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Editorial

The Biological Seal: the Future of Endodontics

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For decades, research in endodontics has focused on improving the physical, chemical, and biological properties of root canal filling materials. Biocompatibility, radiopacity, dimensional stability, ease of handling and adhesive ability are considered essential characteristics in the evaluation of modern endodontic materials. However, one parameter more than any other determines the long-term clinical success of endodontic treatment: the ability to prevent bacterial penetration throughout the root canal system. Endodontic failure is, in most cases, the result of the persistence or reintroduction of microorganisms within the root canal system. In this context, the concept of bacterial microleakage plays a pivotal role, not only as an experimental outcome measure but also as a true determinant of long-term prognosis. The development of bioactive materials has opened new perspectives in endodontic therapy. Calcium silicate-based cements, bioceramic sealers and novel sealing materials promise not only improved adaptation to canal walls but also biological properties capable of promoting hard tissue formation, exerting antimicrobial effects and enhancing the long-term stability of the seal. Nevertheless, no material, regardless of its degree of innovation, can compensate for inadequate cleaning and shaping procedures or insufficient control of contamination during treatment. The filling material represents the final link in a therapeutic chain whose success remains highly dependent on the quality of the clinical procedures performed. Future research should increasingly focus on studies that integrate

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clinically relevant laboratory models with prospective clinical follow-up data, thereby overcoming the traditional gap between in vitro performance and clinical effectiveness. Accordingly, the current issue of the Giornale Italiano di Endodonzia features several studies investigating bacterial microleakage associated with bioceramic and resin-based sealers, as well as bacterial persistence in relation to the design of the endodontic access cavity. Together, these studies highlight how contemporary endodontics is progressively shifting its paradigm from simply "filling" the root canal system to achieving its biological sealing. From this perspective, the success of endodontic treatment depends not only on what is removed from the root canal system but, more importantly, on what is prevented from re-entering it under the strict control of biological principles.. This fundamental distinction defines the true contribution of next-generation endodontic materials to the long-term prognosis of our root canal treatments.

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ORIGINAL ARTICLE

Effect of Traditional and Truss Access Cavity Designs on Residual Bacterial Levels in Mandibular First Molars: An In Vitro Confocal Microscopy Study

Aim: *To quantitatively compare residual bacterial levels in the pulp chambers of mandibular first molars prepared using traditional endodontic access cavities (TEC) and truss access cavities (TAC) following standardized cleaning and shaping procedures.*
Methodology: *This in vitro experimental study included thirty extracted human mandibular first molars, randomly assigned to two groups (n = 15 each): TEC and TAC. After access cavity preparation, all specimens were inoculated with Actinomyces naeslundii and incubated for 10 days to allow biofilm formation. The distal canals were instrumented using Vortex Blue rotary files with continuous irrigation using 5.25% sodium hypochlorite at a flow rate of 1 mL/min. A final irrigation protocol consisting of 5 mL of 5.25% sodium hypochlorite, 17% ethylenediaminetetraacetic acid, and 5 mL of sterile saline was applied. Specimens were sectioned and analyzed using confocal laser scanning microscopy to quantify residual bacterial presence. Percentage bacterial reduction was calculated, and intergroup comparisons were performed using an independent two-sample t test (α = 0.05).*
Results: *The mean (± SD) percentage of bacterial reduction was 32.7% ± 8.0 in the TEC group and 28.4% ± 4.8 in the TAC group. No statistically significant difference was observed between the groups (P = 0.08).*
Conclusion: *Under the conditions of this in vitro study, truss access cavities demonstrated bacterial reduction comparable to traditional endodontic access cavities following cleaning and shaping. These findings suggest that truss access designs may be considered a minimally invasive alternative without compromising intracanal disinfection.*

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Introduction

The primary objective of root canal treatment is to eliminate harmful pathogens from the complex root canal system to preserve teeth and restore their function in the oral cavity (1). However, a combination of structural and microbiological factors may lead to failure of endodontically treated teeth (ETT) (2, 3). Structural factors can include loss of tooth structure from extensive caries or size of access cavity preparation, excess removal of radicular dentin during instrumentation, improper selection of post, or proteolytic and demineralizing actions of root canal irrigants (4-6). Microbiological factors can include incomplete debridement of pulpal tissues and remaining dentinal debris or viable microorganisms (7).

Historically, successful endodontic treatment has emphasized the complete removal of caries and the importance of root canal disinfection. Traditional endodontic access cavities (TEC) are commonly used in endodontic treatment and often result in premature, structural failure-derived loss of ETT, but highly flexible heat-treated rotary instruments and enhanced illumination and imaging technology have decreased the overall failure rate (8,9). Recently, the concept of minimally invasive endodontics has been suggested to increase the success of ETT, promote the preservation of hard dental tissues during root canal treatment, and improve longevity and functionality (10). Despite ongoing debate about the size of the access cavity and root canal preparation, no consensus exists regarding the best approach to ETT (11). Endodontic therapy involves cleaning and shaping, disinfection, and 3-dimensional obturation of the root canal system. During root canal treatment, the goal of an access cavity design is to obtain straight-line access for complete debridement of pulp and to enhance the cleaning and shaping of the root canal system (8). When TEC design is used, the roof of the pulp chamber is completely removed to improve access to the coronal part of the root canal system (12). This process frequently results in removal of tooth structure, which weakens the tooth in the pericervical area, and predisposes it to fractures, which may cause the tooth to be nonrestorable (9-11).

Minimally invasive access cavity preparations, also known as conservative endodontic access cavity designs (CEC), are intended to preserve the pericervical dentin by retaining as much of the pulp chamber roof as possible with the aim of improving the fracture resistance of ETT (13). Truss access cavity (TAC) is a type of CEC that involves creating separate access cavities to treat each canal individually. For example, with mandibular molars, one access cavity is made for the mesial canals and another for the distal canals (14). The primary goal of TEC is to maximize dentin preservation by leaving a truss of dentin between access cavities, thus improving the fracture resistance of ETT (13-15). Improper post selection is a well-documented reason for the failure of ETT (16,17), so a benefit of using TAC is a decreased need for post placement for restoring ETT. In addition, TAC has been reported as less time consuming than TEC (18). However, if the access cavity is too small, it can be challenging to locate the orifices of canals. As such, it can be difficult to carry out the necessary cleaning, shaping, and obturation of the root canal system and may lead to endodontic mishaps like transportation and deviation of root canals (6,10,11,18-21). The importance of preserving dentin cannot be overemphasized and must be balanced with disinfecting abilities to achieve successful endodontic treatment. To date, studies have focused on the fracture resistance of ETT with various types of CEC, but there is limited data about the debridement of the root canals using CEC (14,21-24).

Endodontic infections are typically

polymicrobial in nature and often involve several microbial species that work synergistically to cause infection and progression of pulpal disease (25). Actinomycetes bacteria are anaerobic, Gram-positive rods that are frequently seen in primary and secondary endodontic infections. Actinomycetes work synergistically with Pseudopropionibacterium species, leading to persistent extraradicular infections (25,26). Both bacteria are members of the order of Actinomycetota and have the ability to colonize on external root surfaces. This colonization is the primary cause of persistent endodontic lesions, even in the absence of endodontic infection. In particular, the presence of Actinomyces naeslundii in a root canal system has been correlated with failure of endodontic treatment since this bacterium is difficult to eradicate by chemomechanical debridement (27,28). However, a study by Radclifffe et al. (25) reported several concentrations of sodium hypochlorite lowered the number of colony forming units of Actinomyces naeslundii below the detection limit after 10 seconds of irrigation.

Confocal laser scanning microscopy (CLSM) is a reliable method for quantifying bacteria viability and identifying associations between bacterial presence and endodontic infections (29). To quantify bacteria, fluorescent dyes are applied to a biofilm, and they then penetrate the DNA and RNA of bacterial cells. This procedure allows differentiation between living and dead bacterial cells in the root canal system and is useful for studying the antimicrobial efficacy of endodontic treatments before and after instrumentation (30). Given the complexity and bacterial concerns of successful root canal treatment, Neelakantan et al (14) investigated outcomes when using a TEC or TAC design for treatment. They reported debridement of the pulp chambers of mandibular molars was significantly compromised when TAC was performed (14). Because the TAC design retains a truss of dentin between mesial and distal access cavities in mandibular molars, the authors were able to evaluate the pulp chambers for reduction in microbial load (14). They concluded that the presence of inaccessible bacteria beneath the truss may affect overall success of endodontic treatment (14). Although many studies have investigated the association between fracture resistance of ETT and different cavity designs (19,20,22,24,31,32), few have investigated microbial reduction of ETT when comparing TEC and TAC (21,24,33). Further, to our knowledge, no studies have investigated TEC and TAC for root canals inoculated with Actinomyces naeslundii.

Therefore, the purpose of the current study was to evaluate the impact of access cavity types on the quantity of residual bacteria in the pulp chamber of extracted mandibular first molars after cleaning and shaping during root canal treatment. Specifically, we compared TEC and TAC designs for root canals inoculated with A. naeslundii and hypothesized there would be significant differences in the quantity of residual bacteria between designs.

Materials And Methods

Sample Selection and Preparation

Based on a previous study comparing instrumentation efficacy between TEC and CEC [19], we performed a sample size calculation using G*Power 3.1 software for Windows (Heinrich Heine-Universität Dusseldorf, Germany). Using the effect size of 1.04, α of 0.05, 80% statistical power, and allocation ratio of 1:1 from that study (19), we calculated our sample size required at least 26 teeth to observe a significant difference. Based on this outcome, we included 15 teeth for our 2 experimental groups (TEC and TAC).

Sample Size Analysis

To evaluate the impact of TEC and TAC on residual bacteria after cleaning and shaping during root canal treatment,

Figure 1
TEC and TAC designs used on mandibular first molars and identification of the section used for bacterial quantification.

30 non-carious mandibular first molars were used. Teeth had been extracted and stored in 10% formalin until use (14). To be included in the study sample, teeth were examined under a high magnification microscope (Global microscope, St. Louis, MO, USA) for cracks or vertical root fractures in mesial or distal roots (5,31). If a tooth had a history of previously initiated root canals or root canal treatment, the presence of internal or external resorptive defects, or severe calcifications, it was excluded from the sample. Once teeth were selected for inclusion, they were evaluated for anatomical similarity. To verify all teeth were as similar as possible, we measured from the occlusal surface to the root apex and measured the mesiodistal and buccolingual dimensions of crowns (32). Teeth with 2 mesial and 1 distal canal were selected based on periapical radiographs. For further standardization of the study sample, additional periapical radiographs were obtained from mesiodistal and buccolingual angles (31,33). The debridement of hard and soft tissues remnants on teeth was manually performed using an ultrasonic scaler. In addition to the 30 teeth for the TEC and TAC groups (15 per each experimental group), we also included 4 controls in the study. Control teeth were prepared using TEC with normal saline as an irrigant, and 2 autoclaved teeth served as negative controls (20,24).

The 30 teeth were randomly divided into the 2 experimental groups. Next, TEC or TAC was performed on the mandibular molars under a high magnification microscope using a size #4 round carbide bur and an Endo Z bur (Dentsply Sirona Endodontics, Ballaigues, Switzerland) with a high-speed handpiece and copious amounts of water (Figure 1). The TEC was performed according to current guidelines to achieve complete deroofing of the pulp chamber and provide straight-line access to the root canals with no undercuts (12). For TAC, mesial and distal slots of oval cavities were made to gain access over the individual canals on the mesial and distal sides. The roof of the pulp chamber was left intact between the mesial and distal cavities beneath the truss of the tooth (14). Be-

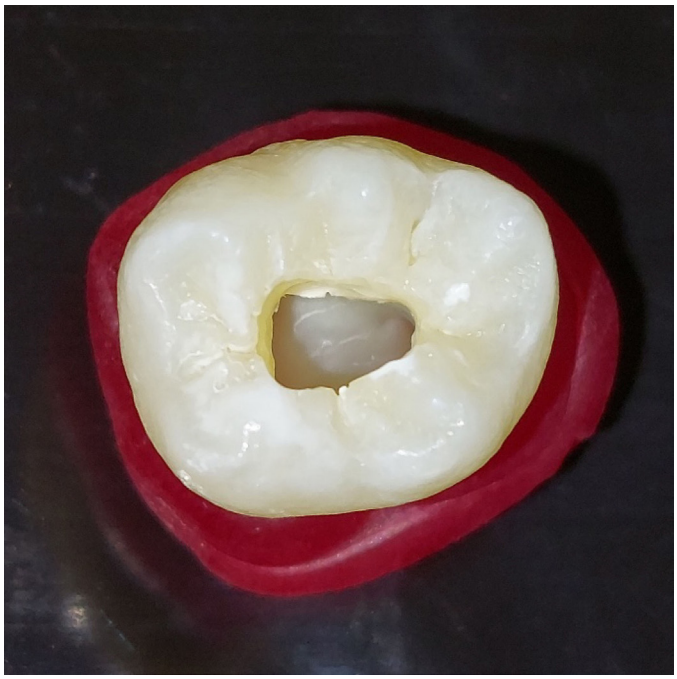

Fig. 1A

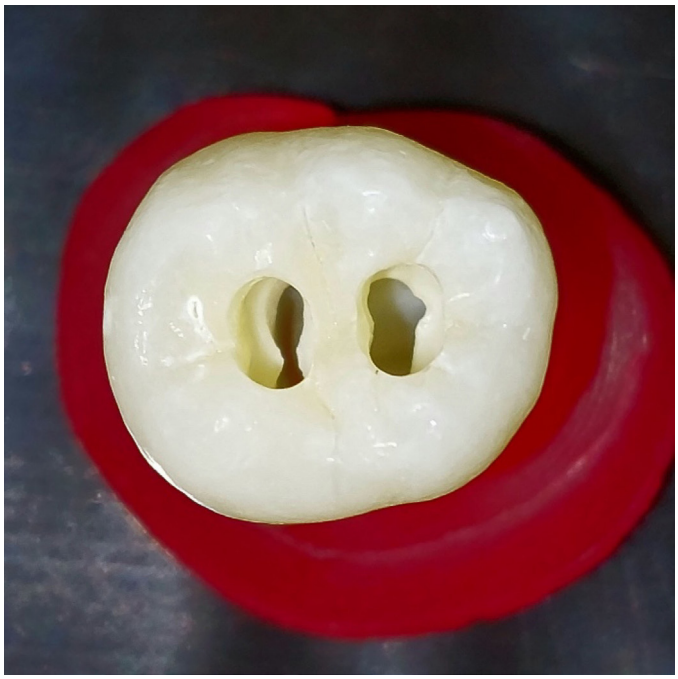

Fig. 1B

cause all teeth in our sample had similar dimensions, we were able to attain some degree of standardization in the size of the access cavities. However, no attempt made to modify the size of the access cavities to gain better access to the canals once cleaning and shaping was initiated. All TEC and TAC procedure were completed by the same endodontics specialist.
The distal canal of the tooth was selected for instrumentation and inoculation of the bacterial sample (Figure 1). The crowns of the teeth were adjusted to have a uniform working length of 18 mm in the distal canals. The apical patency of the distal canal was confirmed by using a #10 K-file (Dentsply Sirona Endodontics, Ballaigues, Switzerland) to advance it out of the apical foramen. The canal was gauged up to a #15 K-file, and the working length was determined to be 1 mm short of the apical foramen. All canals were irrigated using 2 mL of 5.25% NaOCl solution performed at 2 mm short of the working length. To neutralize the effect of the sodium hypochlorite, the teeth were immersed in 10% sodium thiosulfate solution for 4 hours followed by a sterile solution for 20 hours. The external surface of the tooth was painted with 2 layers of nail polish to prevent contamination and to seal the apical foramen (23).

Inoculation of Teeth with Actinomyces naeslundii

Root canals were inoculated with 100 µL of an Actinomyces naeslundii culture (ATCC 12104 LGC, UK). After inoculation, the bacterial suspension was transferred to the working length of the distal root using a manual #15 K-file. The teeth were then incubated by submersion in Eppendorf tubes containing blood heart infusion broth. The incubation time was 10 days under anaerobic conditions. The culture medium was refreshed every 3 days. The growth of Actinomyces naeslundii was confirmed through observation of the turbidity of the solution in the Eppendorf tubes during the incubation period (24).

Root Canal Instrumentation

Teeth were mounted on a metal mounting block, and root canal treatment was performed under a laminar flow hood following strict disinfection protocols. Every treatment was completed by the same individual. All Vortex Blue rotary files (Dentsply Sirona Endodontics, Ballaigues, Switzerland) were attached to a 16:1 gear reduction handpiece (Dentsply, Sirona). Files were used passively to advance into the canal and progress apically. Minimal apical pressure was applied on activation, and 3 easy amplitudes were used in each pass. As suggested by the manufacturer of the Vortex Blue rotary file system, the distal canals in all TEC and TAC teeth were enlarged in a sequence of 15/06, 20/06, 25/06, and 30/06. A standardized volume and duration of irrigant were used for both groups. The canal was irrigated with 1 mL/min of 5.25% NaOCl after every rotary instrument and was recapitulated to working length using a #10 K-file. A hypodermic irrigation needle (30-gauge, side vented, Max-i-Probe, Patterson Dental, USA) was placed passively in the canal and 1 mm short of the apical foramen. The #10 K-file was cleaned with sterile gauze after each recapitulation. A final rinse of 5 mL of 5.25% NaOCl was completed at a rate of 1 mL/min followed by 1 mL/min of rinsing with 17% ethylenediaminetetraacetic acid. An additional rinse was performed using 5 mL/min of sterile saline (34).
The time required to perform the instrumentation and irrigation was recorded and standardized for all (TEC, TAC, and control) groups. Quantification of bacterial load evaluation was performed using CSLM. All teeth were cross-sectioned mesiodistally with a 0.3-mm IsoMet saw at 200 rpm and continuous water. Teeth were stained with BacLight LIVE/DEAD stain (Invitrogen, Carlsbad, CA, USA) for 15 minutes. The CLSM was set at excitation and emission wavelengths of 480 nm

Figure 2
CLSM images of live (green) and dead (red) bacteria in the pulp chambers of teeth using TEC (2A-2B) or TAC (2C-2D) designs for root canal treatment.

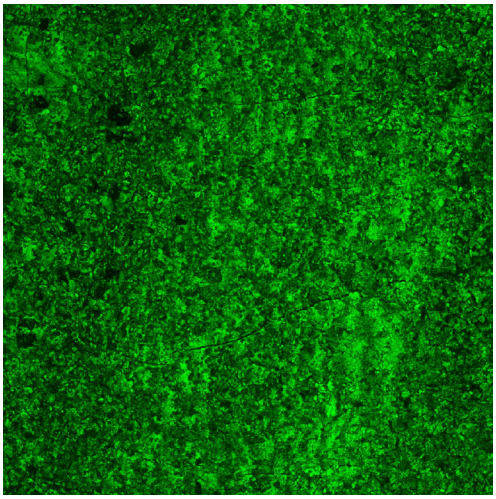

Fig. 2A

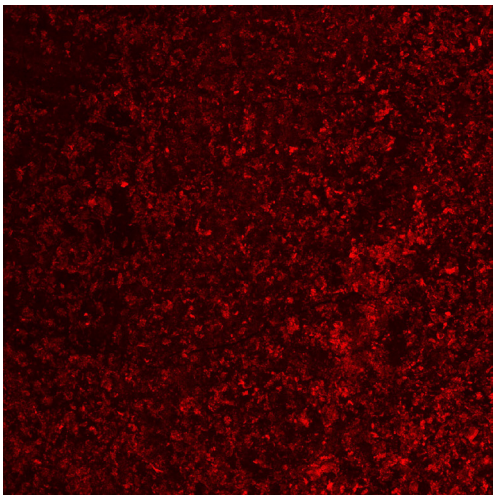

Fig. 2B

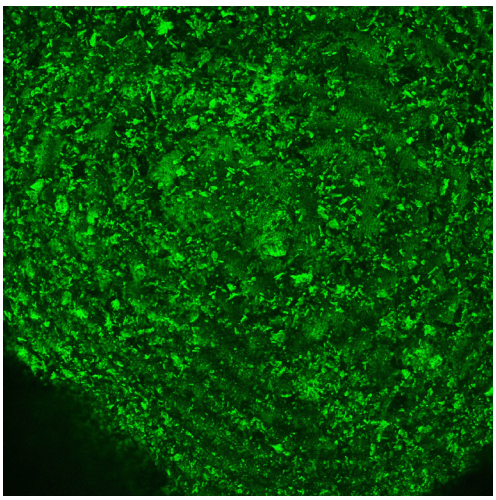

Fig. 2C

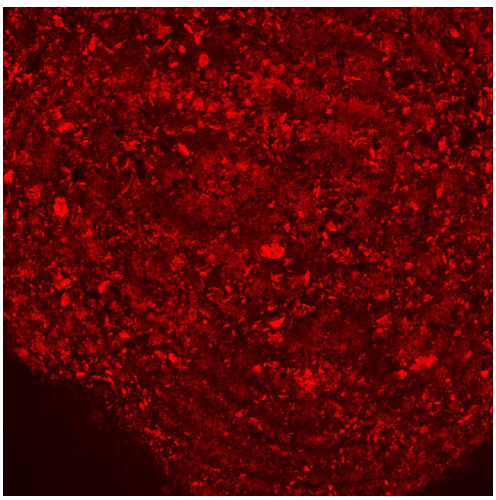

Fig. 2D

and 500 nm. Next, fluorescein diacetate dye was applied, and a 40× magnification oil lens was used to evaluate the teeth. The resulting images were analyzed with ImageJ (NIH, LOCI, University of Wisconsin) to quantify live (stained green) and dead (stained red) bacteria (Figure 2). The measured red and green fluorescence intensities were used to calculate the percentage of dead bacteria for both live and dead bacteria (21). Blinding of the operator was not feasible due to the nature of the access cavity designs. However, the examiner responsible for confocal laser scanning microscopy image analysis was blinded to group allocation.

Statistical Analysis

Bacterial load for all teeth in the TEC and TAC groups was summarized as percentage of bacterial reduction mean and standard deviation (SD). To verify normal distribution of data for percentage of bacterial reduction, a Shapiro-Wilk test was used. For non-normally distributed data, a Wilcoxon-Mann Whitney test was used. For normally distributed data, a 2-sample independent t test was used to evaluate differences in the percentage of bacterial reduction between the TEC and TAC

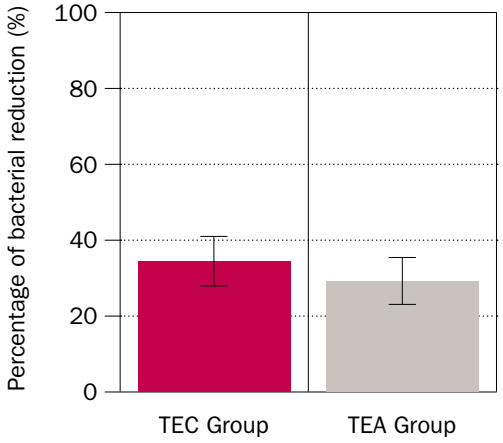

Figure 3
Percentage of bacterial reduction for the TEC and TAC groups.

groups. IBM SPSS Statistics for Windows, Version 27.0 (Armonk, NY; IBM Corp.) statistical software was used for all analyses, and a $P < .05$ was considered significant.

Results

The mean (SD) percentage of bacterial reduction for Actinomyces naeslundii was 32.7 (8.0) with a range of 23.3-48.6 for the TEC group and 28.4 (4.8) with a range of 21.6-39.2 for the TAC group. No difference was found between groups ($P = .08$) (Figure 3).

Discussion

The present in vitro study evaluated the effect of access cavity design on residual bacterial levels in the pulp chamber of mandibular first molars following standardized cleaning and shaping procedures. The results demonstrated no statistically significant difference in the percentage reduction of Actinomyces naeslundii between TEC and TAC. Accordingly, the null hypothesis was rejected. These findings are in agreement with previous laboratory investigations reporting comparable bacterial reduction between conventional and conservative access cavity designs when standardized instrumentation and irrigation protocols are employed (21,23,34).

Effective elimination of intracanal microorganisms is essential for periapical healing and long-term success of endodontic treatment (1). Access cavity design plays a pivotal role in facilitating straight-line access, adequate canal instrumentation, and effective irrigant delivery (18). Traditional access cavity preparation, which involves complete deroofing of the pulp chamber, provides unobstructed access to canal orifices and may enhance irrigant penetration (12). However, this approach is associated with substantial loss of coronal and pericervical dentin, which has been shown to compromise fracture resistance and increase susceptibility to catastrophic failure of endodontically treated teeth (9,13,35).

