Finite element analysis of thermal stress distribution in different restorative materials used in class V cavities

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Abstract

Purpose: Cervical lesions are restored with class V preparation. The aim of this study was to use a three-dimensional finite element method to carry out a thermal analysis of the temperature and stress distributions of three different restorative materials used for class V cavities of maxillary molar teeth.
Materials and Methods: A maxillary left first molar tooth was modeled and a class V cavity was prepared on the cervical 1/3 of the buccal surface. This cavity was restored with three different materials (Group I: Resin composite, Group II: Glass ionomer cement, and Group III: Amalgam). Loads of 400 N were applied at an angle of 90° to the longitudinal axis of the tooth on the restorative material at 5 and 55°C temperatures. Von Mises and thermal stress distributions were evaluated.
Results: In all groups, the von Mises stress values increased with temperature. The highest von Mises stress distribution was observed at 55°C in Group II (144.53 MPa). The lowest von Mises stress distribution was observed at 5°C in Group III (70.81 MPa).
Conclusion: Amalgam is the most suitable restorative material for class V restorations because of minimal stress distribution.

Key words: Amalgam, finite element method, glass ionomer cement, resin composite, thermal stress

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Introduction

In restorative dentistry, the preferred method of treatment for cervical lesions usually involves the preparation of class V cavities. Class V restoration is the preferred method for restoring cavities on the lingual and/or buccal surfaces in the gingival third of all teeth. Early loss of material from cervical defects frequently occurs.[1,2] Cervical lesions are common worldwide and they can be challenging for dentists; it is expected that their prevalence will increase as the population ages. The incidence of the class V lesions that are noncarious in nature is 31–58%. The main difficulty in restorative treatment of these lesions stems from their locations, which can make it more difficult to achieve durable and stable restoration.[3]

Amalgam, resin composites, and glass ionomer cement are usually used to fill the cavity.[4] However, these materials present certain drawbacks: Thermal stress and temperature fluctuations can cause contraction and expansion within the cavity; thermal fluctuation occurs in the cavity after the consumption of hot or cold liquids. The cavity environment can be exposed to thermal fluctuations between 0°C and 67°C. These rapid fluctuations create thermal stress, not only on the tooth but also on the

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material used.[5] The amount of thermal stress that occurs in the restored tooth will depend on the properties of the materials, as well as the techniques and design of the cavity, since these can impact on the adhesive resistance between the material and the tooth surface. During the consumption of the cold liquid, tensile stress is observed on the amalgam material while compression occurs in the resin composite. When a hot liquid is consumed, the opposite effect occurs, with tensile stress on the composite but compression on the amalgam.[6] Much research has focused on stress distribution in the restorative material used in class V cavities under variable occlusal forces and thermal changes.[1,6,7] However, an investigation into thermal stress distribution at the interface between the tooth surface and the restorative material has been very limited.

Finite element analysis (FEA) has been used widely in dental applications for force analysis and assessment of different materials, especially in the restorative domain.[8] In FEA, three-dimensional (3D) imaging and mapping of the tooth topology is done by approximating the tooth geometry using a finite number of points. Stresses, compressions, and strains are then calculated firstly for each of these points individually and then for the elemental body as a whole.[9]

The aim of this study is to use the 3D finite element method to carry out a thermal analysis of the temperature and stress distributions in three different restorative materials at the interface between the restorative material and the tooth in a class V cavity of a maxillary molar tooth.

Materials and Methods

The thermal stress distribution at the interface between the tooth surface and the restorative material in class V cavity of human maxillary left first molar teeth has not been reported in any previously published study. Therefore, the human maxillary left first molar tooth was modeled in this study. A class V cavity was prepared on the cervical 1/3 of the buccal surface of the tooth.

