

Advancements in Diagnosing and Treating External Invasive Cervical Resorption: A Comprehensive Study on Biocompatible Materials and Finite Element Analysis

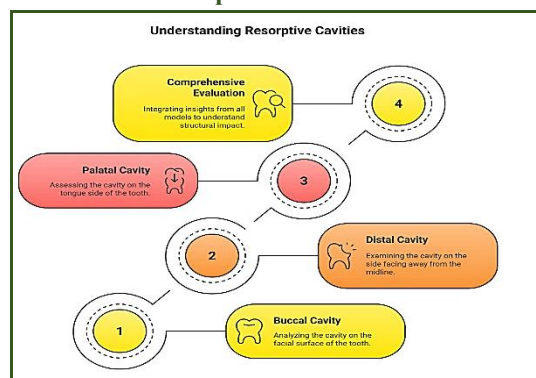
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Highlights

- The aims of ECR treatment involve removing resorptive tissue, sealing the hard tissue defect with a biocompatible material, and preventing recurrence.
- Treatment options include external and internal repair approaches, endodontic treatment, intentional replantation, and extraction for untreatable teeth.
- The choice depends on the severity and location of the resorption.
- Repair materials like Mineral Trioxide Aggregate (MTA) and Biodentine have shown promise for achieving periodontal reattachment.

Graphical Abstract



ABSTRACT

External Invasive Cervical Resorption (EICR) is an erosive dental disease in which the hard structures of the cervical region of teeth are deteriorated by specialized cells. The active disease process tends to progress asymptotically, and its early identification by clinicians is problematic. The lesion is more concentrated towards the cervical part of the teeth, where the crown meets the root. Most modern diagnostic methods rely on Cone-Beam Computed Tomography (CBCT) to provide three-dimensional views of ECR lesions in unprecedented detail. A high-tech imaging centre of this nature enables practitioners to arrive at accurate estimates of the severity of tissue loss, assess invasion of the pulp, and treat in proportion. Successful treatment

ARTICLE INFO



Keywords

External Cervical Resorption (ECR), Cone-Beam Computed Tomography (CBCT), Finite Element Analysis (FEA), Biodentine, Glass Ionomer Cement (GIC).

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of ECR has three principal objectives: removal of resorptive tissue, replacement of compromised hard tissue structure with biocompatible substances, and prevention of recurrence. Treatment ranges from non-surgical external and internal repair to more invasive ones like endodontic therapy, intentional replantation, or extraction in the event of a non-restorable tooth. The treatment process is generally based on the site and degree of resorption. Some newer-generation repair materials like Mineral Trioxide Aggregate (MTA) and Biodentine have also been demonstrated to successfully lead to periodontal reattachment and long-term success. These biocompatible materials seal and are more compatible with the tissue than the conventional ones. The current study employed Finite Element Analysis (FEA) to evaluate stress patterns in 2BP category ECR lesion-damaged maxillary central incisors. These results are of considerable value to clinicians when selecting the most appropriate treatment modes and materials in an effort to optimize the long-term success of involved teeth from this pathologic process.

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INTRODUCTION

Root resorption, a condition characterized by the destruction of dental hard tissues by clastic cells, poses significant challenges within dental practice. Among the various forms of root resorption, External Cervical Resorption (ECR) is particularly concerning due to its location in the cervical region of teeth, often following trauma or damage to the periodontal ligament and the surrounding sub-epithelial cementum [1-3]. ECR is not merely a localized issue; it represents an ongoing pathological process that can involve both periodontal and dental tissues, potentially leading to pulpal involvement in its advanced stages. This complexity underscores the need for effective diagnosis and treatment strategies [4-5].

Diagnosing ECR presents numerous challenges, as it must be differentiated from other types of resorptions, including internal resorption. The progressive and destructive nature of ECR, along with its cervical location, often leads to late recognition in clinical practice. Consequently, many cases of ECR remain asymptomatic and are discovered incidentally during routine dental examinations or radiographic assessments [6-9]. Traditional periapical radiography has limitations in accurately diagnosing ECR; however, Cone-Beam Computed Tomography (CBCT) stands out as a superior diagnostic tool. CBCT offers three-dimensional imaging capabilities, allowing for a comprehensive assessment of lesion structures, pulpal involvement, and the precise localization of entry points. As such, CBCT is highly recommended for both diagnosing ECR and formulating effective treatment plans [7-11]. The treatment of ECR focuses on the removal of resorptive tissue, the closure of hard tissue defects using biocompatible materials, and the prevention of recurrence.

A variety of treatment options are available, including external repair with endodontic treatment, internal repair through root canal procedures, intentional replantation, and, in some cases, extraction when treatment is not feasible [12-15]. The choice of treatment is contingent upon several factors, including the severity and location of the resorption, as well as the restorability of the affected tooth.

Mavridou *et al.* [4] showed characteristic features of ECR in vital teeth, noting the presence of one or more portals of entry and the three-dimensional extension of defects. Supra-bony entry points often lead to crater-like lesions filled with fibrovascular tissue, typically addressed through external repair methods [12-17]. In cases where ECR perforates the root canal system or presents a risk of perforation during repair, endodontic treatment may be necessary. Conditions characterized by narrow and difficult-to-locate entry points are best managed through internal approaches, such as endodontic treatment combined with orthograde restoration of the ECR defect [11-16]. The literature supports the use of repair materials like Mineral Trioxide Aggregate (MTA) and Biodentine, which have shown promise in stimulating periodontal reattachment. Additionally, exposed resorption cavities that are vulnerable to oral fluids can be sealed with various materials, including amalgam, composite resin, Glass Ionomer Cement (GIC), and Resin-Modified Glass Ionomer Cement (RMGIC) [17-24].

To accurately assess the efficacy of these restorative materials, Finite Element Analysis (FEA) emerges as a valuable numerical technique. FEA dissects complex structures into smaller, manageable elements, enabling the calculation of stress and strain distributions without requiring a complete structural analysis.

This approach unveils internal stress patterns and predicts susceptibility to fractures, providing critical insights for clinical treatment planning [25-29]. By employing FEA to compare various restorative materials in maxillary central incisors exhibiting category 2BP ECR, this research aims to deliver a detailed, three-dimensional assessment of stress distribution patterns. Specifically, the study will analyze the performance of Biodentine, GIC, and RMGIC in the context of ECR treatment, thereby contributing to the broader understanding of restorative dentistry and enhancing clinical outcomes for patients with this challenging condition. Understanding stress distribution in maxillary central incisors impacted by ECR is essential for developing effective treatment protocols. By integrating advanced imaging technologies and numerical analysis techniques, dental professionals can make informed decisions that prioritize both the longevity of the restoration and the preservation of the tooth structure. This research not only seeks to illuminate the intricacies of ECR management, but also aspires to enhance the overall quality of care in restorative dentistry.