Fracture remains one of the leading causes of failure in endodontically treated teeth (35). Several studies have demonstrated that conservative access cavity designs, including TAC, improve fracture resistance and result in more favourable fracture patterns compared with TEC (19,32,35). Kishen (35) reported enhanced fracture resistance in teeth prepared with TAC, emphasizing the importance of preserving pericervical dentin. These findings underscore the need to balance structural preservation with effective microbial control to optimize clinical outcomes.

The absence of a significant difference in bacterial reduction between TEC and TAC in the present study suggests that access cavity design alone may have a limited influence on microbial reduction when effective chemomechanical preparation is achieved. Instead, disinfection outcomes appear to be more strongly influenced by instrumentation protocols, irrigant concentration, volume, and contact time. Similar observations were reported by Tüfenkçi and Yılmaz (23), who found no significant difference in Enterococcus faecalis reduction between traditional and conservative access cavities. El-Tayeb and Nabeel (21) also demonstrated comparable bacterial reduction between TEC and TAC, while noting inferior disinfection with ultraconserva-

tive access cavities.

Studies reporting reduced bacterial reduction with ultraconservative access designs suggest that excessive restriction of coronal access may create coronal interferences, limiting effective instrumentation and irrigant delivery (21,33). In contrast, TAC provides independent access pathways to mesial and distal canals while preserving coronal dentin, potentially minimizing such interferences. Neelakantan et al. (14) reported increased residual pulp tissue beneath the truss in TAC preparations but found no significant differences in canal debridement, supporting the concept that adequate canal access can still be achieved with TAC designs.

Instrumentation system selection and canal morphology also influence bacterial reduction. Vieira et al. (20) reported increased residual bacteria with conservative access cavities when using XP-Endo Shaper instruments, possibly due to the interaction between access design and instrument kinematics. Conversely, Krishan et al. (19) reported a higher percentage of untouched canal walls in mandibular molars prepared with conservative access cavities, particularly in oval distal canals, highlighting the importance of instrument selection when employing minimally invasive access designs. The choice of Actinomyces naeslundii as the test microorganism in the present study was deliberate and clinically relevant. Actinomyces naeslundii is a gram-positive, facultative anaerobe frequently associated with persistent primary and secondary endodontic infections and has been implicated in cases of post-treatment apical periodontitis (26–28). Its ability to penetrate dentinal tubules, resist chemomechanical debridement, and survive in harsh intracanal environments makes it a suitable and challenging organism for evaluating disinfection efficacy (26,27). Furthermore, Actinomyces naeslundii has been reported to colonize external root surfaces, contributing to persistent periapical pathology even after technically adequate root canal treatment (28). Therefore, its use in this study enhances the clinical relevance of the findings.

Irrigant-related factors also play a critical role in bacterial elimination. Although NaOCl remains the gold standard irrigant, its antimicrobial efficacy is influenced by concentration, volume, and contact time (28,36,37). Lower concentrations may require prolonged exposure to achieve comparable antimicrobial effects. Given the complex anatomy of the root canal system, including isthmuses and accessory canals, adjunctive irrigation activation techniques such as ultrasonic or laser-assisted irrigation may further enhance disinfection, particularly when conservative access cavity designs are used. Several limitations of this study should be acknowledged. Standardization of canal anatomy was based on periapical radiographs; the use of micro–computed tomography could have provided more precise assessment of canal morphology and reduced anatomical variability. Additionally, only conventional syringe irrigation was evaluated, and adjunctive irrigation activation techniques were not assessed. The in vitro nature of the study also limits direct extrapolation of the findings to clinical conditions. There is a need for future studies focussing on employing novel adjunctives for disinfection (38-40) and also incorporating antimicrobial components into endodontic biomaterials (41).

Within the limitations of this in vitro investigation, bacterial reduction of Actinomyces naeslundii was comparable between traditional endodontic and truss access cavity designs following standardized cleaning and shaping procedures. These findings, in conjunction with existing literature (9,21,23), suggest that TAC may be considered a viable minimally invasive alternative to TEC without compromising intracanal disinfection. Further studies incorporating advanced irrigation strategies, guided access techniques, and three-

dimensional imaging are warranted to optimize disinfection (42), while preserving tooth structure (43).

Conclusion

Within the limitations of this in vitro study, no statistically significant difference was observed in the reduction of Actinomyces naeslundii in the pulp chamber region between TEC and TAC designs following standardized cleaning and shaping procedures. These findings indicate that both access cavity designs provide comparable disinfection of the pulp chamber when effective chemomechanical preparation is performed. Therefore, TAC may be considered a viable minimally invasive alternative to TEC without compromising bacterial reduction.

Clinical Relevance
Preservation of coronal and pericervical dentin is an important consideration in contemporary endodontic practice. The findings of this study suggest that TAC designs can achieve bacterial reduction comparable to TEC when standard instrumentation and irrigation protocols are used. Accordingly, TAC may be clinically adopted in selected cases to support a minimally invasive endodontic approach while maintaining effective root canal disinfection.

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Conflicts of Interest: None

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ORIGINAL ARTICLE

Comparative Evaluation of the Ability of Four Reciprocating System to Remove Obturation Material in Maxillary First Molar: an In vitro Study

Aim: *To evaluate and compare the ability of four reciprocating systems—Reciproc Blue, WaveOne Gold, MicroMega One RECI, and EdgeOne Fire—to remove obturation material using micro–computed tomography (micro-CT).*

Methods: *Twenty-four extracted maxillary first molars featuring Vertucci Type I mesiobuccal canals were shaped and obturated using gutta-percha with AH Plus sealer. After aging, the specimens were randomly divided into four groups and retreated with the corresponding reciprocating systems. Micro-CT imaging measured the initial obturation volume, volume of residual filling material volume, and percentage of residual material across the total, middle, and apical thirds. Operative time was also documented. Statistical analysis employed one-way ANOVA with post-hoc Tukey's test.*

Results: *Baseline obturation volumes were comparable among groups. Post-retreatment analysis revealed significant differences in the apical third ($p = 0.005$). Reciproc Blue showed the least residual volume ($0.48 \pm 0.56\ mm^3$), followed by MicroMega One RECI ($0.52 \pm 0.34\ mm^3$) and WaveOne Gold ($0.99 \pm 0.47\ mm^3$), while EdgeOne Fire demonstrated the highest residual volume ($1.43 \pm 0.41\ mm^3$). Percentage residuals followed similar trends but were not statistically significant ($p > 0.05$). Operative time differed significantly ($p < 0.001$), with EdgeOne Fire being the slowest.*

Conclusion: *Complete removal was not achieved by any system. Reciproc Blue and MicroMega One RECI were most efficient in the apical third, whereas EdgeOne Fire was least effective and significantly slower.*

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Introduction

Non-surgical retreatment remains the preferred therapeutic option for failed endodontic therapy, as it enables preservation of the natural dentition while addressing persistent or recurrent periapical pathology. Failures often arise from missed anatomy, incomplete biomechanical preparation, inadequate obturation, coronal leakage, or degradation of the sealer interface (1,2). The primary objective of retreatment is to regain patency of the apical foramen, remove residual obturation materials, and facilitate effective disinfection, thereby creating conditions favourable for three-dimensional re-obturation and long-term periapical healing(3,4) . Conventional hand instruments and rotary retreatment files have been used for this purpose; however, they are often time-consuming and may leave considerable remnants. In recent years, reciprocating single file systems have gained popularity compared to rotary systems due to their simplicity, reduced procedural time, and enhanced safety(5).
Among these, Reciproc Blue, WaveOne Gold, MicroMega One RECI, and EdgeOne Fire represent contemporary reciprocating systems with distinct metallurgical properties and cross sectional geometries. Comparative data on their retreatment performance remain limited, and most available evidence focuses on canal shaping rather than obturation removal. Micro–computed tomography (micro-CT) provides a non-invasive, gold standard approach for three-dimensional volumetric analysis of endodontic obturation quality(6) .
Therefore, this study aimed to evaluate and compare the efficacy and efficiency of four reciprocating file systems—Reciproc Blue, WaveOne Gold, MicroMega One RECI, and EdgeOne Fire—in removing obturating material from the mesiobuccal canals of maxillary first molars using micro–computed tomography (micro-CT).

Materials and Methods

Study design & Ethical Approval
The study protocol received approval from the Institutional Research Ethics Committee (register No. IGIDSIEC-2023NRP180PGHSCDE). The study samples consisted of extracted human maxillary first molars, both carious and non-carious, collected with informed patient consent.

Sample Selection
Teeth were thoroughly rinsed under running tap water and stored in 0.9% normal saline (Fresenius Kabi India Pvt. Ltd., Pune, India) until use. Inclusion criteria comprised permanent maxillary molars extracted for periodontal reasons or gross decay, with Vertucci type I and mature root apex. Teeth with calcification, immature apices, prior endodontic treatment, resorption, coronal or radicular separation, root fractures, or the presence of a second mesiobuccal canal (MB2) were excluded.

Sample Size calculation and Group Allocation
The sample size was calculated using G*Power software version 3.1.9.4 (Heinrich Heine University, Düsseldorf, Germany). The calculation was based on the primary outcome variable, the amount of remaining filling material, and the statistical test assumed was one-way analysis of variance (ANOVA) for fixed effects with an omnibus comparison among four groups. An effect size (f) of 0.79, derived from the study by Cecagno FL et al.(7), was used with a significance level (α) of 0.05 and statistical power (1–β) of 0.80. The analysis indicated a minimum total sample size of 24 specimens, corresponding to six teeth per group. Accordingly, 24 teeth were included and randomly allocated into four groups after biomechanical preparation and obturation.

- Group 1: Reciproc Blue (25/.08) (VDW, Munich, Germany),
- Group 2: WaveOne Gold (25/.07)

(Dentsply Maillefer, Ballaigues, Switzerland),
- Group 3: MicroMega One RECI (25/.06) (Coltene/MicroMega, Besançon, France), and
- Group 4: EdgeOne Fire (25/.07) (EdgeEndo, New Mexico, USA).

Each sample was randomly numbered from 1 to 24 and cleaned of residual soft tissues, bone fragments, stains, and calculus using an ultrasonic scaler (Woodpecker Dental Ultrasonic Scaler UDS-P, China).

Sample Preparation and Pre-Operative Micro-CT Analysis

For sample preparation, the mesiobuccal root was sectioned at the cementoenamel junction using a diamond disc, and canal patency was confirmed under a dental operating microscope. Biomechanical preparation was performed with WaveOne Gold Primary (25/.07), followed by obturation using WaveOne Gold Primary gutta-percha cones with AH Plus sealer. Excess material was removed with a heated finger plugger. Pre-operative micro-CT scans were obtained using a SkyScan 1273 device (Bruker-microCT, Kontich, Belgium) at 10 µm pixel size, 100 kV, 100 µA, with 180° rotation, a rotation step of 0.4°, camera exposure time of 1,400 ms, and frame averaging of 3. Reconstructions were performed using N-Recon v1.6.3, CTAn v1.12, and CTVol software, with axial sections generated along the long axis of the tooth.

Post-Operative Micro-CT Analysis

For retreatment, samples were assigned to their respective groups. A gutta-percha solvent Endosolv R, (Septodont, Paris, France) was applied, and the designated reciprocating file system was used for removal of filling material. All files were operated in a 6:1 contra-angle handpiece attached to an X-Smart Plus endomotor (Dentsply Maillefer, Ballaigues, Switzerland). The WaveOne Gold group was operated under the WaveOne Gold setting, while the other groups used the Reciproc All setting. Retreatment was continued until the working length was achieved and no filling material was visible on the file flutes, verified under a dental operating microscope at 3.5x magnification, and procedures were carried out by a single experienced operator to reduce operator-related variability. The procedure time was recorded using a digital chronometer, starting at the beginning of obturation removal and ending after completion of reinstrumentation. Radiovisiography was performed to confirm removal, and post-operative micro-CT scans were obtained using the same parameters as the pre-operative scans. Segmentation of dentin and filling materials was performed using CTAn software based on grayscale threshold values.

Micro-CT evaluation focused on volumetric analysis of the apical 3 mm from the working length and the middle 3 mm of the canal, corresponding to approximately 1,000 slices per sample. The micro-CT analysis was performed by a single blinded examiner who was unaware of the experimental groups. The percentage of remaining filling material (RFM) was calculated using the formula: RFM (%) = Volume of remaining filling material/Volume of original filling material x 100.

Statistical Analysis of Data

Normality of data distribution was evaluated using the Shapiro–Wilk test. Intergroup differences in the mean residual filling material and retreatment time among the four reciprocating systems were assessed using one-way analysis of variance (ANOVA). Post hoc pairwise comparisons were conducted with Tukey's test. P value of less than 0.05 was considered statistically significant. All statistical analyses were carried out using SPSS Version 26.0 (IBM Corp., Armonk, NY, 2019).

Results

The comparison of baseline obturation volumes, residual filling material after retreatment, and percentage of residual

Table 1
Comparison of Residual Filling Material Across Root Canal Portions Using Four Reciprocating Systems

Table 2
Time taken for retreatment in seconds

volume across apical, middle, and total canal regions is summarized in Table 1. At baseline, no statistically significant differences were observed among the four groups in any canal portion (apical: p = 0.082; middle: p = 0.110; total: p = 0.726), confirming effective standardization of canal preparation and obturation. Following retreatment, a significant difference was detected in the apical third (p = .005), while the middle (p = .070) and total canal regions (p = 0.067) showed no statistical differences. Tukey's post hoc test indicated that EdgeOne Fire was significantly different from Reciproc Blue and MicroMega One RECI, whereas WaveOne Gold did not differ from any group. Percentage analysis revealed similar trends, with Reciproc Blue and MicroMega One RECI consistently showing the lowest residual percentages and EdgeOne Fire the highest, though these differences were not statistically significant (apical: p = 0.070; middle: p =0.202; total: p =0.097). Overall, the apical third was the most discriminative region, with EdgeOne Fire leaving significantly more residual material compared to Reciproc Blue and MicroMega One RECI.

The operative times are summarized in Table 2. A statistically significant difference was identified among the groups (p < 0.001). Tukey's post hoc analysis revealed that EdgeOne Fire required significantly more time compared to Reciproc Blue, WaveOne Gold, and MicroMega One RECI, whereas no significant differences were observed among the remaining three systems.

Figure 1 shows Three-dimensional micro-CT reconstructions of root canals before and after instrumentation using different reciprocating file systems. Pre-operative scans (red) illustrate the obturation material, while post-operative scans (green) depict the residual obturation material following instrumentation with Reciproc Blue, WaveOne Gold, Micromega One RECI, and EdgeOne Fire systems.

Parameter (Obturation Volume)	Root canal portion	Reciproc Blue	WaveOne Gold	MicroMega One RECI	Edge One Fire	F**	Effect size**	p value**
Total	Apical	8.50±3.98	10.25±1.39	9.89±1.43	12.37±1.97	2.580	0.279	.082
	Middle	16.73±5.04	20.91±2.62	23.97±5.69	24.69±8.57	2.282	0.255	.110
	Total	87.10±11.88	89.91±10.85	90.08±8.51	94.16±11.31	0.441	0.062	.726
After retreatment	Apical	0.48±0.56[a]	0.99±0.47[a]	0.52±0.34[a]	1.43±0.41[b]	5.767	0.464	.005*
	Middle	0.79±0.62	0.88±0.55	0.63±0.35	1.52±0.73	2.742	0.291	.070
	Total	2.23±1.19	2.48±0.83	2.38±0.71	3.66±1.03	2.787	0.295	.067
Percent of residual volume	Apical	4.28±4.04	10.19±6.06	5.44±3.97	10.21±4.06	2.738	0.291	.070
	Middle	4.12±2.89	4.32±2.81	2.81±1.84	7.09±5.17	1.685	0.202	.202
	Total	2.53±1.12	2.75±0.89	2.65±0.82	3.93±1.22	2.412	0.266	.097

All Values are presented in Mean±SD *p<.05 considered significant. **Derived from One Way ANOVA. Values with different superscript letters differ significantly (Tukey's post hoc test, p<.05). In the apical third, EdgeOne Fire ([b]) was significantly different from Reciproc Blue ([a]) and MicroMega One RECI ([a]). WaveOne Gold ([a]) did not differ significantly from any group.

Table 1

Group	Mean±SD	F	Effect size	p value
Reciproc Blue	62.67±7.0[a]	63.209	.905	<.001*
Wave One Gold	63.33±12.11[a]			
MicroMega One RECI	64.50±7.15[a]			
EdgeOne Fire	124.33±10.23[b]			

*p<.05 considered significant. Values with different superscript letters differ significantly (Tukey's post hoc test, p<.05).

Table 2

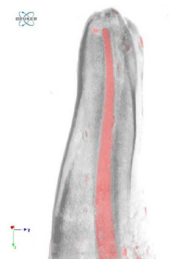
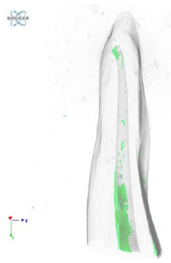
Groups	Reciproc Blue	WaveOne Gold	MicroMega One RECI	Edge One Fire
Pre-operative Micro-CT				
Post-operative Micro-CT				

Figure 1
Micro-CT of all comparative groups

Discussion

The evolution of endodontic instrumentation has profoundly influenced retreatment strategies. The transition from stainless-steel hand files to rotary NiTi systems, and more recently to reciprocating systems, has improved both efficiency and safety during canal preparation(8). Reciprocating instruments operate through alternating clockwise and counter-clockwise motions, which reduce cyclic fatigue and torsional stress while simplifying canal preparation with single-file techniques(9). These mechanical characteristics are particularly advantageous in retreatment procedures, where instruments must negotiate gutta-percha and resin-based sealers while maintaining the original canal anatomy.

Maxillary molars were selected due to their complex canal morphology and higher reported failure rates(10). The mesiobuccal root is often characterized by curvatures and anatomical variations, representing a clinically challenging site for retreatment. Standardization to Vertucci Type I configuration ensured anatomical uniformity and minimized confounding variables(11). Micro-CT served as the gold standard for volumetric evaluation of remaining obturation material. Its non-destructive, high-resolution imaging allows precise quantification throughout the canal system, particularly in the apical third where complete removal of filling material is difficult(12).

Recent micro-CT retreatment studies have evaluated the performance of reciprocating systems. Ahmad A. Madarati et al. compared several reciprocating systems (WaveOne Gold, Reciproc Blue, and R-Motion) with rotary systems (Fanta AF-One and Tango-Endo) for removing calcium silicate–based fillings using micro-CT. Their findings indicated that reciprocating systems were more effective but required longer retreatment time, while the addition of Passive Ultrasonic Irrigation (PUI) significantly enhanced filling material removal.(13) Similarly, Fabio Luiz Ce-

cagno et al. reported using micro-CT that Reciproc, Reciproc Blue, and WaveOne Gold showed no significant difference in the removal of root canal filling materials, and none of the tested systems completely eliminated the obturation material.(7) WaveOne Gold was selected for initial canal preparation to ensure standardized canal shaping across all samples, as it is widely used and provides consistent and predictable preparation outcomes.

Four reciprocating systems incorporating proprietary heat-treated NiTi alloys were evaluated in this study. While all systems demonstrated the ability to remove obturation material within clinically acceptable timeframes, variations in cross-sectional design, tip activity, and metallurgical properties of NiTi alloys may influence retreatment performance.(13,14) Reciproc Blue and WaveOne Gold, with their safety-oriented tip designs and controlled cutting efficiency, allowed predictable canal negotiation. MicroMega One RECI, with its more aggressive cutting tip, facilitated deeper penetration of obturation material (15). EdgeOne Fire exhibited comparable performance, highlighting the potential of newer systems to provide effective retreatment outcomes (14).

Despite the use of EndoSolv R, complete removal of AH Plus sealer was not achieved in any group. This finding is consistent with previous studies demonstrating the strong adhesion and dimensional stability of epoxy resin–based sealers (16). The persistence of residual material, particularly in the apical third, highlights the limitations of mechanical instrumentation alone and supports the use of adjunctive approaches such as ultrasonic activation, supplementary finishing instruments, or improved irrigation strategies to enhance retreatment outcomes (17).

Among the tested systems, Reciproc Blue showed the lowest percentage of residual obturation material, indicating greater removal efficiency, although differences among systems were not statistically significant except in the apical third in post treatment wihtout GP. Its S-shaped cross-section with sharp cutting edges may facilitate effective engagement with gutta-percha and sealer, while deep flutes aid in coronal debris transportation. MicroMega One RECI demonstrated comparable efficiency, possibly due to its asymmetric cutting tip and S-shaped middle region enabling apical penetration and debris evacuation.

WaveOne Gold exhibited slightly higher residual values, which may relate to its conservative parallelogram cross-section and semi-active tip. Although this design minimizes taper lock and enhances shaping safety, it may reduce cutting aggressiveness against hardened obturation materials. EdgeOne Fire showed comparatively higher residual values and required longer retreatment time. Subtle differences in flute depth and tip configuration may influence cutting efficiency and debris removal, particularly in the apical region.

Across all systems, the apical third consistently retained the highest amount of residual material. This observation reflects the anatomical challenges of this region, including narrow diameter, curvature, and accumulation of sealer. Even the most efficient systems were unable to achieve complete removal of obturation material, which is consistent with previous micro-CT retreatment studies. Clinically, residual material in the apical third may limit irrigant penetration and potentially harbor persistent microorganisms, which may compromise retreatment success.

Operative efficiency is also an important clinical consideration. Reciproc Blue, WaveOne Gold, and MicroMega One RECI demonstrated comparable mean working times, whereas EdgeOne Fire required a longer operative duration. These findings suggest that instrument design may influence both retreatment efficiency and procedure time.

Few limitations must be acknowledged.

Rotary instruments are available as both treatment and retreatment-specific files, with retreatment files incorporating active cutting tips and specialized flute designs to enhance removal of obturation materials, particularly in the apical third. In contrast, reciprocating files are primarily designed for canal shaping, and their geometries may limit efficiency in complete removal of obturation materials. Furthermore, the reciprocating systems evaluated are primarily designed as shaping instruments rather than specifically engineered retreatment files, which may influence their efficiency in the removal of obturating materials. Consequently, the observed outcomes should be interpreted within the context of their intended clinical application. The relatively small sample size restricts generalizability, and although adequate for statistical comparison, larger studies are needed to improve reliability. Furthermore, the exclusive use of AH Plus sealer and standardized specimen age may not fully represent clinical variability. To improve retreatment effectiveness and therapeutic application, future in vivo investigations with bigger sample numbers, a wider variety of sealers, and uniform specimen selection are advised. Future studies involving larger sample sizes, different sealers, and clinical conditions are recommended to further evaluate the retreatment performance of reciprocating systems.

Clinical implication

In the present in vitro study evaluating the efficacy of four reciprocating systems in removing obturation material from maxillary first molars, complete removal was not achieved by any of the tested systems, particularly in the apical third. This finding highlights the inherent anatomical complexities of the apical region, including canal curvature, apical ramifications, and isthmuses, which limit the mechanical action of instruments. The persistence of residual obturation material in this region may act as a potential substrate for microbial retention and biofilm persistence, thereby compromising the effectiveness of retreatment procedures. Additionally, remnants of sealer and gutta-percha can hinder the penetration of irrigants and intracanal medicaments into dentinal tubules, reducing disinfection efficacy. However, it is important to consider that the presence of residual material does not necessarily equate to clinical failure, as successful outcomes are also influenced by adequate chemomechanical debridement and the host response. Therefore, while none of the reciprocating systems demonstrated complete removal, their relative efficacy should be interpreted in the context of their ability to enhance overall canal disinfection rather than achieve total material removal.

Conclusion

Within the constraints of this in vitro micro-CT study, none of the tested reciprocating systems completely removed the obturating material. However, Reciproc Blue and MicroMega One RECI demonstrated superior apical cleaning efficiency compared with WaveOne Gold and EdgeOne Fire. These findings emphasize that instrument design characteristics significantly influence retreatment efficacy, particularly in anatomically complex apical regions.

