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Evolution of root canal obturation philosophy and materials: from mechanical filling to biological regeneration

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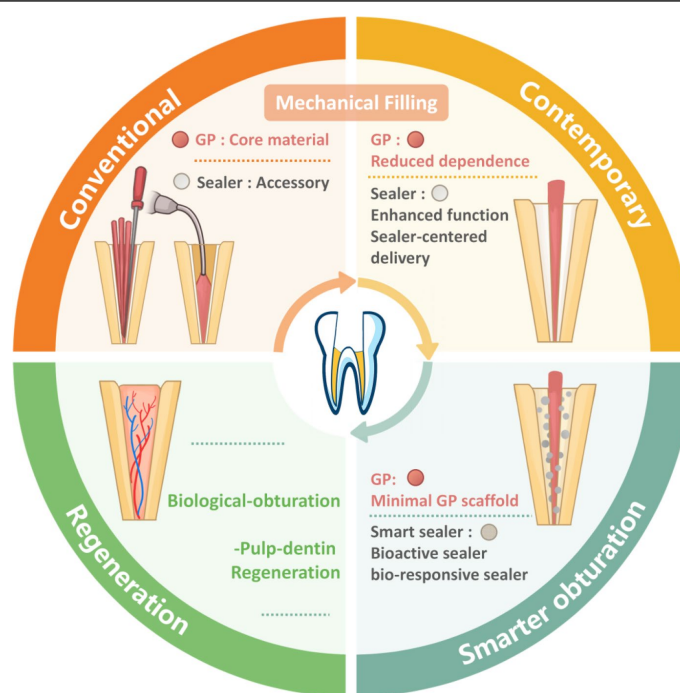
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ABSTRACT: Root canal obturation has evolved over the past two centuries with the advancement in root canal instrumentation and irrigation, as well as endodontic microbiology, biomaterials science and regenerative medicine. Traditionally, obturation was regarded as a mechanical procedure aimed at filling and sealing the disinfected root canal system with inert materials to prevent bacterial leakage and reinfection. The introduction of gutta-percha and root canal sealers established the foundation of modern obturation, while subsequent developments focused on improving sealing ability, dimensional stability, adaptability, and clinical handling through techniques such as lateral condensation, warm vertical compaction, thermoplasticized injectable systems, carrier-based obturation, and contemporary single-cone techniques. However, increasing understanding of biofilm-mediated infection has shifted emphasis toward effective disinfection and biological healing rather than obturation technique alone. The emergence of calcium silicate-based bioceramic sealers and other smart biomaterials has further transformed obturation concepts by introducing bioactive, antimicrobial, mineralizing, and regenerative properties. In addition, regenerative endodontic procedures and tissue engineering strategies have challenged the traditional requirement of canal filling by demonstrating that biologic tissue ingrowth may achieve favorable outcomes under appropriate conditions. Collectively, these developments indicate that obturation is evolving from a passive space filling procedure into a future biologically responsive and patient-specific therapeutic strategy.

KEYWORDS: root canal obturation, mechanical filling, smart biomaterials, regenerative endodontics, tissue engineering



1 Introduction

A successful root canal therapy requires thorough cleaning, shaping, and obturation of the canal space in three dimensions^[1]. Root canal obturation is traditionally intended to create a three-dimensional seal within the disinfected root canal system to entomb residual microorganisms and prevent microleakage. This concept has been central to endodontic treatment philosophy, based on the well accepted principle that microbial persistence within the root canal system remains the primary etiological factor associated with

apical periodontitis and endodontic treatment failure^[2,3,4].

Clinical outcome studies have clearly demonstrated that the quality of obturation significantly influences long-term success of endodontic treatment^[5,6]. In primary root canal treatment, higher success rate is associated with that when root canal filling terminates within 0–1 mm of the radiographic apex and appears radiographically appropriate^[5,6]. In root canal retreatment cases, the canal obturation quality, primarily assessed radiographically, has been well approved as a prognostic factor for successful outcomes^[7,8]. In endodontic apical microsurgery, the root end retrofilling showed higher success than those without fillings^[9], and using materials that provide better margin adaption and apical sealing, such as MTA or Bioceramic putty, showed higher success rate than those using the traditional materials such as amalgam or

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IRM^[10,11]. These clinical studies firmly support the concept that adequate obturation plays an important role in success of endodontics treatment.

Historically, the philosophy of root canal obturation has been largely mechanical in nature. The main goal of the obturation was to occupy the prepared canal space with inert materials capable of preventing bacterial penetration and fluid leakage. Consequently, the development of obturation materials and techniques has traditionally focused on optimizing physical properties such as dimensional stability, adaptability to canal walls, ease of placement, radiopacity, and removability during retreatment if case was failed^[12,13].

The advances in endodontic microbiology and microbiome research have revealed that root canal infections are complex biofilm-mediated processes involving a diverse pool of microbial communities^[14,15]. Biofilms exhibit tolerance to antimicrobial agents, have the capacity to recover after exposure to disinfectants, and may persist even after thorough chemomechanical debridement^[15-18]. This understanding has led to the recognition that obturation must function in conjunction with effective pre-obturation disinfection protocols, and additional benefits may be achieved if antimicrobial or biofilm-control properties are integrated into obturation materials or techniques^[19,20].

More recently, the emergence of regenerative endodontic procedures and advancement of smart dental materials have led to a reassessment of the traditional objectives of root canal obturation. The advanced approaches emphasize the importance of biological compatibility and the interaction between the smart materials and host tissues through bioactive mechanisms such as ion release, antimicrobial activity, stimulation of mineralized tissue formation, and promote wound healing^[21-23]. These developments indicate that the role of obturation evolves from a passive sealing strategy toward a more biologically active and integration.

The purpose of this article is to review the evolution of root canal obturation materials and techniques within the broader context of the advancement of endodontic philosophy. Key obturation materials and techniques from different historical stages will be discussed, and the current biological understanding and the development of new obturation strategies will be summarized. These advances have shaped contemporary obturation concepts and continue to influence future directions in endodontic therapy.

2 Gutta-percha era: the cornerstone of modern Endodontics

2.1 Pre Gutta-percha era: early attempts

The early attempts to treat pulp diseases were primarily focused on alleviating pain. From 18th to mid of 20th century, before the bacterial theory of pulp disease was fully established and accepted, various materials had been used to fill the root canal space after removal of diseased pulp tissue. In 1830s' Dr. Edward Hundson started practicing dentistry in Philadelphia by removing pulp and filling up the cavity and canal. He designed his own pluggers to fill the canals with gold foil. The materials used in that time, such as gold, tin, lead wire, were simply inserted into canal and intended to occlude the space and hope to prevent reinfection^[24]. These early obturation methods were largely empirical and were implemented in the absence of a comprehensive understanding of microbiology or aseptic technique. As a result, many treatments focused on

mechanical canal filling rather than on effective disinfection of the root canal system, led to the failure and tooth extraction^[25].

