta-analyses report RET and apexification both achieve ~85-100% success, but RET results in significantly greater increases in root length and dentin thickness [70,76]. A systematic review reported average gains of 15-20% [70]. Histology suggests the new tissue is often cementum- or bone-like rather than true dentin [88].

Combining bioceramics with scaffolds such as PRF or PRP further improves regenerative outcomes [89]. Figure 3 shows clinical images of a RET performed in our clinic. The patient had a history of dental trauma six years earlier and was diagnosed with pulp necrosis and immature root development. RET was initiated using Biodentine and PRF was used as the scaffold material. At the 3-month follow-up, radiographic evaluation revealed initial signs of periapical healing, accompanied by increased trabeculation in the periapical region, indicating favorable tissue response. Long-term follow-up of the patient is ongoing to further assess root maturation and periapical repair.

The main disadvantages of bioceramics in RET are potential discoloration and rare complications such as ankylosis or canal obliteration, though these are infrequent [70]. Overall, RET provides a biologically based alternative to conventional therapy, re-establishing pulp tissue function and supporting root maturation, with expanding indications in young patients.

Management of Perforations with Bioceramic Materials

Complications such as pulpal floor and strip perforations, or those associated with internal resorption, may occur during endodontic procedures. Prognosis depends on perforation size, location, timing, and delay before repair [90]. The aim of endodontic treatment is to eliminate microorganisms and achieve a hermetic seal, promoting periapical healing and preventing reinfection [34]. Perforations disrupt tooth structure, increase infection risk, and, if left untreated, trigger periodontal inflammation [90]. Studies show ~53% occur during prosthetic procedures and ~47% during endodontic treatment [91].

Pulpal floor perforations often result from access preparation, instrumentation, post space preparation, misdirected instruments, excessive force, or poor visualization [90]. Signs include persistent bleeding in vital teeth, unexpected pain, and later swelling or discharge if infected [90]. Strip perforations, lateral defects in the root wall, occur mainly during preparation of curved canals, often with other complications [92]. Symptoms are pain, swelling, foul discharge, and localized inflammation [93]. Prevention requires careful access, shaping, and knowledge of anatomy.

Perforations should be sealed immediately, as delay worsens prognosis [90]. Small, fresh perforations are often repaired nonsurgically with MTA; larger or chronic cases may require surgical debridement, MTA placement, and sometimes grafts or membranes. In furcation areas, MTA combined with guided tissue regeneration supports bone formation and healthy periodontal reattachment [94,95].

Historically, materials such as amalgam, gutta-percha, calcium hydroxide, Super-EBA, IRM, glass ionomer, and composites were used, but none consistently restored periodontal attachment [96]. Today, bioceramics are the gold standard [95]. MTA is preferred for its marginal seal, ability to set in moisture, biocompatibility, and cementogenic/osteogenic stimulation. It promotes new cementum and fiber reattachment, enabling periodontal regeneration when properly applied [93,95].

Calcium silicate cements like MTA have high pH (~12.5) and induce hydroxyapatite formation, providing antibacterial effects and bonding to dentin [90]. Success rates for MTA in perforation repair range from 80% to 90% [95,97-100]. A meta-analysis of 188 cases reported 72.5% overall success but 81% with MTA [99]. Pontius et al. [100] found 92% success with MTA versus 85% with other materials. Pace et al. [101] observed resolution of symptoms and periapical healing at 5-year follow-up. Collectively, bioceramics show superior and consistent outcomes, enabling successful rehabilitation of cases once considered hopeless.

Repair of Resorption Defects with Bioceramic Materials

Root resorption is the loss of dental hard tissue due to odontoclastic activity [102,103]. In primary teeth it is physiological, but in permanent teeth it may occur internally or externally [104]. Internal resorption, first reported by Bell in 1830, develops during or after endodontic treatment and may involve dentin, the canal, or pulp chamber [105]. Causes include chronic pulpitis, trauma, orthodontics, and bleaching [105]. Most patients are asymptomatic, with diagnosis often radiographic; radiographically, it appears as a round radiolucency centered in the canal [104,105].

External surface resorption is usually noninfective and pressure-related; once the cause is removed, it often arrests and repairs with cementum. Orthodontic forces, impactions, cysts, and tumors are common factors, while prior trauma increases risk [104,106]. Severe lesions may cause substantial root loss. External inflammatory resorption (EIR), seen with chronic apical periodontitis or trauma (e.g., avulsion, luxation), progresses when necrotic pulp allows bacterial invasion. Caries, leakage, and failed root canal therapy are frequent causes [104].