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ORIGINAL RESEARCH

Nano-leakage and Fracture Resistance of Bioceramic Coronal Plug Materials in Immature Teeth: A Micro-CT and Finite Element Analysis

ABSTRACT

Aim: *To evaluate the effect of MTA Repair HP, Biodentine, and Bio-C Repair coronal plugs on nano-leakage and fracture resistance in simulated immature teeth using micro-computed tomography (Micro-CT) and finite element analysis (FEA).*

Methodology: *Sixty-four extracted human maxillary central incisors were standardized to simulate immature teeth with blunderbuss canals and randomly allocated into four groups (n = 16): Group 1, Bio-C Repair; Group 2, Biodentine; Group 3, MTA Repair HP; and Group 4, control group with collagen foam. Nano-leakage was assessed using silver nitrate infiltration and Micro-CT analysis. Leakage was calculated volumetrically and expressed as percentages. Three-dimensional FEA models generated from cone beam computed tomography data were used to evaluate stress distribution, maximum principal stress, failure index, and tooth weakening percentage under simulated functional loading.*

Results: *Bio-C Repair demonstrated the lowest nano-leakage values, whereas the control group showed the highest leakage. Significant differences were observed between Bio-C Repair and MTA Repair HP, Bio-C Repair and the control group, and Biodentine and the control group ($p < 0.001$). FEA demonstrated that untreated immature teeth exhibited the highest stress concentration and failure index. MTA Repair HP and Bio-C Repair showed lower stress concentration and more favourable biomechanical behaviour than Biodentine. Stress concentration was mainly localized in the cervical root region.*

Conclusions*: Bio-C Repair demonstrated superior sealing ability with the least nano-leakage. MTA Repair HP and Bio-C Repair exhibited more favourable stress distribution and reduced fracture susceptibility compared with Biodentine.*

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Introduction

Immature permanent teeth with pulpal necrosis represent a significant clinical challenge in endodontics because of incomplete root development, thin dentinal walls, and wide-open apices (1). Trauma to anterior teeth during the developmental stage is considered the most common cause of pulpal necrosis in immature teeth, although deep caries and developmental anomalies may also contribute to pulpal damage before root maturation is complete (2). The compromised structural integrity of these teeth increases their susceptibility to reinfection and cervical root fracture, thereby adversely affecting long-term prognosis (3).

Conventional management of necrotic immature teeth has historically involved apexification procedures aimed at inducing the formation of an apical hard tissue barrier (4). Calcium hydroxide apexification was widely practiced because of its ability to stimulate mineralized tissue formation. However, the prolonged treatment duration, requirement for multiple appointments, and weakening effect on dentinal walls limited its clinical applicability (5). Mineral trioxide aggregate (MTA) apexification was subsequently introduced to create an artificial apical barrier in a shorter treatment period with improved sealing ability (6). Despite favourable clinical outcomes, apexification procedures do not promote continued root maturation or reinforcement of thin radicular dentin, leaving immature teeth vulnerable to fracture (6).

Regenerative endodontic procedures (REPs) were developed as a biologically based alternative for the management of immature necrotic teeth (7). The primary goal of REP is to restore the functional pulp–dentin complex by promoting continued root development, apical closure, and thickening of dentinal walls (8). Current regenerative protocols emphasize effective disinfection with minimal mechanical instrumentation, induction of intracanal bleeding to create a biologic scaffold, and placement of a bioactive coronal barrier material over the scaffold to prevent coronal microleakage and reinfection (9).

The success of regenerative endodontic procedures is highly dependent on the optimal scaffold with enhanced sealing ability and mechanical behaviour of the coronal plug material (10). An effective coronal barrier should exhibit excellent adaptation to dentinal walls, dimensional stability, biocompatibility, bioactivity, and adequate mechanical properties. Inadequate sealing may result in nanoleakage, allowing penetration of fluids, bacteria, and bacterial by-products through interfacial gaps, ultimately compromising regenerative outcomes (11). Furthermore, immature teeth are structurally weakened because of thin root canal walls and are therefore highly susceptible to fracture under functional loading (12). Consequently, reinforcement of cervical dentin and improvement in fracture resistance are critical considerations in the selection of coronal plug materials for REP (13).

Mineral trioxide aggregate has been extensively used as a coronal plug material in regenerative procedures because of its favourable sealing ability and bioactive characteristics (14). However, disadvantages such as difficult handling characteristics, prolonged setting time, higher cost, and potential tooth discoloration have led to the development of newer calcium silicate–based biomaterials (15). MTA Repair HP, Biodentine, and Bio-C Repair are recently introduced bioactive materials designed to overcome the limitations associated with conventional MTA while maintaining favourable physicochemical and biological properties (16). MTA Repair HP is a high-plasticity calcium silicate cement developed to improve handling properties and reduce discoloration potential (17). Biodentine is a tricalcium silicate–based dentin substitute with improved me-

chanical properties and reduced setting time (18),(19). Bio-C Repair is a ready-to-use bioceramic repair material with enhanced flowability, low cytotoxicity and bioactivity (20). Although these materials are increasingly used in regenerative endodontic procedures, comparative evidence regarding their sealing ability and biomechanical reinforcement in immature teeth remains limited (21),(22),(23).

Micro-computed tomography (Micro-CT) enables non-destructive three-dimensional assessment of interfacial adaptation and nano-leakage patterns with high spatial resolution (24). Finite element analysis (FEA) is a validated computational method widely used for evaluating stress distribution and fracture behaviour under simulated functional loading conditions (25). The combined use of these advanced analytical techniques provides a comprehensive evaluation of the sealing performance and biomechanical behaviour of coronal plug materials used in regenerative endodontics.

Therefore, the present study aimed to evaluate the effect of MTA Repair HP, Biodentine, and Bio-C Repair coronal plugs on nano-leakage and fracture resistance in simulated immature teeth using Micro-CT and finite element analysis. The null hypothesis tested was that there would be no significant difference among the tested materials with respect to nano-leakage and fracture resistance.

Materials and Methods

Study Design

The present in vitro experimental study was designed to evaluate the effect of different calcium silicate–based coronal plug materials on nano-leakage and fracture resistance in simulated immature permanent teeth using Micro-CT and FEA. Ethical approval for the study was obtained from the Institutional Ethics Committee of Malla Reddy Institute of Dental Sciences (IEC/MRIDS/6/2021) and drafted according to PRILE guidelines. The minimum required sample size was determined using G*Power Software Version 3.0.1.0 (University of Düsseldorf, Düsseldorf, Germany) with an alpha error of 0.05 and 90% power. The calculation was based on previously reported data (26), with an effect size of 0.50. The analysis indicated that at least 64 specimens were required, which were equally divided into four primary groups (n = 16 per group). A total of sixty-four extracted human maxillary central incisors were included in the study, and the specimens were equally distributed among three experimental and one control groups, with sixteen samples allocated to each group.

Specimen Collection and Selection

Sixty-four freshly extracted single-rooted maxillary central incisors extracted for periodontal reasons were collected and cleaned under running tap water to remove blood, debris, and adherent soft tissue remnants. Residual soft tissues and calculus deposits were removed using an ultrasonic scaler. The teeth were disinfected by immersion in 1.25% sodium hypochlorite solution for five minutes and subsequently stored in 0.9% physiological saline solution until further use. Radiographic examination was performed in both mesiodistal and labiolingual directions to confirm the presence of a single straight canal and to exclude teeth with internal resorption, calcifications, cracks, fractures, or previous endodontic treatment. Furthermore, the mesiodistal and labiolingual dimensions of the roots at the cementoenamel junction were measured using a digital vernier calliper to ensure dimensional standardization among all specimens. Only teeth with fully formed roots, single straight canals, and absence of intracanal calcification or structural defects were included in the study. Teeth exhibiting curved canals, developmental anomalies, restorations, caries, cracks, fractures, or previous endodontic treatment were excluded.

Preparation of Simulated Immature Teeth

The specimens were standardized to a root length of 12 mm by sectioning the apical portion using diamond discs under continuous water cooling. Standard endodontic access cavities were prepared using a #010 round diamond bur mounted on a high-speed handpiece under water coolant. Pulp tissue was extirpated using barbed broaches. Simulation of immature teeth with blunderbuss canals was achieved using Peeso reamers sizes #2 to #6 to enlarge the coronal and apical 4 mm of the canals. Canal enlargement in the middle third was subsequently completed using K-files until a size #80 K-file (Mani Inc., Japan) passed freely through the canal space. This protocol enabled the development of standardized immature root canal models with thin dentinal walls and open apices.

During instrumentation, irrigation was performed using 5 mL of 2.5% sodium hypochlorite (Cerkamed, Stalowa Wola, Poland) followed by saline irrigation using a 31-gauge side-vented needle (NaviTip; Ultradent Products Inc., South Jordan, UT, USA) positioned 1 mm short of the working length. Between each instrument change. Final irrigation was carried out sequentially using 5 mL of 17% EDTA (MD Cleanser; Meta Biomed, Cheongju, South Korea), 5 mL distilled water, 5 mL of 2.5% sodium hypochlorite, and a final rinse with distilled water. The canals were dried using sterile paper points. To simulate regenerative endodontic clinical conditions, double antibiotic paste was placed as an intracanal medicament, and all specimens were incubated at 37°C in 100% humidity for two weeks.

Following incubation, the intracanal medicament was removed using irrigation with 20 mL of 17% EDTA followed by distilled water. The canals were dried with sterile paper points, and collagen foam was introduced into the canals to simulate the intracanal blood clot scaffold used during regenerative endodontic procedures. The collagen scaffold also enabled standardization of the coronal barrier thickness and prevented apical displacement of the coronal plug material. A periodontal probe was used to confirm a standardized 4-mm space below the cementoenamel junction for placement of the coronal plug.

Placement of Coronal Plug Materials

The specimens were randomly allocated into four experimental groups. In Group 1, a 4-mm-thick Bio-C Repair (Angelus, Londrina, Brazil) coronal plug was placed below the cementoenamel junction. Group 2 received a 4-mm-thick Biodentine (Septodont, Saint Maurdes Fossés, France) coronal plug, whereas Group 3 received a 4-mm-thick MTA Repair HP (Angelus, Londrina, Brazil) coronal plug. Group 4 served as the control group in which the canals contained only collagen foam (Goodwill, India) without placement of any coronal barrier material.

Bio-C Repair was used as a premixed ready-to-use bioceramic material. Biodentine was manipulated according to the manufacturer's instructions by triturating the powder and liquid components. MTA Repair HP was manually mixed according to the manufacturer's recommendations. Placement and condensation of the materials were performed using indirect ultrasonic activation (Acteon® Group, France), wherein an activated ultrasonic tip (Satellac, Switzerland) was placed in contact with a hand plugger for ten seconds during condensation to improve adaptation and reduce void formation.

Following placement of the coronal plug materials, a 2-mm-thick layer of resin-modified glass ionomer cement (Fuji II LC, GC Corporation, Tokyo, Japan) followed by a 2-mm composite resin restoration (Filtek Z350 XT, 3M ESPE, St. Paul, MN, USA) was placed coronally to achieve coronal sealing. The apical ends of all specimens were sealed using a single bond universal

adhesive (3M ESPE, St. Paul, MN, USA) followed by placement of flowable composite resin (Filtek Z350 XT Flowable Restorative, 3M ESPE, St. Paul, MN, USA). Subsequently, all samples were stored in an incubator at 37°C and 100% humidity for one week to ensure complete setting of the materials before further analysis.

Nano-leakage Evaluation Using Micro-CT

For nano-leakage assessment, two layers of nail varnish were applied to all external tooth surfaces except for a 1-mm window surrounding the restoration margins. The specimens were immersed in 50% silver nitrate solution in complete darkness for 15 hours, rinsed under running water for two minutes, and subsequently immersed in a photo-developing solution under light exposure for three hours to allow reduction of silver ions. Care was taken to immerse only the coronal portions of the specimens to avoid false-positive staining.

After rinsing thoroughly under running water, the teeth were embedded in self-cure acrylic resin and scanned using a high-resolution desktop Micro-CT system (Bruker SKYSCAN 2214; Kontich, Belgium). Nano-leakage scores were determined by comparing the volume of leakage areas within the root canal to the volume of the gap between the upper limit of the flowable composite used for apex sealing and the lower limit of the coronal plug, expressed as a percentage. Nano-leakage values were computed by dividing the leakage volume by the root canal volume and were presented as percentages to ensure result reliability.

Finite Element Analysis for Fracture Resistance

Cone beam computed tomography (Carestream Dental, Atlanta, GA) scans of the maxillary anterior region were obtained and exported in Digital Imaging and Communications in Medicine (DICOM) format. The DICOM data were imported into MIMICS software (Materialise NV, Leuven, Belgium) for segmentation and three-dimensional reconstruction of the maxillary central incisor and adjacent supporting structures. The reconstructed model was converted into a stereolithography (STL) file and refined using GEOMAGIC modelling software to obtain an anatomically accurate Computer-Aided Design (CAD) model. Root length standardization was performed before model construction. The mature tooth model demonstrated a root length of approximately 13.5 mm, whereas the immature tooth model corresponding to Cvek's stage III root development demonstrated a root length of approximately 10.5 mm.

The finalized CAD models were imported into ALTAIR HYPERMESH software (Altair Engineering Inc., Troy, Michigan, USA) for finite element mesh generation. Three-dimensional tetrahedral elements were used because of their ability to accurately reproduce complex anatomical geometries. Model validation was performed through element quality assessment and necessary modifications were carried out to improve mesh quality and computational accuracy. A total of six finite element models were generated for the analysis. The first model represented a mature tooth (Model MT), while the second model represented an untreated immature tooth (Model IT). Three regenerative endodontic models were created using different 4-mm coronal plug materials, including MTA Repair HP (Model 1), Biodentine (Model 2), and Bio-C Repair (Model 3). Another immature tooth model was generated with the entire root canal filled with blood clot simulation material (Model 4).

The finite element mesh incorporated enamel, dentin, composite resin, glass ionomer cement, cementum, periodontal ligament, bioceramic materials, foam analogue, cortical bone, and cancellous bone. All materials were considered isotropic, homogeneous, and linearly elastic. The modulus of

Groups	n	Mean	SD	Test statistic	P value
Group 1	16	0.0255100	0.00405412	51.579	0.001*
Group 2	16	0.0409088	0.00185783		
Group 3	16	0.0470791	0.00148608		
Group 4	16	0.0552992	0.00172952		

Table 1
Mean comparison of nano-leakage between the groups

elasticity and Poisson's ratio assigned to each material were obtained from previously published literature. The roots of all tooth models were enveloped by a simulated periodontal ligament and embedded within alveolar bone consisting of cancellous bone surrounded by cortical bone. The alveolar bone extended several millimetres beyond the root apex to simulate physiological support conditions. The superior surface of the alveolar bone was constrained in all directions to prevent displacement during loading. A static load of 240 N was applied on the palatal aspect of the incisal edge at an angle of 120° to the long axis of the tooth to simulate functional loading conditions. Finite element calculations were performed using ALTAIR OPTISTRUCT software (Altair Engineering Inc., Troy, Michigan, USA). The generated results were analyzed and visualized using ALTAIR HYPERVIEW software (Altair Engineering Inc., Troy, Michigan, USA).

Stress distribution and failure index (FI) evaluation

Stress distribution within the models was visualized through stress contour plots, and the maximum principal stress and the Von Mises values were noted. After FEA, the fracture risk estimation was made by FI. FI = σPS/σSM, where σPS - maximum principal stress within a material/tissue . σSM - either the tensile strength (σTS) or the compressive strength (σCS) value of the material, depending on the nature of predominant stress, i.e., tensile or compressive stress acting within a material/tissue. The given formula can calculate the weakening percentage of each model: Weakening% = 100 × (FI(i) – FI (1)) / FI (1). where FI (1) and FI(i) are the maximum value of FI in the model MT and the model being evaluated, respectively.

Statistical Analysis

Statistical analysis for Micro-CT data was performed using SPSS software version 23.0. Nano-leakage values were expressed as mean ± standard deviation. Intergroup comparison was performed using the Kruskal–Walli's test followed by Dunn's post hoc analysis. Statistical significance was established at $p < 0.001$. For fracture resistance, the values of force applied and fracture patterns were recorded for individual models and by using ANSYS 12.1 software (ANSYS Inc, Canonsburg, PA), the finite element equations were assembled and solved. Finite element analysis outcomes were interpreted descriptively based on stress distribution patterns, maximum principal stress, failure index, and weakening percentage values.

Results

Nano-leakage Evaluation Using Micro-CT

Micro-CT analysis demonstrated significant differences in nano-leakage among the experimental groups. Group 1, restored with Bio-C Repair, demonstrated the lowest mean nano-leakage values, whereas the control group exhibited the highest leakage values. The mean nano-leakage values for groups were 0.0255 ± 0.0040, 0.0409 ± 0.0018, 0.0470 ± 0.0014, and 0.0552 ± 0.0017, respectively. Statistical analysis using the Kruskal–Walli's test revealed a statistically significant difference among the groups ($p < 0.001$) (Table 1). Post hoc analysis using Dunn's test revealed that Bio-C Repair demonstrated significantly lower nano-leakage values than MTA Repair HP and the control group ($p < 0.05$). Similarly, Biodentine exhibited significantly lower nano-leakage values than the

Comparison between		Mean difference	P value
Group 1	Group 2	-0.01539	0.139
	Group 3	-0.02156	0.000*
	Group 4	-0.29789	0.000*
Group 2	Group 3	-0.00617	0.139
	Group 4	-0.01439	0.000*
Group 3	Group 4	-0.00822	0.139

Table 2
Post hoc analysis of nano-leakage between the groups

control group ($p < 0.05$). However, no statistically significant differences were observed between Bio-C Repair and Biodentine, Biodentine and MTA Repair HP, or MTA Repair HP and the control group ($p > 0.05$) (Table 2). Representative Micro-CT images (Figure 1) demonstrated silver nitrate penetration along the dentin–material interface, indicating nano-leakage pathways. Bio-C Repair demonstrated superior interfacial adaptation with minimal leakage areas, whereas the control group demonstrated extensive leakage patterns and greater interfacial gaps.

Finite Element Analysis for Fracture Resistance

Finite element analysis demonstrated substantial differences in stress distribution patterns among the evaluated models (Figure 2). The untreated immature tooth model exhibited the highest Von Mises and maximum principal stress values, indicating greater susceptibility to fracture and structural failure. In contrast, the mature tooth model demonstrated the lowest stress

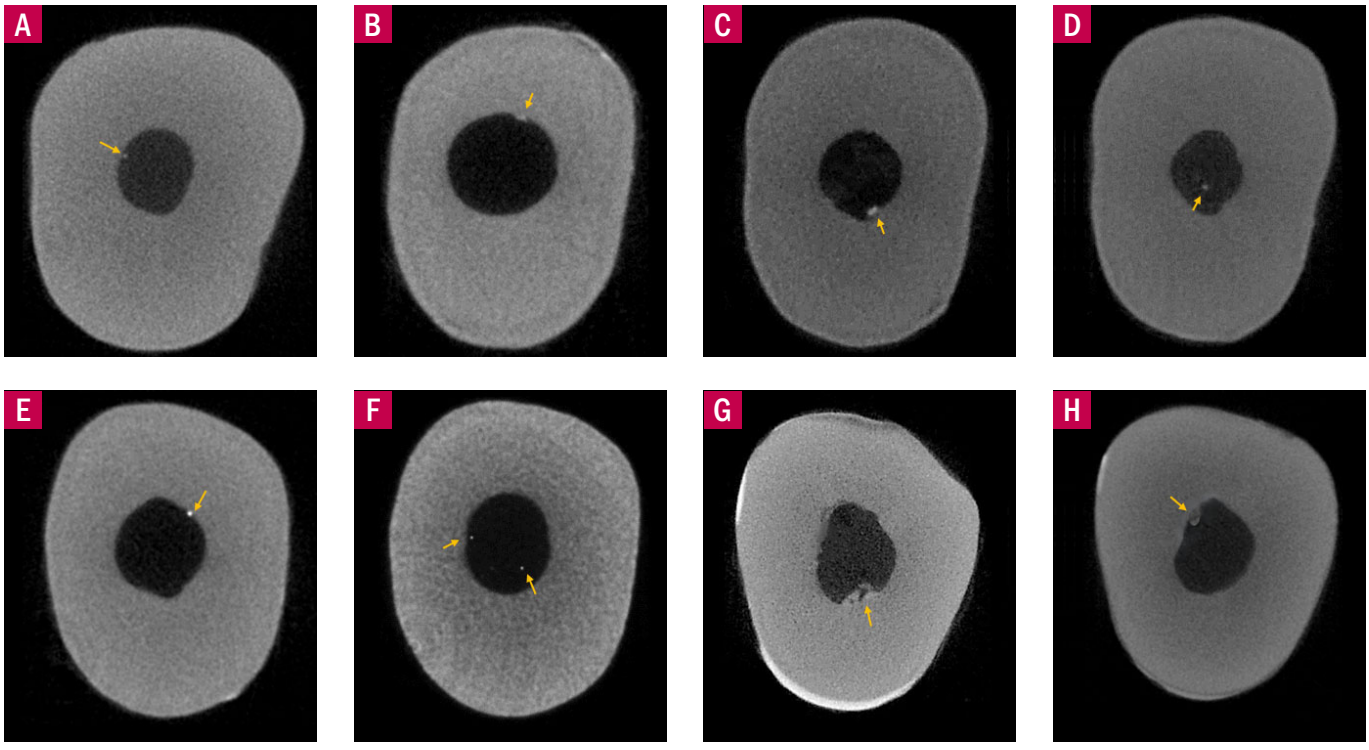

Figure 1
Representative micro-computed tomography (Micro-CT) cross-sectional images demonstrating nano-leakage patterns in simulated immature teeth restored with different coronal plug materials following silver nitrate penetration analysis. Yellow arrows indicate areas of silver nitrate infiltration corresponding to nano-leakage along the dentin–material interface. (**A**, **B**) Bio-C Repair group demonstrating minimal interfacial leakage; (**C**, **D**) Biodentine group showing moderate leakage areas; (**E**, **F**) MTA Repair HP group demonstrating comparatively greater leakage; and (**G**, **H**) control group showing extensive silver nitrate penetration and interfacial gaps in the absence of a coronal plug material.

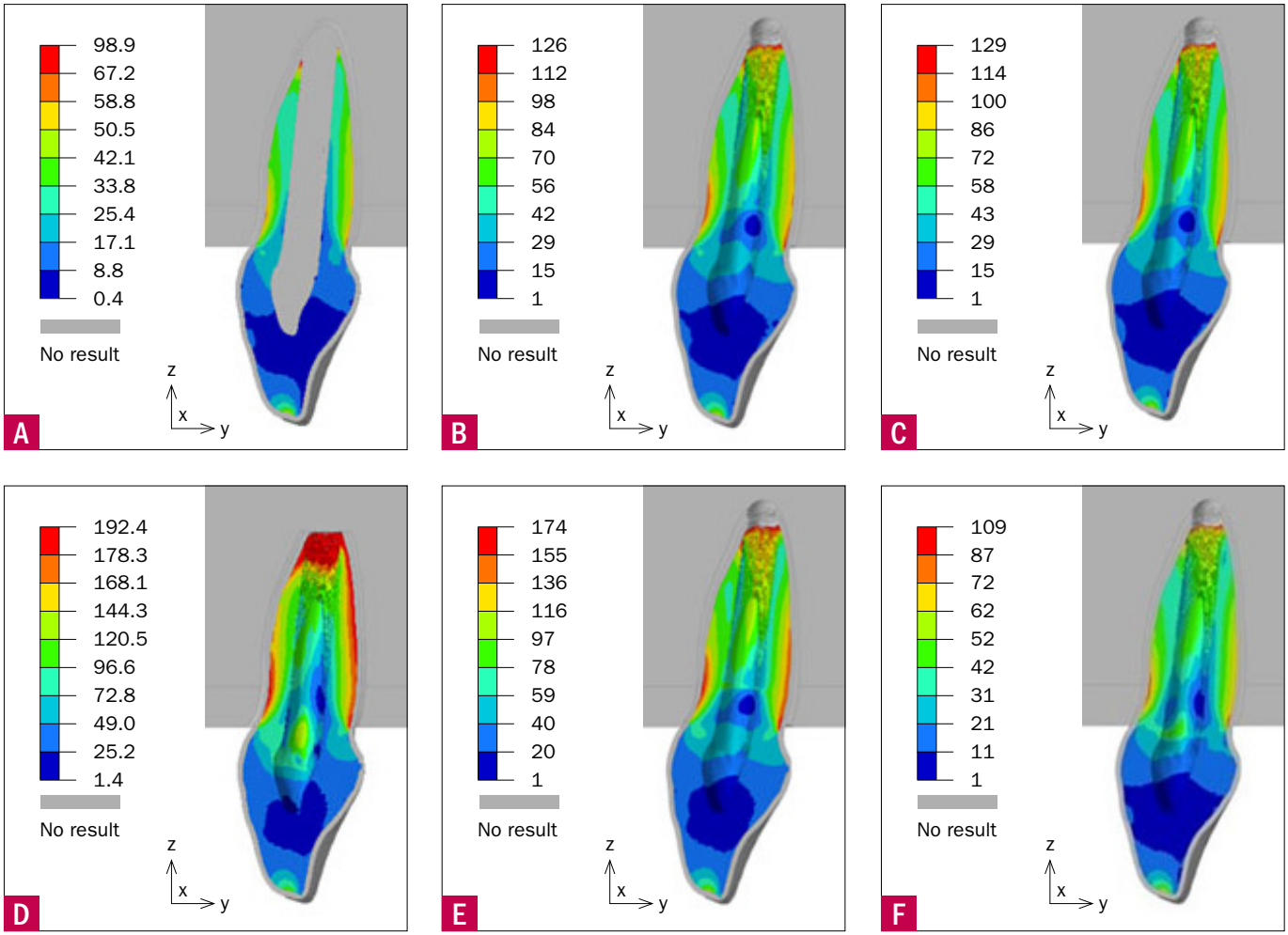

Figure 2
Stress distribution plots in dentine: a. Von Mises stress (in MPa) contour plot in dentin for model MT (Mature tooth); b. Von Mises stress (in MPa) contour plot in dentin for model IT(Immature tooth): c. Von Mises stress (in MPa) contour plot in dentin for model 1 (MTA Repair HP); d. Von Mises stress (in MPa) contour plot in dentin for model 2(Biodentine): e. Von Mises stress (in MPa) contour plot in dentin for model 3 (Bio-C Repair); f. Von Mises stress (in MPa) contour plot in dentin for model 4 (control group).

values and the most favourable biomechanical behaviour.
Among the experimental groups restored with coronal plug materials, the Biodentine model demonstrated the highest stress concentration within dentin, whereas MTA Repair HP and Bio-C Repair exhibited comparatively lower and nearly similar stress values. Stress concentration was predominantly localized within the cervical third of the root, particularly along the lingual aspect, corresponding to regions most susceptible to fracture under functional loading conditions. Analysis of Von Mises stress contour plots demonstrated that the untreated immature tooth model exhibited extensive high-stress regions extending from the cervical region toward the apical portion of the root. In comparison, the experimental models restored with MTA Repair HP and Bio-C Repair demonstrated a more restricted distribution of high-stress areas, indicating improved stress dissipation and reinforcement of radicular dentin. Biodentine demonstrated comparatively greater stress concentration within the cervical region.
Maximum principal stress analysis revealed that the mature tooth model exhibited the lowest stress values, whereas the untreated immature tooth model exhibited the highest values. Among the experimental groups, MTA Repair HP demonstrated the lowest maximum principal stress values, followed closely by Bio-C Repair, while Biodentine demonstrated compara-

tively higher stress concentration within dentin. Failure index analysis demonstrated that the untreated immature tooth model exhibited the greatest weakening percentage relative to the mature tooth model. The immature tooth model demonstrated a weakening percentage of 93%, whereas the MTA Repair HP and Bio-C Repair models demonstrated weakening percentages of 49%. The Biodentine model demonstrated a weakening percentage of 70%, indicating comparatively greater susceptibility to structural failure. The control model demonstrated the lowest weakening percentage among the immature tooth models (Table 3). Overall, MTA Repair HP and Bio-C Repair demonstrated more favourable biomechanical behaviour with lower stress concentration and reduced fracture susceptibility compared with Biodentine, whereas Bio-C Repair demonstrated superior sealing ability with the least nano-leakage among all experimental groups.