2.2 Adoption of Gutta-percha and sealer

Gutta-percha, a natural polymer derived from the latex of trees belonging to the genus *Palaquium*, was first introduced into dentistry in the early 19th century. Initially it was used as a restorative and temporary filling material. In 1847, Dr. Truman introduced the use of gutta percha as a root canal filling material due to its unique physical and chemical properties^[24,25]. The thermoplastic property allows it to soften when heated and return to a solid state upon cooling, enabling better adaptation to canal system^[26,27,28]. Gutta-percha undergoes phase transitions between the alpha and beta crystalline forms when exposed to temperature changes, which can influence the flow characteristics and dimensional stability^[28,29]. Overall, Gutta-percha maintains good dimensional stability and has minimal shrinkage within the root canal. It is considered biologically inert and generally well tolerated by periapical tissues^[29,30]. Numerous studies have demonstrated that gutta-percha elicits minimal inflammatory response when confined within the root canal system, contributing to its long-standing clinical acceptance^[30,31,32]. By the early 20th century, gutta-percha had become the primary material used for root canal filling. It became more widely accepted later when standardized size of gutta-percha cones developed, in correspondence to standardized endodontic instrument, enabling clinicians to achieve more predictable canal filling techniques^[33].

In 1925, Dr. Gustav Emil Rickert proposed "hollow tube effect", stating a hollow and unfilled tube tends to become a site of persistent irritation and inflammation^[34]. Although this theory was refuted later by Dr. Ake Brynstrom^[35,36,37], the poorly obturated or unfilled canal with bacteria contamination is well-accepted key factor leading to the persistent infection. Based on this theory, Dr. Rickert advocated the use of a sealer along with gutta percha for obturating root canals. In 1925, he developed Rickert's sealer, a zinc oxide eugenol based root canal sealer. This was the beginning of the era of root canal sealer^[38].

Sealers play an essential role in filling very fine gaps between the gutta-percha and canal walls. Traditional sealers were based primarily on zinc oxide-eugenol formulations, which has acceptable sealing ability and certain antimicrobial properties due to eugenol release. However, their physical limitations, including solubility, shrinkage upon setting, and microleakage, have been repeatedly demonstrated in leakage and fluid filtration studies^[40]. Calcium hydroxide-based sealers were historically introduced to take advantage of their high pH and antibacterial potential. However, their clinical performance has been limited by physical properties, particularly solubility and dimensional instability over time, leading to a compromised long-term sealing ability^[40,41]. As a result, both calcium hydroxide-based and ZOE-based sealers were progressively recognized as less reliable when used as primary obturation sealer materials^[40,41,42]. Later, epoxy resin-based sealers, particularly AH Plus, were developed by enhancing dimensional stability, flow, and sealing ability. Studies have demonstrated that epoxy resin sealers exhibit low solubility and minimal dimensional change after setting, contributing to improved adaptation to root canal walls compared with traditional sealers^[43-46]. However, despite their improved physicochemical properties, resin-based sealers may still exhibit some degree of polymerization-related shrinkage and incomplete adaptation in complex canal anatomies, which can

contribute to microleakage under certain conditions^[45]. More recently, calcium silicate-based bioceramic sealers have gained popularity due to their bioactivity, dimensional stability, and potential to stimulate mineralized tissue formation^[39] (Table 1).

2.3 Other attempts for core materials

Since gutta-percha was introduced as an obturation material for root canal therapy, it has undergone various modifications by innovative clinicians. In 1883, Drs. Perry and Bowman wrapped gutta-percha around a gold wire and coated gutta-percha points with shellac to facilitate compaction into the root canal. In 1901, Dr. Buest recommended placing a silver wire core inside gutta-percha to provide rigidity. These approaches represented early concepts of carrier-based gutta-percha obturation. In 1895, Dr. Bowman introduced the use of a chloroform solution to dissolve gutta-percha for root canal obturation (chloropercha)^[24]. As a softened and flowable material, chloropercha was intended to improve adaptation to canal walls and anatomical irregularities, reflecting an early effort toward “three-dimensional” obturation^[38,47].

There were also attempts to develop other obturation core materials to replace gutta-percha. In 1890, Dr. Gramm introduced copper points. In 1897, Dr. Tomes also tried to use paraffin to fill the canals, which further advocated by Dr. Prinz in 1912, who recommended high melting-point paraffin for filling root canals. In 1925, Dr. Husband used copper amalgam to fill canals. And in 1933, Dr. Jasper first used silver points for root canal filling. Silver points have rigid metallic structure which allows easy insertion into canal with minimal risk of breakage. Its excellent radiopacity enables clinicians to check on radiography. Silver points were made with standardized dimensions and taper, which facilitates the emerging concept of standardized root canal instruments. The technique required relatively minimal instrumentation and was less technique-sensitive than condensation methods used with other materials. Till the mid-20th century, silver points became widely adopted in clinical practice^[38,47].

Despite their initial popularity, long-term clinical observations revealed significant limitations associated with silver point obturation. The primary concern was corrosion of the metallic surface when exposed to tissue fluids, demonstrated by Dr. Seltzer in 1972. The corroded silver points release cytotoxic silver sulfide and other compounds, not only cause discoloration, but also induce inflammatory reactions^[48]. Compared to thermoplastic materials, the rigidity of silver point also has limitation to adapt the complex

anatomy of root canal system, which create voids for microleakage and lead to higher failure rate^[48,49]. These limitations ultimately led to the gradual abandonment of silver point obturation. In last decades, although numerous attempts have been made to develop new core materials as substitutes for gutta-percha, none have successfully replaced it in clinical practice. Gutta-percha therefore remains the dominant core material used for root canal obturation to date.

Another notable attempt was the Hydron system, introduced during the 1970s^[50]. Hydron was based on poly(2-hydroxyethyl methacrylate) (poly-HEMA), a hydrophilic polymer originally developed for biomedical applications such as soft contact lenses. The material was delivered as an injectable root canal filling system and was intended to undergo slight hygroscopic expansion after placement, thereby improving adaptation to canal walls and reducing leakage^[51,52]. However, later investigations identified several important limitations, including incomplete polymerization and increased solubility over time, leading to dimensional instability and leakage^[53]. Furthermore, the material was difficult to remove during retreatment. Histologic studies also reported variable periapical tissue responses associated with residual monomer release and degradation products^[53-56]. As a result, despite initial enthusiasm, Hydron failed to achieve widespread clinical acceptance. Collectively, these early attempts to find alternative obturation materials highlighted the challenges associated with developing a material capable of simultaneously achieving adequate sealing ability, biocompatibility, dimensional stability, and retreatability.

