Original Article

Numerical Three-dimensional Finite Element Modeling of Cavity Shape and Optimal Material Selection by Analysis of Stress Distribution on Class V Cavities of Mandibular Premolars

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Abstract

Aim: Adhesive restoration does not depend primarily on the configuration of the shape of the cavity. Under varying loading conditions, it is essential to know the stress concentration and load transfer mechanism for distinct cavity shapes. The aim of this study was to evaluate and compare the biomechanical characteristics of various cavity shapes, namely oval, elliptical, trapezoidal, and rectangular shapes of class V cavities on mandibular premolars restored with amalgam, glass ionomer cement, and Cention N using three-dimensional (3D) finite element analysis. **Materials and Methods:** A 3D prototype of a mandibular premolar was generated by Digital Imaging and Communications in Medicine (DICOM) images obtained from the cone beam computed tomography and imported to 3D modeling software tool, SpaceClaim. The four distinct load magnitudes of 100, 150, 200, and 250 N were applied as a pressure load perpendicular to the lingual plane of the lingual cusp of the occlusal surface (normal load) and at 45° to same (oblique load). The stress distribution patterns and the maximum von Mises stresses were analyzed and compared. **Results:** The occlusal stresses were distributed from the force loading point in an approximate actinomorphic pattern, and when the force load was close to the margin, the stress was much greater. **Conclusion:** Ovoid cavity showed lesser stress concentration and deformation for each of the tested restorative material.

Keywords: *Cavity shapes, dental materials, dentistry, finite element analysis, restoration, Stress distribution*

Introduction

Noncarious cervical lesions (NCCLs) are wedge or saucer-shaped defects on the teeth attributed to erosion, abrasion, and occlusal loading.[1] Cervical lesion changes the distribution of stress within a tooth. Grippo[2] suggested that if the lesion were left unrestored, the stress concentration caused by the cervical lesion would facilitate further deterioration of tooth structure. Conventionally, silver amalgam was used as a restorative material in cervical lesions, but its toxic nature due to mercury and unaesthetic appearance hindered its usage. The retention rates of restorative materials significantly depend on the constant occlusal loading and their mechanical properties.[3] Lopes *et al.*[4] suggested that the bond created by adhesive restorative materials structurally reinforced restored tooth when compared to nonadhesive restoration techniques and seals the cavity from oral fluids and bacteria. Composite resins are widely used to restore cervical lesions but

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they have a major drawback of shrinkage due to polymerization reaction, thus creating mechanical stresses between the cavity walls and the filling. Glass ionomer cement (GIC) is an adhesive restorative material, which is less technique sensitive as compared to composite resins, and provides an adequate strength to be used in NCCLs.[5] Under eccentric loading, the frequency of marginal gaps is seen to be higher for the composite when compared with GIC.[6] Alkasites are a new class of dental restorative material, which have toothlike appearance and high flexure strength; hence, their demand has increased in recent past.[7]

As the shape of the cavity depends on the material used for filling, sharp cavity angles in accordance with Black's principle can influence the modified stress and strain distribution, compared to the adhesive cavity type.[8] Studies on the stress distribution on NCCL state that maximum stress is seen at the apex of the lesion.[9,10] It has been proven that the lesion shape and depth influence the development of tensile stresses along the interfaces of the GIC restoration.[11] Researchers have carried out several studies to identify the influence of cavity shapes on the restorative materials and the stress concentration in the restored tooth.[12-14]

The finite element assessment is an emerging technology, which is widely used for modeling and simulating the circumstances of dental treatment, the procedures engaged, and the impacts of posttreatment.[15] Cention N has shown comparable stress values as that of GIC in the cervical lesion.[16] As there are no studies in the literature comparing various cavity shapes and the stress distribution between GIC and Cention N, we hypothesized that there is no influence of the cavity shapes on the material choice for the restoration and the pattern of stress in the cervical area. Hence, the aim of this study was to understand the influence of various class V cavity shapes on mandibular premolars on stress concentration for amalgam, GIC, and Cention N under vertical and oblique occlusal loading.

Materials and Methods

Setting and design

This finite element analysis was performed over 6 months (June 2019 to December 2019) in the institutional computer-assisted designing (CAD) lab after obtaining the institutional ethics committee clearance (IEC number 881-2018).