Discussion

The present study evaluated the nano-leakage and fracture resistance of three calcium silicate–based coronal plug materials, namely MTA Repair HP, Biodentine, and Bio-C Repair, in simulated immature teeth using Micro CT and FEM. Significant differences were observed among the tested materials with respect to sealing ability and biomechanical behaviour. Based on the obtained findings, the null hypothesis was rejected. In the present study, Bio-C Repair demonstrated the lowest nano-leakage values among all experimental groups. The superior sealing ability observed with Bio-C Repair may be attributed to its premixed bioceramic formulation, improved flow characteristics, smaller particle size, and enhanced adaptation to dentinal walls (27). In addition, the hydrophilic nature of the material enables utilization of intrinsic moisture during the setting reaction, thereby improving marginal adaptation and reducing interfacial voids (28). The bioactive potential of calcium silicate–based materials further contribute to hydroxyapatite deposition at the dentin–material interface, which may enhance sealing over time (29). The present findings are consistent with previous studies reporting superior marginal adaptation and sealing ability of premixed bioceramic repair materials (22),(30),(31).

Biodentine demonstrated intermediate nano-leakage values, whereas MTA Repair HP exhibited comparatively greater leakage than Bio-C Repair. Although MTA Repair HP was developed to overcome several disadvantages associated with conventional mineral trioxide aggregate, including poor handling characteristics and discoloration potential, manual manipulation of the material may increase the likelihood of void incorporation during placement. Biodentine demonstrated better sealing ability than MTA Repair HP, which may be related to its improved consistency and reduced setting time. However, slight dimensional alterations during the setting reaction may influence interfacial adaptation and contribute to nano-leakage.

The control group demonstrated the highest nano-leakage values because of the absence of a definitive coronal barrier material. This finding highlights the importance of an effective coronal seal in regenerative endodontic procedures (32). Representative Micro-CT images revealed silver nitrate penetration along the dentin–material interface in all groups, although the extent of penetration varied according to the material used. Bio-C Repair demonstrated minimal interfacial gaps and more homogeneous adaptation to dentinal walls compared with the other tested materials. Micro CT was selected for nano-leakage evaluation because it enables non-destructive three-dimensional assessment of leakage pathways with high spatial resolution. Unlike conventional dye penetration methods that provide only two-dimen-

sional information, Micro-CT permits volumetric analysis of leakage and allows accurate visualization of interfacial adaptation. Furthermore, the use of silver nitrate as a radiopaque tracer enabled precise identification of leakage pathways within the canal space.

Finite element analysis demonstrated that the untreated immature tooth model exhibited the highest Von Mises stress values, maximum principal stress, and failure index among all evaluated models, confirming the structurally compromised nature of immature teeth with thin radicular dentin. Stress concentration was predominantly localized within the cervical third of the root, particularly along the lingual aspect. This observation is clinically relevant because cervical root fracture is one of the most common catastrophic complications associated with immature teeth (33). Among the experimental groups, MTA Repair HP and Bio-C Repair demonstrated more favourable biomechanical behaviour with lower stress concentration and reduced failure indices compared with Biodentine. The improved stress distribution observed with MTA Repair HP and Bio-C Repair may be related to their elastic modulus being relatively closer to that of dentin, thereby permitting more homogeneous stress dissipation throughout the radicular structure (21). Materials with mechanical properties approximating those of dentin are believed to reduce stress concentration within weakened roots and improve resistance to fracture under functional loading conditions.

Biodentine demonstrated comparatively greater stress concentration and higher tooth weakening percentage among the experimental groups. Although Biodentine has been widely recommended as a dentin substitute because of its bioactivity and favourable compressive strength, its comparatively higher elastic modulus may have resulted in increased stress concentration within the surrounding dentin. This may explain the higher failure index and stress values observed in the present study.

The finite element models used in the present investigation simulated periodontal ligament support, cortical bone, cancellous bone, and functional occlusal loading conditions to approximate the clinical scenario more closely. The combined use of Micro-CT and finite element analysis enabled comprehensive evaluation of both sealing ability and biomechanical performance of the tested materials. The present findings suggest that Bio-C Repair exhibited superior sealing ability with the least nano-leakage, whereas both Bio-C Repair and MTA Repair HP demonstrated more favourable stress distribution patterns and lower fracture susceptibility compared with Biodentine. These observations indicate that the physicochemical characteristics, handling properties, and elastic behaviour of calcium silicate–based materials may significantly influence their clinical performance in regenerative endodontic procedures (34). From a clinical perspective, materials demonstrating lower nano-leakage and improved biomechanical behaviour may contribute to enhanced long-term prognosis of immature teeth treated using regenerative protocols by minimizing reinfection and reducing the risk of cervical root fracture. The findings of the present study suggest that Bio-C Repair and MTA Repair HP may provide more favourable outcomes when used as coronal plug materials in regenerative endodontic procedures.

Despite the promising findings, certain limitations of the present study should be considered. The in vitro design may not completely reproduce the complex biologic and mechanical conditions of the oral environment. In addition, the finite element models assumed homogeneous, isotropic, and linearly elastic behaviour of materials, which may not fully represent the anisotropic nature of dental tissues. Only static loading conditions were evaluated, whereas clinical masticatory forces are dy-

namic and cyclic in nature. Furthermore, long-term aging and fatigue behaviour of the materials were not assessed. Therefore, further long-term in vitro investigations and clinical studies are required to validate the present findings and establish their clinical applicability. With future emphasis on developing promising bioceramics that can be used for various regenerative purposes (35),(36).

Conclusion

Within the limitations of the present study, Bio-C Repair demonstrated superior sealing ability with the least nano-leakage among the tested materials. MTA Repair HP and Bio-C Repair exhibited more favourable biomechanical behaviour and reduced fracture susceptibility compared with Biodentine in simulated immature teeth.

Clinical Relevance
Selection of an appropriate coronal plug material is critical for the long-term success of regenerative endodontic procedures in immature teeth. Bio-C Repair demonstrated superior sealing ability, while both Bio-C Repair and MTA Repair HP showed improved biomechanical behaviour, suggesting their potential to reduce reinfection and cervical root fracture in structurally compromised immature teeth.

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ORIGINAL ARTICLES

Bacterial leakage of bioceramic versus resin sealers in different obturation techniques: an in-vitro study

ABSTRACT

Aim: *To compare bacterial leakage of Neo-sealer (a bioceramic sealer) and AH-Plus (an epoxy resin-based sealer) using different obturation techniques.*
Methodology: *Ninety mandibular molars without caries, cracks, fractures, resorption, open apices, or prior endodontic treatment were selected. Mesial roots were standardized in length; distal roots were discarded. Samples were randomly divided into six groups: (1) Neo-sealer + single cone; (2) Neo-sealer + lateral compaction; (3) Neo-sealer + warm vertical compaction; (4) AH-Plus + single cone; (5) AH-Plus + lateral compaction; and (6) AH-Plus + warm vertical compaction. Canals were prepared to size #30 with 4% taper and irrigated using 5% NaOCl and saline. Each group was obturated according to its protocol. Bacterial leakage was evaluated by a blinded operator, and the time to leakage was recorded. Statistical analysis was performed using two-way ANOVA and Tukey's test (α=0.05)*
Results: *Mean leakage times (in days) were: 9.64, 17.53, 13.21, 12.47, 7.73, and 8.53 for groups 1–6, respectively. No significant differences were found among sealers, techniques, or their combinations (P>0.05).*
Conclusions: *Neo-sealer and AH-Plus showed similar effectiveness in preventing coronal bacterial leakage across all obturation techniques. The single cone method was comparable to lateral and warm vertical compaction in sealing ability.*

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Introduction

Long-term endodontic success depends on many factors: instrumentation, chemical and mechanical preparation, isolation, obturation, and post-endodontic restoration. All of these factors have the same goal which is to prevent bacteria from leaking through the canal and affecting the periapical region. The role of obturation is the three-dimensional seals of the canal for the long term. Many materials and obturation techniques have been introduced for obturation (1-6).

Various factors can influence the occurrence of apical micro-leakage and the quality of root canal obturation, including the quality of the obturation materials, root canal obturation techniques, and the presence or absence of the smear layer, all of which can contribute to treatment failure (7).

Different techniques are used for filling root canals, such as cold lateral compaction, warm vertical compaction, hybrid Tagger, single cone technique, carrier-based gutta-percha, and thermoplastic injectable techniques (7)(8).

Many studies have identified the cold lateral compaction technique as the standard method for root canal filling (9). This technique is cost-effective, predictable, and safe, offering long-term success (10). However, common issues with cold lateral compaction include void formation, incomplete filling in curved root canals, and an increased risk of vertical root fracture due to high compaction forces (11,12).

As a simpler alternative, the single cone technique with an adaptive taper has been introduced. This method relies less on the operator's skill and poses a lower risk of damage to the dentin walls of the root canal (13). Other advantages include easy handling, lower costs, and reduced treatment time (14,15). However, its drawbacks include the potential for unfilled spaces, especially in large canals, as well as shrinkage during sealer setting (16). To optimize this technique, it has been suggested that sealers with good physical and chemical properties, such as proper flow along the canal walls and void spaces, should be used (13).

It is believed that the most important component of the obturation is the sealer used, as it is the only anti-microbial obturation component offering resistance against bacteria and leakage (8). Resin-based sealers, such as AH-Plus, have been used for a long time in endodontics and have their advantages: the ability to bond to composite resin restorations, good wettability, and penetration into dentinal tubules. It has some disadvantages: it has shrinkage and may cause voids (9, 10). The properties of AH-Plus have been known for a long time, and somehow it has become the gold standard in endodontic treatments (11, 12). Recently bioceramic sealers such as Neo-sealer have been introduced. Its advantages include biocompatibility and setting without shrinkage. It has been studied in single cone obturation technique, and some studies suggest that it has superior sealing ability compared to resin-based sealers with single cone obturation technique (13).

However, there are limited studies on bioceramic sealers used in different obturation techniques like warm vertical and lateral compaction obturations. Some studies have shown that these sealers may lose their properties in hot temperatures (14-16). Also, the lateral compaction obturation technique may have better sealing ability than the single cone technique used with bioceramic sealers (17).

Since there are limited and conflicting studies on this subject matter, the current experiment was designed to compare two types of sealers (AH-Plus as a resin-based sealer and Neo-sealer as a bioceramic sealer) in combination with different obturation techniques (single-cone, lateral compaction, and warm vertical obturation) in preventing coronal bacterial leakage.

Materials and Methods

Sample selection

This experimental study was approved by the Research Ethics Committee (IR.MUI.DHMT.REC.1403.109) at the Isfahan University of Medical Science and reported based on the PRILE 2021 checklist. A total of 90 mandibular molars were collected (15 samples in each group). The teeth included had closed apices and without any fracture, caries, resorption, and previous endodontic treatment. Teeth that did not match these criteria were excluded from the study. Teeth had Schneider curvature between 10-30 degrees based on placing a K-file #10 into the canal and taking a radiograph (18). The teeth were decornated at the level of the cementoenamel junction to match all roots for the same length, mesial roots were collected and distal roots were discarded. Mesiobaccal canals were treated for this study. Roots were stored in normal saline at room temperature.

Root canal preparation

At first, the glide path was determined using K-file #10 (Dentsply Maillefer, Ballaigues, Switzerland), and the working length was determined using K-file #10 passing through apical foramen and then canals were instrumented 1 mm shorter than the anatomical apex. Roots were instrumented using S1, S2, F1, and F2 ProTaper universal rotary files (Dentsply Sirona, Ballaigues, Switzerland) using the crown-down technique. Canals were irrigated with NaOCl %5 (Cerkamed, Stalowa Wola, Poland) with a syringe with a 25-gauge needle, and at the final stage irrigated with normal saline (DarouPakhsh, Tehran, Iran). Canals were dried with multiple paper points (Diadent, Chungcheongbuk-do, Korea).

Obturation

After preparation, the roots were divided into 6 groups: Group 1: roots were obturated using a single cone of gutta-percha and NeoSealer (Avalon Biomed, Texas, USA) as the sealer. First, the sealer was injected into the canal, then one gutta-percha point size #30 with %4 taper was coated with the sealer and then placed into the canal. Then obturation material was cut with a heat carrier (Fast Pack, Eighteeth) device.
Group 2: roots were obturated with NeoSealer as the sealer with the lateral compaction method. A master gutta-percha point size #30 with %2 taper was chosen, coated with the sealer, and placed into the canal. A spreader was placed into the canal to compact the obturation material and accessory gutta-percha points were used to fill the gap until the spreader could not enter the canal. Then obturation was cut using a heat carrier device.
Group 3: roots were obturated with NeoSealer as the sealer with the warm vertical compaction method. A gutta-percha point size #30 with %4 taper was coated with the sealer and then placed into the canal. Then it was cut with a heat carrier device 5 mm to the apex, after that a plugger (DiaDent, Cheongju, Korea) size #50 was used to downpack the obturation. Then, a thermoplastic gutta-percha was injected into the canal using a backfill device (Fast Fill, Eighteeth). A plugger size #60 was used to downpack the obturation.
Group 4: roots were obturated using a single cone of gutta-percha and AH-Plus (Dentsply Sirona) as the sealer. Obturation was done similarly to Group 1.
Group 5: roots were obturated with AH-Plus as the sealer with the lateral compaction method. Obturation was done similarly to Group 2.
Group 6: roots were obturated with AH-Plus as the sealer with the warm vertical compaction method. Obturation was done similarly to Group 3.

Bacterial leakage testing

The bacterial leakage test were accomplished according to the Yanpiset et al. protocol (19) by an operator blinded to the experiment. Briefly, all root surfaces were coated with two layers of varnish, except for the apical 2 mm,

which remained unsealed. A cut microcentrifuge tube (Eppendorf, Hamburg, Germany) was made for each obturated root. A segment of approximately 5 mm of the root was inserted through the cut end of a microcentrifuge tube, with about 9 mm positioned inside the tube. To ensure a tight seal between the root and the tube, cyanoacrylate adhesive (3M Super Glue Gel; 3M Company, Maplewood, MN, USA) was applied. Sterilization of the assembly was carried out using ethylene oxide gas. Brain Heart Infusion (BHI) broth (Difco Laboratories, Detroit, MI, USA) was sterilized in a glass bottle, into which the microcentrifuge tube was placed. Under aseptic conditions, approximately 2 mm of the apical root tip was submerged in the BHI broth.
A reference strain of Enterococcus faecalis (ATCC 29212) was cultured on BHI agar plates. Selected colonies were suspended in 3 mL of BHI broth and incubated overnight at 37 °C. The bacterial concentration was adjusted to match a 0.5 McFarland standard, equivalent to 1×10^8 CFU/mL. The upper chamber of the setup was inoculated with 400 µL of the E. faecalis suspension and incubated at 37 °C. To maintain bacterial viability, the culture medium was refreshed every 48 hours under sterile conditions.
Bacterial leakage was assessed daily over a 60-day period by observing turbidity in the BHI broth. Turbid samples were further analyzed using Gram staining and bacterial culturing to confirm the presence of E. faecalis. The time to leakage, measured in days, was recorded and validated

Statistical analysis
Data was entered into SPSS software version 22 (IBM; Chicago; IL, USA), and the mean and standard deviation of the days that leakage occurred for the samples were calculated. The normality of the data was checked by the Shapiro-Wilk test. The data did not have a normal distribution, so the Napierian logarithm of the data was calculated and analyzed.
The difference is measured by two-way ANOVA and Tukey-test, and a difference of more than 95% is considered significant.

Results

In this study, 90 mandibular molars were examined. When preparing the samples for the bacterial leakage test, 2 samples were excluded from the experiment due to not being sterile when applying the BHI culture. Six examination groups were tested, and each group contained 15 samples.

The variables were the sealer type (two types) and the obturation technique (three obturation techniques).
The mean and standard deviation of the groups were 9.64 (14.773), 17.53 (18.639), 13.21 (20.196), 12.47 (14.272), 7.73 (8.892), and 8.53 (10.398) days for group 1 to 6 respectively (Table 1).

By using the two-way analysis of variance, the means of leaked days were compared between groups for sealer and obturation variables. Based on these results, no significant difference was found between two types of sealer and three types of obturation, as well as the combination of sealers and obturations (Table 2).

Table 1
Mean and Standard Deviation of bacterial leakage (days)

Obturation Technique	Sealers	N	Mean	Std. Deviation
Single-Cone	AH-Plus	15	12.47	14.272
	Bio-C	14	9.64	14.773
	Total	29	11.10	14.326
Cold Lateral Compaction	AH-Plus	15	7.73	8.892
	Bio-C	15	17.53	18.639
	Total	30	12.63	15.190
Warm Vertical Compaction	AH-Plus	15	8.53	10.398
	Bio-C	14	13.21	20.196
	Total	29	10.79	15.783
Total	AH-Plus	45	9.58	11.347
	Bio-C	43	13.56	17.900
		88	11.52	14.960

Source	Type III Sum of Squares	df	Mean Square	F	P value
Corrected Model	5.580a	5	1.116	.927	0.468
Intercept	301.438	1	301.438	250.329	0.000
Obturation	1.227	2	0.613	0.509	0.603
sealer	.867	1	0.867	0.720	0.399
Obturation * sealer	3.389	2	1.694	1.407	0.251
Error	98.742	82	1.204		
Total	406.620	88			
Corrected Total	104.322	87			

Table 2
Tests of Between-Subjects Effects.

Discussion

The final aim of endodontic treatment is to prevent coronal bacteria from leaking through the canal and reaching the periapical region (20). Cleaning and shaping cannot sterilize the canal from bacteria and their by-products, so a sealed obturation is necessary to avoid bacterial leakage, leading to the long-term success of the treatment (21, 22). This study investigated the bacterial leakage of two resin (AH-Plus) and bioceramic (Neo-sealer) sealers in different obturation methods to identify the better root canal sealing protocol.
The bacterial leakage of AH-Plus and Neo-sealer in combination with different obturation techniques showed that there was no statistical difference between the groups. AH Plus is an epoxy resin-based sealer characterized by optimal flowability and viscosity, which facilitates deeper penetration into the root canal system. It interacts with the dentinal surface by creating a mild etching effect, exposing collagen fibers and thereby enhancing its adhesion to the dentinal walls. On the other hand, Neo-sealer is a bioceramic sealer that was introduced to endodontics recently and got more attention because of its biocompatibility, hydrophilicity, antibacterial properties, high pH, and no shrinkage after setting (2). In addition, it is usually recommended with the single-cone technique. This technique is easier to use and takes less time for application (23).

Kaul et al. study compared the sealing ability of resin, bioceramic, and silicon sealers. They concluded that the resin and bioceramic sealers had no differences in sealing ability when applied in the single cone obturation technique (5). Also, Lanker et al, concluded that bioceramic and resin sealers had the same sealing ability in lateral and vertical condensation techniques (1). The results of these studies are consistent with the current study. The similarity in the sealing ability results, in resin and bioceramic sealers, may be due to the thorough application of the sealer into the canal to prevent the formation of voids (1-5).
However, some studies have results contradictory to the current study. Antunovic et al. investigated the sealing ability of five sealers including four bioceramic sealers and a resin-based sealer, in single cone technique and lateral condensation technique. They concluded that TotalFill BCS sealer is superior to the other bioceramic sealers and resin-based sealers in sealing ability (24). They claimed that TotalFill BCS sealer releases more calcium hydroxide which leads to higher PH and antibacterial properties (24). In the other study, Trivedi et al. concluded that in comparing one resin-based and two bioceramic sealers, the Bio C sealer is superior to the others in sealing ability (6). They also claimed that Bio C sealer stimulates regeneration (6). Nevertheless, in these studies, some groups of bioceramic and resin-based sealers had no

differences in sealing ability.
The difference in chemical properties of different bioceramic sealers used in these studies may lead to different results obtained. Also, the evaluation method is one of the differences that may cause study results contradictory. Furthermore, the irrigation system used (using EDTA or maleic acid) in the studies can improve the sealing ability of the sealers (2). Standardization of canal morphology is also essential when comparing the sealing performance of different obturation protocols (25). Such variability may influence sealer distribution and leakage outcomes, underscoring the importance of using canals with comparable anatomy when evaluating sealing ability. To achieve more comprehensive results the sealers and obturation techniques should be examined mutually. This study tried to experiment with the sealers and obturation techniques in combination with each other but the results shouldn't extend to all the cases. For future studies, different bioceramic sealers in combination with obturation techniques should be investigated to achieve more reliable results.

Conclusions

The comparison between Neo-sealer as a bioceramic sealer and AH-Plus as a resin-based sealer in different obturation techniques revealed that no difference was found in coronal bacterial leakage. In clinical practice based on the situation, the clinicians can use either of the techniques and materials.