Because vital pulp is needed for internal resorption, immediate treatment is essential. Conventional root canal therapy principles apply, with emphasis on sealing the resorptive cavity. Due to irregular geometry, gutta-percha alone is insufficient; thermoplastic techniques, particularly warm vertical compaction, provide superior sealing [107]. When perforation occurs, defects are repaired with bioceramic hydraulic cements (MTA, Biodentine), sometimes in combination with gutta-percha [108]. If internal repair is not possible, surgical access, debridement, and bioceramic repair may be required. Severely compromised teeth may necessitate extraction [104].

External surface resorption management focuses on eliminating the cause. Orthodontic-related cases may stabilize after pausing or stopping treatment; lesions often arrest within 6-12 months post-appliance removal [109,110]. For EIR, root canal therapy disinfects the canal and halts progression; in trauma-related cases, treatment should not be delayed (7-10 days for avulsed teeth). Calcium hydroxide dressings for weeks to months are commonly used; antibiotic–corticosteroid combinations may reduce inflammation but lack strong evidence [111].

Bioceramic root filling materials are advantageous in EIR due to their biocompatibility, sealing, and support for periodontal reattachment [112]. In external cervical resorption, MTA filling helps preserve healthy tissue, inhibit osteoclasts through its alkaline pH, and stimulate cementum/bone formation [104].

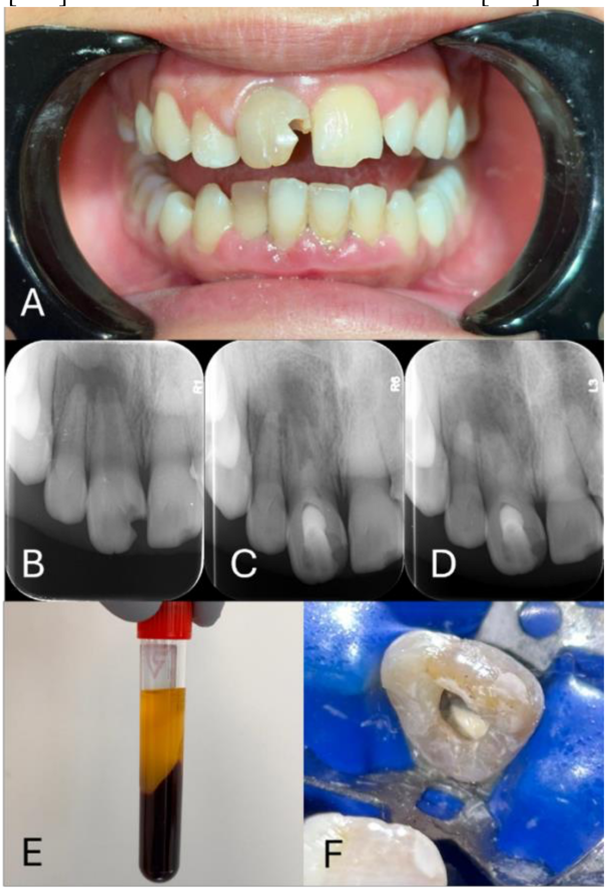

Figure 3. Clinical and radiographic views of a regenerative endodontic treatment case. (A) Preoperative intraoral view showing coronal fracture. (B) Initial periapical radiograph prior to treatment. (C) Immediate postoperative radiograph following regenerative procedure. (D) Three-month follow-up radiograph demonstrating progressive periapical healing. (E) Platelet-rich fibrin (PRF) tube prepared for use as a biological scaffold. (F) Intraoral view following placement of Biodentine as a coronal barrier.

Bioceramics in Apical Surgery

In endodontic surgical procedures, following curettage of the periapical lesion and resection of the root tip, it is essential to seal the canal apically with a retrograde filling. In the past, materials such as amalgam, gutta-percha cones, Cavit (3M ESPE, St. Paul, MN, USA), glass ionomer cements, zinc oxide-eugenol reinforced cements (IRM, Super-EBA), composite resins (Retroplast), compomers, and polymers (Diaket) were used. Today, however, MTA and related bioceramics are the materials of choice for retrograde filling [113].

The superiority of MTA in retrograde filling lies in its tissue-friendly nature and ability to set in moist or even bleeding apical environments. Moreover, when applied to the resected root end, MTA demonstrates excellent adaptation with surrounding bone and periodontal tissues, induces minimal inflammation, and gradually promotes the formation of a hydroxyapatite-like layer at the root tip, thereby enhancing the apical seal [113,114].