FE model generation

The study used Digital Imaging and Communications in Medicine (DICOM) images obtained from cone beam computed tomography (CBCT) to generate a three-dimensional (3D) prototype of a mandibular premolar. The images in DICOM format were imported to 3D modeling software tool, SpaceClaim. The obtained file was converted to Initial Graphics Exchange Specification (IGES) format, and the model included All the layers of the tooth-enamel, dentin and cementum. The CAD software tool was used to refine the layout of internal contours, edges, and occlusal anatomy. The finite element (FE) analysis was performed in ANSYS Workbench version 19.0 (Swanson ANSYS, Houston, Pennsylvania).

Material properties

The mechanical properties of the considered materials for the analysis were assumed homogeneous, isotropic, and linearly elastic and are listed in Table 1. The cavities were tested with three distinctive restorative materials, namely amalgam, GIC, and Cention N, which have different bonding mechanisms to the tooth structure.

Preparation of the cavity

A cavity with a continuous cross section across the mesio-distal-occlusal wall was made with a depth of 1 mm axially such that, 0.5 mm of the cavity was in cementum. The occluso-gingival length was 1.5 mm and the mesio distal width was maintained at approximately 3 mm for the various cavity shapes.[3] Four distinct cavity forms, namely crescent, ovular ellipse, trapezium, and rectangular, were regarded to examine the impact of cavity form over stress concentration. These cavities were developed so that the cervical margins were symmetrical. The region of the cavities considered was therefore equivalent to the surface area of the cavities. To eliminate other factors, the surface area of cavities was taken into consideration and was kept equal. Further, the characteristics of each material were assigned.

Meshing

The CAD model was then exported to finite element analysis software ANSYS Workbench software, version 19, and subjected to medium meshing and was refined using body sizing feature with element size 0. 5 mm with tetrahedral elements. Figure 1 shows finite element meshed model of mandibular premolar tooth of different cavity shapes.

Table 1: Mechanical properties of the tooth and supporting structures used in the study

Materials	Modulus of elasticity (MPa)	Poisson's ratio(μ)	Reference
Enamel	84,100	0.33	[16]
Dentin	13,700	0.31	[16]
Cementum	18,600	0.31	[16]
Cention N	13,000	0.3	[16]
Glass ionomer	10,800	0.3	[16]
Amalgam	35,000	0.35	[16]

Boundary conditions

The load was applied on the occlusal surface of the tooth to simulate a mastication process. Two cases were considered; in the first case, the occlusal load was applied normally to the cuspal inclines, whereas in the second case, two loads were applied, one load acting normally to the cuspal inclines and the other load acting at an angle of 45° to the occlusal surface. The portion of the restorative material, inserted was regarded as fixed support. The four distinct load magnitudes of 100, 150, 200, and 250 N were applied as a pressure load perpendicular to the lingual plane of the lingual cusp of the occlusal surface (normal load) and at 45° to the same (oblique load).[17]

Mesh convergence test

The mesh convergence test plays a crucial role in determining the precision with computational reduction. The density of gross, medium, and fine mesh is considered for mesh convergence research. The study assesses and determines the effect of mesh quality on the results of simulation. All tooth layers were smoothened with adaptive size and varied the center of relevance to coarse, medium, and fine mesh with the maximum pressurized load of 250 N for trapezium-shaped cavity.[18]

Results

FE analysis

The mesh convergence test performed shows that the values of stress variation and deformation rates are approximately less than 2%–5% as shown in Table 2. The variation in the values of stress and total deformation were negligibly small when a mesh type of medium and fine was considered. The study was carried out with the medium mesh type with 55,037 nodes and 31,011 elements. In addition, an optimized mesh density test for the mesh convergence test in the cavity region took into account the element size of 0.5 mm.