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NARRATIVE REVIEW

Endodontic therapy or extraction and tooth replacement with implants? Decision-making criteria

ABSTRACT

Objective: *The decision between preserving a compromised tooth through endodontic therapy or replacing it with a dental implant remains a frequent clinical dilemma. This narrative review aims to evaluate the available evidence regarding clinical outcomes, success rates, prognostic factors, and patient-related considerations associated with endodontic treatment and implant therapy to support evidence-based clinical decision-making.*

Materials and Methods: *A comprehensive literature search was performed in electronic databases including PubMed, EMBASE, Wiley Online Library, Cochrane Library, and ScienceDirect up to October 2025. Studies evaluating outcomes of endodontic therapy and dental implant treatment in human subjects were included. A total of 13 studies (including cohort, case-control, cross-sectional, and one randomized controlled trial) were selected. Data extraction focused on study characteristics, interventions, follow-up duration, and clinical and patient-reported outcomes. Risk of bias was assessed using a domain-based approach adapted from the RoB 2 tool, modified to account for the inclusion of predominantly non-randomized studies.*

Results: *Both endodontic therapy and dental implant treatment demonstrated high long-term survival rates when performed under appropriate clinical conditions. Endodontically treated teeth showed survival rates exceeding 85–90%, while implant survival ranged from 90% to 97%. However, heterogeneity in study design, follow-up duration, and outcome definitions limited direct comparisons. Most included studies presented some concerns to high risk of bias, primarily related to confounding, participant selection, and variability in outcome assessment. Patient-reported outcomes indicated comparable levels of satisfaction and quality of life between treatments, although implant therapy was associated with higher reported levels of pain and fear in some studies. Biological complications differed between modalities, with peri-implant diseases affecting implants and persistent infection or restoration failure influencing endodontic outcomes.*

Conclusions: *Both treatment modalities represent predictable therapeutic options. Preservation of the natural tooth through endodontic therapy should generally be considered the first-line approach when prognosis is favorable, while dental implants serve as a reliable alternative when tooth preservation is not feasible. Clinical decision-making should integrate biological, restorative, systemic, and patient-centered factors. The strength of the evidence is limited by the predominance of observational studies and the overall moderate to high risk of bias across included studies.*

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Introduction

The preservation of natural dentition in a healthy and functional state remains a fundamental objective in clinical dentistry. However, in certain situations, conservative treatment approaches may fail, necessitating tooth extraction and replacement. Determining whether to retain a compromised tooth or proceed with extraction continues to represent a longstanding clinical challenge and an area of ongoing debate among clinicians (1).
Treatment planning, particularly when deciding between root canal therapy and single-tooth implant placement, is frequently discussed in both scientific literature and routine clinical practice. (2) Each treatment modality presents distinct advantages, limitations, and prognostic considerations, making direct comparisons complex and often dependent on individual clinical scenarios.
A critical component of contemporary dental care is informed consent, which requires clinicians to provide patients with accurate, evidence-based information regarding the potential risks, benefits, and expected outcomes of available treatment options. Consequently, treatment planning should be regarded as a collaborative process in which clinical evidence, practitioner expertise, and patient preferences are integrated. Patients ultimately make decisions based on individual priorities, including predictability, safety, cost-effectiveness, longevity, and overall treatment experience.
Given the variability in reported outcomes, study designs, and patient-reported measures in the literature, there is a need to synthesize and critically appraise the available evidence to better inform clinical decision-making.

Materials and Methods

The present review evaluated the available literature on the clinical outcomes of endodontic therapy and dental implant treatment. A comprehensive search and screening process initially identified a large number of studies, of which 13 studies met the inclusion criteria and were included in the final analysis. The included studies comprised cohort studies, case-control studies, one randomized controlled trial, and one cross-sectional study involving human participants. The interventions assessed included primary root canal treatment, non-surgical retreatment, surgical endodontic procedures, and dental implant placement. Where applicable, comparisons were made between endodontically treated teeth and dental implants in terms of clinical outcomes and long-term prognosis. The primary outcomes evaluated were success and survival rates, biological and mechanical complications, radiographic healing, and treatment failure. In addition, patient-reported outcomes such as quality of life, satisfaction, pain perception, and treatment preferences were analyzed. Follow-up durations varied across studies, ranging from short-term to long-term evaluations. Furthermore, prognostic factors including local anatomical conditions, systemic health, restorative and mechanical variables, clinician-related factors, and technological advancements were considered, as these variables may influence treatment outcomes and clinical decision-making.

Search Strategy

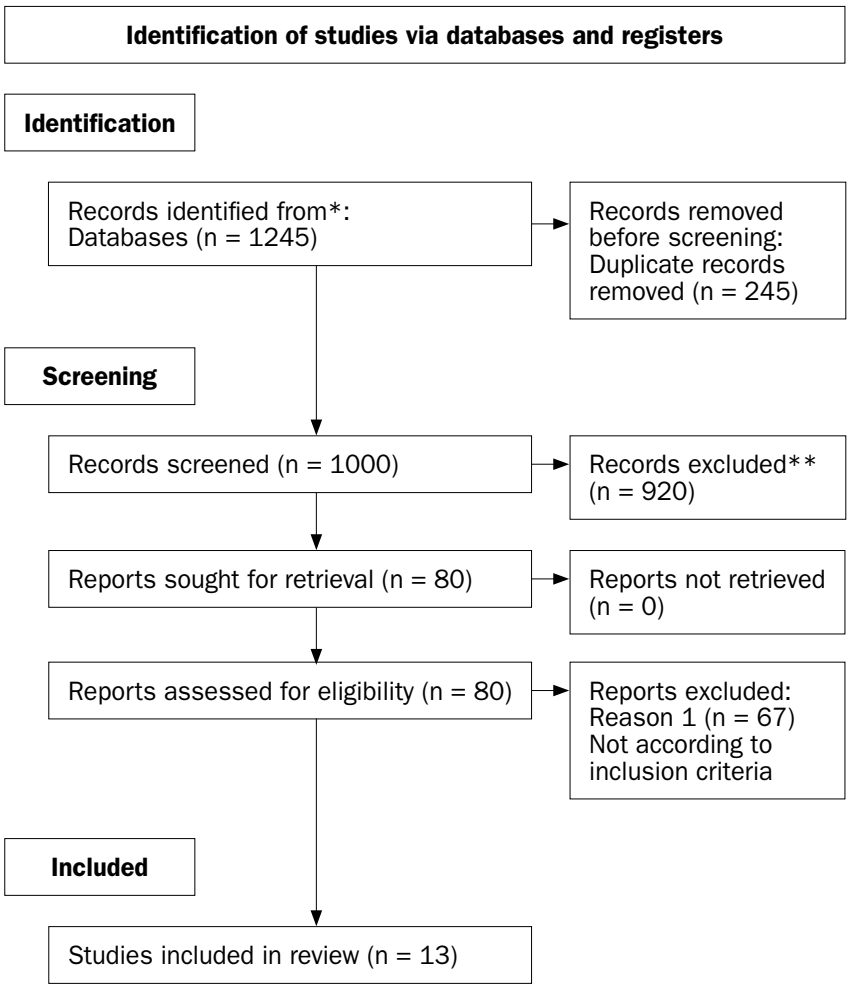
A comprehensive electronic search was conducted in PubMed, EMBASE, Wiley Online Library, Cochrane Library, and ScienceDirect for studies published up to October 2025. The search was limited to full-text articles published in English and involving human subjects. The search terms applied were: implant AND endo AND outcome; outcome OR success AND endo; outcome OR success AND implant; implant AND versus AND endo; failure AND implant; failure AND endo; systematic AND implant; systematic AND endo; survival

AND implant; survival AND endo; prospective OR retrospective AND implant; prospective OR retrospective AND endo; prognosis AND implant OR endo. In addition to the database search, the reference lists of all included studies were manually screened to identify any additional relevant publications.

Eligibility Assessment

Two independent reviewers (SSV and HAS) assessed the eligibility of studies for inclusion in the review. Studies were considered eligible if they were published in English, involved human participants, reported clinical outcomes of endodontic treatment and/or dental implant therapy, and provided sufficient data for extraction. Studies such as case reports, case series, abstracts, letters, and those containing incomplete or methodologically inadequate data were excluded. Articles focusing solely on technical or procedural aspects without reporting clinical outcomes were also excluded, as were studies published in languages other than English. Any disagreements between reviewers were resolved through discussion and consensus.

Figure 1
PRISMA Flow chart.



Data Extraction

Data extraction was independently performed by two reviewers (SSV and HAS). The following data were extracted: root canal treatment outcomes, including influencing factors; implant treatment outcomes, including influencing factors; studies with direct comparisons between the two treatment modalities; patient satisfaction criteria and surveys evaluating factors influencing patient choice; and relevant guidelines where applicable. Additional extracted variables included study characteristics such as author, year, study design, sample size, intervention type, follow-up duration, and clinical outcomes including success, survival, complications, and failure. Patient-reported outcomes such as quality of life, satisfaction, pain perception, and decision-making factors were also recorded. The extracted data were summarized in tabular form to facilitate comparison across studies. Any discrepancies between reviewers were resolved by consensus.

Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using a domain-based approach adapted from the RoB 2 tool. Given that the majority of included studies were observational in design, the standard RoB 2 domains were modified to enable consistent assessment across different study types (Figure 2 and 3). The evaluation focused on key domains including bias due to confounding and baseline differences, participant selection, outcome measurement, complete-

Groups	D1	D2	D3	D4	D5	Overall
Doyle et al 2006	+	-	-	+	+	-
Hannahan et al 2008	+	+	+	X	+	X
Gatten et al 2011	+	+	+	X	+	X
Torabinjad et al 2014	+	-	X	X	+	X
Chatzopoulos et al 2018	+	+	+	+	-	-
Vahdati et al 2019	+	+	-	+	-	-
Hanasha et al 2019	+	+	-	+	+	-
Esposito et al 2020	+	+	X	X	+	X
Lee et al 2022	+	-	+	+	+	-
Sanz et al 2022	+	+	X	+	+	X
Zang et al 2023	+	X	+	+	-	X
Suganna et al 2024	+	-	+	-	-	-
de España et al 2025	+	+	+	+	+	+

D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended interventions.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement: + High - Some concerns X Low

Figure 2
Risk of bias graph.

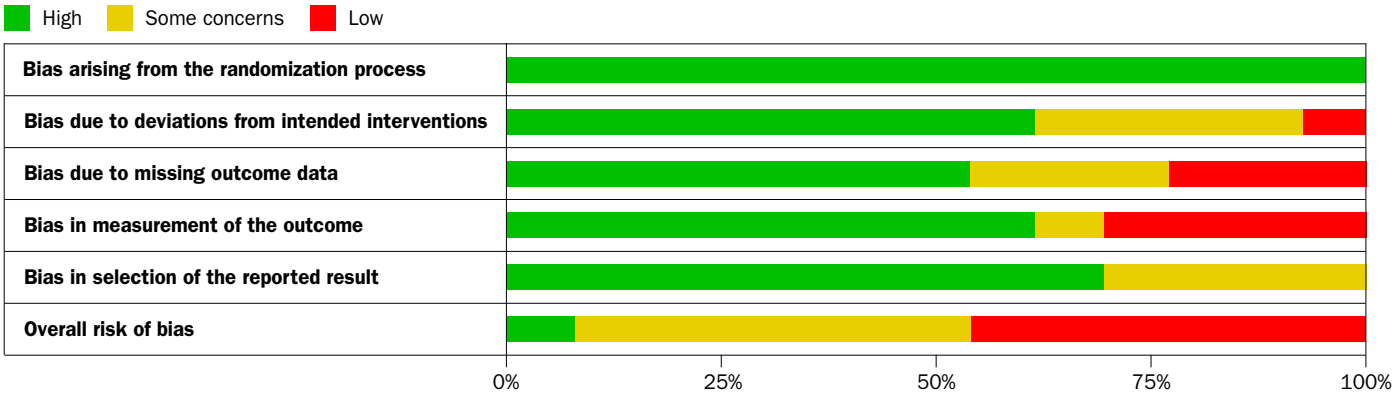
Figure 3
Risk of bias summary.

ness of follow-up data, and selective reporting. Each study was judged as having low risk, some concerns, or high risk of bias within each domain. An overall risk-of-bias judgment was then assigned based on the highest level of bias identified across domains. Overall, the included studies demonstrated variability in methodological quality, with most studies showing some concerns to high risk of bias. This was primarily attributed to confounding factors, retrospective and non-randomized study designs, heterogeneity in outcome definitions, and variations in follow-up duration and outcome assessment.

Results

Study Identification

The study identification process is summarized in Figure 1. A comprehensive search of the electronic databases yielded a large number of records. Following screening and removal of duplicates, 80 studies were assessed for full-text eligibility, of which 67 were excluded. Consequently, 13 studies were included in the final analysis. The methodological characteristics and extracted data of the included studies are presented in Table 1. The risk of bias of the included studies (Figures 2 and 3) was assessed using a domain-based approach adapted from the RoB 2 tool. The assessment demonstrated variability across studies, with the majority being observational in design and showing some concerns to high risk of bias, primarily related to confounding, participant selection, and heterogeneity in outcome definitions. Overall, outcome measurement and reporting were generally consistent across studies; however, differences in study design and methodological approaches limited direct comparability



Author (Year)	Country	Study Design	Sample Size (RCT / DI)	Population Characteristics	Intervention Details	Follow-up Duration	Outcomes Extracted	Key Notes for Extraction
Doyle (2006)(3)	USA	Case-control	196 / 196	Adults, matched by treatment area	NSRCT vs single implant	1 year	Survival, success, failure, complications	Matched comparison within similar anatomical regions
Hannahan (2008)(4)	USA	Cohort	143 / 129	Adult patients	RCT vs implant therapy	1.8–3 years	Success, failure, complications	Unequal follow-up durations
Gatten (2011)(5)	USA	Cohort	17 / 20	Adults	Endodontic vs implant therapy	1–6 years	QoL (OHIP)	Focus on patient-reported outcomes
Torabinejad (2014)(6)	USA	Cohort	24 / 24	Adults ≥18 years	RCT vs single implant	1 year	Pain, satisfaction, complications	Detailed patient-centered outcomes
Chatzopoulos (2018) (7)	USA	Cohort	8,915 / 4,519	Mixed adult population	RCT vs implants	Up to 5 years	Survival, failure	Large retrospective dataset
Vahdati (2019)(8)	USA	Case-control	170 / 170	Same patients (paired)	NSRCT vs implants	~7.5 years	Survival, success, complications	Within-subject comparison
Hamasha (2019)(9)	Saudi Arabia	Case-control	150 / 150	Adults, tooth-matched	RCT with post-core vs implant	1 year	Survival, QoL (OHIP), success	Includes patient QoL assessment
Esposito (2020)(10)	Italy	Randomized controlled trial	10 / 10	Adults with uncertain prognosis	Retreatment vs implant	Up to 5 years	Success, failure, complications	Only RCT; small sample size
Lee (2022)(11)	USA	Cohort	Multiple groups	Adults	Various endodontic approaches vs implants	Up to 5 years	Survival, success	Multiple treatment subgroups
Sanz (2022)(12)	Spain	Case-control	26 / —	Adults	RCT vs implant	2 years	Pain, QoL	Focus on patient experience
Zang (2023)(13)	China	Cohort	76 / 76	Adults	NSRCT vs implant	5 years	Success	Includes economic considerations
Suganna (2024)(14)	India	Cohort	176 / 145	Adults	RCT vs implant	2 years	Survival, success, failure	Recent comparative cohort
de España (2025)(15)	Spain	Cross-sectional	144	Adults treated in anterior zone	RCT, re-treatment, and single implant	5 years	QoL (OHIP-14), satisfaction, pain, fear, decision-making factors	Long-term patient-reported outcomes; esthetics identified as key decision factor; higher fear/pain in implant group

Table 1
Summary of the Methodological and Clinical Characteristics of Included Studies.

between studies.
Clinical decision-making should consider two broad categories of factors, namely objective and subjective parameters. Objective factors include reported success rates, measured outcomes, and mechanical, systemic, local, iatrogenic, and technological variables. Subjective factors include pain control, cost-effectiveness, and patient satisfaction.

Outcome Assessment and Comparison Between Endodontic Therapy and Implants

One of the principal approaches in clinical decision-making between endodontic therapy and implant placement is the analysis of reported outcome studies. However, comparisons between these treatment modalities remain challenging due to significant heterogeneity in study design, outcome definitions, follow-up periods, and evaluation criteria. The lack of standardization among studies often results in inconsistent conclusions regarding treatment success and survival rates. Outcome assessment in both endodontics and implantology is typically based on a combination of clinical, radiographic, and patient-reported parameters, which contributes to variability in interpretation and reporting (16).
A major limitation of the included studies is the inconsistent differentiation between success and survival (Table 2, 3, 4). Survival generally refers to the continued presence of the tooth or implant in the oral cavity, whereas success implies the absence of pathology and optimal functional and biological conditions. Because survival criteria are less stringent, survival rates are frequently higher than success rates in both endodontic and implant studies

Outcome Category	Specific Outcomes Evaluated	Method of Assessment
Primary clinical outcomes	Success rate, survival rate of endodontically treated teeth and dental implants	Clinical examination and long-term follow-up evaluation
Radiographic outcomes	Presence or absence of periapical radiolucency, marginal bone loss around implants, radiographic evidence of healing	Periapical radiographs and cone-beam computed tomography (CBCT) where applicable
Biological complications	Periapical pathology, persistent infection, peri-implant mucositis, peri-implantitis	Clinical signs, probing depth, radiographic changes
Mechanical complications	Crown fracture, restoration failure, implant mobility, prosthetic complications	Clinical examination and prosthetic evaluation
Treatment failure indicators	Persistent symptoms, implant loss, extraction of endodontically treated tooth	Clinical and radiographic diagnosis
Prognostic factors influencing outcomes	Pre-operative periapical lesions, quality of root canal filling, coronal restoration quality, systemic health conditions, anatomical factors	Evaluation of patient records and radiographic analysis
Patient-reported outcomes	Pain perception, patient satisfaction, treatment cost considerations	Patient surveys and clinical follow-up interviews

Table 2
Outcomes assessed among included studies evaluating endodontic therapy and dental implant treatment

(2,17,18). Radiographic interpretation further complicates comparisons due to inter-observer variability and differences in radiographic angulation or imaging techniques. Moreover, some periapical lesions may remain undetected using conventional radiography, leading to potential underestimation of disease prevalence (19). These variations are reflected in the included studies and are summarized in the data extraction tables.

Another important issue in longitudinal studies is the progressive reduction in the number of cases available for follow-up evaluation. Loss of participants over time can significantly affect the reliability and clinical relevance of the results. Consequently, meaningful comparisons between endodontic and implant outcomes require standardized definitions of success and failure, comparable follow-up periods, adequate sample sizes, and consistent outcome measures (2).

In addition to methodological limitations, discrepancies in diagnostic criteria for implant-related diseases and endodontic failure contribute to further confusion in interpreting clinical outcomes. For example, implant failure has been described using various parameters including mobility, radiographic bone loss, bleeding on probing, suppuration, and peri-implant pocket formation. Similarly, endodontic failure is often defined as the persistence or development of periapical radiolucency following treatment. The absence of universally accepted diagnostic thresholds for these conditions has led to variations in reported success rates across studies (20).

Definitions of Peri-Implant and Endodontic Conditions

Several definitions have been proposed in the literature to clarify implant-re-

Table 3
Prognostic factors influencing the outcomes of endodontic therapy and implant treatment

Factor Category	Variables Considered	Influence on Outcome
Local anatomical factors	Bone quality, root morphology, periodontal status	May affect implant stability or endodontic healing
Systemic health factors	Diabetes, smoking, immune disorders	Associated with delayed healing and increased complication risk
Mechanical/restorative factors	Quality of root canal filling, coronal restoration, implant prosthesis	Poor restoration increases fracture or failure risk
Infection-related factors	Presence of periapical lesions, bacterial contamination	Reduces success rates
Clinician-related factors	Operator skill, treatment planning	Influences technical quality of procedures
Patient-related factors	Oral hygiene, compliance, cost considerations	Affects long-term maintenance and success

Parameter	Endodontic Therapy	Dental Implants
Treatment objective	Preserve natural tooth	Replace missing tooth
Success rate	High long-term survival	High survival rates
Biological complications	Persistent infection, periapical lesions	Peri-implant mucositis, peri-implantitis
Mechanical complications	Tooth fracture, restoration failure	Implant mobility, prosthetic complications
Retreatability	Retreatment possible	Limited options if implant fails
Cost	Generally lower	Higher initial and maintenance cost
Treatment time	Usually shorter	May require surgical and healing phases

Table 4
Comparison between endodontic therapy and dental implant treatment.

lated and endodontic pathologies. Peri-implant mucositis is generally described as a reversible inflammatory reaction affecting the soft tissues surrounding an implant without bone loss (21). In contrast, peri-implantitis is characterized by an inflammatory process associated with progressive loss of supporting bone around an osseointegrated implant (21). Histological studies have demonstrated that peri-implantitis lesions contain higher numbers of plasma cells and macrophages compared with mucositis lesions (22).
Another important pathological entity is apical peri-implantitis, also known as retrograde peri-implantitis. This condition presents as a symptomatic periapical radiolucency that develops shortly after implant placement while the coronal portion of the implant remains osseointegrated (23). Residual infection from previously extracted teeth or untreated endodontic lesions of adjacent teeth has been suggested as a possible etiological factor.
In endodontics, treatment success has traditionally been defined by the absence of clinical symptoms and radiographic evidence of periapical pathology, with restoration of normal periodontal ligament structures around the root apex (24). Conversely, endodontic failure is frequently associated with persistent periapical radiolucency or recurrent symptoms following treatment (24). Teeth that cannot be predictably restored or maintained are often classified as failed teeth, whereas structurally weakened or pathologically compromised teeth may be considered compromised teeth requiring restorative intervention or further treatment.

Implant Success Criteria

Several authors have proposed criteria for implant success, reflecting differences in interpretation of clinical outcomes. One of the most widely cited criteria describes successful implants as those exhibiting stable osseointegration, absence of pain or mobility, and limited marginal bone loss following placement (25). Other authors have suggested alternative thresholds for marginal bone loss or additional clinical parameters such as absence of exudate and peri-implant inflammation(25). These variations highlight the absence of a universally accepted definition of implant success, which complicates direct comparisons between studies evaluating implant survival and those assessing the outcomes of endodontic therapy.

Endodontic Therapy: Outcomes and Prognostic Factors

Root canal treatment aims to eliminate infection within the root canal system and prevent or treat apical periodontitis. The healing process following endodontic therapy may take several months or even years, as periapical tissues gradually regenerate after removal of the microbial source of infection (26). Consequently, radiographic signs of healing may appear long after clinical symptoms have resolved.
Unlike implants, which initially demonstrate high success rates that may decline over time, the outcome of root canal treatment may improve gradu-

ally as healing progresses. Long-term studies have reported survival rates exceeding 85–90% for endodontically treated teeth over extended follow-up periods(26,27). A review reported survival rates of approximately 93% at 5 years and 87% at 10 years after treatment(28).

Several factors have been identified as influencing the prognosis of endodontic therapy. Preoperative periapical lesions represent one of the most significant prognostic factors, reducing treatment success compared with teeth without apical pathology.(29) Other important factors include the quality of root canal filling, adequacy of coronal restoration, and presence of coronal leakage. Regenerative endodontics also have shown promising roles in improvising the overall endodontic treatment outcomes in long run (30,31).

The role of restorative treatment is particularly critical in determining the long-term survival of endodontically treated teeth. Studies have shown that teeth lacking proper coronal restoration are significantly more prone to fracture and subsequent extraction. Placement of a definitive restoration following root canal treatment substantially improves long-term survival rates (29).

Endodontic retreatment also represents an important therapeutic option when primary treatment fails. Non-surgical retreatment aims to remove residual infection and improve canal disinfection, while surgical endodontic procedures allow direct access to the periapical region. Systematic reviews have reported success rates ranging from approximately 77% to over 80% for nonsurgical retreatment procedures(26). Advances in microsurgical techniques and modern biomaterials have further improved the outcomes of surgical endodontic procedures.

Implant Therapy: Success Rates and Complications

Dental implants have become a predictable treatment option for replacing missing teeth since their introduction in modern dentistry. Numerous studies have demonstrated high survival rates for implants, typically ranging between 90% and 97% over long-term follow-up periods (32). Despite these favorable outcomes, implant therapy is not free from complications. Biological complications such as peri-implant mucositis and peri-implantitis represent major causes of implant failure. Epidemiological studies have reported mucositis prevalence rates between 20% and 50%, while peri-implantitis has been observed in approximately 10–40% of implant cases over long-term follow-up periods (21).

Implant failures can be classified as early or late failures. Early failures occur before prosthetic loading and are often associated with surgical trauma, infection, inadequate primary stability, or impaired healing. Late failures typically occur after functional loading and are frequently associated with microbial infection or mechanical overload (33). In addition to biological complications, prosthetic complications may also affect implant restorations. Screw loosening, prosthetic fracture, and loss of retention have been reported in a significant proportion of implant-supported restorations (33). Literature has suggested that prosthetic complications may occur more frequently in implant-supported restorations compared with tooth-supported prostheses (33).

Another important factor influencing implant outcomes is bone quality. Implants placed in poor-quality bone, particularly in the posterior maxilla, have been associated with higher failure rates compared with those placed in denser mandibular bone (34). Similarly, systemic factors such as smoking, uncontrolled diabetes, and history of periodontitis may negatively influence implant survival.

Mechanical, Systemic and Local Factors Influencing Treatment Outcomes

Several additional factors may influ-

ence the prognosis of both endodontic and implant therapies. Mechanical factors such as occlusal loading and absence of proximal contacts may increase the risk of fracture in endodontically treated teeth. In addition to mechanical factors such as occlusal loading and the absence of proximal contacts, the quality of the coronal seal provided by the final restoration should also be emphasized, as it is critical to preventing reinfection and significantly influences the long-term prognosis of endodontically treated teeth. Implants, on the other hand, lack periodontal ligament proprioception, resulting in reduced tactile feedback and potentially higher occlusal forces transmitted to the implant restoration (35).