2.4 Monoblock concept

The interface between obturation materials and dentin, and between sealer and core material, is a critical determinant of obturation quality. Ideally, the sealer should provide a stable interface with dentin and the cone material that minimizes microleakage. This consideration has driven the development of adhesive obturation strategies aimed at improving interfacial integrity within the root canal system.

The monoblock concept in endodontics refers to the creation of a mechanically homogeneous and bonded unit within the root canal system, in which the obturation material, sealer, and dentinal walls function as a single cohesive structure. The term “monoblock,” meaning a single unit, was adapted from restorative dentistry and later introduced into endodontics with the development of adhesive obturation systems. Drs. Tay and Pashley classified endodontic monoblocks into primary, secondary, and tertiary forms according

Table 1 Classification of root canal sealers.

Category	Main Composition	Key Properties	Advantages	Limitations	Examples
Zinc oxide–eugenol (ZOE)	ZnO + eugenol	Antimicrobial, moderate flow, soluble over time	Long clinical history, easy handling	High solubility, weak bonding	Grossman-type sealers
Calcium hydroxide-based	Ca(OH) ₂ in resin or ZOE base	Alkaline pH, antimicrobial potential	Biologic activity, mild tissue compatibility	Unstable sealing, dissolves over time	Sealapex
Glass ionomer-based	Fluoroaluminosilicate glass	Ionic bonding to dentin	Low solubility, fluoride release	Brittle, difficult retreatment	Ketac-Endo
Epoxy resin-based	Epoxy resin matrix	Strong adhesion, low solubility	Excellent sealing, long-term stability	Cytotoxic before setting	AH Plus
Methacrylate resin-based	Methacrylate monomers	Adhesive, polymerizable	Potential monoblock effect	Polymerization shrinkage, technique sensitive	Epiphany/RealSeal
Silicone-based	Polydimethylsiloxane	Flowable, inert	Biocompatible, low shrinkage	No adhesion to dentin	GuttaFlow
Bioceramic/calcium silicate-based	Calcium silicates, phosphate, radiopacifiers	Bioactive, forms hydroxyapatite, alkaline pH	Highly biocompatible, moisture setting	Variable flow	EndoSequence BC Sealer

to the number of interfaces between the core material, sealer, and dentin. A primary monoblock contains a single interface between the material and canal wall, whereas secondary and tertiary monoblocks contain two or more bonded interfaces^[57].

The monoblock concept gained considerable attention with the introduction of resin-based obturation systems such as Resilon, used in combination with resin sealers including Epiphany or RealSeal. These systems were designed to bond simultaneously to dentin and the core filling material, theoretically improving sealing ability, reducing microleakage, and reinforcing endodontically treated roots against fracture. Several *in vitro* studies reported increased fracture resistance in teeth obturated with Resilon compared with conventional gutta-percha-based systems^[58-61]. However, subsequent systematic reviews demonstrated inconsistent results regarding bond strength and long-term clinical superiority. A recent systematic review found that tertiary monoblock obturation systems did not consistently outperform conventional obturation techniques in physicomaterial properties, although comparable bond strength was observed when warm vertical compaction was used^[62]. Consequently, although the monoblock concept remains an important theoretical framework in adhesive endodontics, its clinical advantages over traditional gutta-percha and sealer systems have not been conclusively established.

3 Classical obturation techniques

3.1 Lateral condensation

Cold lateral condensation has historically been widely taught and utilized obturation techniques. In this technique, a master gutta-percha cone is placed to the working length and subsequently compacted laterally using spreaders to create space for accessory cones. This process is repeated until the canal is densely filled with gutta-percha and sealer. This technique offers several advantages, including relative simplicity, predictable length control, and minimal requirement for specialized equipment.

However, the method also presents certain limitations: it generates internal stress within the root, potentially increasing the risk of vertical root fracture. The cold lateral condensation also often produces heterogeneous fillings and may contain voids. Furthermore, cold compaction methods are limited in their ability to adapt gutta-percha to the complex internal anatomy of the root canal system^[26].

3.2 Warm compaction technique

Root canals frequently contain fins, isthmuses, accessory canals, and other irregular morphologies that cannot be filled by rigid gutta-percha cones alone^[26]. These anatomical complexities led the exploration of methods for thermoplasticizing gutta-percha to improve its flow characteristics during obturation. Dr. Schilder first introduced the concept of warm vertical compaction in the late 1960s, emphasizing the importance of continuously compacting softened gutta-percha in an apical-to-coronal direction to achieve a three-dimensional seal^[1]. In this approach, heated instruments are used to soften gutta-percha within the canal and compact it apically, allowing it to flow and adapt to canal irregularities and accessory anatomy^[27,28]. The rationale for thermoplastic obturation techniques is to achieve a more homogeneous and three-dimensional root canal filling. Compared with traditional cold lateral condensation, warm vertical compaction techniques have

consistently demonstrated the ability to produce denser root canal fillings with fewer voids and superior adaptation of gutta-percha to canal walls^[63-65]. Traditional warm vertical compaction techniques generally involved repeated cycles of heat application using heated pluggers followed by incremental vertical condensation. Although effective, these methods were often technique-sensitive, time-consuming, and associated with risks of overextension or inconsistent heat transfer.

To simplify and improve the efficiency of warm obturation, Dr. Buchanan later introduced the continuous wave of condensation technique, which became one of the most widely adopted modifications of warm vertical compaction^[66]. In this technique, a plugger connected to an electrically controlled heat source is driven apically in a single continuous motion through the master cone, simultaneously softening and compacting the gutta-percha. The apical portion is condensed during the “down-pack” phase, followed by thermoplasticized backfilling of the remaining canal space. Compared with traditional stepwise warm vertical condensation, the continuous wave technique reduces procedural complexity and operative time while maintaining dense and homogeneous obturation patterns^[67,68].

Numerous studies have demonstrated that continuous wave obturation produces fillings with improved adaptation to canal walls and fewer voids compared with cold lateral condensation. In addition, the technique has shown favorable penetration of gutta-percha into lateral canals and irregular canal anatomy^[70-72]. Nevertheless, as with other thermoplasticized techniques, excessive heat generation, apical extrusion of material, and technique sensitivity remain potential limitations^[73].

3.3 Injectable and warm techniques

The development of injectable thermoplasticized gutta-percha systems represented another advancement in root canal obturation. These systems were designed to soften gutta-percha within a specialized heating device until it reached a flowable consistency, allowing delivery through a narrow-gauge needle or cannula into the prepared root canals^[73]. The underlying rationale was to improve the three-dimensional adaptation of gutta-percha to canal walls, lateral canals, isthmus and other anatomical irregularities that are often inadequately filled by conventional cold compaction techniques.