Von Mises (VM) stress concentration and total deformation of the cavity were recorded for the different magnitude of loads, distinct cavities, and different restorative materials as shown in Table 3. In every model, the peak VM stress occurred at the force load sites, and the VM stress was spread from the loading point in an approximate actinomorphic pattern on the occlusal surface. The VM stress improved dramatically as the cavity margin approached the load points. In both cases of normal and combined (vertical plus oblique) loading, the stresses in the cavity with restorative material amalgam were highest, and that of GIC was minimal. The distribution of VM stress on class V restored cavity when a normal load and a combination of normal and oblique load were applied is shown in Figures 2 and 3, respectively, for the four models considered in the study.

The maximum and minimum stress values are compared with the vertical and oblique occlusal forces of enamel, dentin, and dental fillings of restored teeth

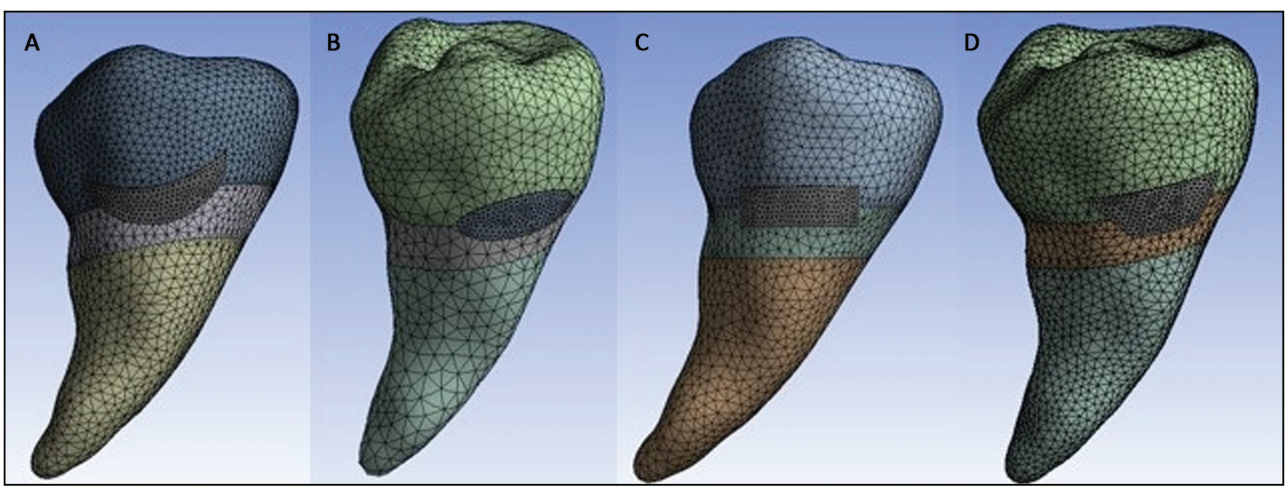

Figure 1: Finite element meshed model of mandibular premolar tooth. (A) Crescent. (B) Oval. (C) Rectangle. (D) Trapezium

Table 2: Mesh convergence study

Type	Nodes	Elements	von Mises stress (in MPa)		Total deformation (in mm)	
			Maximum	Minimum	Maximum	Minimum
Coarse	40,160	23,000	169.42	30.099	0.112	0.03501
Medium	55,037	31,011	160.3	29.79	0.11307	0.0358
Fine	79,453	45,153	160.35	30.315	0.11333	0.03603

Table 3: Distribution of von Mises stress for class V restored cavity

Shape	Material	von Mises stress (MPa)							
		Normal load				Normal + oblique load			
		100 N	150 N	200 N	250 N	100 N	150 N	200 N	250 N
Crescent	Cention	0.53	0.80	1.06	1.33	1.12	1.68	2.25	2.81
	Amalgam	0.86	1.29	1.73	2.16	2.60	3.90	5.20	6.50
	GIC	0.49	0.73	0.97	1.21	1.05	1.58	2.11	2.64
Oval	Cention	0.49	0.73	0.97	1.22	1.03	1.55	2.06	2.58
	Amalgam	0.98	1.47	1.96	2.45	1.77	2.66	3.55	4.43
	GIC	0.45	0.67	0.89	1.12	0.96	1.43	1.91	2.39
Trapezium	Cention	0.52	0.77	1.03	1.29	1.30	1.96	2.61	3.26
	Amalgam	1.09	1.63	2.17	2.72	2.66	3.99	5.32	6.65
	GIC	0.46	0.69	0.92	1.15	1.25	1.87	2.49	3.12
Rectangle	Cention	0.51	0.77	1.03	1.28	1.17	1.76	2.35	2.94
	Amalgam	0.91	1.37	1.83	2.28	2.59	3.89	5.19	6.49
	GIC	0.47	0.70	0.93	1.17	1.11	1.66	2.21	2.76

