Mutlu *et al. BMC Oral Health* (2026) 26:48
https://doi.org/10.1186/s12903-025-07604-9

BMC Oral Health

RESEARCH Open Access

Effect of deep margin elevation and cavity configuration on the mechanical behavior of endocrown restorations: a 3D finite element study

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Abstract

Background Restorative procedures following endodontic treatment are crucial for preserving the functional integrity of the tooth, preventing coronal leakage, and protecting the root canal system from contamination. The present study aims to compare the effects of different marginal elevation strategies and restorative material combinations on stress distribution and fatigue life, using three-dimensional (3D) finite element analysis (FEA) of mandibular first molar models prepared with DO, MO, and MOD cavity designs.

Methods The anatomical structure of tooth number 36 was scanned using cone beam computed tomography. Three different cavity types were then created on the tooth. In the same model, deep margin elevation (DME) was applied in single and double layers of filler materials, each with 1 mm step increments. For the FEA, bulk-fill composite, conventional composite, hybrid composite, and flowable composite (Smart Dentin Replacement; SDR) were used as filling materials, whereas polymer-infiltrated ceramic networks (PICN) and lithium disilicate (LDS) were used as endocrown materials. After modeling, the stress values obtained from the analysis were evaluated according to the von Mises stress criterion and the results were reported in megapascals (MPa).

Results The DME technique provided uniform stress distribution, increased fracture resistance, and increased the incidence of repairable fractures. Among the restorative materials studied, SDR demonstrated superior stress management and marginal adaptation. PICN restorations provided more uniform load distribution, supporting overall restoration integrity. This in silico study suggests that the application of the DME technique, combined with the appropriate selection of restorative and crown materials, may have a positive influence on stress distribution and fracture behavior in endodontically treated molars. However, as this study was conducted solely based on FEA and relies on an in vitro modeling approach, the findings need to be supported by long-term clinical data. Further laboratory and clinical studies are required to validate these mechanical findings under real-world clinical conditions.

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Conclusions The use of DME combined with appropriate material selection can significantly improve the mechanical behavior of restorative treatments. These findings can guide clinicians in selecting materials and techniques for optimal long-term outcomes.

Keywords Deep margin elevation, Endocrown, Finite element analysis

Background

Restorative procedures following endodontic treatment are crucial for preserving the functional integrity of the tooth, preventing coronal leakage, and protecting the root canal system from contamination. The long-term success of restorations in endodontically treated teeth depends not only on the efficacy of endodontic procedures but also on the biomechanical suitability of the implemented restorative approach. Specifically, when restoring posterior teeth with extensive loss of tooth structure, the selected treatment protocol must be planned to preserve as much remaining healthy dentin as possible [1, 2].

Traditionally, post and core and full crown restorations have been widely favored for tooth rehabilitation; however, literature reports that these approaches reduce the risk of restorative failure only in cases where all coronal walls have been lost [3]. In teeth with less material loss, post placement must be carefully considered, as it can lead to the removal of healthy dentin, and thereby, adversely affect the biomechanical resistance of the restoration. Moreover, the risk of complications such as root perforation or vertical root fracture during post placement has led to the development of more conservative restorative techniques.

Recent advances in adhesive systems have brought minimally invasive endocrown restorations to the forefront. Specifically, CAD/CAM materials such as lithium disilicate (LDS) and polymer-infiltrated ceramic networks (PICN), which are commonly used in posterior regions, offer high mechanical strength and favorable esthetic properties. The elastic modulus of these materials closely approximates that of natural tooth structure, facilitating more uniform distribution of applied forces, thereby contributing to increased restoration longevity [4].

Flowable composite (Smart Dentin Replacement; SDR) as a bulk-fill composite with a low elastic modulus, exhibits the ability to absorb polymerization shrinkage stresses, thereby mimicking dentin-like mechanical behavior and contributing to a more balanced distribution of stress within the restorative system. Studies have shown that SDR provides superior marginal adaptation and significantly reduces microleakage, particularly in deep proximal cavities, when compared to hybrid composites and conventional bulk-fill materials [5, 6].

Because of structural weakening, dentin dehydration, and changes in elastic modulus, endodontically treated teeth show changed biomechanical behavior following root canal therapy, increasing their vulnerability to unfavorable fracture patterns.

The shift to minimally invasive adhesive restorative ideas is supported by the fact that excessive removal of radicular dentin to create post space has been linked to increased stress concentration and a higher incidence of root fractures [7, 8].

Onlays and endocrowns are examples of conservative CAD/CAM-based techniques that use optimized geometry and adhesive bonding to boost mechanical resistance while preserving pericervical dentin.

Stress distribution in endodontically treated teeth is greatly influenced by restorative design and material combinations, according to recent finite element analysis (FEA) research, highlighting the clinical significance of tissue preservation and strategic restorative planning.

The mechanical and structural behavior of materials and biological structures can be predicted mathematically and non-destructively using FEA, in contrast to in vitro investigations [8, 9].

The finite element method provides substantial benefits for quantitatively evaluating stress distributions inside these intricate structures because dental tissues are heterogeneous, anisotropic, and multicomponent. Its use in restorative dentistry is further supported by recent CAD-based FEA studies that show how cavity shape and adhesive restorative techniques greatly affect stress concentrations in teeth that have undergone endodontic treatment [10].

Additionally, biomechanically optimized restorative materials can improve stress distribution and lower peak tensile forces, according to material engineering studies that incorporate functional elasticity gradients into crown designs. This highlights the significance of computational simulations in predicting restorative performance [11].

In cases involving deep proximal lesions following endodontic treatment, the restorative margins often extend subgingivally, complicating isolation and impairing marginal adaptation. The deep margin elevation (DME) technique, developed to address such clinical scenarios, involves placing composite resin material onto the proximal dentin to elevate the restorative margin to a supragingival level. This approach facilitates isolation and enables adhesive restorations to be applied with improved biological, mechanical, and esthetic outcomes [5, 6, 12–14].

In cases where orthodontic extrusion or surgical crown lengthening could compromise aesthetics or result in biologic width violations, DME has become a therapeutically useful treatment for controlling subgingival margins in posterior teeth.