One of the earliest and most widely used injectable systems were the Ultrafil and Obtura device, which enabled low-temperature and high-temperature injection of thermoplasticized gutta-percha, respectively^[74-75]. During obturation, softened gutta-percha was typically delivered incrementally and compacted vertically with pluggers to enhance density and minimize void formation. Studies demonstrated that injectable thermoplasticized techniques could produce more homogeneous fillings, improved adaptation to canal irregularities, and facilitated more efficient obturation^[69,70,77].

Despite these advantages, injectable thermoplasticized techniques were associated with several limitations: Precise control of temperature, injection pressure, and apical control^[72]. Excessive heating could also alter the physical properties of gutta-percha, whereas rapid cooling and shrinkage occasionally contributed to void formation or compromised sealing ability^[73]. Consequently, injectable thermoplasticized gutta-percha systems eventually evolved into adjunctive tools used primarily for the backfilling phase of warm vertical compaction procedures. Following creation of a dense apical plug using Schilder’s warm vertical compaction or

Buchanan's continuous wave technique, thermoplasticized gutta-percha could be efficiently injected to backfill the remaining canal space^[66]. This combination, particularly the integration of the System B heat source and Obtura systems, became one of the most widely adopted modern evolutions of Schilder's original three-dimensional obturation concept.

3.4 Carrier-based systems

Carrier-based obturation systems were developed as an alternative approach to thermoplasticized obturation. In these systems, a central carrier coated with gutta-percha is heated in a specialized oven and subsequently inserted into the prepared canal to the working length. As the softened gutta-percha flows around the carrier, it adapts to the canal walls and fills the canal space.

One of the earliest and most widely known carrier-based systems is Thermafil. The original Thermafil obturator consisted of a plastic carrier surrounded by a layer of alpha-phase gutta-percha that becomes plasticized when heated. The device is heated in an oven and then inserted into the canal to deliver a uniform mass of gutta-percha^[64,78]. More recently, carrier-based systems have evolved to include cross-linked gutta-percha carriers, such as GuttaCore. Unlike earlier plastic carriers, these systems utilize a central core composed of condensed gutta-percha material, which facilitates easier retreatment compared with plastic-based carriers^[79,80].

Carrier-based obturation systems offer several potential advantages. The technique is relatively simple and efficient, often requiring less time than traditional condensation methods. Additionally, the pre-manufactured design of the obturator can provide consistent delivery of thermoplasticized gutta-percha and reduce operator variability^[81]. However, several limitations have also been reported: Removal of carrier-based obturators during retreatment may be challenging, particularly when plastic carriers are used. In addition, improper placement or excessive pressure during insertion may lead to stripping of gutta-percha from the carrier or apical extrusion of material.

3.5 The "single cone" philosophy: decline and resurgence

The single-cone technique originally emerged as a simplified alternative in which a single master gutta-percha cone, matched as closely as possible to canal preparation dimensions, is placed with sealer to fill the root canal space. Early implementations of this technique were limited by the physical properties of conventional gutta-percha cones and sealers, particularly their inadequate adaptation to canal irregularities and reliance on relatively large volumes of sealer to occupy unfilled spaces. Consequently, the technique was widely regarded as inferior to lateral or warm vertical compaction techniques. However, recent advances in canal shaping, taper-matched cones, and advanced sealer materials have promoted a resurgence of the single-cone philosophy.

3.5.1 Early single-cone techniques

The original conception of the single-cone technique relied on standardized gutta-percha cones placed into prepared canals with a layer of sealer occupying the peripheral space. Conventional gutta-percha cones often poorly approximated the actual three-dimensional geometry of instrumented canals, particularly when hand preparation produced irregular or nonuniform tapers. These mismatches resulted in substantial sealer thickness, particularly in the apical third, which served as a source for micro gaps permitting fluid and bacterial penetration^[81-83]. In addition, conventional sealers

used in these early single-cone approaches, such as zinc oxide-eugenol, exhibit linear dimensional shrinkage upon setting. When these sealers are present in relatively large volumes, shrinkage can exacerbate gap formation at both the sealer-dentin and sealer-gutta-percha interfaces, therefore further compromising the seal^[83].

Early in vitro studies utilizing dye penetration and bacterial leakage models consistently demonstrated higher microleakage associated with single-cone fillings relative to cold lateral compaction or warm vertical techniques^[82,83,84]. MicroCT evaluations and histological analysis of single-cone fills demonstrated voids and incomplete adaptation in multiple canal regions, contributing to the perception that this technique was inferior to lateral or vertical compaction methods which designed to minimize sealer volume^[85,86]. As a result, the single-cone philosophy experienced a period of decline in mainstream endodontic practice.

3.5.2 Technological advancements

The introduction and continuous improvement of nickel-titanium (NiTi) rotary instrumentation represented a milestone in root canal shaping. NiTi instruments produce more predictable taper profiles with smooth canal walls and reduced ledging and canal transportation when compared to traditional stainless steel hand files^[87,88]. This consistency in preparation geometry enabled the development of matched taper gutta-percha cones, which are correspond precisely to the taper and apical dimensions of specific rotary file systems^[85,89].

Matched taper cones confer two primary benefits relevant to single-cone obturation: reduction of sealer volume by improving core fit and enhancement of interface contact between gutta-percha and canal walls. Studies showed that matched cones, compared to nonmatched cones, demonstrated increased sealer penetration depth and surface area coverage in dentinal tubules, particularly in the apical third of the canals^[71,89,90]. These findings suggest that improved geometric adaptation may overcome some of the historical limitations associated with the single-cone technique by reducing void formation and enhancing three-dimensional adaptation within the canals.

High-resolution imaging studies have further demonstrated that canals prepared with contemporary Niti rotary instrumentation systems generally exhibit more centered and uniformly tapered geometries, thereby facilitating the placement of a single matched-taper cone with a reduced volume of interfacial sealer^[71,88]. Micro-computed tomography (MicroCT) analyses have shown that, under well-controlled conditions, matched-taper single-cone obturations may produce void distribution patterns and interfacial adaptation comparable to those achieved with more technique-sensitive condensation methods^[71,80,81,90]. Collectively, these advances in canal preparation, cone standardization, and obturation materials have contributed to renewed interest in the single-cone concept as a clinically viable obturation strategy.

3.5.3 Bioceramic sealers and hydraulic condensation

The most significant development driving the modern resurgence of the single-cone philosophy is the advancement of bioceramic sealers, particularly calcium silicate-based sealers (CSBS). These materials exhibit several properties that distinguish them from traditional sealers, including excellent biocompatibility, negligible shrinkage, and the bioactivity to form a mineralized layer with dentin^[92-94].