Systemic conditions may also affect treatment outcomes. Diabetes mellitus has been associated with impaired healing of periapical lesions and may influence implant osseointegration, although well-controlled diabetic patients generally demonstrate acceptable implant survival rates.(36) Smoking has also been recognized as a significant risk factor affecting both endodontic and implant outcomes due to its detrimental effects on immune response and wound healing. Even the altered protocols of treatments in root canal irrigation (37,38) or choice of intracanal medicament(39) among the clinicains, could also have some influence on the outcomes. Local factors such as bone density, periodontal status, and oral hygiene also play a critical role in treatment success. Patients with untreated periodontal disease have demonstrated increased risk of implant complications and bone loss around implants (36). Adequate oral hygiene and maintenance programs are therefore essential to ensure long-term implant success. From an aesthetic perspective, preservation of the natural tooth may be preferable in certain situations, particularly in the anterior region where gingival architecture and soft tissue contours are critical for optimal aesthetic outcomes (35).

Patient-Related Considerations

Beyond clinical factors, patient-centered considerations also play an important role in treatment planning. Pain perception, treatment cost, and patient satisfaction may influence treatment preference. Studies have shown that postoperative discomfort following implant surgery may be greater than that experienced after root canal therapy (2). Nevertheless, many patients continue to perceive root canal treatment negatively due to misconceptions regarding pain associated with the procedure.

Economic considerations may also influence decision-making. In many clinical settings, endodontic therapy followed by restoration is generally less expensive than implant therapy. However, cost-effectiveness analyses have suggested that implant therapy may become more economical in cases requiring extensive endodontic retreatment or complex restorative procedures. Patient satisfaction studies have shown that both implant therapy and endodontic treatment significantly improve oral health-related quality of life. Nevertheless, aesthetic concerns such as gingival recession, soft tissue changes, or implant malposition may negatively affect patient perception of implant treatment outcomes.

Discussion

It has been reported that the number of remaining teeth in individuals aged 65–74 has increased over the last 50 years, mainly due to advancements in techniques and materials, particularly in endodontics. Both implantology and endodontology have demonstrated, over recent decades, the ability to achieve predictable long-term outcomes as a result of continuous technological progress (36). However, the lack of standardization in study design and outcome assessment makes comparisons between endodontic treatment and

implant therapy largely empirical and often confusing. This confusion is further compounded by inconsistent definitions and evaluation criteria for similar pathological conditions, leading to variability in reported results.

In many studies evaluating success rates of endodontic or implant treatments, outcomes are based on a combination of clinical, radiographic, and subjective parameters, while the distinction between success and survival is often unclear or not explicitly defined. Additionally, interobserver variability in radiographic interpretation, combined with non-standardized imaging angulations, further limits the reliability of outcome assessment (40). It has also been demonstrated that extensive bone lesions may remain undetected in conventional radiographic examinations. Moreover, although some studies include sufficiently long follow-up periods, the number of patients available for evaluation often decreases significantly over time, potentially compromising the validity and clinical relevance of the findings (26). Therefore, meaningful comparisons require studies with similar follow-up durations, adequate sample sizes, and standardized outcome measures.

Despite the large number of studies reporting success rates for each treatment modality, relatively few investigations directly compare endodontic therapy and implant placement under comparable clinical conditions. Available comparative studies generally report similar success rates for both approaches; however, implant-supported restorations often require more frequent maintenance visits, which may increase the overall cost of treatment. Furthermore, practitioner-related factors such as year of graduation, level of training, and clinical experience have been shown to significantly influence treatment decision-making.

From a biological perspective, both implants and natural teeth are susceptible to plaque accumulation and calculus formation. However, the structural differences in peri-implant tissues make implants more prone to inflammatory processes. Peri-implant inflammation tends to be more aggressive and may lead to faster and more severe tissue destruction compared with periodontal disease affecting natural teeth (41).

This review evaluated outcome measures, definitions of success and survival, biological and mechanical complications, as well as systemic, local, and patient-related prognostic factors, including cost, pain perception, and satisfaction. The findings indicate that both endodontic therapy and implant placement demonstrate high long-term survival rates. However, direct comparison remains challenging due to heterogeneity in study design, outcome definitions, and follow-up protocols, as well as the moderate risk of bias identified among the included studies. Endodontically treated teeth often exhibit favorable long-term survival and offer the advantage of retreatment in cases of failure. In contrast, implant therapy is generally associated with higher costs and potential biological complications such as peri-implantitis.

Overall, clinical decision-making should not rely solely on reported success rates but must incorporate patient-specific factors, biological considerations, restorative feasibility, and economic aspects. Preservation of the natural tooth should remain the preferred approach whenever feasible, while implant therapy serves as a reliable alternative when the prognosis of the natural tooth is unfavorable. Advances in microsurgical techniques and modern biomaterials have further improved the outcomes of surgical endodontic procedures (42).

Several limitations should be considered when interpreting the findings of this review. First, the included studies demonstrated substantial heterogeneity in study design, outcome definitions, and follow-up durations, which limits direct comparison between endodontic and implant outcomes. Second, many

studies reported survival rather than strict success criteria, potentially leading to an overestimation of treatment effectiveness. Third, variability in radiographic interpretation, diagnostic thresholds for peri-implant disease, and criteria used to define endodontic failure may have influenced reported outcomes. Additionally, the progressive loss of participants during long-term follow-up periods may affect the reliability of survival estimates. Finally, although a considerable number of studies were included, relatively few directly compared endodontic therapy and implant treatment under similar clinical conditions, limiting the strength of the conclusions.

Future research should focus on well-designed prospective and randomized clinical studies that directly compare endodontic treatment and implant therapy under standardized conditions. The adoption of uniform definitions for success and survival is essential to improve comparability across studies. Long-term investigations with adequate sample sizes are needed to better understand biological and mechanical complications associated with both treatment modalities. Furthermore, future research should incorporate patient-centered outcomes such as quality of life, functional performance, and patient satisfaction, alongside economic evaluations of treatment costs and maintenance. Novel modifications in imaging, root canal irrigation,(43, 44) biomaterials,(45), and minimally invasive techniques(46) may further influence treatment outcomes, highlighting the need for ongoing evidence-based evaluation.

Conclusion

Clinicians frequently face the complex decision of whether to preserve a compromised tooth or replace it with a dental implant, particularly given the limited high-quality evidence favoring one approach over the other. Both endodontic therapy and implantology have demonstrated predictable long-term outcomes due to significant technological advancements, and professional organizations such as the American Association of Endodontists and the American Dental Association provide guidance to support evidence-based clinical decision-making. Although reported success rates are comparable, endodontically treated teeth often demonstrate stable long-term survival and offer the possibility of retreatment in cases of failure, whereas implant therapy is generally associated with higher costs and more limited management options following complications. Therefore, preservation of the natural tooth should remain the primary treatment objective whenever feasible, with retreatment strategies considered prior to extraction and implant placement. Nonetheless, implants represent a reliable alternative when the prognosis of the natural tooth is poor. Ultimately, treatment decisions should be individualized and based on informed consent, ensuring that patients are fully aware of the benefits, risks, and long-term outcomes of each option.

Clinical Relevance

The decision between preserving a compromised tooth through endodontic therapy or replacing it with a dental implant represents a common clinical challenge in contemporary dental practice. The findings of this review indicate that both treatment modalities achieve high survival and success rates when performed under appropriate conditions. However, treatment planning should not rely solely on reported success rates and must instead consider multiple prognostic factors, including the structural integrity of the remaining tooth, periodontal status, presence of infection, systemic health conditions, and restorative feasibility, as well as patient-related factors such as cost and treatment expectations. Preservation of the natural tooth through endodontic treatment and re-

treatment should generally be considered the first-line approach when the prognosis is favorable. Dental implants provide a predictable and effective alternative when the natural tooth cannot be reliably restored or maintained. Therefore, individualized treatment planning and effective patient communication are essential to support evidence-based decision-making and achieve optimal long-term outcomes.

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REVIEW ARTICLES

Self – Healing Bioactive Composites: A Review Of Emerging Strategies In Restorative Dentistry

ABSTRACT

Bioactive composite materials with self-healing capabilities have been suggested as an emerging solution to the drawbacks associated with traditional dental material, especially with regard to microcracking and degradation issues. The purpose of this review is to analyze peer-reviewed literature with respect to self-healing techniques, bioactive composites, and applications of these materials in restorative dentistry. This literature includes laboratory research, experimental studies, and reviews published between 2000 and 2026.

As seen from current evidence, the use of such materials ensures the occurrence of spontaneous self-repair along with bioactive properties such as ion release and remineralization under controlled laboratory conditions. However, these findings are mostly derived from in vitro models or studies, which cannot completely replicate or mimic the complex oral environment. While incorporation of self-healing agents and bioactive fillers has shown potential to improve material performance, robust clinical evidence supporting enhanced restoration longevity or prevention of secondary caries remains limited.

Therefore, although self-healing bioactive composites represent a promising area of research, further well-designed in vivo and clinical studies are required to validate their long-term clinical effectiveness.

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Introduction

Resin composites in dentistry have numerous significant uses, and these include, though are not limited to, fillings, cements of single or multiple tooth prostheses, orthodontic devices, inlays, onlays, cores and build-ups, root canal posts, and provisional restoratives (1). Generally, composite materials are prone to failure because of microcracks that develop as a consequence of thermal and mechanical fatigue. Various studies have sought to enhance the fracture toughness of composite materials, and these include enhancing the volume of filler materials, incorporating nanosized silica fillers, and incorporating reinforcing fillers such as whiskers, fibers, and nanotubes, enhancing resin-filler interfaces, and optimizing the monomer chemical composition and the polymerization reaction (2,3). Despite all the improvements, fracture and failure of composite materials are common occurrences that require further investigation to improve them.

The application of self-healing as a solution to prevent failure and improve the life of composite materials without affecting their properties is gaining popularity as a reliable option (4).

Self-healing polymer matrix composite is defined as a composite that is capable of healing damages caused by external factors. Such composite materials have the ability to heal themselves without any external assistance, thus creating a replica of the self-healing process that is naturally found in biological systems (5). With the self-healing property, it is expected that safety and reliability will be enhanced, the cost of maintaining artificial composite materials will reduce, and the lifespan of the materials will increase. This field has experienced tremendous development for more than a decade and has recorded various outstanding achievements (6). Apart from the self-healing properties, the materials can also have fillers for the development of other properties, such as reinforcing fibers. Research examining the benefits and limitations of self-healing properties across different matrix materials remains scarce, even though this review encompasses all three categories of composite materials.

Review Methodology

Literature Review and Data Collection

The review was conducted using a detailed literature search process. For this research, data focusing on self-healing approaches, bioactive composite systems, microcapsule-based materials, and their application in restorative dentistry were gathered from peer-reviewed publications.

Keyword Selection

For conducting the literature search, relevant keywords for this topic were generated by the research team. Keywords such as "self-healing dental composites," "bioactive restorative materials," "microcapsule-based healing," and "remineralizing dental materials" were used in the search strategy.

Article Selection

A search was conducted through scientific databases, including PubMed, Scopus, Web of science and Google Scholar, to select pertinent peer-reviewed articles. The search was limited to articles published within the last 26 years (2000–2026) to ensure retrieval of current and relevant information while avoiding duplication of findings.

Inclusion Criteria

Articles chosen for inclusion into this review include laboratory investigations, experiments, literature reviews, and systematic reviews published during the past 26 years (2000–2026). In addition, selected articles were published in English and obtained from scientific databases and search engines. This category of articles were selected to ensure a thorough understanding of

self-healing and bioactive composite properties as they pertain to restorative dentistry.

Exclusion Criteria

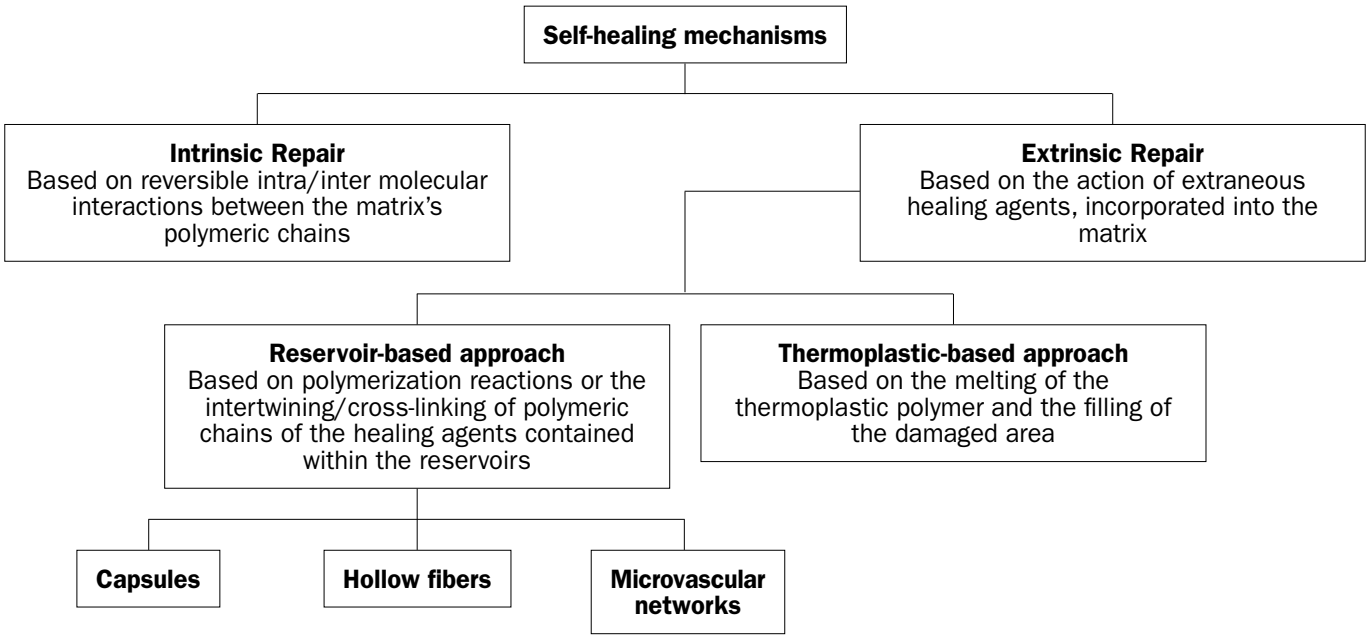
Peer-reviewed papers that focus exclusively on the application of self-healing composite materials in engineering but do not address their use in dental restorations and oral health, were not considered.

Study selection involved the identification of relevant literature, where the mechanism of action, material properties, and translational relevance received priority. Given the heterogeneity of study designs and outcomes, a qualitative synthesis approach was adopted rather than a quantitative meta-analysis.

Fundamental Mechanisms Of Self-Healing

Self-healing in polymer composites refers to the ability of a material to repair damage autonomously or in response to external stimuli, thereby restoring its structural integrity. These mechanisms are broadly classified into extrinsic (autonomous) and intrinsic (non-autonomous) systems (4,5) (Figure 1).

Figure 1
Classification of Self-healing Composites



Extrinsic (Autonomous) Healing Systems

Extrinsic systems rely on the incorporation of external healing agents within the material matrix, typically in the form of microcapsules or vascular networks. Upon crack formation, these reservoirs rupture and release healing agents into the damaged region, where they polymerize and seal the crack.

Microcapsule-based systems are the most extensively studied approach. These typically consist of polymeric shells encapsulating monomers or reactive agents, which are released upon mechanical damage. The concept of autonomic self-healing via microcapsules was first proposed by White et al. in 2001. In this approach, microcapsules composed of a urea–formaldehyde shell encapsulate a healing agent, typically dicyclopentadiene combined with a catalyst. Following the formation of the crack, the rupturing of the microcapsules results in the release of the healing agent, which is further pulled into the plane of the crack by capillary forces. (7) Wertzberger et al. (2010) used White's self-healing mechanism in a highly filled dental resin composite for investigating the healing capacity and

mechanical properties of the system (8). Similarly, H. Hu et al. have designed an epoxy-based composite that includes dual microcapsules which contains epoxy monomers (12 wt%) and an amine curing agent (8 wt%), where rupture of the microcapsules causes chemical reaction within the crack plane resulting in the in situ polymerization and crack repair (9).

Most extrinsic self-healing systems use microcapsules loaded with curing agents (10–300 µm diameter) whose core is composed of a polymeric shell such as poly(urea-formaldehyde), encapsulating liquid monomers. Following the development of the crack, the microcapsules are ruptured releasing the healing agent, which polymerizes using the embedded catalyst thereby sealing the crack and partially restoring the material's mechanical integrity (10). (Figure 2) Although these systems exhibit significant healing efficiency, they can be utilized only once due to the limitation in the quantity of the healing agents present in them.

Another form of extrinsic approach is the vascular network systems where hollow channels/fibers (40–200 µm) are incorporated in the structure facilitating controlled and repetitive delivery of healing agents to the cracks (12,13). (Figure 3) Although these systems offer better healing capacity, their clinical translation in dental materials is restricted by the fabrication process.

In general, the extrinsic self-healing process is more efficient, cost-effective, and more suitable for a wide range of materials. On the other hand, intrinsic healing requires reversible interactions at the molecular level and typically require specific activation conditions, often depending on external stimuli such as heat or UV light which may limit their application for clinical use.

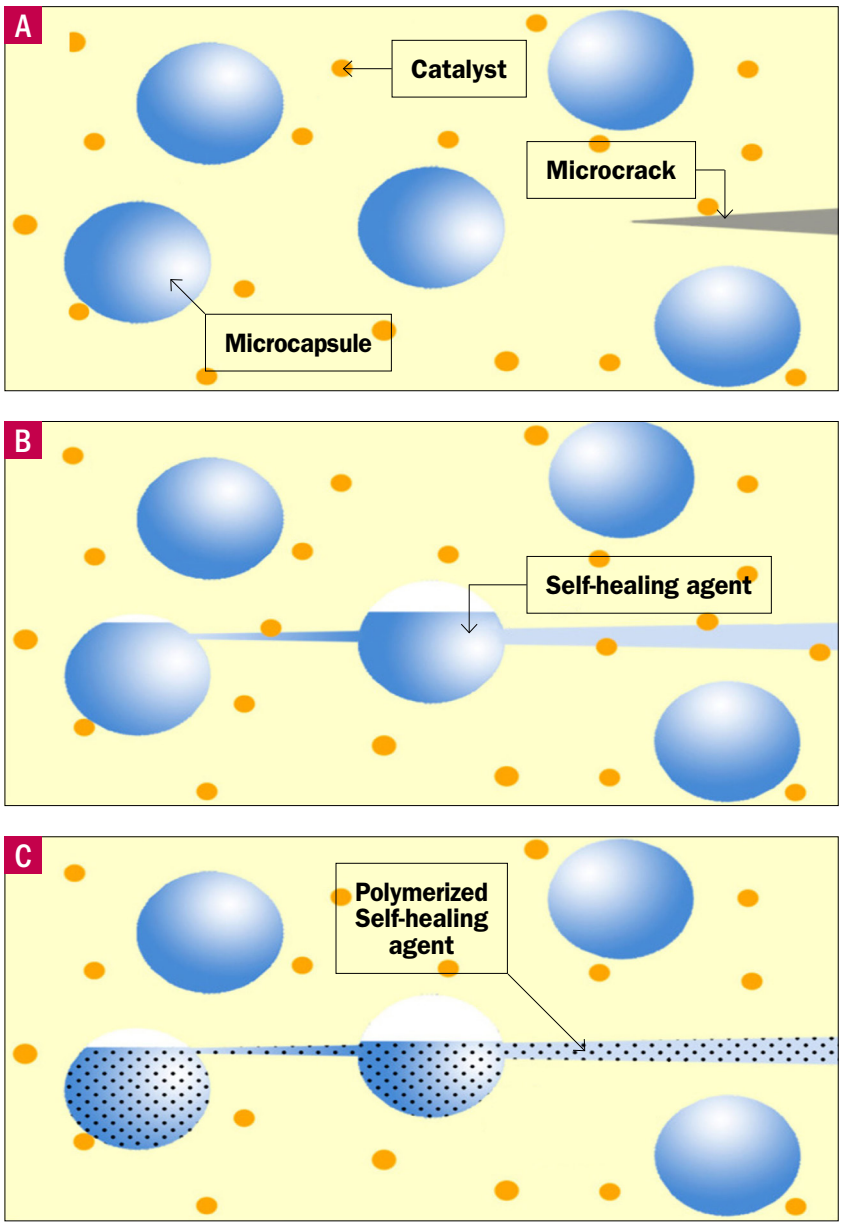


Figure 2
Principal diagram of microcapsule-based self-healing materials. (11) (**A**) Perception stage. (**B**) Delivery stage. (**C**) Reaction stage.

Intrinsic (Non-Autonomous) Healing Systems

In contrast, intrinsic systems rely on reversible physical or chemical interactions within the material itself, eliminating the need for embedded healing agents (14). These systems typically involve dynamic covalent bonds or supramolecular interactions that can reform upon exposure to external stimuli such as heat, light, or mechanical stress (15). Extrinsic systems have been used in dental composites. However, currently, more research is being conducted on extrinsic systems due to their simplicity (16) (Figure 4).

Intrinsic systems offer the advantage of repeatable healing and better mate-

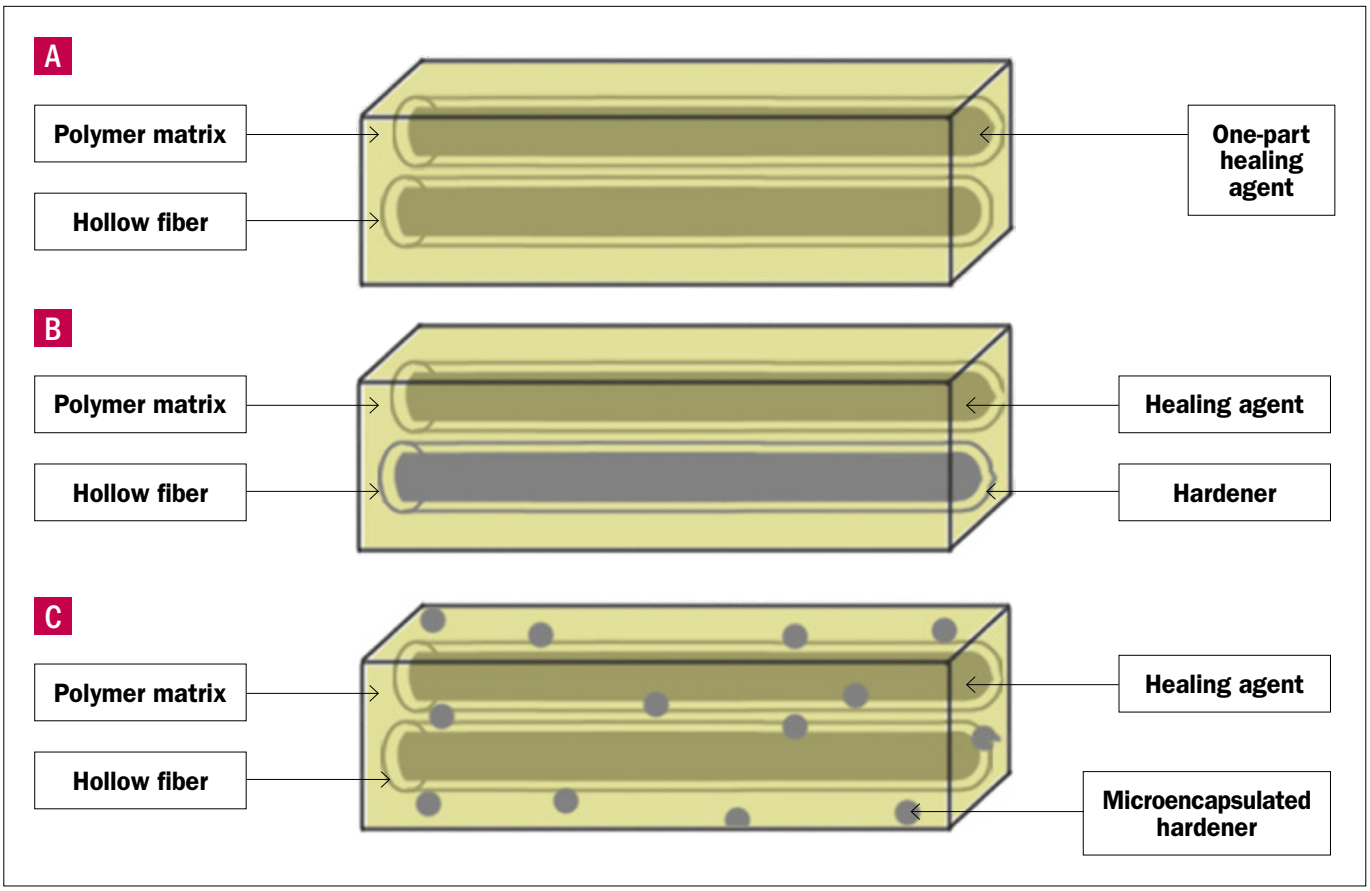


Figure 3
Diagram illustrating hollow-fiber–based self-healing systems (13): (**A**) encapsulation of a single healing agent within hollow fibers; (**B**) separate encapsulation of resin and hardener within hollow fibers; (**C**) encapsulation of the healing agent in hollow fibers with a catalyst uniformly dispersed in the polymer matrix.