GIC = glass ionomer cement

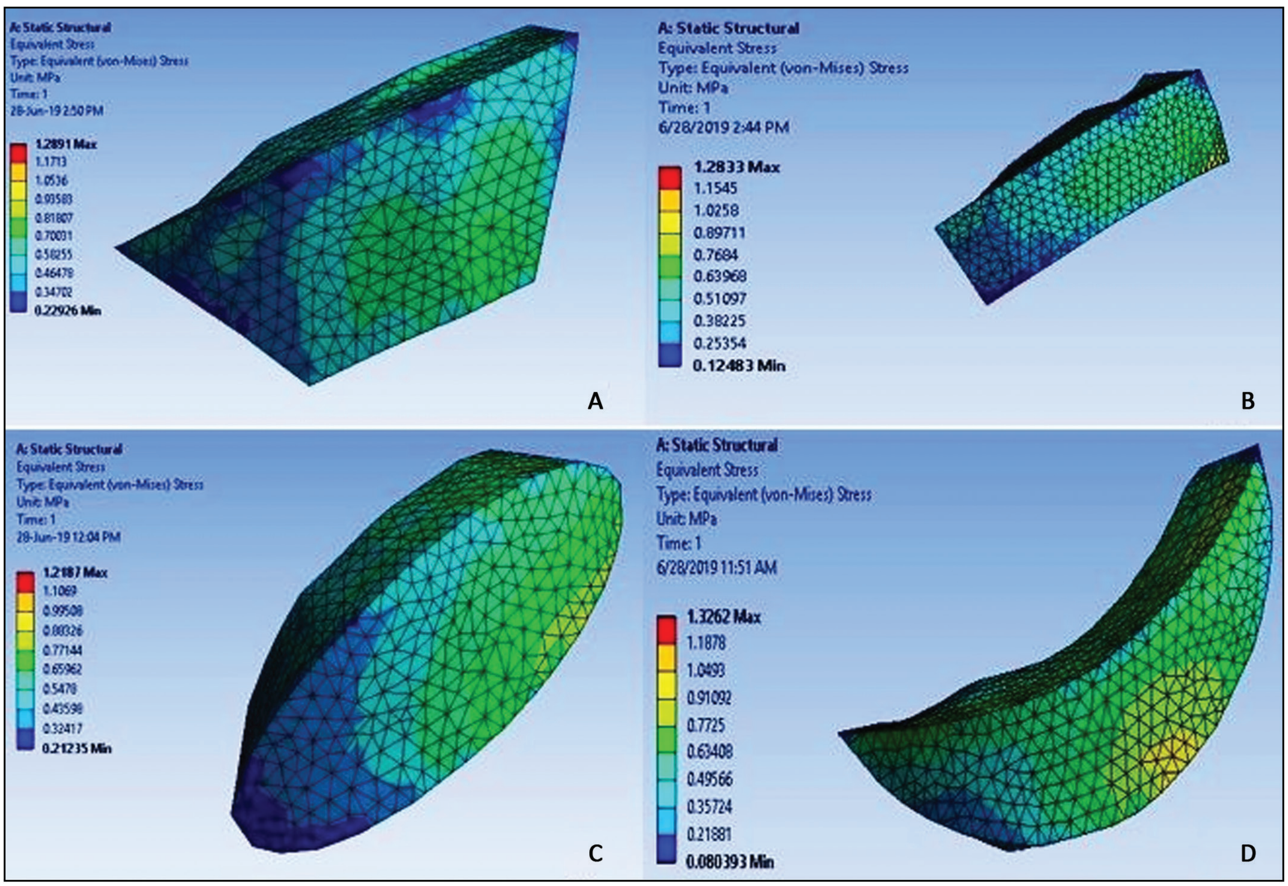

Figure 2: The distribution of von Mises stress on the class V restored cavity for a normal load of 250 N. (A) Trapezium. (B) Rectangle. (C) Oval. (D) Crescent

with different materials with different cavity shapes. The total deformation is observed in the restored cavity region to decide on the retention of the restorative material for the longer duration for enhanced life.