EXPERIMENTAL SECTION

Materials and methods

This study utilized three-dimensional (3D) Finite Element Analysis (FEA) to examine stress distribution patterns in maxillary central incisors affected by External Cervical Resorption (ECR) classified under category 2BP. Given the prevalence of cervical external root resorption in maxillary central incisors, a human maxillary central tooth was selected as the model for this investigation. The modeling process began with the scanning of a human maxillary central incisor using micro-Computed Tomography (micro-CT) to generate DICOM images. These images were subsequently processed with Mimics software, where appropriate threshold values were established to differentiate tooth structures from pulpal tissues. After segmentation, the processed data were exported to 3-matic software for refinement and converted into STP files. Each anatomical part of the tooth was meticulously segmented using mask tools to create comprehensive three-dimensional models. To accurately represent the surrounding anatomy, both cortical and cancellous bone morphologies were modeled using three-dimensional calculation commands. ECR cavities were created based on Patel's 2BP classification system, with a spherical ellipsoid modeled to contact the root surface, positioned 3 mm coronal and 3 mm apical to the CementoEnamel Junction (CEJ). The volume of this ellipsoid was then digitally removed to form the

resorptive defect. Three distinct analytical cavity models were prepared, bonded to the labial, distal, and palatal surfaces of the tooth.

In the restoration process, composite resin material was utilized for the coronal restoration of the analytical cavity. For the radicular portion, three different restorative materials were employed: Glass Ionomer Cement (GIC), Resin-Modified Glass Ionomer Cement (RMGIC), and Biodentine. Material properties, including elastic modulus and Poisson's ratio for each modeled structure (enamel, dentin, periodontal ligament, cortical bone, cancellous bone), as well as the restorative materials, were incorporated into the FEA program. Four distinct loading conditions were simulated to reflect various functional scenarios: normal mastication, maximum chewing force, protrusive movement, and tearing action. Standard chewing forces of 100 N and maximum chewing forces of 235.5 N were applied at a 45-degree angle to the oblique plane formed between the incisal edge and the middle tubercle of the palatal surface. Protrusive movement was simulated with a 15 N force applied perpendicularly to the tooth's longitudinal axis on the palatal surface, while tearing forces were modeled at 50 N, at an oblique angle of 60 degrees. Finite element software, either Abaqus or ANSYS, was employed for the analysis of stress distribution. The process included importing the processed geometries, assigning appropriate material properties, establishing force vectors and boundary conditions, and creating optimized mesh configurations to reduce computational errors. The Von Mises stress values were specifically assessed in the dentin and restorative materials. The final results, encompassing stress, strain, and displacement data, were exported through the software's run protocols for further analysis and interpretation. The FEA was conducted using ANSYS software (Version 2023 R1; ANSYS, Inc., Canonsburg, PA, USA). A linear static structural analysis was performed to simulate the biomechanical behavior under various loading conditions. The model was solved using the sparse direct solver, which is suitable for linear static problems. To ensure the accuracy and independence of the results from the mesh density, a convergence study was undertaken, as detailed in a subsequent section.

The applied forces and boundary conditions are illustrated schematically in Fig. 5. To simulate realistic clinical scenarios, the external surfaces of the surrounding cortical and cancellous bone were fully constrained in all degrees of freedom (fixed support), representing the physiological anchorage of the tooth within the alveolar socket [29].

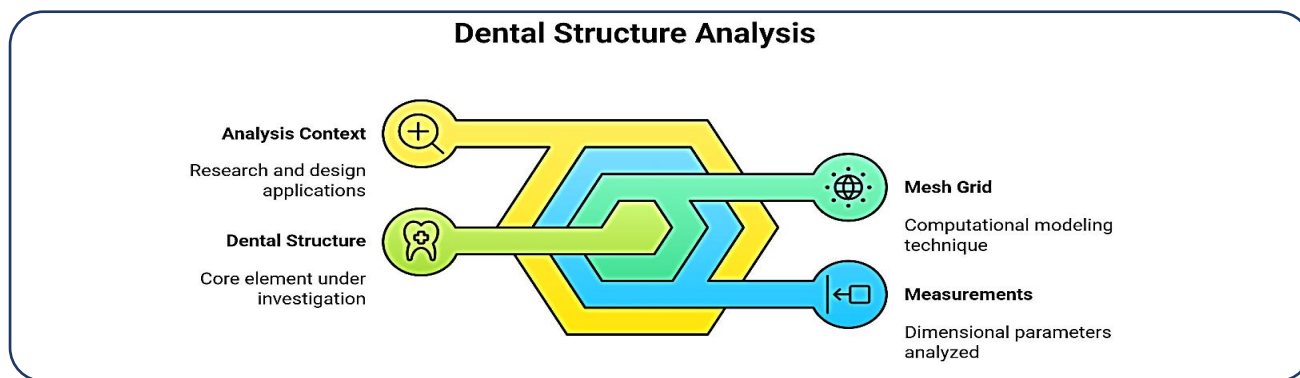


Fig. 1: Schematic of dental treatment decision-making framework.

The loading conditions were defined based on established literature for maxillary incisor biomechanics [16-18]. A standard chewing force of 100 N and a maximum force of 235.5 N were applied at a 45-degree angle to the oblique plane on the palatal surface. A protrusive movement was simulated with a 15 N force applied perpendicular to the tooth's longitudinal axis, and a tearing force was modeled at 50 N at an oblique angle of 60 degrees.

All materials, including dental tissues and restorative materials, were assumed to be homogeneous, isotropic, and linearly elastic. The mechanical properties, namely Young's modulus (E) and Poisson's ratio (ν), used in this study are summarized in Table 1. These values were adopted from previous finite element studies in dental biomechanics to ensure consistency and comparability [25, 29, 31]. The restorative materials (Biodentine, GIC, RMGIC) were modeled as distinct geometric volumes that fully occupied the digitally created resorptive defects. This approach allowed for a clear definition of the material interface between the restoration and the surrounding dentin, enabling a more accurate analysis of stress transfer at these critical junctions. The geometry of the restored cavities is visually depicted in Fig. 5.

RESULT AND DISCUSSION

To ensure a high-quality mesh and mitigate numerical artifacts such as artificial stress concentrations at material interfaces, explicit geometric partitioning was implemented. The interfaces between the restorative materials and the dentin, as well as the composite resin and the tooth, were defined using Boolean operations to create shared nodes at these boundaries. Furthermore, the sharp edges of the resorptive cavities were intentionally rounded with a fillet radius of 0.1 mm during the model creation phase to better simulate clinical conditions and avoid unrealistic stress singularities, a practice recommended

in biomechanical FEA [25]. This study used three-dimensional FEA to explore how stress is distributed in maxillary central incisors affected by category 2BP ECR and restored with different materials. Using micro-CT scans, we created detailed 3D models of the tooth and its ECR lesions on the labial, distal, and palatal surfaces.