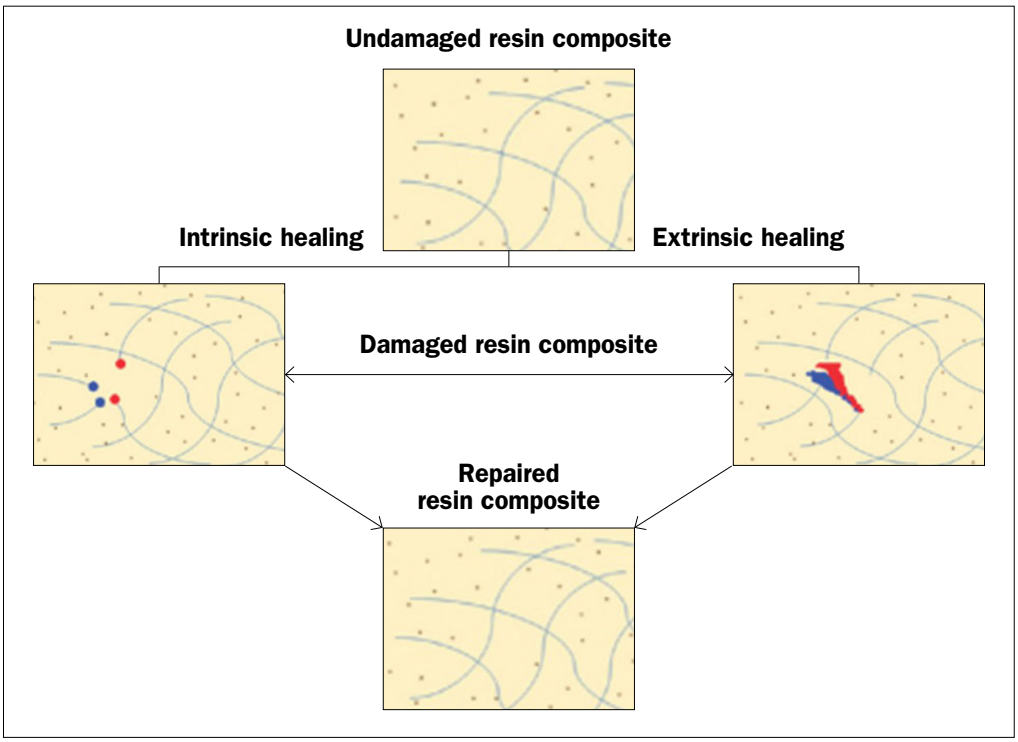


Figure 4
Diagram illustrating self-healing resin composites, highlighting both intrinsic and extrinsic mechanisms. (16)

rial homogeneity. However, they often require specific environmental triggers and may involve more complex material design, which has limited their widespread application in dental composites compared to extrinsic systems (17,18,19).
While extrinsic systems are currently more widely explored due to their simplicity and immediate healing response, intrinsic systems present a promising direction for achieving long-term, repeatable self-repair. A clearer distinction between these mechanisms is essential, as each presents unique advantages and limitations relevant to clinical translation.

Bioactive Self-Healing Composites
In addition, the occurrence of secondary caries is another significant reason for the failure of restoratives, which is often related to the accumulation of biofilm. Therefore, the exploration of self-healing restorative materials with bioactivity is one of the major trends in the field of restorative dentistry. In recent years, some researchers have proved that microcapsule-based self-healing restorative materials with the addition of bioactive substances, such as 2-methacryloyloxyethyl phosphorylcholine, can not only exhibit self-healing properties but also reduce the accumulation of plaque (20).
Additionally, the bioactive fillers, such as amorphous calcium phosphate, bioactive glass, and calcium silicate, allow for the therapeutic release of ions, thus facilitating remineralization in the tooth-restoration interface (21). Such an approach, where structure and biological activity are improved, will lead to the increased lifespan of the restoration.
Huyang G et al. developed a microcapsule-based self-healing resin composite incorporating silica microcapsules filled with polyacrylic acid and a resin matrix containing strontium fluoroaluminosilicate glass. Upon microcrack formation, capsule rupture released the healing agent, which reacted with the glass to form a glass ionomer–like phase that sealed cracks and partially restored mechanical properties. While demonstrating effective autonomous crack repair with acceptable baseline strength in vitro, limitations remain regarding long-term durability, repeat healing potential, and clinical translation (22).

Properties Of Self-Healing Bioactive Composites
Self-healing dental composites have demonstrated promising mechanical and biological properties, particularly in terms of fracture toughness recovery (7, 23, 24) and bioactivity. Studies report recovery of approximately 50–80% of original mechanical strength, depending on factors such as microcapsule concentration, size, and distribution (25, 26).
Overall, these studies have proven that self-healing efficiency is highly dependent on material composition and microcapsule distribution. Renewable efficiency, as shown by Wu et al. in their study, showed that there was a 65% recovery of the initial fracture toughness and that there was no adverse effect on the elastic modulus and flexural strength of the resin if the microcapsules are less than 15wt% (25). In contrast, Kang Ning et al. reported healing efficiencies of up to 76%, attributed to increased microcapsule diameter and concentration. Larger microcapsules (~198 ± 43 μm) significantly enhanced fracture toughness and overall self-healing performance of the resin composites (27).
Despite these improvements in healing efficiency, a trade-off with mechanical properties is evident. Althaqafi et al. examined the correlation of the mechanical properties of the self-healing dental composite with SiO2 nanoparticles with the amount of microcapsules with TEGDMA monomer and DHEPT amine. The mechanical properties were not significantly affected, apart from the reduction in flexural strength from 80 MPa to 55 MPa with an increase in

microcapsules up to 10 wt% (28).
As for the biocompatibility of these materials, Menikheim et al showed that the polyurethane nanocapsule-based self-healing dental resin system showed good in vitro biocompatibility with human epithelial cells, implying low cytotoxicity and potential for clinical use (29).
The bioactivity of the composite is mainly ascribed to the calcium- and phosphate-releasing fillers. These fillers not only enhance the remineralization properties of the composite material but also display antibacterial properties. Studies on amorphous calcium phosphate (ACP) nanoparticles have demonstrated that this material can exhibit self-healing, antibacterial, and remineralization capabilities. The reported healing efficiency of ACP-based systems ranges between approximately 65% and 81% (25). However, the optimized composite material also displays properties such as flexural strength, elastic modulus, and wear resistance comparable to the conventional composite material. Self-healing property further makes it possible for the material to show high fatigue resistance by stopping the crack propagation (30).
One of the major drawbacks of current research in this field is the inconsistency between the in vitro efficiency of self-healing and its clinical utility. While self-healing capacity and bioactivity are always shown to be consistent in the laboratory experiments, it is still difficult to predict how the material would behave under in vivo conditions, particularly when the material is exposed to various physical parameters including moisture, pH variation, enzyme activity, multispecies biofilms, and mechanical loading. Moreover, interactions between biofilm development and self-healing properties need to be studied extensively. These factors can weaken microcapsule integrity, alter healing agent release, and influence the durability of the material. Additionally, the effect of bacterial biofilms on self-healing processes is still not well-understood, and the antibacterial or ion-releasing properties demonstrated in vitro cannot always be replicated in vivo. Consequently, the predominance of short-term laboratory evidence limits confidence in clinical performance, highlighting the need for standardized in vitro models that better simulate oral conditions and, critically, well-designed long-term in vivo and clinical studies to establish true translational potential.

Bioinspired Self-Healing Composites
Bacteria-induced biomineralization has shown promise as a technique for the creation of self-healing dental resin-based composites, as this technique utilizes the potential of certain bacteria to induce mineralization of calcium carbonate within the microcracks. In this technique, bacterial spores or active cells are added to the resin along with a nutrient source. Once the microcrack occurs and the bacteria are exposed to the oral fluids, the bacteria are activated and start the calcium precipitating mechanism, leading to mineralization. This leads to the closing of the microcrack, thus restoring the integrity of the structure (31).
Han Y et al developed and optimized a novel class of microbial self-healing dental resin composites utilizing bacteria-induced mineralization to repair structural damage. The study incorporated multiple bacterial strains capable of precipitating calcium carbonate ($CaCO_3$) into resin matrices and systematically evaluated their healing efficiency under simulated oral conditions. Upon formation of microcracks, ingress of moisture and oxygen activated the embedded bacteria, triggering biomineralization that effectively sealed the cracked site. The findings suggest that such composites not only restore mechanical integrity after damage but also hold significant clinical potential in reducing fracture propagation, minimizing secondary caries, and extending the longevity of dental restorations (32).

Triple Benefit Dental Composites

Recently a new class of composites has been developed, with three functional and beneficial characteristics: self-repair, antibacterial properties, and remineralization abilities (21). The self-healing resin composite was formulated by incorporating poly(urea–formaldehyde) (PUF) microcapsules encapsulating triethylene glycol dimethacrylate (TEGDMA), along with the antibacterial monomer dimethylaminohexadecyl methacrylate (DMAHDM) and the remineralizing agent nanoparticles of amorphous calcium phosphate (NACP). DMAHDM was integrated into the BisGMA–TEGDMA resin matrix at a mass fraction of 10%. (33). Additionally, the BisGMA-TEGDMA resin system contained 20% NACP for the release of Ca and P ions and the remineralization process, along with 35% glass fillers for reinforcement. Subsequently, the BisGMA–TEGDMA resin system was blended with the microcapsule phase at mass fractions of 0%, 2.5%, 5%, 7.5%, and 10%. Flexural testing demonstrated no significant differences in strength or elastic modulus among groups containing up to 7.5% microcapsules. However, at a 10% microcapsule loading, a significant reduction in mechanical properties was observed (21). The enhanced self-healing performance and restoration of load-bearing capacity were attributed to the substantial in situ polymerization of the released TEGDMA, triggered by free-radical initiation. The liberated healing agents subsequently polymerized within the crack, effectively arresting crack propagation and facilitating repair of the fractured interfaces. In addition, the composite exhibited pronounced antimicrobial activity. Both the metabolic activity and acid production of biofilms formed on DMAHDM-containing composites were significantly reduced compared to conventional composites. Furthermore, incorporation of DMAHDM at all evaluated mass fractions resulted in a 3–4 log reduction in biofilm colony-forming units (CFU) relative to the control composite lacking DMAHDM (21). This was accomplished with a mass fraction of microcapsules ranging from 0 to 10%, thus demonstrating that incorporation of the microcapsule did not interfere with the antibacterial activity.

As for the effectiveness of antibacterial agents, the efficacy of DMAHDM is attributed to its positive charge from the quaternary ammonium groups that interacts with the negative charge of the bacterial cell membrane, thereby causing disruption and leakage of cytoplasm. (34) In addition to its self-healing and antibacterial functions, the composite demonstrated a third advantage through the release of calcium (Ca) and phosphate (P) ions, facilitating remineralization. Notably, the incorporation of the remineralizing agent (NACP) and the antibacterial monomer (DMAHDM) into the self-healing composite did not compromise its healing performance, which remained comparable to that of formulations lacking these functional additives.

Advantages With Self-Healing Composites

Self-healing bioactive composites also provide a number of advantages that contribute to enhanced clinical performance. These materials are effective in enhancing resistance to crack propagation and fatigue failure. Therefore, the longevity of the restoration is increased. In addition, the bioactive composites are effective in providing antibacterial and remineralization properties. Therefore, marginal integrity and the occurrence of secondary caries are minimized. Finally, the bioactive composites are effective in mimicking the principles of biomimetic and regenerative dentistry.

Limitations

Despite their promising potential, self-healing bioactive composites face several constraints that limit clinical applicability. High microcapsule load-

ing can adversely affect mechanical properties, particularly flexural strength and wear resistance (25). In addition, extrinsic self-healing systems are inherently limited by the finite availability of healing agents, resulting in diminished efficacy over repeated damage cycles. The incorporation of bioactive fillers and microcapsules may also compromise optical properties such as translucency and polishability, restricting their use in esthetically demanding regions (35). It is important to note that current data have been mostly obtained through in vitro tests with short durations, which cannot accurately mimic the complex oral environment, especially considering variations in pH levels, enzymatic functions, and masticatory muscle fatigue, among other factors.

Knowledge gaps

Many challenges exist in translating self-healing dental composites into clinical practice. There is still a need for long-term in vivo data on restoration survival in response to thermal, mechanical, and oral environmental stresses. Currently, the healing systems exhibit partial and short term recovery of the mechanical properties, where the duration and durability of the multiple healing processes are unclear.

Biocompatibility and safety concerns about the newly introduced chemical formulations for the healing process also need more investigation. In addition to that, the absence of standardized testing procedures, which include crack generation, loading scenarios, and healing efficiencies, is another barrier towards the application of such restorative material in clinical practice.

Materials-wise, optimizing microcapsule parameters (size, distribution, concentration) is difficult because it might compromise structural performance. Manufacturing consistency, storage stability, and scalability also hinder clinical translation.

Future research should prioritize biocompatible, durable systems supported by standardized evaluation methods and robust long-term clinical studies.

Future trends:

The next generation of self healing dental materials are likely to employ complementary techniques or mechanisms as opposed to a sole mechanism; microcapsules will be used as part of a rapid autonomous crack sealing , which will also include dynamic covalent bonding systems (e.g., disulfide exchange) for delayed stimulus-responsive repair of larger defects. The inclusion of bioactive fillers, which are capable of releasing calcium and phosphate ions in an acidic environment, further supports apatite formation, enhancing marginal sealing and reducing secondary caries. To ensure effective clinical translation, there is a need for standardized in vitro models simulating fatigue loading, thermocycling, and biofilm formation, along with rigorous evaluations of biocompatibility going further than cytotoxicity tests and including genotoxicity, immunogenicity, and interaction with microbiomes. Equally important is the cooperation between academia and industry addressing issues related to scale-up and regulatory pathways. It is imperative that any self-healing material undergoes extensive preclinical and clinical testing , demonstrating both self-healing properties and superior longevity and cost-effectiveness compared to the existing materials (16).

Conclusion

Self-healing bioactive dental composite resins constitute a relatively novel but theoretically intriguing approach in modern restorative dentistry, characterized by self-repairing capabilities alongside bioactivity. Laboratory trials and studies have confirmed their capacity to regain mechanical integrity following damage and facilitate ion-dependent remineralization under controlled conditions.

Nevertheless, the existing body of research on the subject matter consists

mainly of in vitro experiments, rendering it unclear how well they would perform in vivo. Claims regarding improved restoration longevity and prevention of secondary caries should therefore be interpreted cautiously, as they are not yet supported by robust long-term clinical data.
Future research should focus on standardized testing protocols, long-term in vivo studies, and clinical trials for evaluating their translational possibilities and ascertaining their superiority over current restorative systems.

Acknowledgments
Not Applicable.

Informed Consent Statement
Not Applicable. This is a literature review and does not involve human participants or identifiable patient data.

IRB Statement
Not Applicable. This is a literature review and does not involve primary research with human participants, animals, or biological material.

Data Availability Statement
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Conflicts of Interest
The authors have no competing interests to declare.

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Francesco Maggiore
Presidente della Società Italiana di Endodonzia

Lettera DEL PRESIDENTE

Cari Soci e Amici,

Cvi scrivo in questi giorni che precedono la pausa estiva per fare il punto sulle numerose attività che stanno animando la nostra Società in questo periodo ricco di soddisfazioni. Il ricordo più recente e vivido è senza dubbio il nostro Closed Meeting di Ischia. È stato un evento straordinario, dove attività culturali, societarie e ludiche si sono alternate in perfetta armonia, facendo di quei giorni un'esperienza che sicuramente rimarrà tra i ricordi più belli di chi ha avuto la fortuna di partecipare. Abbiamo lavorato con serietà nelle riunioni delle commissioni, ci siamo lasciati affascinare dalla storia con la visita al Castello Aragonese, abbiamo gustato i sapori autentici dell'isola durante la cena del sabato in un ristorante tipico, e ci siamo confrontati durante il momento culturale e l'Assemblea dei Soci della domenica. La serata sociale, con la sua gastronomia, con la musica e il ballo, ha saputo sciogliere ogni formalità, creando un'atmosfera di vera e spensierata convivialità. Un momento che racchiude lo spirito dell'incontro é stato sicuramente la gita in barca attorno all´isola del lunedì che ci ha regalato ore indimenticabili, rafforzando quei legami umani che sono il fondamento più autentico della nostra comunità.

L'impegno culturale della Società prosegue con slancio: i nostri webinar continuano a riscuotere grande partecipazione, il Corso Certificato SIE Ready to Work sta formando con dedizione i giovani colleghi, e sono lieto di annunciarvi che a fine anno partirà un nuovo percorso ancora più avanzato, dal titolo Level Up - ready to advance - pensato per chi desidera portare la propria preparazione clinica a un livello superiore. A questi si aggiungono le giornate organizzate con ANDI e gli eventi di macroarea, che testimoniano la nostra volontà di essere presenti e attivi sul territorio, al fianco di tutti i professionisti.

Tutte queste iniziative ci conducono idealmente verso l'appuntamento clou dell'anno: il Congresso Nazionale del 29-31 Ottobre. Ogni Congresso Nazionale rappresenta per la nostra Società molto più di un

semplice appuntamento scientifico: è un momento di incontro autentico, di crescita condivisa e di confronto tra professionisti che ogni giorno vivono con passione la nostra disciplina. Il tema che accompagnerà questa edizione, "Il dente: vita silenziosa di un organo vivente. Perché recuperarlo e come proteggerlo", nasce dalla volontà di riportare al centro del dibattito il valore biologico dell'elemento dentale e la responsabilità clinica che abbiamo nel preservarlo, curarlo e proteggerlo nel tempo. Attraverso il contributo di relatori di altissimo profilo, sessioni scientifiche, discussioni cliniche e momenti di dialogo, affronteremo insieme le più attuali strategie terapeutiche e le nuove prospettive dell'endodonzia moderna, con l'obiettivo di offrire strumenti concreti e immediatamente applicabili nella pratica quotidiana. Il congresso sarà inoltre preceduto dal corso teorico del Dott. G. Fichera sul recupero dell´ elemento singolo nell´ ambito del piano di trattamento e dal corso teorico-pratico di Endodonzia Chirurgica del Dott. A. Castellucci.
Credo profondamente che occasioni come questa rappresentino anche un momento importante per rafforzare il dialogo, il confronto costruttivo e il senso di appartenenza alla nostra Società. La SIE è cresciuta negli anni grazie al contributo, alle idee e alla passione di tanti Colleghi diversi tra loro, ma accomunati dall'amore per l'endodonzia e dal desiderio di far crescere la nostra disciplina. Sono certo che Verona saprà accoglierci nel migliore dei modi e regalarci tre giornate ricche di contenuti, entusiasmo e partecipazione.

Il filo che ci unisce ogni giorno é rappresentato dalla passione per il nostro lavoro e il piacere di condividerla. Ora però è il momento di staccare la spina e dedicarci al meritato riposo. Vi auguro di cuore buone vacanze estive, con l'augurio che possiate rigenerare corpo e mente, per ritrovarci tutti insieme, più carichi che mai, a Verona.
Vi aspetto con grande piacere.

Con affetto e stima,
Il Presidente
Dott. Francesco Maggiore

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Socio onorario
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COME DIVENTARE SOCIO ATTIVO/AGGREGATO

Scaricabile dal sito **www.endodonzia.it**

SOCIO AGGREGATO

Per avere lo status di Socio Aggregato si dovrà presentare la documentazione descritta nel sito www.endodonzia.it che sarà valutata dalla Commissione Accettazione Soci. La documentazione che verrà presentata dovrà mostrare con rigore, attraverso casi clinici, l'interessamento del candidato alla disciplina endodontica.
Un meccanismo a punti è stato introdotto per valutare l'ammissibilità del candidato allo "status" di Socio Aggregato: i punti saranno attribuiti in base al tipo di documentazione presentata. Possono accedere alla qualifica di Socio Aggregato tutti i Soci Ordinari della SIE, in regola con le quote associative degli ultimi tre anni, che completino e forniscano la documentazione alla Segreteria Nazionale (Via Pietro Custodi 3, 20136 Milano) entro i termini che verranno indicati all'indirizzo web: www.endodonzia.it.
La domanda dovrà essere firmata da un Socio Attivo, in regola con la quota associativa per l'anno in corso, il quale è responsabile della correttezza clinica e formale della documentazione presentata.

DOCUMENTAZIONE NECESSARIA PER DIVENTARE SOCIO AGGREGATO

Qualsiasi Socio Ordinario, con i requisiti necessari, può presentare la documentazione per ottenere la qualifica di Socio Aggregato. Un meccanismo a punti è stato introdotto per valutare il candidato: un minimo di 80 punti è richiesto per divenire Socio Aggregato.
La documentazione clinica per ottenere la qualifica di Socio Aggregato dovrà presentare almeno sei casi, di cui non più di tre senza lesione visibile nella radiografia preoperatoria e non più di uno di Endodonzia Chirurgica Retrograda.
Nella domanda non potranno essere presentati casi la cui somma superi i 120 punti per la qualifica di Socio Aggregato.
L'aspirante Socio Aggregato potrà presentare la documentazione clinica in più volte, con un minimo di 40 punti per presentazione, in un arco massimo di tre anni. Il mancato rinnovo della quota associativa, anche per un solo anno, annulla l'iter di presentazione dei casi.

SOCIO ATTIVO

Per avere lo status di Socio Attivo si dovrà presentare la documentazione descritta nel sito www.endodonzia.it che sarà valutata dalla Commissione Accettazione Soci. La documentazione che verrà presentata dovrà mostrare con rigore, attraverso documentazione scientifica e casi clinici, l'interessamento del candidato alla disciplina endodontica.
Un meccanismo a punti è stato introdotto per valutare l'ammissibilità del candidato allo status di Socio Attivo: i punti saranno attribuiti in base al tipo di documentazione clinica e scientifica presentata. Possono accedere alla qualifica di Socio Attivo tutti i Soci Ordinari della SIE, in regola con le quote associative degli ultimi tre anni, che completino e forniscano la documentazione alla Segreteria Nazionale (Via Pietro Custodi 3, 20136 Milano) entro i termini che verranno indicati all'indirizzo web: www.endodonzia.it.
La domanda di ammissione allo status di Socio Attivo rivolta al Presidente della SIE dovrà essere firmata da un Socio Attivo in regola con la quota associativa per l'anno in corso, il quale dovrà aver esaminato e approvato la documentazione. Quest'ultimo è responsabile della correttezza clinica e formale della documentazione presentata.

DOCUMENTAZIONE NECESSARIA PER DIVENTARE SOCIO ATTIVO

Qualsiasi Socio Ordinario, con i requisiti necessari, può presentare la documentazione per ottenere la qualifica di Socio Attivo. Il Socio Aggregato che volesse presentare la documentazione scientifica e clinica a integrazione di quella clinica già approvata dalla CAS per lo status di socio Aggregato, potrà farlo già dall'anno successivo all'ottenimento della sua qualifica.
Un meccanismo a punti è stato introdotto per valutare il candidato a Socio Attivo. Un minimo di 200 punti è richiesto per divenire Socio Attivo.
Nella domanda non potranno essere presentati casi la cui somma superi i 240 punti per la qualifica di Socio Attivo.
La documentazione scientifica potrà essere presentata, a completamento della documentazione clinica, solo per la domanda per divenire Socio Attivo e non potrà superare i 80 punti.
La documentazione clinica dovrà presentare un minimo di sei casi, di cui almeno 4 di molari pluriradicolati con delle precise tipologie: tra questi casi almeno uno deve essere un ritrattamento con lesione visibile nella radiografia preoperatoria e dei restanti tre almeno due devono avere una lesione visibile nella radiografia preoperatoria.
La documentazione clinica non deve presentare più di un caso di Endodonzia Chirurgica Retrograda con immagini e non più di uno senza immagini.
La documentazione scientifica non potrà presentare più di due articoli come coautore.

MODALITÀ DI DOCUMENTAZIONE DEI CASI CLINICI

Criteri e modalità per la valutazione dei casi clinici idonei ad accedere alle qualifiche di Socio Aggregato e di Socio Attivo sono espressi nell'apposita sezione del Regolamento

della Società Italiana di Endodonzia (SIE) all'indirizzo web: www.endodonzia.it.