Digital modeling of the tooth

An extracted human maxillary left first molar tooth with a fully formed roots and absence of cracks, fractures, and caries was used as the basis of a 3D tooth model. A 0.5 mm cross-sectional images of the tooth were acquired using a spiral computed tomography (CT) scanner (Aquillion 16, Toshiba, Tokyo, Japan). The contours of the enamel, dentine, and pulp boundaries were determined based on the CT images. These sections were obtained in digital imaging and communication in medicine format and the data were input into the computer. Using the software Materialize' Interactive Medical Image Control System (Mimics 9.0; Materialise, Leuven, Belgium) and SolidWorks (Solidworks Corporation, USA), these cross-sections were converted into a 3D model [Figure 1]. The model was exported to ANSYS 13 Workbench software (Swanson ANSYS Inc., Houston, PA, USA).

Meshing

A mesh was obtained automatically using the ANSYS 13 Workbench software [Figure 2]. The mesh contained 72,621 elements and 104,665 nodes.

Preparation of the cavity

The cavity was excavated in the computer model. A class V cavity measuring 2.5 mm gingivo-occlusally, 3 mm mesio-distally, and 2 mm in depth was held constant, with the occlusal margin in the enamel and the gingival margin in the dentine. The internal line angles of the cavity were rounded to prevent any concentration of stress [Figure 3].

Load

After meshing and cavity preparation, the cavity was restored in the computer model according to the mechanical and thermal properties of the tooth and restorative materials. The mechanical and thermal properties of the tooth and the restorative materials are given in Table 1.[6,10] The cavity was restored with three different restorative materials and these were assigned to three groups:

- Group I - Restored with a resin composite;
- Group II - Restored with a glass ionomer cement;
- Group III - Restored with an amalgam.

Simulating the environmental temperature in the mouth, an initial temperature of 36.5°C was applied as the base temperature [Figure 4a]. Loads of 400 N at an angle of 90° were then applied on the restorative material in the longitudinal axis of the tooth at temperatures of 5 or 55°C [Figure 4b and c]. The stress distribution was analyzed using ANSYS 13 Workbench software. The calculation of the von Mises stress distribution was read at the tooth restorative material interface.

Results

The von Mises stresses in each of the models were studied. Table 2 represents the maximum von Mises stress values