The restorative materials investigated included Biodentine, Glass Ionomer Cement (GIC), and Resin-Modified Glass Ionomer Cement (RMGIC). Our analysis revealed that Biodentine displayed the highest von Mises stress levels in the ECR defects, particularly on the distal surface, whereas RMGIC exhibited the lowest stress values.

Notably, stress distribution varied significantly depending on the surface and loading conditions, with the maximum stress occurring under 100 N force and the minimum is under 15 N. The distal surface generally experienced higher stress, while the palatal surface had the least. These findings enhance our understanding of material performance in restorative dentistry for ECR cases, guiding better clinical decisions.

Fig. 1 shows the generic model of dental treatment decision-making that addresses the central clinical question "What dental intervention is indicated?" The model shows three autonomous therapeutic lines radiating from one decision point, each representing an alternating philosophy of care.

Fig. 2 illustrates an integrated analysis model referred to as "Understanding Resorptive Cavities" that charts a rational four-step procedure for evaluating dental resorptive defects from four anatomically varied perspectives, arranged in a circular flow manner reflective of the continuous process of evaluation. The process begins with Step 1, Buccal Cavity (yellow), which says that examination of the cavity on the facial surface of the tooth, where most of them tend to occur and are clinically apparent.

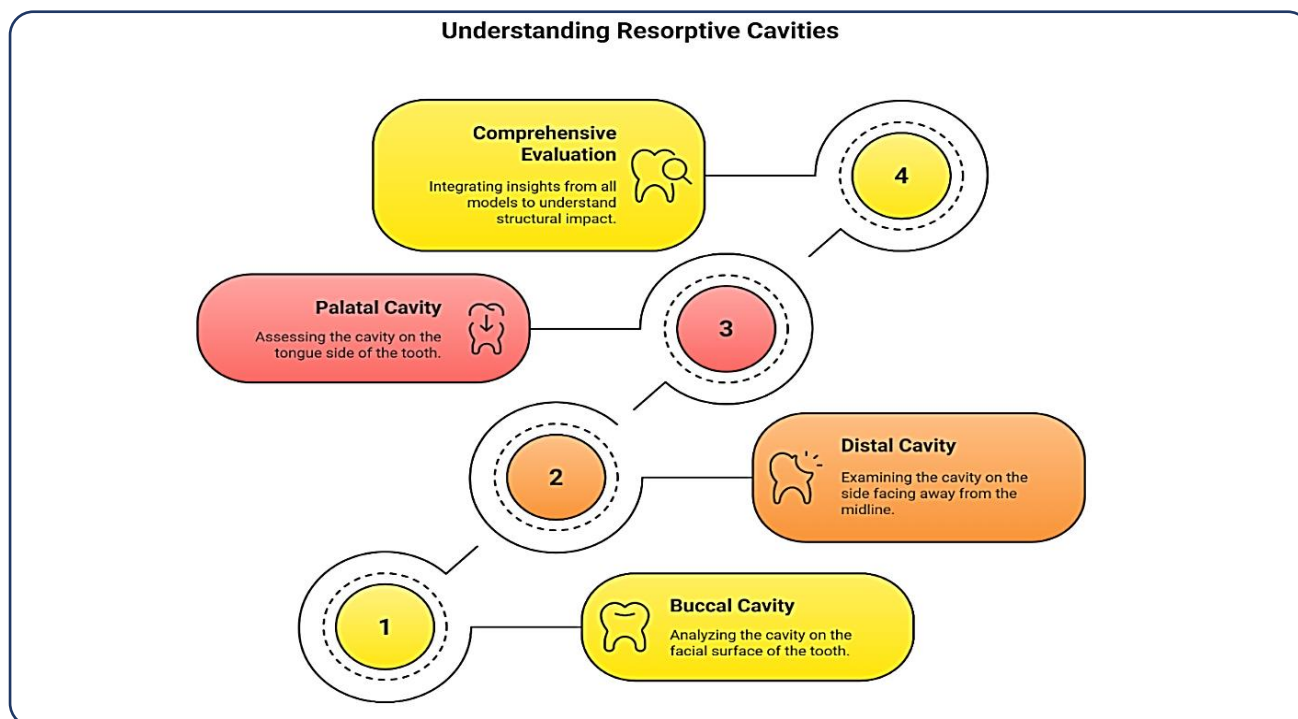


Fig. 2: Schematic of understanding resorptive cavities.

Tooth Preservation (green with protective shield symbol) is dedicated to the preservation of the natural tooth using active treatment approaches, with restoration and conservative approaches for the conservation of existing tooth structure. Middle line Conservative Monitoring, exemplified in blue using the magnifying glass icon, is to wait out the tooth and observe without doing anything right away, a "wait and see" approach, where practitioners would observe the condition of the tooth over time before resorting to active treatment. To the right, Definitive Removal (red with an "X" symbol) encompasses cases where retention is not possible and leads to extraction, reserved for cases where the tooth cannot be retained or is clinically unsafe. This visual guide provides dental clinicians with a step-by-step approach to cover the entire gamut of treatment modalities, from the most conservative strategy of watchful waiting through active preservation efforts to the most ultimate intervention of extraction, to enhance evidence-based clinical decision-making on the basis of the distinctive case presentation and prognosis. Step 2 proceeds to the Distal Cavity examination (in orange), a direct visual examination of the cavity on the other side of the midline, gathering data on the lateral size and three-dimensional character of the resorptive process. Step 3 moves on to Palatal Cavity examination (as noted in pink/coral), where it views the cavity on the tongue side of the tooth, offering a close-up view of the lingual extension and posterior access for therapeutic planning.

The process is finalized in Step 4, the Comprehensive Evaluation (yellow), where results of all three models of anatomy are combined to ascertain the total structural impact of the resorptive cavity on tooth integrity, biomechanical behavior, and treatment result. Fig. 3 shows a close match of stress patterns of distribution, i.e., on the palatal surface of incisors with External Inflammatory Cervical Resorption (EICR) when three different restorative materials are employed to restore them under controlled loading. The results show that the three materials possess remarkably close values for maximum stress, with Bio-dental registering $1.3959\text{e}7$ Pa, while both GIC and RMGIC share the same peak stress value of $1.3943\text{e}7$ Pa, showing minimal variation in maximum stress generated on the palatal side regardless of the material employed.

This science philosophy enables dental professionals to thoroughly assess resorptive cavities from all major anatomical perspectives and verify that treatment planning incorporates the full three-dimensional aspect of the pathological process and optimizes restorative intervention by location, size, and structure implications for long-term survival and function of teeth [30-34].