DME improves clinical accessibility and restorative results by facilitating isolation, enhancing adhesive control, and permitting supragingival completion of margins. Potential drawbacks, such as marginal gap creation, elevated polymerization stress, and adhesive failure risk under high occlusal load, have drawn criticism. Because of their lower elastic modulus and controlled polymerization kinetics, stress-relieving flowable bulk-fill materials like SDR have been demonstrated to enhance marginal adaptation and lessen shrinkage-induced stress, offering advantageous stress management in deep proximal margins and endodontically treated teeth [6, 13–17].

Numerical modeling methods such as FEA play a critical role in the long-term evaluation of the restorative success achieved with DME. FEA provides a mathematical framework for analyzing the structural behavior of teeth and restorative materials within a simulated environment [12]. Regardless, the existing literature reveals a paucity of comprehensive studies that simultaneously examine varying cavity designs, DME application techniques, and combinations of restorative materials. Given the heterogeneous, anisotropic, and multicomponent nature of dental tissues, the finite element method offers significant advantages for quantitatively assessing stress distributions within these complex structures.

Accurate modeling of occlusal forces is essential when evaluating the biomechanical behavior of restorative systems in endodontically treated posterior teeth. In the literature, it has been reported that physiological masticatory forces applied to molars is typically 200–600 N, with parafunctional habits (e.g., bruxism) increasing this load to 800–1000 N. [15–17] Furthermore, significant sex-related differences in maximal bite forces have been reported: average maximum bite forces in men are generally 500–700 N, whereas in females they are 300–500 N. [18, 19] These physiological variations represent important biomechanical parameters that must be considered when assessing the loads endured by restorative systems. Prior FEA studies have applied loads of 200–1400 N to molar teeth, encompassing physiological and extreme loading scenarios [20, 21].

The present study aims to compare the effects of different marginal elevation strategies and restorative material combinations on stress distribution and fatigue life, using three-dimensional (3D) FEA of mandibular first molar models prepared with disto-occlusal (DO), mesio-occlusal (MO) and mesio-occlusal-distal (MOD) cavity designs. These findings may guide clinical decision-making regarding material and technique selection.

Thus, in this study, the hypothesis is that neither the type of composite material used nor the crown material (LDS vs. PICN) nor the application of the DME technique will have a significant effect on the stress distribution within the restorations.

Methods

The subgingival defect model used in this study was designed to simulate clinical conditions such as tissue loss caused by deep proximal caries lesions frequently observed in endodontically treated molars, or iatrogenic tissue loss extending below the cemento-enamel junction. Such tissue loss typically necessitates the use of deep margin elevation (DME) techniques to move the restorative margin to a supragingival position.

A standard and uniform subgingival margin geometry was preferred in all models to allow for comparable evaluation of stress distribution among different cavity configurations (MO, DO, MOD), restorative materials, and DME applications.

In this study, the anatomical structure of tooth number 36 was scanned using cone beam computed tomography (CBCT). CBCT images were obtained using the Morita 3D Accuitomo 170 (J Morita Mfg. Corp., Kyoto, Japan) device. The size of the imaging volume was a cylinder with a diameter of 40 mm and a height of 40 mm, centered on the X-ray rotation axis. The images were acquired with standard parameters of 90 kVp (X-ray tube voltage) and 5 mA (current), which could be adjusted for different applications. The images were captured with an exposure time of 160 μm and 17.5 s. The obtained dicom format data were imported into the Mimics (Mimics 12.00, Leuven, Belgium) software and segmentation was performed. During segmentation, the enamel, dentin, and pulp structures were extracted separately, and .stl files were generated for each structure. The resulting .stl files were then imported into Geomagic Design X (Geomagic Design X 2020.0) software, where surface editing was performed, and .stp format files were generated.

The generated .stp files were transferred to SolidWorks 2023 (Solidworks corp., Waltham, MA, USA) software, where they were embedded into a box representing the jawbone. For the region of the tooth embedded in the bone, a 0.2-mm thick periodontal ligament (PDL) was designed to surround the tooth [22]. Three different cavity types were then created on the tooth: MOD cavity, MO cavity and DO cavity. A 40-μm thick cement layer was designed inside the cavity, and endocrown restorations were modeled for all the structures. [23] (Fig. 1).

On the same model, DME was applied in single and double layers of filler materials, each with 1 mm step increments. In the models where two-layered DME was performed, SDR was used as the bottom layer, and other composite materials were used as the top layer.

Fig. 1 Representative 3D Models of the Restored Teeth without Marginal Elevation: (**I**) Endocrown, (**II**) Cement, (**III**) Enamel, (**IV**) Dentin, (**V**) Gutta Percha, (**VI**) PDL, (**VII**) Cortical Bone, (**VIII**) Trabecular Bone, (**IX**) Model, (**X**) Model Section

Additionally, a 10-μm thick adhesive (bond) layer was applied beneath the filling material. The endocrown design was recreated using the same methodology as the previous models (Fig. 2). Once all the model designs were completed, .stp files were generated for FEA and transferred to Abaqus (2020 Dassault Systems Simulation Corp., Johnston, RT, USA) software.

For the FEA, bulk-fill composite, conventional composite, hybrid composite and SDR were used as filling materials, whereas PICN and LDS were used as endocrown materials. In Abaqus software, the mechanical properties of all materials (elastic modulus and Poisson's ratio) were defined in the "Properties" section (Table 1). All materials, were considered isotropic linear elastic materials. In the "Interaction" section, all components were connected using the "tie" method. In the "Load and Boundary" section, a vertical force of 600 N was applied to the occlusal surface, and the movement and rotation of the bone in all directions were constrained, allowing for stress analysis. (Fig. 3).

Each model was discretized using linear tetrahedral elements (C3D4), with mesh refinement concentrated in critical regions such as the adhesive interfaces, cavity margins, and cusp tips. A convergence test was performed by successively refining the mesh until stress variation between iterations was below 5%. The mesh, nodes, and element properties used in FEA for the tooth and cement thickness are shown in Table 2.

The stress values obtained from the analysis were evaluated according to the von Mises stress criterion, and the results were reported in megapascals (MPa).