Discussion

Cervical lesions are prevalent, and dentists find their treatment a significant challenge due to the place at which these lesions are present. Long-term success is therefore difficult to achieve. This study used FEM

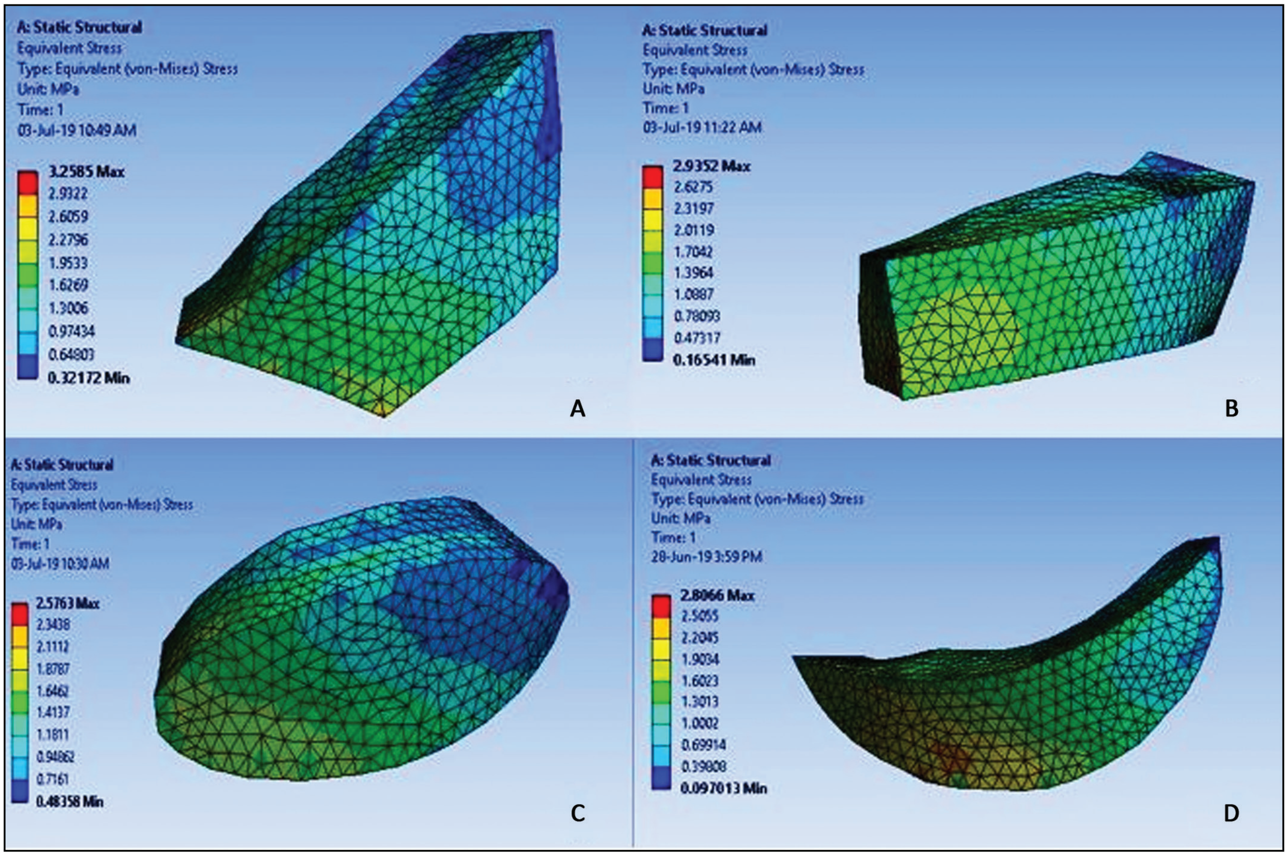

Figure 3: The distribution of von Mises stress on class V restored cavity for a combined (normal and oblique) load of 250 N. (A) Trapezium. (B) Rectangle. (C) Oval. (D) Crescent