However, the minimum stress values uncover larger differences, in which Bio-dental has the highest minimum stress of $6.6052\text{e}-8$ Pa compared to GIC with $3.6441\text{e}-8$ Pa and RMGIC at $3.844\text{e}-8$ Pa, which shows Bio-dental to have higher baseline levels of stress along the tooth structure.



Fig. 3: Stress distribution patterns on incisors with EICR using three restorative materials under load.

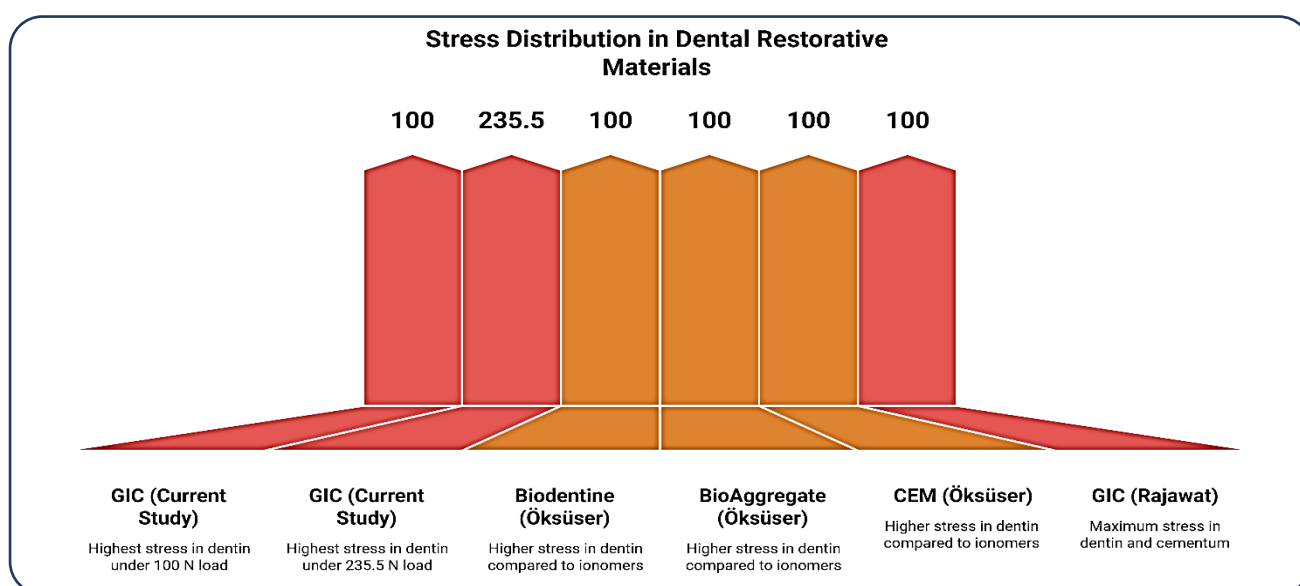


Fig. 4: Schematic of stress distribution in dental restorative materials.

The stress distribution patterns indicate that Bio-dental generates cervical concentration with a gradient transition nature, while GIC generates the same but more restricted stress concentrations localized in small regions of the tooth structure. RMGIC behaves very much the same as GIC, indicating that alteration of the resin does not actually modify the intrinsic stress distribution nature on the palatal surface. This makes it clear that by a palatal surface perspective, all three materials differ not much in terms of peak stress generation behavior, but differ as far as the morphology of the total stress field is concerned, the ionomer-based materials (GIC and RMGIC) showing more favorable stress containment characteristics when contrasted with the Bio-dental material under conditions of EICR treatment [35-39]. Fig. 4 is a broad comparative summary of stress distribution outcomes from a range of research studies comparing assorted dental restorative materials under various loading conditions, hence offering

a meta-analysis summary of material performance for dental applications. This schematic shows six various research cases in a bar chart format, where relative stress is shown by the height, and red is used to denote studies from the current research and orange for results obtained from previous work by Öksüser and Rajawat [31]. The current study involved demonstrating that GIC always induces the highest concentration of stresses in dentin under both 100 N and 235.5 N load, with 235.5 N force inducing much higher stresses, as evidenced by the higher bar height. The comparative results of Öksüser's research show that bio-based products, including Biodentine, BioAggregate, and CEM, all yield higher stress concentrations in dentin than those that are generated by ionomer-based products, which contradict the outcomes of this research and thereby confirm the complexities involved in measuring the performance of materials under different experimental conditions.

Rajawat's research confirms that GIC induces the highest stress in cementum and dentin structures, as was concluded by the present study regarding GIC's tendency to induce high concentrations of stress. Conflicting research highlights the importance of considering various factors—such as loading conditions, defect shape, material behavior, and analysis techniques—when evaluating restorative materials for challenging cases like ECR. Effective stress management is essential for the long-term care of affected teeth. EICR poses significant challenges, including limited access to lesions, the complete removal of granulation tissue, moisture contamination that can wash out restorative materials, and the need to support compromised tooth structures. The size and location of resorption, along with the mechanical properties of restorative materials, greatly influence treatment outcomes by affecting stress levels and distribution. This study investigated the impact of different restorative materials on stress distribution and biomechanical performance in maxillary central incisors with ECR under various conditions and loads. Although breaking strength tests measure the maximum force dental structures can endure, they are limited by anatomical variations and do not reflect stress from functional forces over time. FEA shows distinct advantages, allowing detailed stress examination in specific areas and simulating various loading conditions, making it the ideal method for this research.

External cervical resorption

ECR is most conspicuous on maxillary central incisors, with *Heithersay* and *Mavridou* finding [6, 7, 14] ECR in 29.2% and 28.8% respectively, out of 257 and 337 clinically diagnosed teeth, so a maxillary central incisor μ CT model would be appropriate. Shannon Patel's classification system is a novel three-dimensional clinical classification system for ECR based on lesion height, circumferential distribution, and proximity to the root canal parameters, making Patel's classification system suitable for an inclusion study. Current research evidence indicates that GIC is the least suitable for the restoration of 2BP ECR defects, with the maximum dentin stress levels below 100 Newton and 235.5 Newton loads. Experiments by *Gurbuz et al.* [29] showed that dentin stress increases as material's elasticity modulus decreases; the lowest elastic modulus is reported for GIC among the three material types reported for GIC. These results conform with laboratory investigations wherein some researchers reported higher VMS values of GIC repair in dentin compared to Biodentine, BioAggregate, and

CEM products, and wherein *Akansha Rajawat* reported the highest von Mises stress values in dentin in all the lesions for GIC restoration. To the author's surprise, maximum dentin stresses were achieved when Biodentine was utilized to restore labial ECR models with 50N forces and distal ECR models with 15N forces.