The hydraulic condensation concept utilizes the flowability and

bioactivity of CSBS to achieve three-dimensional canal fills without the need for lateral or vertical mechanical compaction. In this method, CSBS is introduced into the prepared canal, and a matched taper gutta-percha cone is inserted to hydraulically distribute sealer into canal irregularities and dentinal tubules^[93,95]. This approach relies on the sealer's flow and chemical interaction with canal walls rather than only mechanical densification to achieve adaptation.

Systematic reviews and meta-analyses of clinical outcomes have indicated that single-cone obturation using bioceramic sealers yields success rates comparable to those reported for traditional warm vertical and lateral compaction techniques^[91,96]. *In vitro* investigations have further demonstrated that void volume and sealer penetration in single-cone obturations are similar to those observed in warm vertical condensation techniques^[90,91,97]. Notably, the effectiveness of hydraulic condensation may be influenced by canal anatomy, with complex canal configurations and severe curvatures continuing to present technical challenges.

The contemporary single-cone technique offers a simplified and highly standardized obturation protocol. By reducing procedural steps and eliminating the need for mechanical compaction, this approach is associated with decreased technique sensitivity and reduced chair time, making it advantageous in both general and endodontic practice settings^[86,97].

3.6 Paste-only obturation systems

Historically various pastes and cements were introduced as sole obturation materials. Most formulations consisted primarily of zinc oxide, eugenol, and chloroform, thereby providing limited antimicrobial activity. However, their long-term dimensional stability and biocompatibility were inconsistent, and treatment outcomes remained unpredictable.

In 1959, Dr. Angelo Sargenti and Dr. Richter introduced N2 paste, a paraformaldehyde-containing root canal cement that remained in clinical use for more than four decades^[98,99]. The material typically contained approximately 6.5% paraformaldehyde in addition to zinc oxide-eugenol components. N2 paste was promoted for its antimicrobial properties and tissue-fixative effects, which were intended to induce so-called "mummification" of residual pulp tissue. However, subsequent investigations demonstrated significant cytotoxicity and adverse tissue reactions associated with paraformaldehyde-containing sealers, including periapical inflammation, bone necrosis, paresthesia, and systemic distribution of formaldehyde-related compounds^[100,101]. Consequently, the use of N2 paste became highly controversial and was progressively abandoned in contemporary endodontic practice.

More recently, mineral trioxide aggregate (MTA) based paste obturation concepts have been introduced as a new paste-only obturation strategy. This approach based on the well-documented bioactivity of MTA, including its ability to release calcium ions, induce hydroxyapatite formation, and promote cementogenesis at the root apex^[102-104]. From a biologic standpoint, MTA has demonstrated favorable tissue compatibility and the potential to enhance periapical healing through stimulation of hard-tissue deposition and reduction of inflammatory response, particularly when in direct contact with periapical tissues^[102]. Preliminary experimental and clinical studies have suggested that MTA-based obturation may provide acceptable sealing ability and encouraging apical tissue responses, especially in cases with open apex or immature root development^[105-107]. However, the high viscosity and poor flow characteristics of MTA limit its ability to fully adapt to

complex canal irregularities. In addition, its relatively slow setting reaction and susceptibility to washout in moist environments during early stages of placement, and time needed for procedure present clinical challenges^[108]. Furthermore, retreatability remains highly limited, as set MTA is difficult to remove. These factors have slowed down widespread adoption of MTA as a standalone obturation material^[106,107].

4 Clinical outcomes of different obturation techniques

Clinical outcomes of root canal obturation techniques have been extensively investigated, and the available evidence indicates that treatment success is primarily determined by adequate chemomechanical disinfection and effective coronal sealing rather than the specific obturation technique applied. Across cold lateral condensation, warm vertical compaction, thermoplasticized gutta-percha techniques, and contemporary single-cone obturation approaches, reported healing rates generally range from approximately 80% to 95% in teeth without preoperative apical periodontitis, with reduced success in cases presenting with pre-existing periapical disease^[6,109].

Comparative clinical studies and systematic reviews have demonstrated no consistent or clinically meaningful superiority of warm vertical compaction over cold lateral condensation in terms of long-term periapical healing^[76,110,111]. Thermoplasticized gutta-percha techniques, including continuous wave condensation, have been shown to improve adaptation and reduce void formation in laboratory studies; however, clinical outcome studies have not consistently demonstrated superior success rate compared with conventional techniques^[112,113]. Contemporary single-cone obturation with CSBS has been evaluated, and results showed comparable success rates to warm vertical compaction when adequate cleaning, shaping, and irrigation protocols are achieved^[90]. However, the current evidence base remains predominantly short- to medium-term follow up, and long-term clinical data are still emerging.

Dr. Sjögren et al. identified preoperative apical periodontitis and the quality of root canal disinfection as the strongest prognostic factors influencing outcome, while obturation quality was of secondary importance^[4]. Drs. Ricucci and Siqueira demonstrated that microbial persistence within complex canal anatomy is the principal cause of post-treatment disease^[15]. Similarly, Dr. Ng et al. reported that obturation technique was not a significant predictor of healing when other clinical variables were controlled^[116]. Collectively, these findings reinforce a biologically centered paradigm of endodontic success.

5 Philosophical shift in obturation: from mechanical space filling to biological sealing

The philosophy of obturation has been evolving in last two decades. The earlier endodontic obturation prioritized mechanical sealing of the root canal space to prevent bacterial leakage. With contemporary evidence showing that the clinical success of root canal therapy is not only depends on obturation, but also on canal disinfection, restorative work and host response, the mechanical filling is shifting to modern perspectives increasingly emphasize a biological rationale, leading to the emerging view of obturation more as a biological interface (Fig. 1).