to analyze this problem, as it is an appropriate way to perform clear and objective biological systems monitoring.[15] The effect of different cavity shapes and restoration materials, in terms of possible changes at the restorative material–tooth interface, was studied. The results indicated that both restorative material and cavity shape influence the stress concentration around the cervical region. Cavities having large cavosurface angle tend to have a low concentration of stress, which are confirmed by finite element analysis of axis symmetric models.[19] As class V cavities are mainly present at the fixed end/fulcrum point of the tooth, they tend to fail due to flexural stress.[20]

In this study, the VM stress values increased when the loads were increased. It was seen to be higher in the oblique loading as compared with the normal occlusal loading. The least amount of stress was seen in oval-shaped cavity, restored with GIC, and the highest was seen in trapezoidal cavity restored with amalgam. The ovoid-shaped cavity showed the least stress values with all the three restorative materials. This is in agreement with a similar study by Ziemiecki *et al.*[19] who suggested that deep notch-shaped lesions were less effective in retaining adhesive restorations than shallow saucer-shaped lesions, and attributed to the fact that shapes having sharper edges tend to have high stress concentration. A wedge-shaped cavity with a shorter occlusal wall, restored with giomers and adhesive, with a tensile strength exceeding 25 MPa has been suggested by a FEM study.[21] Turning a wedge-shaped cavity into a wedge-shaped cavity with a shorter occlusal wall (a minimally invasive maneuver in comparison with creating a round-shaped cavity), and restoration with giomers can increase the retention of the restoration.[22] It has been determined that the thickness of dentin around the cavity plays a significant role in stress and strain distribution.[23] However, in this study, the surface area of all the shapes was kept constant and only the shapes were altered. Therefore, the shape of the cavity is a determining factor for stress distribution. GIC and Cention N bond to the tooth structure unlike amalgam. These two materials have shown comparable stress distribution. Cention N is a new dental material, which is an Alkasite consisting of a special patented filler (Isofiller), which acts as a shrinkage stress reliever. When the material polymerizes, there is a cross-linking between the monomer chains located on the fillers and the silanes.[7] These forces between the individual fillers come into play, which place stress on the cavity walls.

The failure of cervical restorations has been reported to be higher in materials having high Young's modulus, and in mandibular teeth.[24,25] Amalgam with the highest modulus of elasticity has shown higher stress value. Stress concentration can be further reduced by establishing a well-defined finish line or chamfer line along the cervical edge of the defects.[26] Further, in this study, total deformation of all three tested materials was less in oval design at increasing load in normal and oblique direction. It has been suggested that to reduce stress, use of more compliant restorative materials, that is, flexible materials, such as GIC, flowable composites, or nano-filled adhesives, under resin dental filling materials, could be helpful.[27]

On the basis of this FEM simulation, clinically, it can be implied that an ovoid preparation in the cervical area with a chemically bonded restorative material has lesser stress distribution and deformation. Hence, the null hypothesis was rejected. More investigations are needed to understand what may be the optimal cavity shape, which reduces crack failure risks, and optimization procedures could be integrated in the proposed CAD–FEM approach. There is a scope for further clinical trials for the comparison of the retention rate of GIC and Cention N.

Conclusion

The following conclusions were derived from this study:

1. Oblique occlusal load showed more stress as compared with normal occlusal with an increase in magnitude.
2. Trapezoid cavity filled with amalgam showed the highest stress concentration but produced relatively less deformation of the cavity for the same amount of load.
3. Ovoid-shaped cavity showed less stress concentration and deformation, compared to all the other shapes under consideration.
4. Minimum stress was observed in GIC, and the results are comparable with that of Cention N.

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Nil.

Conflicts of interest

There are no conflicts of interest.

Author contributions

Not Applicable.

Ethical policy and institutional review board statement

This study was approved by the institutional ethics committee, IEC No. 883–2018, dated December 11, 2018. All the procedures have been performed as per the ethical guidelines laid down by the Declaration of Helsinki (2013).

Patient declaration of consent

Not Applicable.

Data availability statement

Not Applicable.

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