A study by *Shubhashini* with FEA to restore class V cavities with different materials concluded micro-filled composite to be most effective, followed by flowable composite, GIC, and RMGIC, with GIC producing less dentin stress than RMGIC, opposite to the findings in the current study, GIC was highest in stress, and RMGIC was lowest. Comprehensive studies by *Van Meerbeek* showed correlations with enhanced clinical performance and decreased Young's modulus of restorative materials, as low modulus allows restorations to deflect with teeth, reducing the risk of debonding. Results show the lowest VMS in restorative materials with RMGIC, except for distal ECR models under 15N force, where Biodentine showed the lowest stress, as seen in research by *Rajawat et al.* [31]. *Sevinc Askerbeyli* [34], simulating EICR cavities with pulp invasion requiring direct pulp capping with *Biodentine* alone or 1mm *Biodentine* and resin composite or GIC showed that the use of GIC in dentin-limited EICR is advisable, whereas Biodentine is preferable for pulp-proximate EICR, regardless of whether or not root canal intervention is needed, except where circumferential coverage of the cavity is more than 90 degrees, where GIC may have greater benefits.

These results are in accordance with previous research where EICR lesions organized according to 2BP Patel classification have circumferential measurements between 90-180 degrees with pulp invasion. *Mudita Manaktala* evaluated stress distribution in endodontically treated ECR lesions restored with MTA and Biodentine using FEA, hypothesizing supracrestal or subcrestal EICR with 70- or 130-degree circumferential extension, and determined both materials showed even stress distribution throughout ECR lesions with no meaningful differences by lesion location or size, with high-stress concentrations near restorations, especially in subcrestal lesions, though overall stress magnitudes were similar between materials, reflecting equal biomechanical performance. When the force level and material are identical, and von Mises stress is measured on different EICR surfaces, the minimum VMS is on palatal surfaces and maximum on distal surfaces, which shows that distal surface contact in EICR lesions increases the likelihood of restoration failure through high VMS [39-42].

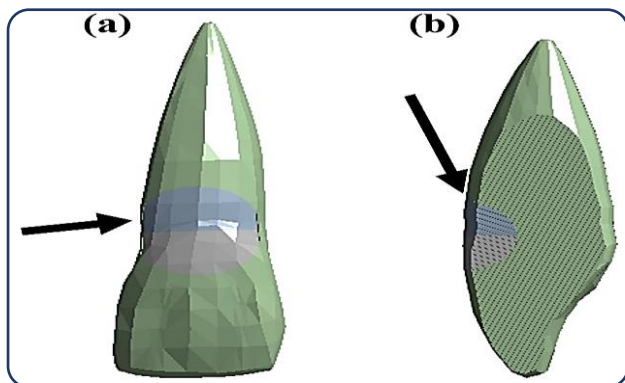


Fig. 5: Schematic comparing stress distribution patterns of three restorative materials within a simulated ECR defect under load.

Variations between current studies and previous literature may result from study design specifics, variations in dental models, and varying treatment styles, with numerous factors like the material, geographical locations, surrounding tissue types, directions and magnitudes of applied forces, differences in elastic modulus, variety of tooth, and status of development all playing a role in differential results [43–46]. Materials are assumed to have homogeneous, isotropic, and linear elastic behavior, with dentin histological properties showing hardness variability from the pulp end to the outer surface, which varies dentin mechanical properties. With assumptions of maxillary central incisor anatomical uniformity, clinical outcomes of force, bending stress, and permanent deformation show variability and call for future *in vitro* studies to confirm the results achieved.

Tooth stress analysis

In this study, Tooth No. 1, identified as the central incisor, was selected for analysis due to its significance as one of the primary anterior teeth in the maxilla, to examine its mechanical behavior under various chewing loads and applied forces in simulated clinical conditions. A 3D model of the tooth was initially created using CAD software and imported into the ANSYS environment, incorporating different components—enamel, dentin, pulp, and periodontal ligament—modeled in layers to accurately reflect the biological structure's behavior. Mechanical properties for each component were assigned based on biomechanical data from relevant scientific literature. Boundary conditions were established to fix the regions surrounding the root within the alveolar bone, while vertical and oblique forces were applied to the tooth's surface to simulate loading conditions. A stress analysis of the model was then conducted to assess its response under these loads.

Fig. 5 (a-b) shows the schematic representation of stress distribution in various dental restorative materials.

This illustration shows how different materials respond under functional loading, showcasing their mechanical properties and stress patterns. By analyzing the distribution of stress, clinicians can better understand how each material performs in real-world applications, particularly concerning factors like durability and patient comfort. The schematic serves as a valuable tool for evaluating the effectiveness of restorative options and guiding material selection in dental practice.

Fig. 5 is a schematic representation illustrating the comparative stress distribution profiles of different dental restorative materials under functional load. It visually characterizes the mechanical behavior of Biodentine, GIC, and Resin-Modified Glass Ionomer Cement (RMGIC) within a simulated ECR defect. The schematic highlights key performance metrics, such as the magnitude and gradient of stress concentration within the restorative material and at the material-tooth interface. It serves to validate the FEA data, demonstrating that RMGIC exhibits a more homogeneous and lower magnitude stress distribution compared to the higher, more localized stress concentrations associated with GIC.

Fig. 6 (a-c) shows a three-dimensional surface plot quantifying the VMS values (in MPa) within the dentin structure for ECR defects restored with three different materials (Biodentine, GIC, RMGIC) across three anatomical surfaces (Labial, Palatal, Distal) under a 15 N applied force. The Z-axis represents the stress magnitude, allowing for a direct comparison of how each material influences dentinal stress. This visualization confirms the quantitative finding that GIC restoration results in the highest stress concentrations within the dentin, particularly on the distal surface, while RMGIC demonstrates a favorable reduction in stress transmission. The plot underscores the critical impact of restorative material selection on the biomechanical loading of the residual tooth structure.

Fig. 7 (a-c) is a complementary 3D surface plot to Fig. 6, showing the VMS distribution within the restorative composite material itself for the same parameters: three materials, three surfaces, and a 15 N load. The plot contrasts the internal stress experienced by each restorative material, revealing that Biodentine sustained the highest stress levels within the defect repair. RMGIC showed the most favorable performance with the lowest internal stress concentrations. The result is crucial for understanding a material's ability to withstand functional loads without excessive deformation or potential failure, with RMGIC showing superior mechanical integrity under the conditions tested.