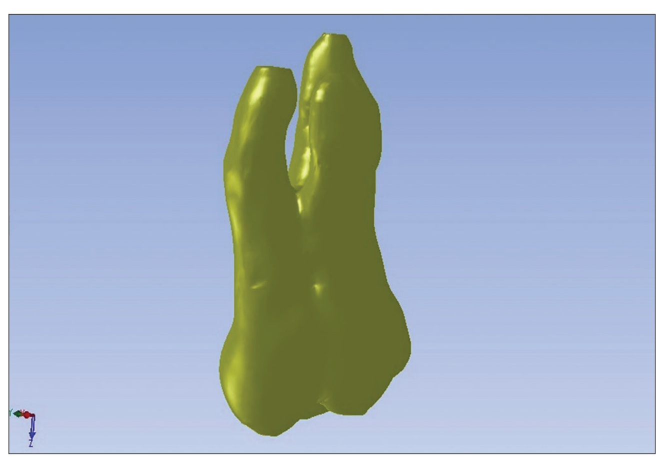

Figure 1: Three-dimensional model

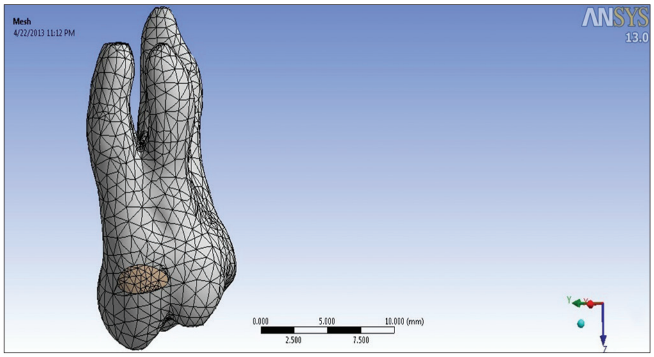

Figure 2: The meshed model

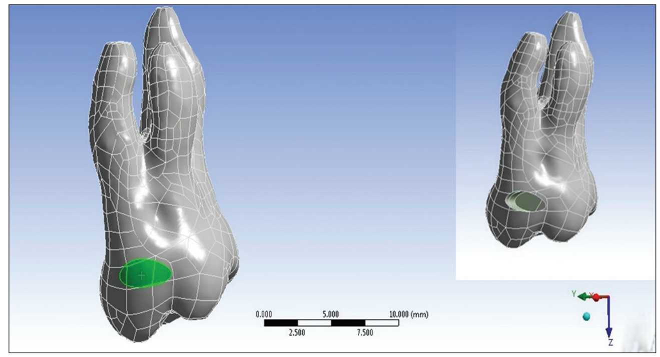

Figure 3: The preparation of class V cavity

Table 1: The mechanical and thermal properties of the tooth and the restorative materials used in this study

Materials	Modulus of elasticity (GPa)	Poisson's ratio	Spesific heat (J/kg °C)	Thermal expansion coefficient (1/°C)	Thermal conductivity (W/m °C)	Density (kg/m³)
Enamel	80	0.33	750	11×10^{-6}	0.84	2800
Dentine	20	0.31	1302	11.4×10^{-6}	0.63	2000
Pulp	0.003	0.45	4200	180.1×10^{-6}	0.0418	1000
Resin composite	15	0.24	820	34×10^{-6}	1.26	2000
Glass ionomer	10.8	0.30	1177	35×10^{-6}	0.615	2100
Amalgam	35	0.35	240	25×10^{-6}	23.1	10500

Table 2: von Mises stress values of study groups

Study groups	von mises stress values (Mpa)	
	5 °C	55 °C
Group I: Resin composite	82.64	126.45
Group II: Glass ionomer cement	94.46	144.53
Group III: Amalgam	70.81	108.37

recorded for the 3D tooth models prepared with the three different restorative materials at 5 or 55°C temperatures. Figure 5 represents the von Mises stress distribution of the three groups. In all groups, the von Mises stress values increase as the temperature rises to 55°C. The highest von Mises stress value (144.53 MPa) was recorded at 55°C in Group II (glass ionomer cement); the lowest von Mises stress value (70.81 MPa) was recorded at 5°C in Group III (amalgam).

Discussion

This study investigated the effect of thermal changes on the interface between the tooth and various restorative materials that are known to be recommended or used for class V cavity applications. The consequences of using different cavity techniques and restoration materials, in terms of possible changes at the restorative material-tooth interface, were studied in detail.

The tooth is exposed to different environmental conditions varying in temperature, acidity, and mechanical load. Our study mainly focused on stress and thermal analysis of a restored tooth under 400 N occlusal load and different thermal conditions, using FEA to construct a 3D model of a tooth and calculate the stresses and thermal fields present. A number of factors affect the spatial arrangement of the material, such as the flow conditions of the liquid used over the restorative material and/or the thermal changes. These two factors can either work in a coherent manner or in disharmony.[11]

Conventional methods such as thermal mechanical analysis and FEA have previously been used for investigating the thermal properties of restorative materials and dimensional changes in the restorative materials have been studied.[11] With advances in software technology and modeling methods, FEA has become a very solid tool for biomechanical applications due to its reliability and accuracy. Dentistry also makes use of FEA techniques especially for cases in which the experimental approach does not provide enough information.[12] Simulation of the studied environment under different loads and conditions can shed light into real world examples that would otherwise be impossible to image, observe, and calculate. It can give good and accurate information about the stress field even for nonuniform structures. FEA can easily analyze and extract the required information from a proper computerized design, which in turn saves time and expense by decreasing the number of the test subjects needed for real world experiments. With advances in technology, computer systems, and software, FEA has become an invaluable tool for biomedical research. However, it has certain drawbacks: Data must be input by a user, so it is prone to user mistakes; it takes a lot of time to carry out complex calculations; and