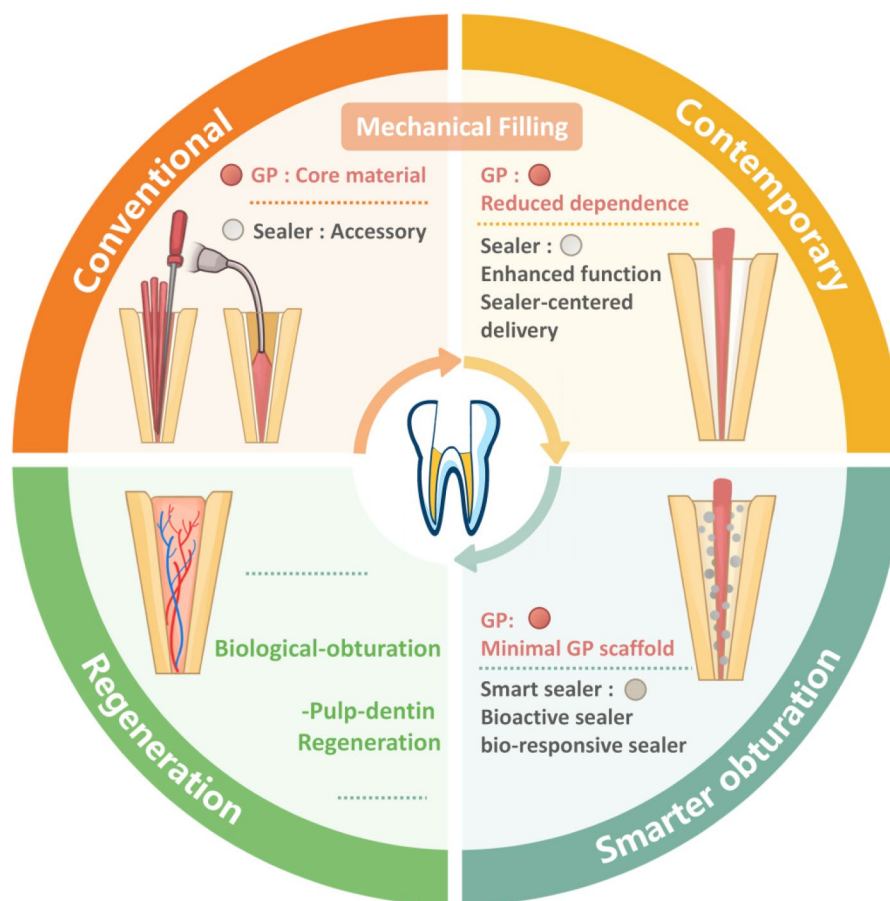


Figure 1 Conceptual evolution of root canal obturation philosophy from conventional mechanical filling toward biologically oriented and regenerative approaches. In the conventional obturation philosophy, gutta-percha (GP) functions as the primary obturation material, whereas the sealer serves mainly as an adjunct to fill minor interfacial gaps. Contemporary obturation concepts increasingly emphasize the role of sealers, particularly calcium silicate-based bioceramic sealers, with gutta-percha functioning more as a carrier for sealer delivery and less as the dominant core material. Emerging smart obturation strategies incorporate bioactive and bioresponsive sealers capable of antimicrobial, mineralization and interaction with the surrounding biological environment. In the regenerative paradigm, traditional mechanical obturation may be replaced by biologic tissue ingrowth and regeneration of pulp- and dentin-like tissues (“bio-obturation”)

5.1 Traditional philosophy

Historically, the obturation phase of root canal treatment was emphasized to achieve a three-dimensional “hermetic seal”^[114]. This concept was derived from the fundamental aim of preventing bacterial and fluid movement between the root canal system and surrounding periapical tissues after chemo-mechanical debridement. Within this scope of concept, gutta-percha is used in combination with sealers, with the intention that the obturation material provide a bacteria- and fluid-tight barrier that entombs residual microorganisms. Techniques such as cold lateral compaction, warm vertical compaction, and carrier-based obturation were developed to compact core and sealer materials into canal irregularities, based on the assumption that denser fills would provide superior sealing and reduced microleakage^[14,16,17].

5.2 Contemporary understanding

In contemporary root canal therapy, with the advancement in obturation materials, particularly the development of bioceramic sealers which have reduced shrinkage and improved chemical and biocompatible properties, it prompted a re-evaluation of the traditional view of sealers as merely adjunctive materials. Increasing evidence suggests that sealer materials may play a more substantive role in the obturation process, challenging the long-standing

dominance of gutta-percha as the primary filling material. This evolving perspective has led to the concept that gutta-percha may function more as a carrier for sealer delivery rather than as the principal obturating material. Consequently, the requirement to closely match gutta-percha to the root canal morphology may be less critical in certain obturation strategies.

These developments have influenced instrumentation philosophies as well. The emphasis on preparing canals to large, standardized shapes has been questioned, with growing interest in minimally invasive approaches that aim to preserve tooth structure while still enabling effective disinfection and sealing. Nevertheless, the clinical implications of these shifts remain an area of ongoing investigation^[115,116].

Another major conceptual shift is the recognition that disinfection plays a dominant role in treatment outcomes. Even the most technically well-executed obturation cannot prevent reinfection if microorganisms persist within canal complexities or dentinal tubules^[16,18]. Instead, mechanical instrumentation combined with chemical irrigation are essentially steps to reduce the microbial load in canal system. The increase of knowledge on biofilm indicated that biofilms exhibit increased resistance to conventional irrigation methods, further underscoring that effective canal disinfection is more critical for periapical healing than the

obturation technique alone^[18].

Over the past decades, a range of advanced irrigation techniques and devices have been introduced, including sonic and ultrasonic activation, apical negative pressure systems, multisonic irrigation system (e.g. GentleWave System), and laser-assisted irrigation. These adjunctive approaches theoretically enhance debridement and disinfection, but it is still lack of robust clinical evidence supporting their superiority^[117,118,119]. These developments have also influenced traditional concepts of canal instrumentation and obturation. Historically, one objective of instrumentation was to create sufficiently large canal spaces to facilitate irrigation with conventional syringe-based delivery. In contrast, the adoption of adjunctive irrigation technologies may reduce the need for extensive canal enlargement, contributing to the growing interest in minimally invasive instrumentation strategies that aim to preserve tooth structure while maintaining adequate disinfection^[115].

5.3 Further evolving: smart obturation

5.3.1 Smart bioactive obturation materials

One of the profound advancements in obturation is the recognition that obturation materials and techniques interact dynamically with dentin tissue and periapical tissue, as well as immune responses and healing cascades, rather than merely serving as inert space fillers. This perspective intersects with developments in material science, particularly the rise of bioactive obturation materials, and the growing appreciation of host response modulation as an integral factor in treatment outcomes.

Bioactive materials are the smart biomaterials that induce a specific biological response at the tissue-material interface after placement or contact with tissues, cells, or body fluids^[120]. Bioactive materials provide beneficial therapy such as antibacterial, regeneration and drug delivery by releasing the therapy “uncontrollably” after being installed in the site^[121].

One of the early development of bioactive sealing materials in endodontics was the MTA. First introduced as a calcium silicate cement, MTA has been extensively characterized for its bioactivity, high alkalinity, biocompatibility, and tissue-inductive potential. When hydrated, MTA forms calcium silicate hydrate and calcium hydroxide, generating a sustained release of calcium ions and high pH conditions that promote mineralized tissue formation and exert antimicrobial effects. These properties explain its widespread application in vital pulp therapy, apical barrier formation, perforation repair, and regenerative protocols^[103-105].

Next-generation bioceramics, including premixed hydraulic calcium silicate materials like Biodentine and EndoSequence BC, retain the core bioactive properties of MTA while addressing clinical limitations such as setting time and handling. *In vitro* studies demonstrate that these materials support proliferation and differentiation of dental stem cells such as stem cells from apical papilla (SCAP) and dental pulp stem cells (DPSCs), and induce odontogenic gene expression more effectively than traditional sealers^[121,122].