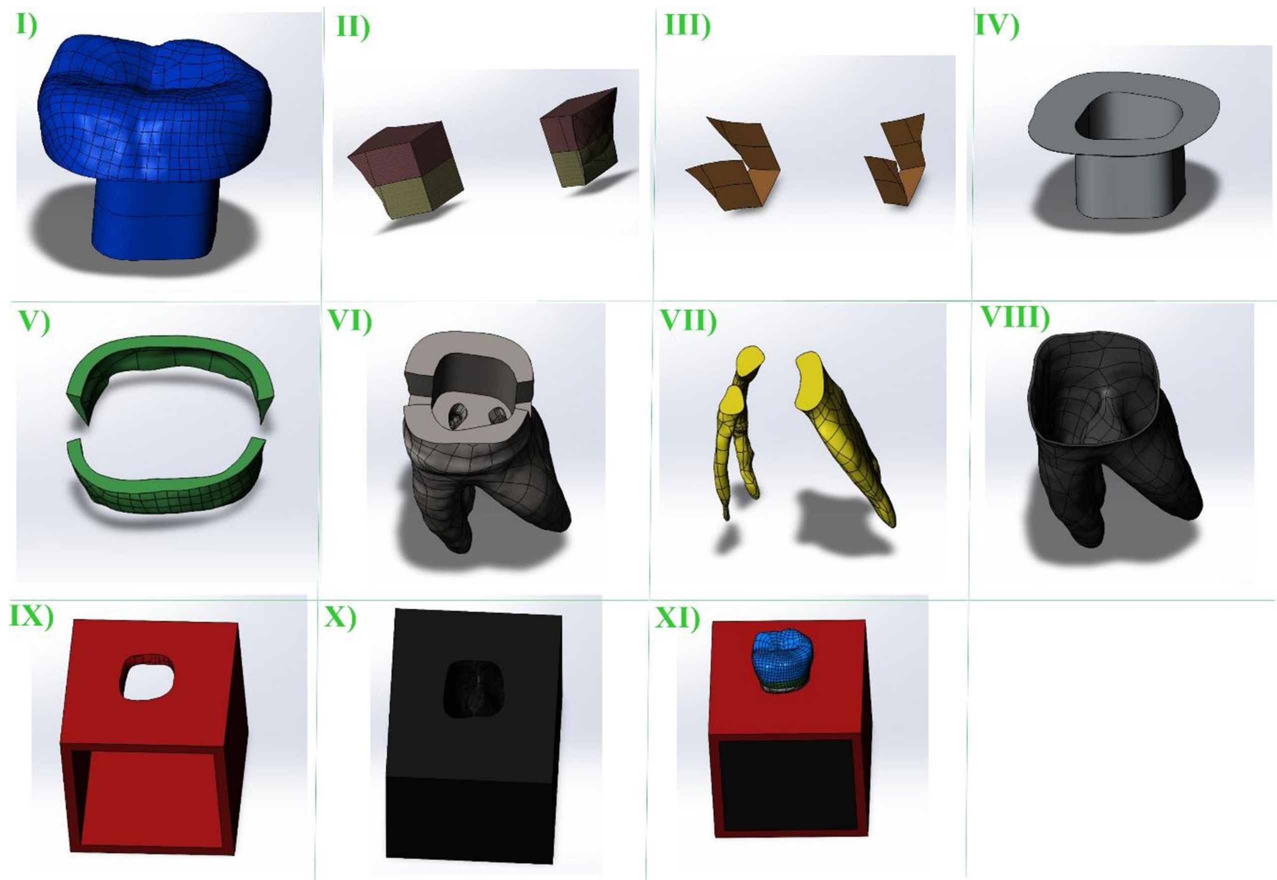

Fig. 2 Deep Margin Elevated Tooth Models: (**I**) Endocrown, (**II**) Filling Material, (**III**) Adhesive Layer, (**IV**) Cement, (**V**) Enamel, (**VI**) Dentin, (**VII**) Gutta Percha, (**VIII**) PDL, (**IX**) Cortical Bone, (**X**) Trabecular Bone, (**XI**) Model

Table 1 Mechanical properties of dental tissues and restorative materials [24–28]

Material	Young's Modulus (MPa)	Poisson's Ratio
Dentin	18,600	0.31
Enamel	84,000	0.33
LDS	102,700	0.22
PICN	30,100	0.23
Cement	7,700	0.3
Bulk-fill composite	12,000	0.25
Conventional composite	16,600	0.24
Hybrid composite	22,000	0.27
SDR	8,000	0.2
Adhesive	1,000	0.24
PDL	68.9	0.45
Gutta-percha	140	0.45
Cortical bone	13,700	0.3
Spongy(cancellous) bone	1,370	0.3

Results

Models with MOD, MO, and DO cavity designs were first restored solely with endocrowns—without DME using PICN and LDS materials. The von Mises stress values in the enamel, dentin, restoration, and cement layers of these models are summarized in Tables 1, 2. Enamel stress values were higher in the PICN groups than in the LDS groups (PICN–MOD: 115.4 MPa; MO: 108.4 MPa; DO: 112.1 MPa vs. LDS–MOD: 87.75 MPa; MO: 79.77 MPa; DO: 90.71 MPa). Conversely, dentin and restoration von Mises stresses were higher in the LDS groups than in the PICN groups (PICN–MOD: 17.94 MPa; MO: 17.18 MPa; DO: 17.79 MPa vs. LDS–MOD: 18.66 MPa; MO: 17.95 MPa; DO: 18.49 MPa). Furthermore, in the cement layer, stresses were greater in PICN-restored models across all cavity types (PICN–MOD: 13.32 MPa; MO: 14.07 MPa; DO: 16.54 MPa vs. LDS–MOD: 12.35 MPa; MO: 13.18 MPa; DO: 15.23 MPa) (Figs. 4, 5 and 6).

Next, MOD, MO, and DO models underwent single-layer DME, after which restorations were again completed with endocrowns. PICN and LDS served as the restorative endocrown materials, while the DME layer was built up using bulk-fill composite, conventional composite, hybrid composite, and SDR. In these restored models, stress distributions in tooth tissues and restorative components were evaluated according to the von Mises criterion; the results are presented in the tables below (Figs. 4, 5 and 6).