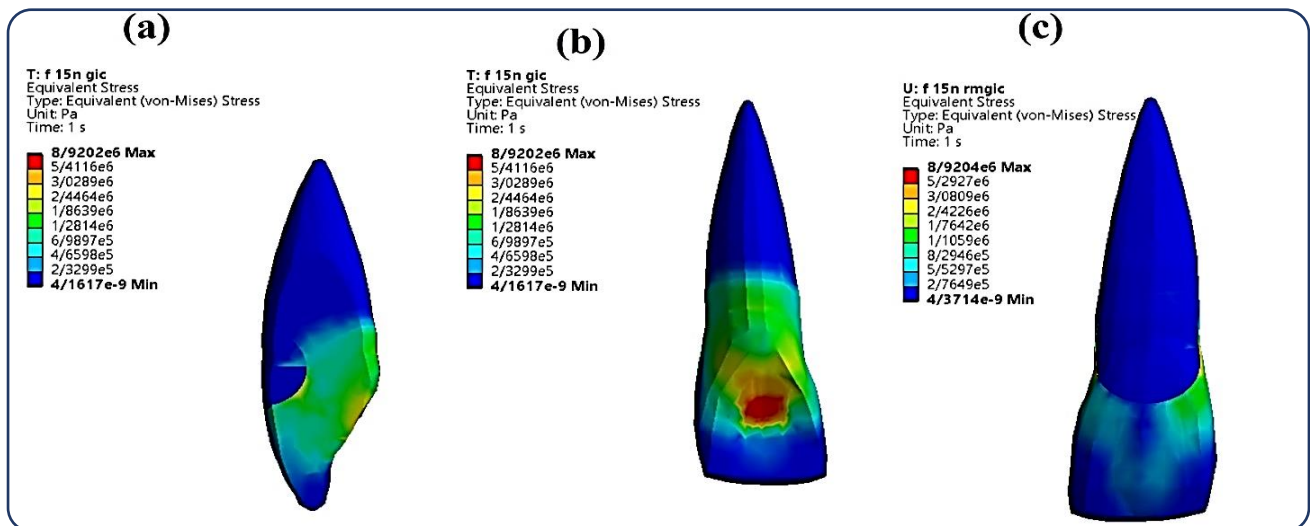


Fig. 6: 3D plot of von Mises stress in dentin for three surfaces and materials under a 15 N applied force.

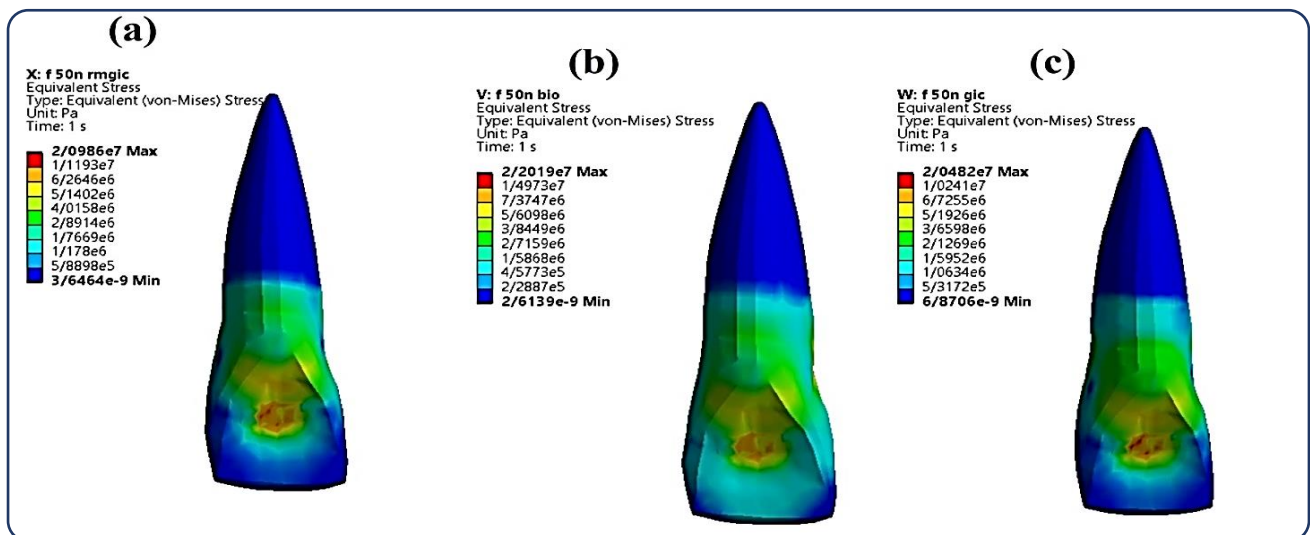


Fig. 7: 3D plot of internal VMS within three restorative materials under a 15 N applied force.

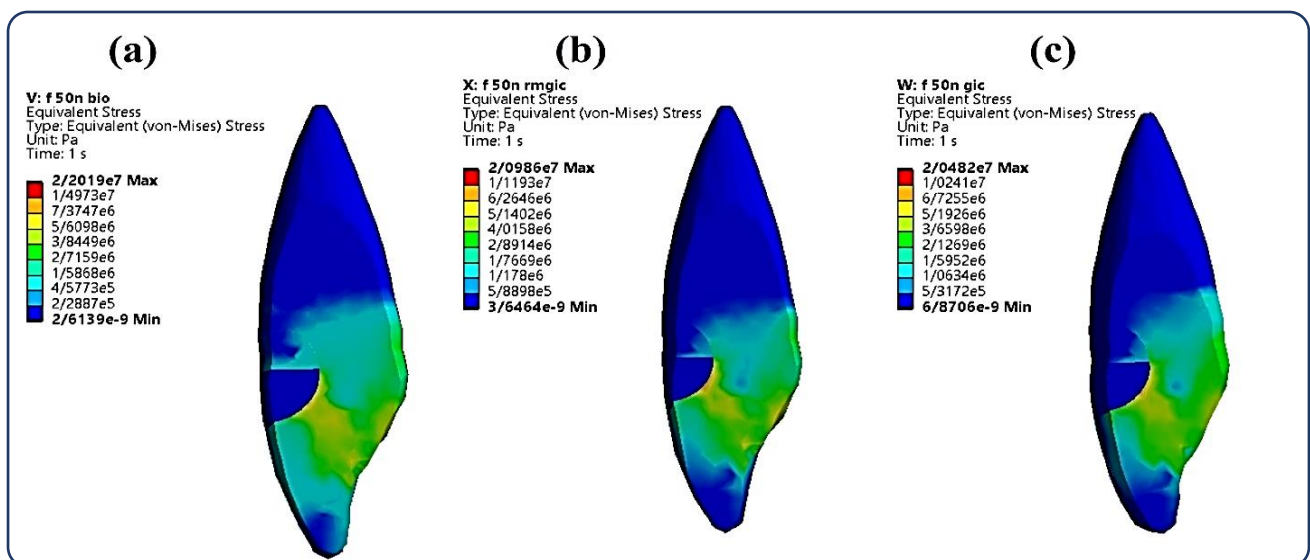


Fig. 8: Dentin VMS for three materials under a higher 50 N load, showing amplified but consistent patterns.

Table 1: Total stress values in the studied groups at a force of 15 newtons (MPa).

