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 mechanical 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

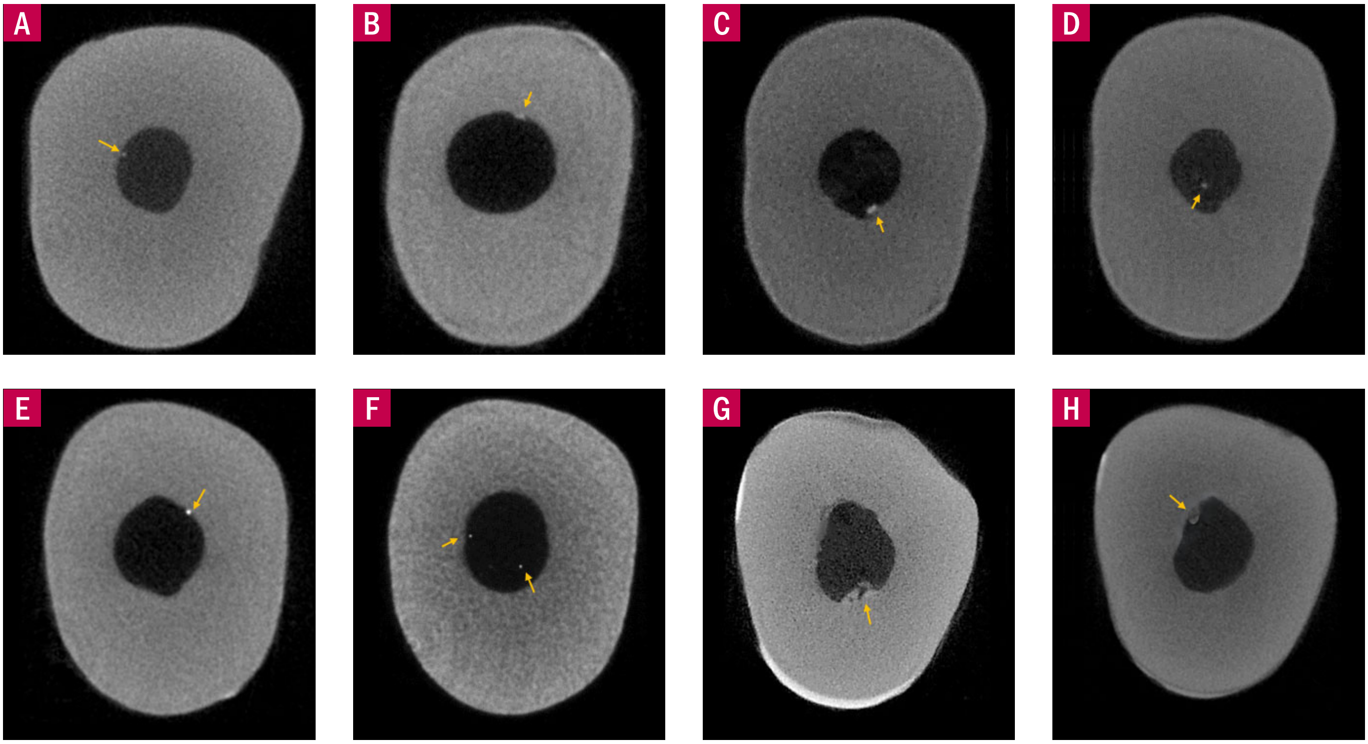

Figure 1
Representative micro-computed tomography (Micro-CT) cross-sectional images demonstrating nano-leakage patterns in simulated immature teeth restored with different coronal plug materials following silver nitrate penetration analysis. Yellow arrows indicate areas of silver nitrate infiltration 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.