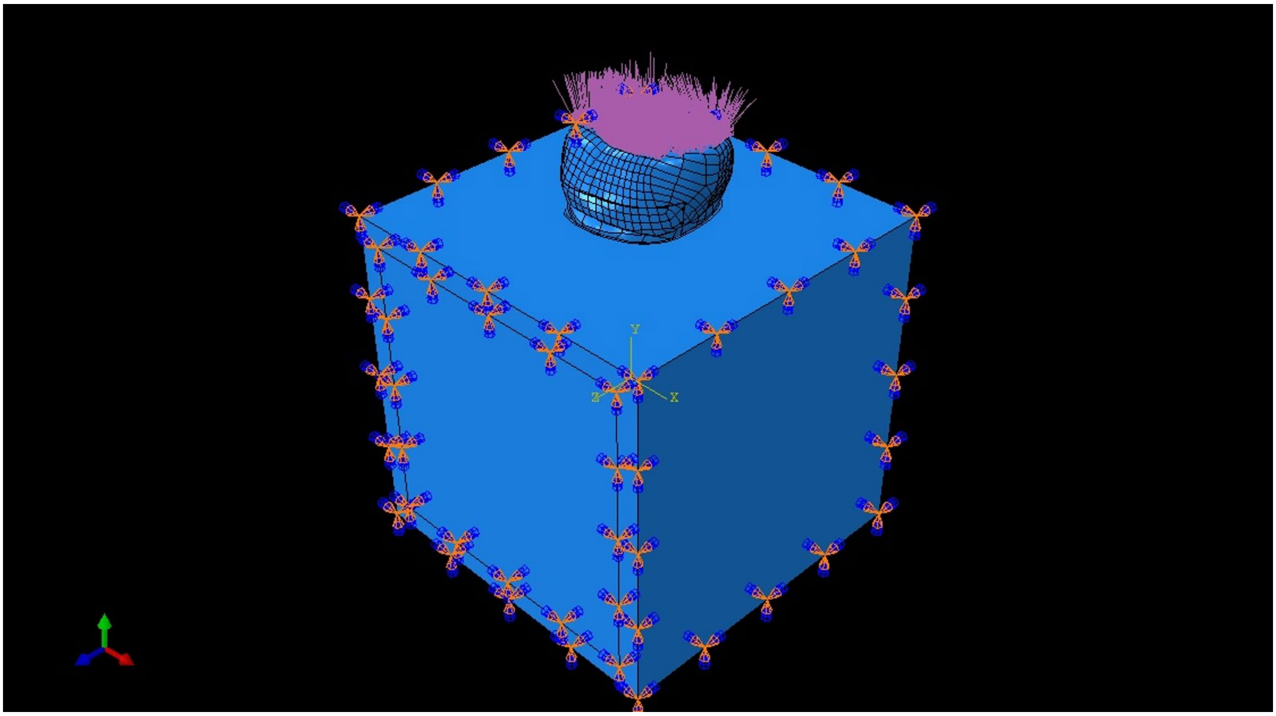

Fig. 3 Load and boundary conditions

Table 2 Nodes and elements for the different tested model

	Model	Total Elements	Total Nodes	Mesh Type
Single layer DME	DO	4,121,858	800,045	Linear tetrahedral elements of C3D4
	MO	4,124,406	800,285	Linear tetrahedral elements of C3D4
	MOD	4,136,369	804,009	Linear tetrahedral elements of C3D4
Double layer DME	DO	4,151,541	806,166	Linear tetrahedral elements of C3D4
	MO	4,160,932	808,423	Linear tetrahedral elements of C3D4
	MOD	4,196,918	817,128	Linear tetrahedral elements of C3D4
Endocrown	DO	4,082,209	791,466	Linear tetrahedral elements of C3D4
	MO	4,090,570	792,876	Linear tetrahedral elements of C3D4
	MOD	4,061,475	787,692	Linear tetrahedral elements of C3D4

In single-layer and MOD configurations, enamel stress was highest in the PICN group, with the PICN–SDR combination exhibiting the greatest value (125.3 MPa). The lowest enamel stress occurred with the LDS–hybrid composite pairing (94.80 MPa). Dentin stresses were similar for both endocrown materials, ranging narrowly between 18.42 and 19.41 MPa. Moreover, stress accumulated within the endocrown itself peaked in the LDS group—specifically in the LDS–SDR combination (32.99 MPa)—and was lowest in the PICN–hybrid composite group (18.50 MPa). Cement layer stresses were highest for the PICN–SDR combination (16.36 MPa) and lower in the LDS models (13.49 MPa). Among DME composites, the greatest stress concentration was observed for the PICN–hybrid composite combination (10.31 MPa), and the LDS–SDR pairing showed the lowest composite stress (5.815 MPa). Finally, adhesive layer stresses reached their maximum in the PICN–SDR group (7.573 MPa) and minimum in the LDS–hybrid composite group (4.277 MPa) (Fig. 6).

In summary, for MOD cavity configurations with single-layer DME followed by endocrown restorations, the highest stress concentrations in enamel, the adhesive interface, and the composite layer were observed in the PICN–hybrid composite and PICN–SDR combinations. Conversely, the lowest stresses in the adhesive layer and composite bulk occurred with the LDS–hybrid composite combination (Fig. 6).