Surface involved	Groups	Dentin	Composite	Restorative materials
Labial	A1: Biodentine	8.91	0.014	1.93
	A2: GIC	8.92	0.015	0.99
	A3: RMGI	8.92	0.016	0.60
Palatal	Biodentine: B1	8.60	0.0152	3.27
	B2: GIC	8.61	0.0158	2.18
	B3: RMGI	8.60	0.0159	2.10
Distal	C1: Biodentine	12.53	0.0098	4.14
	C2: GIC	83.86	0.0094	9.55
	C3: RMGI	8.58	0.0056	2.93

Table 2: Total stress values in the studied groups at a force of 50 newtons (MPa).

Surfaces involved	Groups	Dentin	Composite	Restorative materials
Labial	A1: Biodentine	22.01	0.036	5.97
	A2: GIC	20.84	0.047	2.91
	A3: RMGI	20.98	0.042	2.93
Palatal	Biodentine B1	13.95	0.023	4.51
	B2: GIC	13.94	0.021	2.84
	B3: RMGI	13.94	0.020	2.84
Distal	C1: Biodentine	19.60	0.046	17.36
	C2: GIC	18.01	0.028	8.82
	C3: RMGI	16.75	0.024	6.90

Table 3: Material properties used in the finite element model.

Material	Young's Modulus (E) [MPa]	Poisson's Ratio (v)	Reference
Enamel	84,100	0.33	[29]
Dentin	18,600	0.31	[29]
Periodontal Ligament	68.9	0.45	[25]
Cortical Bone	13,700	0.30	[25]
Cancellous Bone	1,370	0.30	[25]
Biodentine	22,000	0.30	[31]
Glass Ionomer Cement (GIC)	10,000	0.30	[31]
Resin-Modified GIC (RMGIC)	8,000	0.28	[31]
Composite Resin	12,000	0.30	[29]

Fig. 8 (a-c) illustrates the VMS distribution within the *dentin* for the same set of restorative materials and lesion locations, but under a higher 50 N applied force. This plot demonstrates the effect of increased load magnitude on stress patterns. The elevated force amplifies the stress values across all scenarios, but the relative performance hierarchy of the materials remains consistent with the 15 N condition. The distal surface continues to show the highest stress concentration, affirming its biomechanical vulnerability. Fig. 8 is essential for simulating high-load scenarios.

A mesh convergence analysis was performed to ensure that the results were independent of the element size and to minimize discretization errors. The global mesh size was progressively refined from an initial coarse mesh of 0.5 mm down to a fine mesh of 0.1 mm. The maximum von Mises stress in the dentin structure, adjacent to the restoration was selected as the convergence criterion.

Statistical analysis

Figs. 9 and 10 show the distributions of dentine and composite (Table 1) across restorative materials and surfaces, respectively. The Kruskal-Wallis non-parametric

statistical test was used for dentine and composite across restorative material groups for each surface involved separately to compare the distributions of them among the three restorative material groups and examine the significance of the difference in stress. Considering the labial surface, the p-values of 0.3679 for both composite and dentine indicate that there are no statistically significant differences across the three restorative materials. By examining the p-values for the other two surfaces, Palatal and Distal, it does not indicate that there are significant differences across the 3 restorative groups.

Figs. 11 and 12 show how dentine and composite (Table 2) are distributed across the different restorative materials and surfaces. Similar to the analysis performed for the data in Table 1, we applied the Kruskal-Wallis non-parametric test on the data in Table 2. Although Tables 1 and 2, show 2 distinct experimental conditions, the Kruskal-Wallis non-parametric test yielded the same outcome. Recent studies have continued to emphasize the critical role of CBCT in the three-dimensional assessment and classification of ECR lesions, which is fundamental for accurate treatment planning [9, 28].

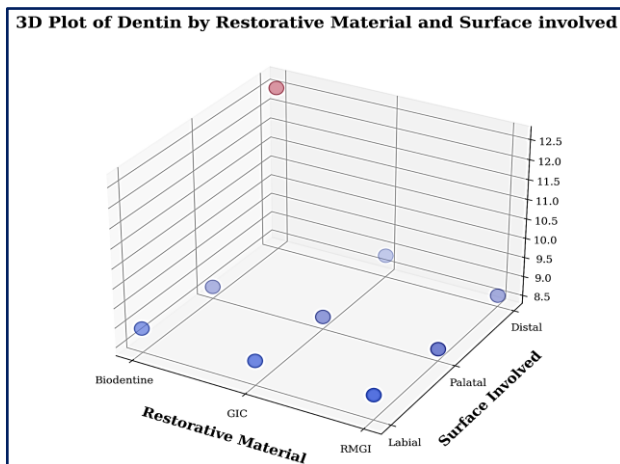


Fig. 9: 3D plot showing dentine distribution across various restorative materials (Biodentine, GIC, and RMGI) and surfaces (Labial, Palatal, and Distal) at a force of 15 Newtons (MPa).

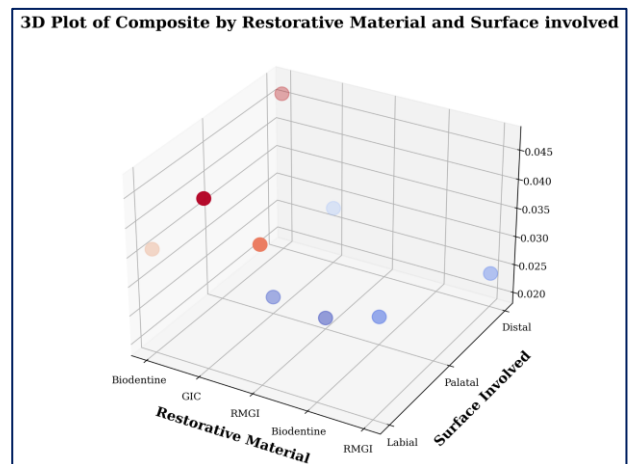


Fig. 12: 3D plot showing composite distribution across various restorative materials (Biodentine, GIC, and RMGI) and surfaces (Labial, Palatal, and Distal) at a force of 50 Newtons (MPa).

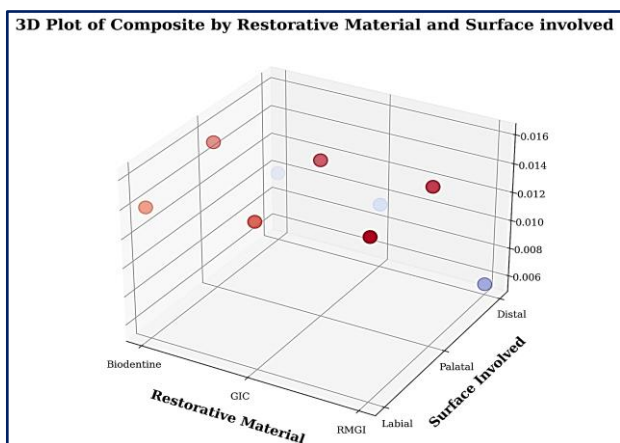


Fig. 10: 3D plot showing composite distribution across various restorative materials (Biodentine, GIC, and RMGI) and surfaces (Labial, Palatal, and Distal) at a force of 15 Newtons (MPa).