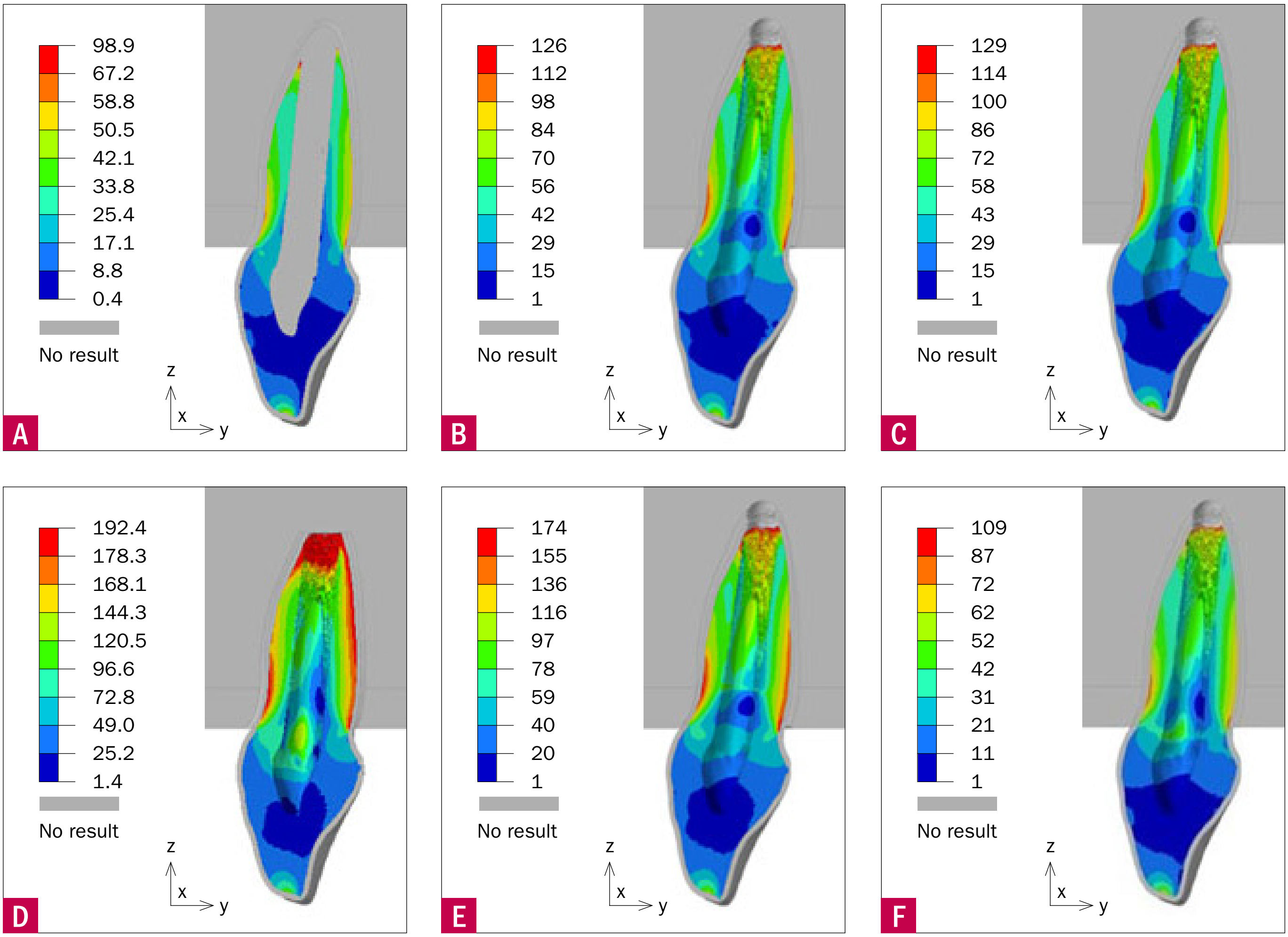

Figure 2
Stress distribution plots in dentine: a. Von Mises stress (in MPa) contour plot in dentin for model MT (Mature tooth); b. Von Mises stress (in MPa) contour plot in dentin for model IT(Immature tooth): c. Von Mises stress (in MPa) contour plot in dentin for model 1 (MTA Repair HP); d. Von Mises 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 comparatively 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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