In the single-layer DME and MO models, the maximum enamel stress was observed in the PICN–SDR combination (121.0 MPa), and the minimum stress was observed in the LDS–hybrid composite combination (90.73 MPa). Dentin stresses were very similar between LDS and PICN models, with only minimal differences

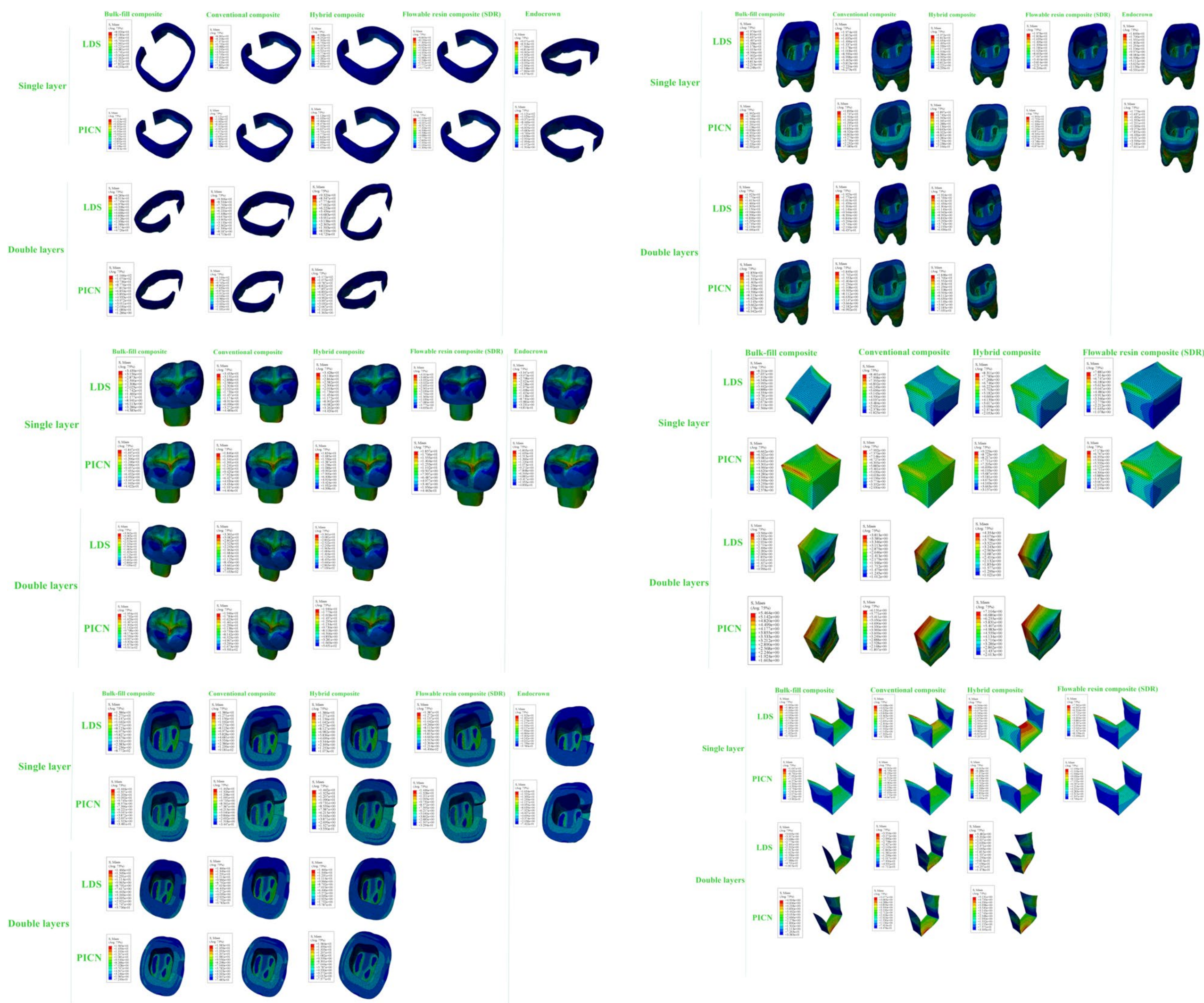

Fig. 4 Stress Distribution Patterns in a Disto-Occlusal (DO) Cavity Model Restored with and without Deep Margin elevation

(18.90–18.69 MPa). Stress accumulated within the endocrown material was highest in the LDS–SDR combination (37.92 MPa) and was lowest in the PICN–hybrid composite combination (19.61 MPa). Overall, LDS-based models exhibited greater stress accumulation than PICN models. In the cement layer, the highest stress was observed in the LDS–SDR combination (15.94 MPa), and the lowest in the PICN–conventional composite combination (13.83 MPa). Among the DME composites, the greatest stress concentration was observed in the PICN–hybrid composite combination (10.24 MPa), whereas the LDS–SDR combination exhibited the lowest composite stress (5.75 MPa). Adhesive layer stress was highest in the PICN–SDR combination (8.27 MPa) and lowest in the LDS–hybrid composite combination (5.10 MPa) (Fig. 5).

Thus, for MO cavity designs with single-layer DME, the greatest stress accumulation in enamel, adhesive layer, and composite build-up was observed in the PICN–hybrid composite and PICN–SDR combinations, whereas the lowest stresses occurred with the LDS–hybrid composite combination (Fig. 5).

For DO cavity designs with single-layer DME, von Mises stress analysis yielded the following results: the highest enamel stress occurred with the PICN–hybrid composite combination (112.6 MPa), and the lowest with the LDS–bulk-fill composite combination (89.20 MPa). Dentin stresses peaked in the LDS–SDR combination (19.78 MPa) and were lowest in the PICN–hybrid composite combination (18.97 MPa). However, the difference between the groups remained minimal. Stress values on the endocrown material were greatest in the LDS–SDR combination (40.14 MPa) and lowest in the PICN–hybrid composite combination (18.34 MPa). Generally, higher stress accumulation was observed in LDS models compared to PICN. The highest stress values on the cement layer were observed in the PICN–SDR combination