The antibacterial potential of modern bioceramics arises from their sustained alkaline microenvironment and the release of ions such as calcium and silicate, which disrupt bacterial cell walls and biofilm architecture. Moreover, nano-engineered bioceramic variants with tailored compositions can modulate bacterial adhesion and host tissue responses, broadening the therapeutic scope of these smart materials^[123,124]. CSBS also release calcium and

hydroxyl ions at the sealer–dentin interface, stimulating mineralization and creating an alkaline environment that favors tissue repair^[125]. *In vitro* and *in vivo* studies indicate that bioactive sealers can promote hydroxyapatite formation, support periapical hard tissue deposition, and exhibit low cytotoxicity compared to traditional resin-based or zinc oxide-eugenol sealers^[125,126]. Additionally, obturation materials can modulate host immune responses. Animal studies demonstrate that different sealer compositions elicit varying degrees of inflammation, angiogenesis, and tissue repair, suggesting that obturation may actively influence periapical healing rather than passively filling space^[124,127]. These findings support the concept of biological sealing, in which obturation materials provide both a physical barrier and a biochemical interface that engages host repair mechanisms.

5.3.2 Smart bioresponsive obturation materials

Bioresponsive or stimuli-responsive biomaterials can “sense” a specific stimulus, such as light, temperature, pH changes, electrical and magnetic fields change, to then “respond” by releasing a pre-programmed therapy^[23]. Smarter materials than bioactive materials in endodontics are bioresponsive materials defined by their ability to respond dynamically to the local environment of the root canal and periapical tissues, exhibiting controlled ion release, bioactivity, and adaptive functionalities^[23,128]. These materials are engineered to interact with biological tissues in ways that modulate cellular behavior, promote mineralization, and provide feedback-dependent therapeutic responses, therefore enhancing tissue healing and regeneration.

One example is the novel bioactive and therapeutic root canal sealers with antibacterial and remineralization properties, through their capacity for ion exchange with surrounding tissue fluids. Controlled release of calcium, silicate, and phosphate ions supports the precipitation of apatite and enhances differentiation of progenitor cells toward odontogenic and osteogenic lineages. Such ion release not only contributes to the physicochemical sealing of dentinal tubules but also creates biochemical cues that can drive reparative processes in periapical tissues^[20].

Another example is the piezoelectric biomaterials, which are a special class of smart materials that produce electrical charges upon mechanical stimulation. For example, when subjected to external stress and deformation, such as bending or stretching, these materials undergo a change in their internal structure, leading to the redistribution of electric charges and the generation of electric potential. Piezoelectric materials, such as barium titanate BaTiO₃, have shown excellent biocompatibility and been widely used in the medical and dental fields. Specifically, piezoelectric materials have proven different therapeutic effects including bone regeneration, drug delivery, and tissue engineering^[129,130]. Recently, piezoelectric materials have demonstrated promising antibacterial effects against different oral pathogens^[131]. The produced electrical charges can interfere with bacterial cell membranes, disrupt cellular processes, and ultimately cause bacterial death^[130,132]. The activation of piezoelectric charges is induced by the physiological mastication force^[134]. BaTiO₃ modified hydrogel also showed enhanced bone marrow stem cell (BMSC) viability and osteogenic differentiation by upregulating expression of *RUNX2*, *COL1A1*, and *ALP*^[133]. Adding piezoelectric particles to endodontic sealers may enhance the antimicrobial effect and promote osteogenesis effect, therefore increase the chances of success of root canal treatments and wound healing.

6 Regenerative era: “biological obturation”

6.1 Evolution of clinical regenerative endodontic therapy

Regenerative endodontic therapy (RET) was developed to overcome limitations of traditional apexification, targeting on the tooth with necrotic pulp and incomplete root development^[135]. Although the ultimate goal of RET aims to regenerate functional pulp-dentin complex, the current achievement limited to the relief of clinic symptom, increasing the root length and width, and closing the root apex. In some cases, tooth regains the positive response to the sensibility test, suggesting the regeneration of nerve fibers in the canals^[136].

Although the case selection of RET was originally focusing on the tooth with incomplete root developments, there were attempt to apply the treatment to the tooth with mature root in recent years^[137]. Arslan et al completed a randomized clinical study to compare RET vs. conventional RCT and found that RET has similar outcome compared to RCT regarding the relief the clinic symptom and resolution of apical radiolucency, therefore it has the potential to be used a treatment option for mature teeth with large periapical radiolucency^[138]. A systemic review and meta-analysis done by Glynis et al also found there is no significant difference of RET vs RCT regarding treat the mature necrotic teeth with periapical lesions^[139].

It is of considerable interest to determine what tissues, if any, are formed within and occupy the canal space following RET. Histologic evidence from animal studies and human case reports has demonstrated that, in immature teeth treated with RET, the newly formed hard tissues are predominantly cementum-like, dentin-like and bone-like tissues, whereas the soft tissues largely consist of fibrous connective tissue with vascular components and periodontal ligament-like tissue, with only limited areas of pulp-like tissue have been identified^[140]. Similarly, histologic analyses of human clinical cases have reported the presence of bone-like and cementum-like tissues within the canal space, with occasional findings of empty canal spaces, further suggesting the absence of true pulp and dentin tissue regeneration^[141-143]. In mature teeth treated with RET, histologic evaluation has likewise revealed the ingrowth of fibrous connective tissue containing bone-like tissue and vascular structures, which are consistent with those reported in immature teeth^[144]. Collectively, these observations support the concept that RET primarily results in tissue repair rather than true biologic regeneration.

An even more intriguing question arises from the observation that, in many clinically successful RET cases, the canal space is occupied by irregular biologic tissues that may not provide the dense three-dimensional fill achieved by conventional gutta-percha and sealer obturation. Nevertheless, these teeth often remain asymptomatic and functional without evidence of reinfection. Thus, the canal space may not be conventionally ‘obtured,’ but rather biologically “occupied”. Provided that appropriate disinfection has been achieved and reinfection is prevented, the tooth may remain clinically successful despite the absence of a traditional obturation materials. This concept echoes the classic work of Torneck and subsequent investigations disputing the so-called “hollow tube effect”^[35, 36]. Therefore, the requirement of traditional obturation may warrant reexamination, particularly in the era of enhanced disinfection strategies and advanced irrigation technologies. The successful application of RET in mature teeth not only achieves

primary goals of conventional root canal treatment, such as the resolution of apical pathosis, but may also provide additional biological benefits, including the regeneration of functional pulp-like and dentin-like tissue, restoration of immune function and recovery of sensory function to detect subsequent injury^[145]. Rather than simply replacing conventional obturation materials or techniques, RET may ultimately redefine the concept of obturation, shifting its objective from filling the root canal with inert materials to the concept of biological tissue obturation (Fig 1).