Clinical studies and systematic reviews conducted over the past decade have consistently reported high success rates for apical surgeries using MTA as a retrograde filling. When performed with proper microsurgical technique, apical surgeries with MTA retrograde fillings yield success rates of 90-95% over 1-4 years [115,116]. In a 4-year study by Öğütlü et al. [117] success rates were 92.9% with MTA retrograde fillings compared with 89.3% for Super-EBA; although the difference was not statistically significant, the trend favored MTA. Another study [118] comparing MTA with the zinc oxide-eugenol-based IRM reported ~85.6% success for MTA and ~75.5% for IRM. Collectively, these findings demonstrate that bioceramic materials are at least as effective as traditional materials, and in many cases provide more consistent outcomes as retrograde filling agents.

In modern endodontic microsurgery, retrograde cavity preparation is typically performed using ultrasonic tips, and MTA or newer premixed bioceramic putties (e.g., EndoSequence BC RRM, TotalFill RRM) are employed [113]. This has largely eliminated the problems of coronal leakage and tissue irritation previously associated with amalgam retrofills. A 10-year follow-up study involving 119 teeth [119] found that apical surgeries with MTA retrograde fillings achieved complete healing of lesions in 86% of cases, while 93% of teeth remained functional in the oral cavity.

In summary, MTA and related bioceramics have become indispensable in modern apical surgery, significantly improving the prognosis of teeth with severe periapical pathologies and increasing the likelihood of long-term tooth retention.

Bioceramics in Periodontology, Implantology, and Restorative Dentistry

Bioceramic materials, while primarily developed for endodontics, have also found meaningful applications in periodontology, implantology, and restorative dentistry. In periodontal therapy, MTA and Biodentine are used to seal root surface defects such as furcation lesions and endo-perio communications; placed during surgery, they not only occlude exposed dentinal tubules to prevent bacterial penetration but also promote cementum and bone regeneration owing to their osteogenic potential. Both animal and clinical studies have demonstrated that MTA can support the reattachment of collagen fibers and the development of new periodontal ligaments, particularly when combined with guided tissue regeneration techniques, leading to improved long-term healing in furcation sites [94,95,120]. In implantology, although evidence is still limited, bioceramics have been applied in the management of rare conditions such as retrograde peri-implantitis, where apical cavities around implants are filled with MTA or related materials to promote periapical sealing [121].

Additionally, case reports suggest the potential of customized β-tricalcium phosphate scaffolds in reconstructing large alveolar ridge defects, achieving successful bone regeneration with reduced morbidity compared with autogenous grafts, highlighting a promising but still experimental role for bioceramics in peri-implant surgery [122,123].

In restorative dentistry, bioceramics are not typically used as definitive occlusal restorative materials but play a supportive role as core build-up substances or as dentin substitute bases in deep cavities.

Biodentine, in particular, has been shown to exhibit mechanical properties similar to dentin, a dentin-like elastic modulus that favors stress distribution, and protective effects against secondary caries, allowing it to serve as a temporary core before definitive crown placement [86,124]. Clinical studies have reported comparable fracture resistance of Biodentine cores to resin-modified glass ionomer and composite cores, with some authors even suggesting it may be the most suitable core material for certain clinical contexts [125].

Nevertheless, due to their immediate curing and superior mechanical strength, resin composites remain the predominant choice for permanent cores, while Biodentine is more often employed as a liner or base layer to biologically reinforce restorations [1,86,124,125]. Taken together, current evidence indicates that bioceramics, by combining sealing ability, biocompatibility, and regenerative potential, offer distinct advantages in interdisciplinary applications, and their role in periodontology, implantology, and restorative dentistry is likely to expand as further high-quality studies confirm their clinical benefits [94-126].

Conclusion

The introduction of bioceramic materials into dentistry over the past three decades has led to a paradigmatic shift in clinical practice, significantly improving treatment outcomes across a wide spectrum of procedures, including apexification, vital pulp therapy, perforation repair, root canal filling, regenerative endodontic procedures, and apical surgery. Initiated with the development of MTA, this evolution has expanded with newer formulations such as Biodentine, BioRoot RCS, the iRoot series, and EndoSequence BC. Their superior biocompatibility, bioactivity, antibacterial effects derived from high alkalinity, and chemical bonding to dentin promote dentin bridge and cementum formation, thereby supporting both hard and soft tissue healing. Nonetheless, certain limitations remain, including handling difficulties, prolonged setting times, risk of tooth discoloration, and challenges in retreatment cases. Current literature indicates that, when applied with proper case selection and careful adherence to clinical protocols, bioceramic-based materials continue to represent an indispensable component of modern endodontic practice, ultimately enhancing long-term tooth survival and offering patients more biologically oriented and conservative treatment options.

Conflict of interest: None to declare.

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