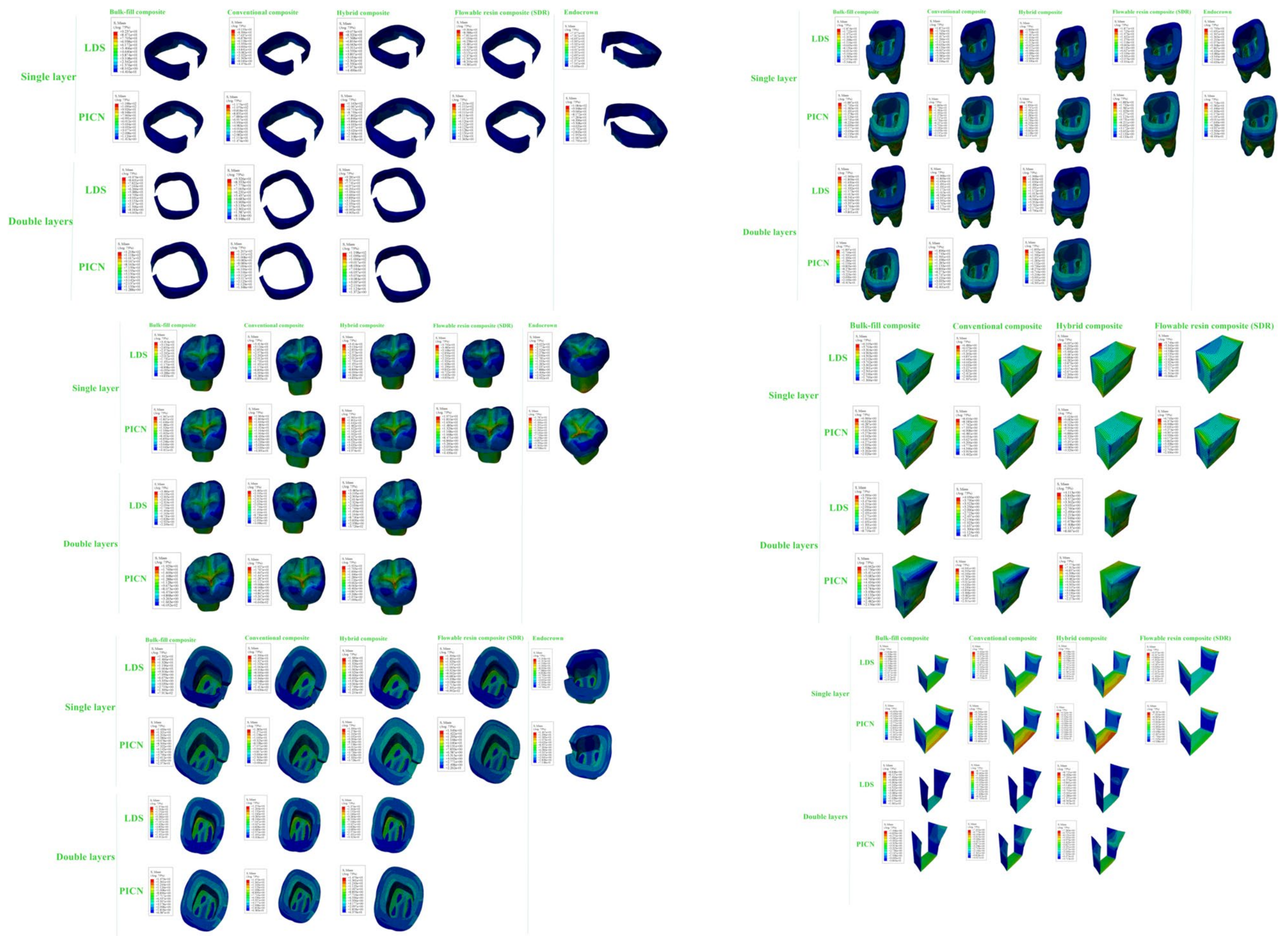

Fig. 5 Stress Distribution Patterns in a Mesio-Occlusal (MO) Cavity Model Restored with and without Deep Margin Elevation

(14.46 MPa). Additionally, it was determined that the models restored with PICN in the cement area accumulated higher stress than the LDS group, but this difference was minimal (14.46 MPa vs. 13.86 MPa). For the DME composite layer, the highest stress value was observed in the PICN–hybrid composite combination (9.23 MPa) and the lowest value was observed in the PICN–bulk-fill composite combination (6.66 MPa). Adhesive layer stress was highest in the PICN–SDR combination (11.99 MPa) and was lowest in the LDS–hybrid composite combination (4.34 MPa) (Fig. 4).

Accordingly, in DO cavity models with single-layer DME, the highest stress concentrations in enamel, composite, and adhesive regions were observed in the PICN–hybrid composite and PICN–SDR combinations. In contrast, the lowest stress accumulation occurred with LDS–bulk-fill or LDS–hybrid composite combinations (Fig. 4).

Following two-layer DME in MOD cavity designs, the maximum enamel stress was observed in the PICN–bulk-fill composite combination (123.8 MPa), whereas the minimum stress was observed in the LDS–hybrid composite combination (94.44 MPa). In dentin tissue, the maximum stress value was recorded in the LDS–bulk-fill composite combination (19.65) and the minimum stress value was recorded in the PICN–hybrid composite combination (18.92). However, the difference between the groups remained minimal (Fig. 6).

On the endocrown material (crown), the highest stress value was observed in the LDS–bulk-fill composite combination (33.37) and the lowest stress value was observed in the PICN–hybrid composite combination (20.03). Cement layer stresses were higher in PICN-restored groups compared to LDS groups (15.61 MPa vs. 14.48 MPa). However, no significant difference was observed between the sub-combinations of each group. For the DME composite layer, the highest stress value was observed in the LDS–hybrid composite combination (9.47 MPa), and the lowest in the PICN–bulk-fill composite combination (6.28 MPa). On the adhesive layer, the highest stress value was measured in the LDS–bulk-fill composite combination (8.694 MPa) and the value was measured in the PICN–hybrid composite combination (7.092 MPa).