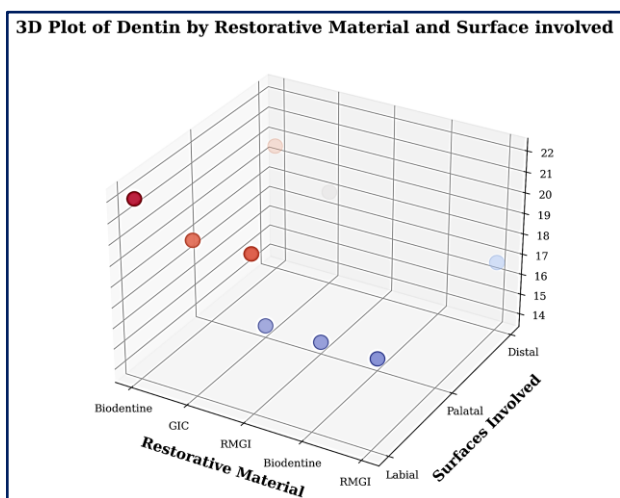


Fig. 11: 3D plot showing dentine distribution across various restorative materials (Biodentine, GIC, and RMGI) and surfaces (Labial, Palatal, and Distal) at a force of 50 Newtons (MPa).

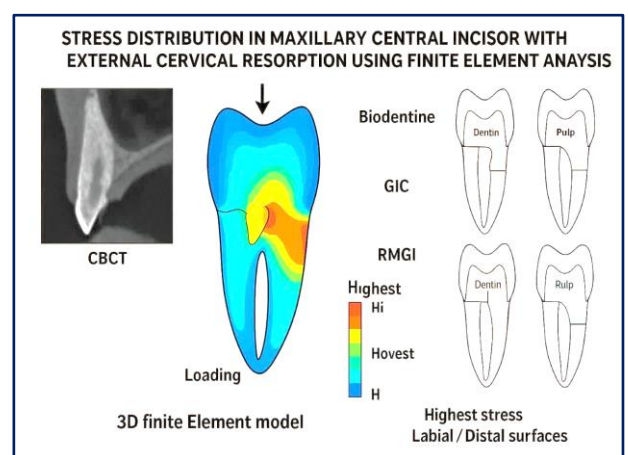


Fig. 13: Stress distribution in maxillary central incisors with ECR, analyzing the effects of Biodentine, GIC, and RMGI using FEA.

Furthermore, the exploration of advanced biocompatible materials and their biomechanical performance through FEA have become a focal point in contemporary restorative dentistry research [30, 31, 34, 35]. Fig. 13 shows the Comparative Analysis and the study's results, potentially showing how different materials and techniques perform under various conditions. It serves as a visual summary of the key research outcomes.

Fig. 14 shows the conceptual representation of ECR, showing how CBCT diagnosis leads to treatment strategies involving biocompatible materials, and illustrating the importance of understanding stress distribution in dental restoration. Recent advancements in dental materials and wound healing technologies are noteworthy. A friction-induced PTFE coating has been developed for dental restorative resin, showing ultralow friction and wear properties.

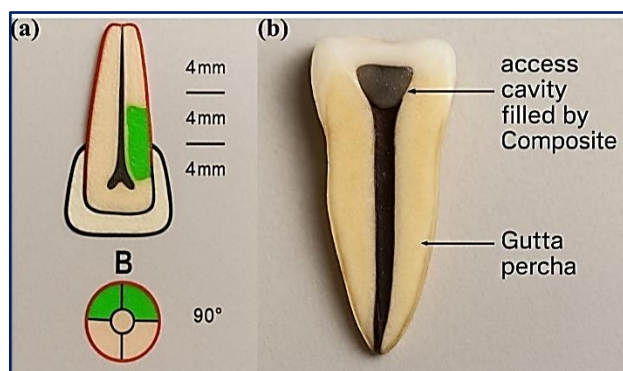


Fig. 14: Access cavity filled by composite and gutta percha schematic.

Janus hydrogels designed as "double-sided protectors" are being explored for skin and mucosal wound repair, highlighting their applications and mechanisms [47-50]. Additionally, research has reviewed hydrogels as scaffolds for dental pulp regeneration, while gelatin/heparin-coated polyurethane fibers have been introduced for small-caliber artificial blood vessel grafts, showcasing innovative approaches in tissue engineering [51-54]. Many studies investigate mechanical properties using FEM analysis as a common research paradigm in bone tissue engineering, too [55-58], where advanced manufacturing techniques for creating scaffolds are coupled with computational modeling to rationally design and predict their structural and biological performance [59-63]. The results were considered converged when a further refinement of the mesh from 0.2 mm to 0.1 mm resulted in a change of less than 2% in the maximum von Mises stress value. Consequently, a global element size of 0.2 mm was adopted for the final analysis, generating a model with approximately based on Table 3 nodes 5 elements, which provided an optimal balance between computational accuracy and efficiency.

CONCLUSION

This study shows the importance of the selection of restoration material in the treatment of maxillary central incisor ECR. In this study, using sophisticated FEA, researchers evaluated the impacts of three materials—Biodentine, GIC, and Resin-Modified Glass Ionomer Cement (RMGI)—on stress distribution patterns of compromised teeth. Results indicated that even though Biodentine generated the highest stress concentrations within the restorative material itself, GIC generated the highest stress values within the framework of the surrounding dentin structure, and thus could be a less-than-ideal choice for ECR repairs. The location of the resorptive lesion

within the anatomy also played a significant role in determining stress patterns, the maximum stress loads are experienced by distal surfaces, and palatal surfaces experience minimal stress concentrations. These critical remarks point out that effective treatment with ECR is contingent upon careful attention to the biomechanical behavior of repair materials as well as the inherent characteristics of lesions. By basing informed material choices on mechanical behavior, clinicians can effectively augment tooth preservation and minimize risks of treatment failure. The research suggests a more individualized treatment of ECR, using more advanced diagnostic equipment such as Cone-Beam Computed Tomography (CBCT) for precise lesion assessment and optimal treatment planning. Future research into the long-term clinical conduct of various restorative materials used in ECR treatments will be required in order to maximize therapy protocols and eventually improve patient outcomes based on evidence-based treatment regimens.

Conflict of Interest

The authors received no financial support or sponsorship from commercial entities that might have influenced the research findings.

Data Availability

The research datasets from this study remain confidential to protect participant privacy and maintain ethical standards, though they may be made available to qualified academic researchers upon completion of proper approval processes.

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