6.2 Tissue engineering to improve biological obturation

A major limitation of current clinical RET is its inability to consistently regenerate a true pulp-dentin complex, due to the limited capacity to precisely control tissue regeneration within the root canal system. Achieving this goal will require coordinated application of tissue engineering principles integrating stem cells, scaffolds and bioactive signaling molecules^[146]. Induced apical bleeding during RET forms an intracanal blood clot that serves as a provisional scaffold and also provides growth factors and signaling molecules^[147,148]. In addition, irrigation protocol of RET releases bioactive molecules from the dentin matrix that influence stem cell recruitment, proliferation and differentiation^[149-152]. Despite the presence of stem cells, scaffolds, and signaling molecules, they function in an uncoordinated and unpredictable manner. The lack of precise spatial and temporal control of their interactions likely explains why current RET generally results in tissue repair rather than predictable regeneration of a functional pulp-dentin complex. The following tissue engineering approaches have been introduced to improve the regenerative outcome of RET:

Optimization of scaffold and signaling molecules: a wide range of biomaterial-based scaffolds has been studied^[153]. Natural polymers, including collagen, chitosan and hyaluronic acid, provide extracellular matrix-mimetic environments that promote DPSCs attachment, proliferation, and odontogenic differentiation, whereas synthetic polymers such as poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and gelatin methacryloyl (GelMA) offer tunable mechanical properties and degradation profiles that can be tailored to tissue healing^[153,154]. Hydrogel-based scaffolds have received particular attention because of their injectability, adaptability to the complex root canal anatomy, and ability to support cell survival and differentiation^[156,157]. To further enhance regeneration, smart scaffold systems increasingly incorporate controlled-release platforms for growth factors such as vascular endothelial growth factor (VEGF), bone morphogenetic protein-2 (BMP-2), and transforming growth factor- β (TGF- β), enabling localized regulation of stem cell recruitment, angiogenesis and differentiation^[158-160]. These multifunctional scaffolds can also deliver antimicrobial and anti-inflammatory agents to simultaneously support disinfection and tissue regeneration^[161-164]. Furthermore, nanotechnology-based scaffold modifications have enhanced cellular attachment, proliferation, differentiation and tissue formation, while emerging immunomodulatory scaffold designs that promote pro-regenerative macrophage polarization have demonstrated the ability to improve stem cell survival, attenuate inflammation, and stimulate angiogenesis, thereby creating a favorable microenvironment for functional pulp regeneration^[165-166].

Stem cell therapy: In contrast to the current cell-homing strategy used in most clinical RET, a more controlled and potentially predictable approach is cell-based therapy, which involves transplantation of *ex vivo* expanded stem cells, including DPSCs,

SCAPs, and stem cells from human exfoliated deciduous teeth (SHED), into the disinfected root canal system^[167–170]. By providing greater control over stem cell proliferation and differentiation, this strategy, when combined with biomaterial scaffolds and bioactive signaling molecules, aims to enhance regeneration of the functional pulp–dentin complex^[167–170]. Both autologous and allogeneic stem cell therapies have demonstrated favorable safety profiles in translational and early clinical studies, with reports of complete periapical healing and recovery of pulp sensibility in mature teeth, suggesting reestablishment of functional vital tissue^[171–175]. Pioneering studies by Nakashima and colleagues further advanced total pulp regeneration using autologous DPSCs, initially in animal models with collagen scaffolds containing granulocyte colony-stimulating factor (G-CSF)^[176], and subsequently in clinical studies showing pulp-like tissue regeneration and progressive mineralized tissue formation in mature necrotic teeth using autologous DPSCs combined with demineralized dentin matrix scaffolds^[177,178]. These studies consistently emphasize that effective root canal disinfection remains a prerequisite for successful regeneration, as persistent bacterial infection and inflammation impair stem cell survival, differentiation, and tissue organization^[179]. Despite their considerable regenerative potential, stem cell-based therapies continue to face significant challenges, including stem cell sourcing, *ex vivo* expansion, maintenance of cell viability, regulatory requirements, and the high costs associated with clinical translation and commercialization.

Pulp autotransplantation: it has recently emerged as a biologically based alternative for regenerative endodontic therapy. Unlike conventional RET strategies that rely on cell homing or stem cell transplantation, this approach introduces viable pulp tissue directly into the disinfected root canal to facilitate organized tissue regeneration. Clinical case reports have demonstrated favorable outcomes following transplantation of autologous deciduous pulp tissue, including resolution of apical pathosis, recovery of pulp sensibility, and, in immature teeth, continued root development and apical maturation^[180,181]. More recently, minced pulp tissue grafts have also shown promising clinical success in mature permanent teeth, although intracanal calcification has been reported in some cases^[182,183]. Collectively, these preliminary findings suggest that pulp autotransplantation is a promising regenerative strategy; however, the current evidence is limited to case reports and small case series, and well-designed clinical studies are needed to establish its safety, efficacy, and long-term predictability.

7 Future of obturation: personalization and beyond

The trajectory of endodontics is increasingly shaped by artificial intelligence (AI), digital personalization and smart biomaterials science. As precision, efficiency, and patient-centered care rise to the forefront of clinical priorities, emerging technologies promise to transform how clinicians perform endodontic therapies. Regarding the obturation, AI holds potential to influence smart biomaterial selection and personalized obturation strategies.

One major direction involves the development of bio-smart obturation materials. Emerging biomaterials are being designed not only to seal the root canal system but also to actively interact with the surrounding biological environment. These next-generation materials may possess antimicrobial, mineralizing, anti-inflammatory, and/or regenerative properties that respond

dynamically to local conditions such as pH, moisture, enzymatic activity, or bacterial load. Bioresponsive sealers and scaffolds capable of controlled drug release or stimulation of mineral deposition have been proposed to enhance healing and improve long-term treatment outcomes. In parallel, self-healing biomaterials incorporating microcapsule-based technologies may help restore structural integrity after microcrack formation, potentially improving the longevity and stability of obturation seals under functional stresses.

A second major trend is the emergence of personalized obturation strategies. AI-driven analysis of CBCT imaging, canal morphology, microbiological profiles, and patient systemic health and patient specific clinical factors may allow clinicians to select obturation materials and techniques customized and optimized for each individual case. Integration of AI with digital workflows, and advanced 3D or 4D printing technologies could enable fabrication of patient-specific obturation constructs that conform precisely to complex root canal anatomies. Ultimately, the convergence of intelligent biomaterials, artificial intelligence, and digital technologies will redefine obturation from a passive filling procedure into a biologically responsive or regenerative, and patient-specific therapeutic strategy.

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