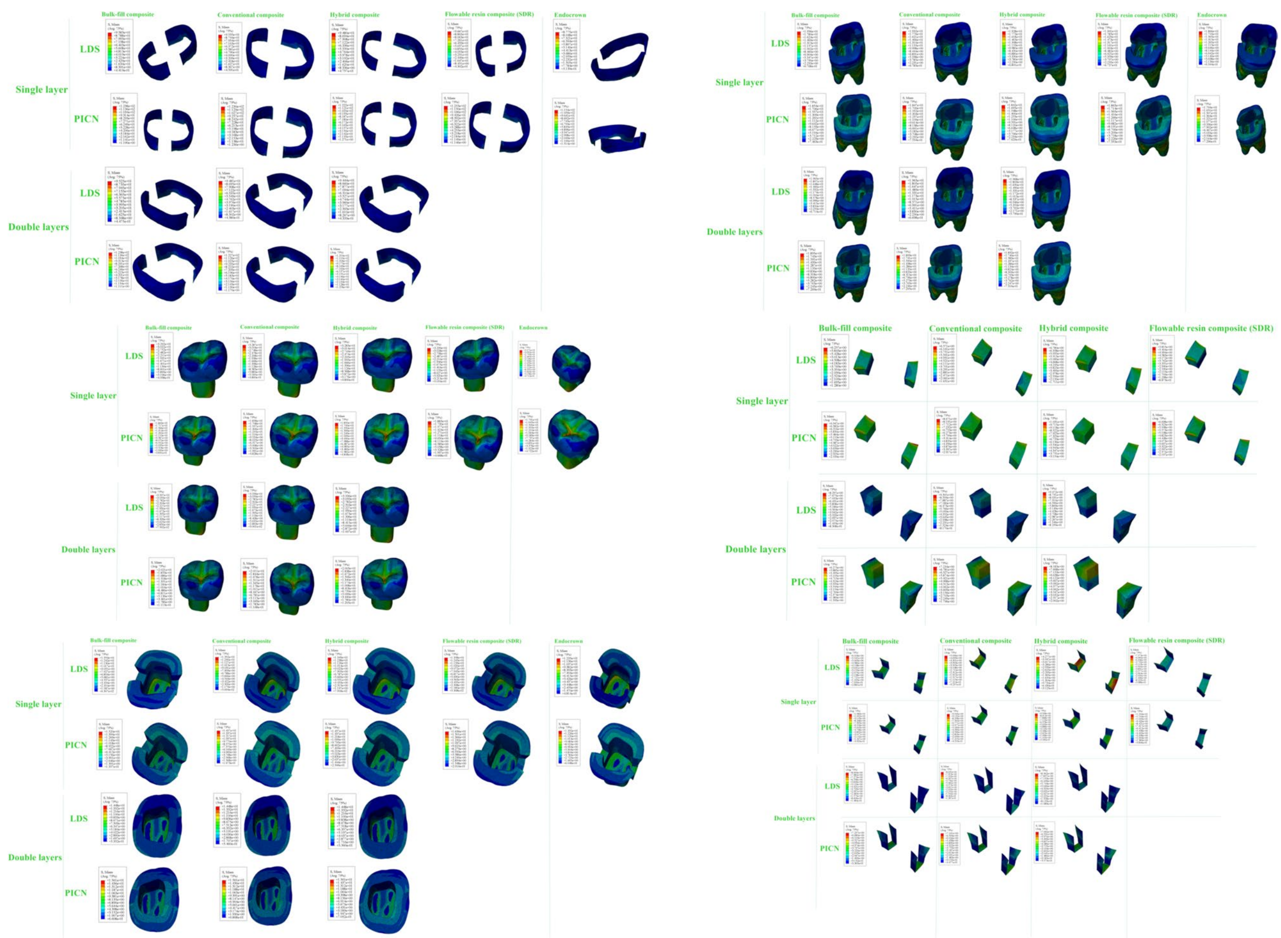

Fig. 6 Stress Distribution Patterns in a Mesio-Occlusal-Distal (MOD) Cavity Model Restored with and without Deep Margin Elevation

In MO cavity designs with two-layer DME, von Mises stress values obtained were as follows: The highest stress value on enamel tissue was recorded in the PICN–bulk-fill composite combination (121.8 MPa) and the lowest value was recorded in the LDS–hybrid composite combination (92.81 MPa). On dentin tissue, the highest stress value was observed in the LDS–bulk-fill composite combination (19.69 MPa) and the lowest value was measured in the PICN–hybrid composite combination (18.95 MPa). However, no significant difference was observed between the sub-combinations of each group. Endocrown material stresses were greatest in the LDS–bulk-fill group (34.86 MPa) and lowest in the PICN–hybrid composite combination (19.25 MPa). However, no significant difference was observed between the sub-combinations of each group. On the cement layer, the highest stress values were recorded in the PICN subgroups and the lowest values were recorded in the LDS subgroups (14.79 MPa vs.13.76 MPa). The highest DME composite material stress was observed in the PICN–hybrid composite combination (7.77 MPa), while the lowest value was observed in the LDS–bulk-fill composite combination (3.99 MPa). Adhesive layer stress peaked with the LDS–bulk-fill combination (8.84 MPa) and was lowest in the PICN–hybrid composite combination (7.28 MPa) (Fig. 5).

In DO cavity designs with two-layer DME, von Mises stress values obtained were as follows: The highest stress value on the enamel tissue was observed in the PICN–hybrid composite combination (117.2 MPa) and the lowest value was observed in the LDS–bulk-fill composite combination (92.89 MPa). In dentin, the highest stresses were recorded in the LDS–bulk-fill and LDS–conventional composite groups (each 19.25 MPa), while the lowest values were recorded in the PICN–hybrid composite combination (18.48 MPa). Stress values on the endocrown material were highest in the LDS–bulk-fill combination (33.62 MPa) and lowest in the PICN–hybrid composite combination (19.40 MPa). Cement layer stresses were highest for both PICN–bulk-fill and PICN–conventional composite combinations (15.85 MPa) and lowest across all LDS subgroups (14.66 MPa) (Fig. 4).

In the DME composite layer, the highest stress value was observed in the PICN–hybrid composite combination (7.10 MPa) and the lowest value was observed in the LDS–bulk-fill composite combination (3.57 MPa). Adhesive layer stress was highest for the PICN–hybrid composite combination (5.13 MPa) and lowest for the LDS–hybrid composite combination (3.48 MPa).

Discussion

The primary objective of this study was to evaluate using FEA the effects of different composite materials, crown substrates (LDS or PICN), and the DME technique on stress distribution and fracture behavior in the restoration of deep proximal cavities. The initial hypothesis posited that these variables would not produce a significant difference in the mechanical behavior of the restorative system.