CRITERI DI VALUTAZIONE

I casi clinici verranno valutati nel loro complesso, coerentemente con gli scopi e fini della SIE, e devono essere presentati dai Candidati considerando non solo l'aspetto clinico, ma anche quello formale della documentazione presentata.
La documentazione scientifica verrà valutata considerando la classificazione ANVUR delle Riviste Scientifiche, i documenti scientifici dovranno essere tutti di pertinenza endodontica.

ADEMPIMENTI DEL CANDIDATO

La domanda di ammissione allo status di Socio Aggregato/Attivo, rivolta al Presidente della SIE, dovrà pervenire, insieme alla documentazione di seguito elencata, alla Segretaria della SIE con un anticipo di 20 giorni sulle date di riunione della CAS, sufficiente per poter organizzare il materiale dei candidati. Le date di scadenza saranno rese note sul sito. La domanda dovrà essere firmata da un Socio Attivo in regola con la quota associativa per l'anno in corso, il quale dovrà aver esaminato e approvato la documentazione. Quest'ultimo è responsabile della correttezza clinica e formale della documentazione presentata.

PRESENTAZIONE DEI CASI ALLA COMMISSIONE

La presenza del Candidato è obbligatoria durante la riunione della CAS; è altresì consigliabile la presenza del Socio presentatore.

LA COMMISSIONE ACCETTAZIONE SOCI

La CAS (Commissione Accettazione Soci) è formata cinque Membri di indiscussa esperienza clinica, quattro Soci Attivi con almeno cinque anni di anzianità in questo ruolo eletti a ogni scadenza elettorale dall'Assemblea dei Soci Attivi e Onorari e uno dei Past President della Società incaricato dal CD a ogni riunione. Compito della CAS è quello di esaminare e valutare la documentazione presentata dagli aspiranti Soci Aggregati e Soci Attivi. Per rispetto del lavoro dei Candidati e per omogeneità di giudizio, in ogni riunione CAS verranno valutati non più di 12 candidati a Socio Attivo; resta libero, invece, il numero dei candidati a Socio Aggregato valutabile in una singola riunione. Il Consiglio Direttivo (CD) incaricando la Commissione Accettazione Soci (CAS) la rende responsabile dell'applicazione delle regole descritte nell'articolo 2 del regolamento. Il giudizio della CAS è insindacabile.

MEMBRI DELLA COMMISSIONE ACCETTAZIONE SOCI BIENNIO 2025-26

Francesco Riccitiello
Maurizio Boschi
Marco Colla
Claudia Dettori
Giuseppe Multari

ENDO HOUR 26

H 20.30

Un sorso di cultura

6 WEBINAR

Un'unica passione

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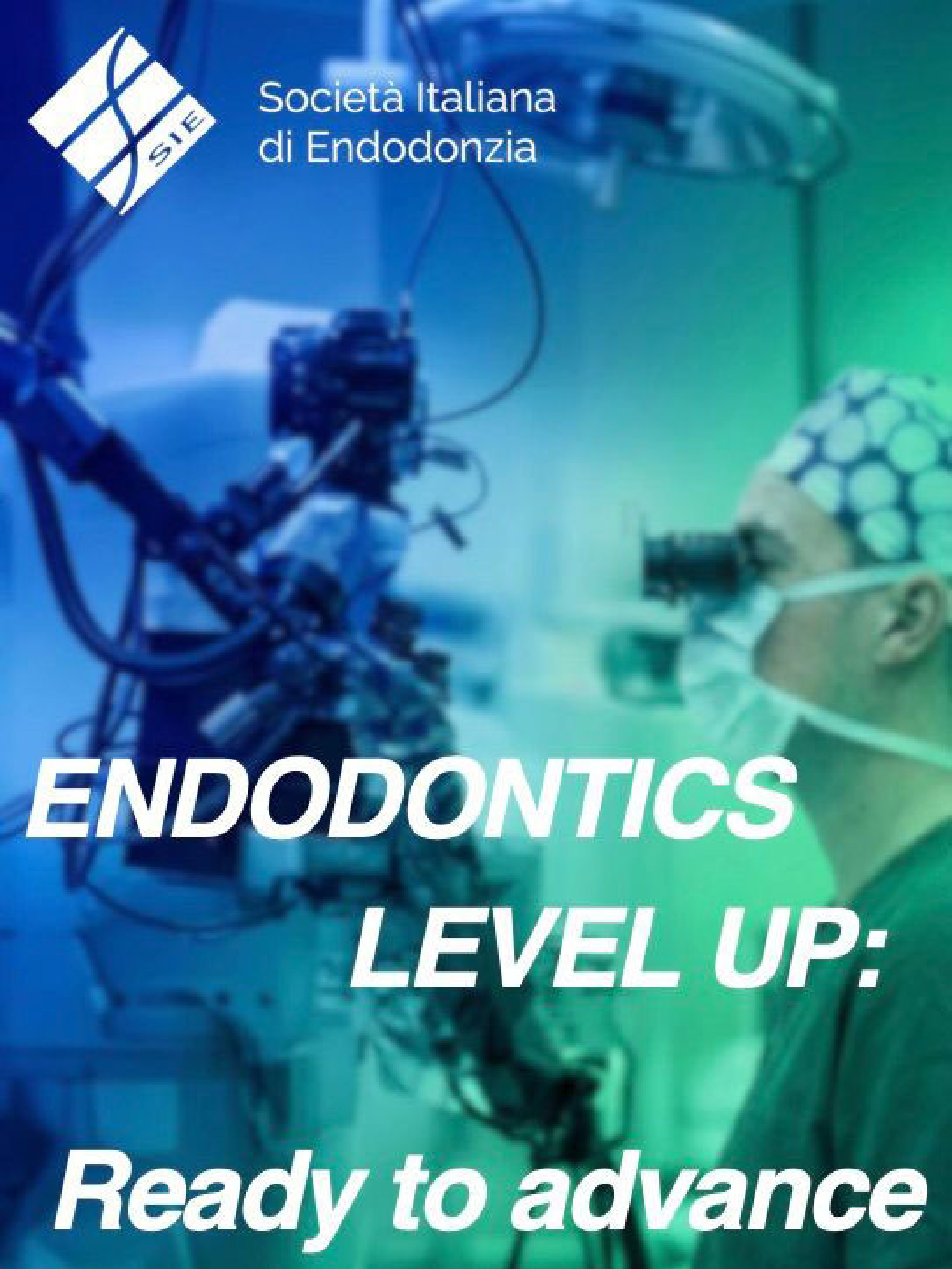
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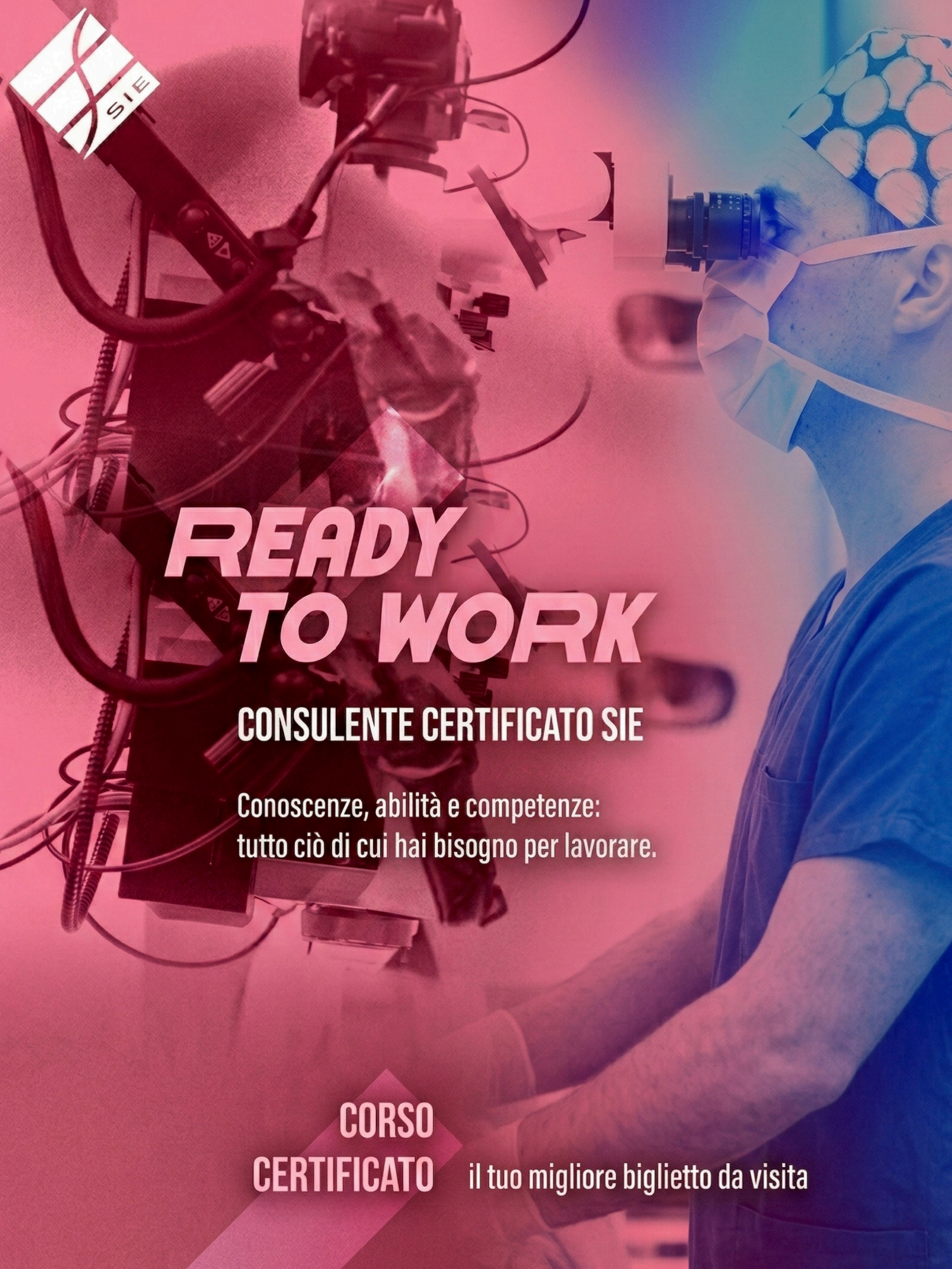
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TO WORK
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Conoscenze, abilità e competenze:
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IL DENTE

VITA SILENZIOSA
DI UN ORGANO VIVENTE

GUIDELINES FOR AUTHORS

Giornale Italiano di Endodonzia (GIE) was founded in 1987 and is the official journal of Società Italiana di Endodonzia, SIE (Italian Society of Endodontics) https://www.endodonzia.it/

It is a peer-reviewed journal, only available in electonic format and publishes original scientific articles, reviews, clinical articles and case reports in the field of Endodontology. Scientific contributions dealing with health, injuries to and diseases of the pulp and periradicular region, and their relationship with systemic well-being and health. Original scientific articles are published in the areas of biomedical science, applied materials science, bioengineering, epidemiology and social science relevant to endodontic disease and its management, and to the restoration of root-treated teeth. In addition, review articles, reports of clinical cases, book reviews, summaries and abstracts of scientific meetings and news items are accepted. Please read the instructions below carefully for details on the submission of manuscripts, the journal's requirements and standards as well as information concerning the procedure after a manuscript has been accepted for publication in Giornale Italiano di Endodonzia. Giornale Italiano di Endodonzia is indexed in Scopus, Science Direct, Embase and published online by Tecniche Nuove, Milan, Italy and hosted by PAGEPress, Pavia, Italy. All articles are available on www.giornaleitalianoendodonzia.it.

We publish, monthly, new articles in the Early View section while the full Journal is issued twice a year, in June and November.

Authors are encouraged to visit www.giornaleitalianoendodonzia.it for further information on the preparation and submission of articles and figures.

Ethical guidelines

Giornale Italiano di Endodonzia adheres to the below ethical guidelines for publication and research.

Authorship and Acknowledgements

Authors submitting a paper do so on the understanding that the manuscript has been read and approved by all authors and that all authors agree to the submission of the manuscript to the Giornale Italiano di Endodonzia. Giornale Italiano di Endodonzia adheres to the definition of authorship set up by The International Committee of Medical Journal Editors (ICMJE). According to the ICMJE, authorship criteria should be based on 1) substantial contributions to conception and design of, or acquisiation of data or analysis and interpretation of data, 2) drafting the article or revising it critically for important intellectual content and 3) final approval of the version to be published. Authors should meet conditions 1, 2 and 3. It is a requirement that all authors have been accredited as appropriate upon submission of the manuscript. Contributors who do not qualify as authors should be mentioned under Acknowledgements.

Manuscript preparation

Manuscripts should be uploaded as Word (.doc) or Rich Text Format (.rtf) files (not write-protected) plus separate figure files: TIF, EPS, JPEG files are acceptable for submission.

The text file must contain the **abstract, main text, references, tables and figure legends**, but no embedded figures or title page. The title page should be provided as a separate file. In the main text, please reference figures as for instance **figure 1, figure 2** etc to match the tag name you choose for the individual figure files uploaded.

Please note that **manuscripts must be written in English**. Authors whose native language is not English are strongly advised to have their manuscript checked by a language editing service or by a native English speaker prior to submission.

Manuscript Types Accepted

Original Scientific Articles must describe significant and original experimental observations and provide sufficient detail so that the observations can be critically evaluated and, if necessary, repeated. Original Scientific Articles must conform to the highest international standards in the field.

Systematic Review Articles reconsider and bring previously published systematic reviews up to date. This allows authors to present changes to the review while avoiding unwarranted duplication in the literature. A guiding principle for an update is that it is an event that is discrete and distinct from the conduct and reporting of the original systematic review (or previously updated review). This means that at a minimum the search for studies will have been brought up to date and that any changes to the results and conclusions of the original review (or a previously updated review) are described. Systematic review updates will not usually warrant publication of a new full-length article. However, any published update will be an independent publication. It will not be part of the original review publication (or previously updated review).

We encourage authors to be innovative in how they report and present systematic review updates. Systematic review updates are not appropriate for corrections/errata. Authors must clearly acknowledge and reference any previously-published work they are updating.

Review Articles are accepted for their broad general interest; all are refereed by experts in the field who are asked to comment on issues such as timeliness, general interest and balanced treatment of controversies, as well as on scientific accuracy. Reviews should generally include a clearly defined search strategy and take a broad view of the field rather than merely summarizing the authors´ own previous work. Extensive or unbalanced citation of the authors´ own publications is discouraged.

Mini Review Articles are accepted to address current evidence on well-defined clinical, research or methodological topics. All are refereed by experts in the field who are asked to comment on timeliness, general interest, balanced treatment of controversies, and scientific rigor. A clear research question, search strategy and balanced synthesis of the evidence is expected. Manuscripts are limited in terms of word-length and number of figures.

Clinical Articles are suited to describe significant improvements in clinical practice such as the report of a novel technique, a breakthrough in technology or practical approaches to recognised clinical challenges. They should conform to the highest scientific and clinical practice standards.

Case Reports or **Case Series** illustrating unusual and clinically relevant observations are acceptable, but they must be of sufficiently high quality to be considered worthy of publication in the Journal. On rare occasions, completed cases displaying nonobvious solutions to significant clinical challenges will be considered. Illustrative material must be of the highest quality and healing outcomes, if appropriate, should be demonstrated.

Case reports should be written using the **Preferred Reporting Items for Case reports in Endodontics (PRICE) 2020 guidelines.** A PRICE checklist and flowchart (as a Figure) should also be completed and included in the submission material. The PRICE 2020 checklist and flowchart can be downloaded from: http://pride-endodonticguidelines.org/price/. It is recommended that authors consult the following papers, which explains the rationale for the PRICE 2020 guidelines and their importance when writing manuscripts:

- Nagendrababu V, Chong BS, McCabe P, Shah PK, Priya E, Jayaraman J, Pulikkotil SJ, Setzer FC, Sunde PT, Dummer PMH. *PRICE 2020 guidelines for reporting case reports in Endodontics: a consensus-based development.* Int Endod J. 2020 Feb 23. Doi: 10.1111/iej.13285. https://onlinelibrary.wiley.com/doi/10.1111/iej.13285.
- Nagendrababu V, Chong BS, McCabe P, Shah PK, Priya E, Jayaraman J, Pulikkotil SJ, Dummer PMH. *PRICE 2020 guidelines for reporting case reports in Endodontics: Explanation and elaboration.* Int Endod J. 2020 Mar 28. Doi: 10.1111/iej.13300. https://onlinelibrary.wiley.com/doi/abs/10.1111/iej.13300.

Manuscript Format

The **official language** of the publication is **English**. It is preferred that manuscript is professionally edited. All services are paid for and arranged by the author and use of one of these services does not guarantee acceptance or preference for publication.

Authors should pay special attention to the **presentation** of their research findings or clinical reports so that they may be communicated clearly.
Technical **jargon** should be avoided as much as possible and clearly explained where its use is unavoidable. **Abbreviations** should also be kept to a minimum, particularly those that are not standard. Giornale Italiano di Endodonzia adheres to the conventions outlined in *Units, Symbols and Abbreviations: A Guide for Medical and Scientific Editors and Authors.* If abbreviations are used in the text, authors are required to write full name+abbreviation in brackets [e.g. Multiple Myeloma (MM)] the first time they are used, then only abbreviations can be written (apart from titles; in this case authors have to write always the full name). If names of equipments or substances are mentioned in the text, brand, company names and locations (city and state) for equipment and substances should be included in parentheses within the text.
The **background** and **hypotheses** underlying the study, as well as its main conclusions, should be clearly explained.
Titles and abstracts especially should be written in language that will be readily intelligible to any scientist.

Structure
All manuscripts submitted to Giornale Italiano di Endodonzia should include Title Page, Abstract, Main Text, References, Clinical Relevance, Conflict of Interest, Acknowledgements, Tables, Figures and Figure Legends as appropriate.
Title Page should bear:

I. Title, which should be concise as well as descriptive (no more than 150 letters and spaces);
II. Initial(s) and last (family) name of each author;
III. Name and address of department, hospital or institution to which the work should be attributed;
IV. Running title (no more than 30 letters and spaces);
V. Three to five key words (in alphabetical order);
VI. Name, full postal address, telephone, fax number and e-mail address of author responsible for correspondence (Corresponding Author).

Abstracts should be no more than 250 words giving details of what was done.

Abstract for Original Scientific Articles should be no more than 250 words giving details of what was done using the following structure.
Aim: give a clear statement of the main aim of the study and the main hypothesis tested, if any.
Methodology: describe the methods adopted including, as appropriate, the design of the study, the setting, entry requirements for subjects, use of materials, outcome measures and statistical tests.
Results: give the main results of the study, including the outcome of any statistical analysis.
Conclusions: state the primary conclusions of the study and their implications. Suggest areas for further research, if appropriate.

Abstract for Systematic Review Articles should be divided into Aim, Methodology, Result, Conclusion.
Aim: Provide an explicit statement of the main objective(s) or question(s) the review addresses.
Methodology: Specify the inclusion and exclusion criteria for the review, the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched. Specify the methods used to assess risk of bias in the included studies and the methods used to present and synthesis of studies.
Results: Give the total number of included studies and participants and summarise relevant characteristics of studies. Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).
Conclusion: Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision) and a general interpretation of the results and important implications.

Abstract for Review Articles should be non-structured, no more than 250 words giving details of what was done including the literature search strategy.

Abstract for Mini Review Articles should be non-structured of no more than 250 words, including a clear research question, details of the literature search strategy and clear conclusions.

Abstract for Case Reports and **Case Series** should be no more than 250 words using the following structure.
Aim: give a clear statement of the main aim of the report and the clinical problem which is addressed.
Summary: describe the methods adopted including, as appropriate, the design of the study, the setting, entry requirements for subjects, use of materials, outcome measures and analysis if any.
Key learning points: provide up to five short, bullet-pointed statements to highlight the key messages of the report. All points must be fully justified by material presented in the report.

Abstract for Clinical Articles should be no more than 250 words using the following structure.
Aim: give a clear statement of the main aim of the report and the clinical problem which is addressed.
Methodology: describe the methods adopted.
Results: give the main results of the study.
Conclusions: state the primary conclusions of the study.

THE STRUCTURE

Main text for Original Scientific Articles should include Introduction, Materials and Methods, Results, Discussion and Conclusion.
Introduction: should be focused, outlining the historical or logical origins of the study and gaps in knowledge. Exhaustive literature reviews are not appropriate. It should close with the explicit statement of the specific aims of the investigation, or hypothesis to be tested.
Material and Methods must contain sufficient detail such that, in combination with the references cited, all clinical trials and experiments reported can be fully reproduced.
(I) Clinical Trials: should be reported using the CONSORT guidelines available at www.consort-statement.org A CONSORT checklist and flow diagram (as a Figure) should also be included in the submission material.
(II) Experimental Subjects: experimentation involving **human subjects** will only be published if such research has been conducted in full accordance with ethical principles, including the World Medical Association Declaration of Helsinki (version 2008) and the additional requirements, if any, of the country where the research has been carried out. Manuscripts must be accompanied by a statement that the experiments were undertaken with the understanding and written consent of each subject and according to the above mentioned principles. A statement regarding the fact that the study has been independently reviewed and approved by an ethical board should also be included. Editors reserve the right to reject papers if there are doubts as to whether appropriate procedures have been used. When **experimental animals** are used the methods section must clearly indicate that adequate measures were taken to minimize pain or discomfort. Experiments should be carried out in accordance with the Guidelines laid down by the National Institute of Health (NIH) in the USA regarding the care and use of animals for experimental procedures or with the European Communities Council Directive of 24 November 1986 (86/609/EEC) and in accordance with local laws and regulations. All studies using human or animal subjects should include an explicit statement in the Material and Methods section identifying the review and ethics committee approval for each study, if applicable. Editors reserve the right to reject papers if there is doubt as to whether appropriate procedures have been used.
(III) Suppliers of materials should be named

and their location (Company, town/city, state, country) included.
Results should present the observations with minimal reference to earlier literature or to possible interpretations. Data should not be duplicated in Tables and Figures.
Discussion may usefully start with a brief summary of the major findings, but repetition of parts of the abstract or of the results section should be avoided. The Discussion section should progress with a review of the methodology before discussing the results in light of previous work in the field. The Discussion should end with a brief conclusion and a comment on the potential clinical relevance of the findings. Statements and interpretation of the data should be appropriately supported by original references.
Conclusions should contain a summary of the findings.

Main Text of Systematic Review Articles

should be divided into Introduction, Methodology, Results, Discussion, Conclusion.
In the case of systematic reviews, whether with or without meta-analyses, strict adherence to the PRISMA guidelines (http://www.prisma-statement.org/) is mandatory. Additionally, authors must submit a PRISMA checklist (http://www.prisma-statement.org/PRISMAStatement/Checklist.aspx) and flowchart (http://www.prisma-statement.org/PRISMAStatement/FlowDiagram) along with the manuscript.

Main Text of Review Articles

should be divided into Introduction, Review and Conclusions.
The Introduction section should be focused to place the subject matter in context and to justify the need for the review. The Review section should be divided into logical subsections in order to improve readability and enhance understanding. Search strategies must be described and the use of state-of-the-art evidence-based systematic approaches is expected. The use of tabulated and illustrative material is encouraged. The Conclusion section should reach clear conclusions and/or recommendations on the basis of the evidence presented.

Main Text of Mini Review Articles

should be divided into Introduction, Review and Conclusions; please note that the Conclusions section should present clear statements/recommendations and suggestions for further work. The manuscript, including references and figure legends, should not normally exceed 4,000 words.

Main Text of Case Reports and Case series

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British Endodontic Society - Guidelines for root canal treatment. Giornale Italiano di Endodonzia 1979;16:192-5.

Journal supplement
Frumin AM, Nussbaum J, Esposito M. Functional asplenia: demonstration of splenic activity by bone marrow scan (Abstract). Blood 1979;54 (Suppl. 1):26a.

Books and other monographs
Personal author(s)
Gutmann J, Harrison JW. Surgical Endodontics, 1st edn Boston, MA, USA: Blackwell Scientific Publications, 1991.

Chapter in a book
Wesselink P. Conventional rootcanal therapy III: root filling. In: Harty FJ, ed. Endodontics in Clinical Practice, (1990), 3rd edn; pp. 186-223. London, UK: Butterworth.

Published proceedings paper
DuPont B. Bone marrow transplantation in severe combined immunodeficiency with an unrelated MLC compatible donor. In: White HJ, Smith R, eds. Proceedings of the Third Annual Meeting of the International Society for Experimental Rematology; (1974), pp. 44-46. Houston, TX, USA: International Society for Experimental Hematology.

Agency publication
Ranofsky AL Surgical Operations in Short-Stay Hospitals: United States-1975 (1978). DHEW publication no. (PHS) 78-1785 (Vital and Health Statistics; Series 13; no. 34.) Hyattsville, MD, USA: National Centre for Health Statistics.

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