Contrary to this hypothesis and in agreement with existing literature our results demonstrated that specific materials and techniques exert a meaningful influence on restorative performance. Specifically, the DME procedure, by relocating the restorative margin to a supragingival position, enhanced field isolation and optimized adhesive bonding. Samartzi et al. [6] reported that DME reduces stress concentration, improves marginal adaptation, and increases resistance to biomechanical loads.

The SDR material used in the present study, owing to its low elastic modulus and high filler content, absorbed internal polymerization stresses and favorably influenced fracture resistance of the restoration. This finding is consistent with results reported by Ilie and Hickel [29] and Ende et al. [30] Conversely, models using conventional composites exhibited higher stress accumulation.

Comparisons between crown substrates revealed distinct differences in load distribution between LDS and PICN. The elastic modulus of PICN more closely approximates that of natural dentin, which resulted in more uniform stress dispersion and reduced stress concentration within the restoration. Lin et al. [21] and Jie Lin et al. [31] similarly reported that, particularly with DME, PICN restorations distribute stress more evenly throughout the restorative structure.

These observations gain further significance when considered in the context of the 600 N vertical occlusal loading protocol employed in our study. According to the literature, physiological masticatory forces applied to the molar region typically range between 200 and 600 N, while parafunctional habits (such as bruxism) can elevate these forces up to 800–1000 N. Therefore, the 600 N load used in our study represents a valid approximation of maximum physiological stress and is appropriate for evaluating the biomechanical behavior of the restorative system, particularly in endodontically treated posterior teeth. The vertical direction of load application was chosen to simulate functional occlusal forces under standardized conditions and allowed for consistent assessment of stress concentration and distribution within the restored tooth structure [32].

Our analysis revealed that under this load, DME-treated models exhibited more homogeneous stress distribution and lower stress concentrations at the restorative margins, indicating a more physiological and protective mechanical behavior. Conversely, non-DME models showed stress accumulation at the restorative margins and cervical region, correlating with a higher risk of catastrophic failure.

Fracture-type analysis further demonstrated that DME groups experienced a greater incidence of repairable fractures, whereas non-DME groups were prone to catastrophic failures. This result is consistent with the findings of de Assis et al. [33] and Ilgenstein et al. [34] and underscores the beneficial effect of DME on stress control.

Thus, our data refute the original null hypothesis (that neither the material nor the technique used have a significant effect on restorative stress distribution and fracture behavior), and both the choice of material and the application of DME produced clinically significant differences in stress distribution and fracture behavior of the restorative system.

Although this FEA-based investigation provides valuable insights into stress transfer and fracture mechanics in restorative systems, certain limitations warrant caution. The study did not account for long-term material aging or biological factors such as salivary environment, temperature fluctuations, and periodontal support. Therefore, caution should be exercised before generalizing these results to clinical conditions. Sterzenbach et al. [35] and Brosh et al. [36] have emphasized the necessity of corroborating in silico results with in vivo and clinical trials. The stress distribution observed in this FEA model suggests that DME combined with restorative materials exhibiting dentin-like elastic behavior can enhance the long-term mechanical behavior of endodontically treated teeth. This is consistent with previous clinical and in silico studies demonstrating improved restoration longevity [37–39].

Conclusions

In this study, the effects of different restorative materials (conventional composite, hybrid composite, SDR), crown substrates (LDS and PICN), and the presence or absence of DME on stress distribution and fracture behavior in endodontically treated mandibular molars were evaluated using 3D FEA.

The findings show that DME application creates a more homogeneous stress distribution by shifting the restorative margins to the gingiva and is associated with more repairable fracture patterns. Among the restorative materials examined, SDR with a low elastic modulus was found to be more advantageous in terms of stress management; and in terms of crown materials, PICN restorations with an elastic modulus closer to dentin provided a more balanced load distribution.

Within the limitations of this in silico study, it was concluded that the DME technique, when used in conjunction with appropriate restorative and crown materials, can positively affect the biomechanical performance of restorations. However, further in vitro and long-term clinical studies are needed to translate these findings into clinical applications.

Limitations

This study has several limitations. First, our FEA-based model does not completely replicate the complex biological environment of the oral cavity. Important factors such as the PDL, salivary flow, temperature fluctuations, variations in masticatory direction, and biological tissue responses were not simulated. Second, only static, idealized vertical loading was applied; the complex dynamic loading scenarios of natural mastication (e.g., lateral and oblique forces) were not considered. Third, the effects of material aging—including thermal cycling, water sorption, and fatigue—were not incorporated into the model. Finally, individual patient variables (e.g., differences in occlusal force, sex, age, and parafunctional habits) were not accounted for. Therefore, these findings should be supported by long-term, multicenter, patient-based randomized clinical trials before being applied to clinical decision-making.

Abbreviations

3D	Three-Dimensional
FEA	Finite Element Analysis
DME	Deep Margin Elevation
MPa	Megapascals
PICN	Polymer-Infiltrated Ceramic Network
LDS	Lithium Disilicate
CAD/CAM	Computer Aided Design/ Computer Aided Manufacturing
SDR	Smart Dentin Replacement
CBCT	Cone Beam Computed Tomography
MO	Mesio-Occlusal
DO	Disto-Occlusal
MOD	Mesio-Occlusal-Distal
PDL	Periodontal Ligament

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-07604-9.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Supplementary Material 4.

Supplementary Material 5.

Supplementary Material 6.

Supplementary Material 7.

Supplementary Material 8.

Supplementary Material 9.

Supplementary Material 10.

Supplementary Material 11.

Supplementary Material 12.

Supplementary Material 13.

Supplementary Material 14.

Supplementary Material 15.

Supplementary Material 16.

Supplementary Material 17.

Supplementary Material 18.

Supplementary Material 19.

Acknowledgements

Not applicable.

Authors' contributions

Design: SNM, DS, RM; Data collection or data entry: RM; Analysis and interpretation: RM, DS; Literature review: SNM, DS, RM; Writing: SNM, DS, RM.

Funding

and support.

This study was funded by any institution.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the Necmettin Erbakan University Faculty of Dentistry Ethics Committee for Non-Drug and Medical Device Research (Turkey, Konya) (2025/562- 23600).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 10 August 2025 / Accepted: 24 December 2025

Published online: 06 January 2026

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