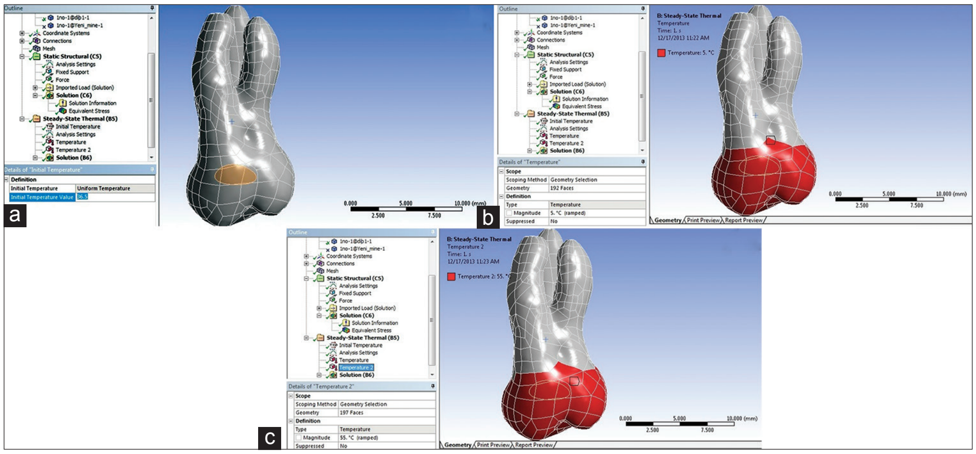

Figure 4: (a) The base temperature (36.5°C). (b) First thermal load (5°C). (c) Second thermal load (55°C)

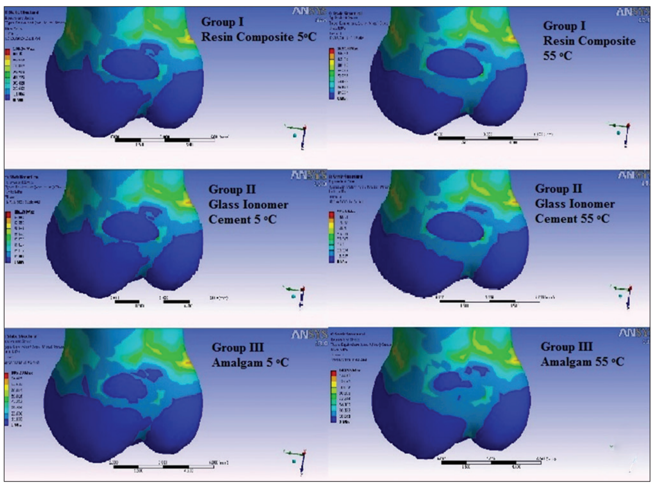

Figure 5: The distribution of von Mises stress according to groups

the capability of the system determines the reliability and accuracy of the analysis.[12-14]

Poor outcomes of class V restorations have been explained by Heymann *et al*.'s theory of tooth flexure.[15] According to this theory, there are two mechanisms of restoration failure: Either tensile stress on the interface, which is the result of the lateral excursive movement due to lateral cuspal movement, or distracting shear and compressive stress on the interface, which is borne by vertical deformation of the tooth (also known as barreling ZX), caused by strong forces on the centric occlusion.[15] Here we found that the thermal changes that occur in the oral cavity can produce stress at the tooth restoration material interface. As such we propose that this third mechanism should also be included.

In their research using FEA, Toparli *et al*.[6] found that composite resin shows better behavior than amalgam when cold liquid (15°C) is used. On the contrary, amalgam is more satisfactory when hot liquid (60°C) is used.[6] However, we found that the lowest von Mises stress was at the tooth-amalgam restorative interface at both 5°C and 55°C temperature. The results of our study are not in agreement with those of Toparli *et al*. This difference may be related to different experimental condition of our study.

Narayanaswamy *et al*.[4] used FEA to compare glass ionomer cement with flowable and microfilled composites under different occlusal loads and found that glass ionomer had the higher stress value. In our work, the stress at the interface between the tooth and the restorative material was evaluated under constant force and thermal variables. We can conclude that the positive overlap of these two research findings suggests that stress that occurs in the restorative material is also reflected in the tooth material interface.

Conclusion

It was found that when thermal changes at the tooth material interface are taken into consideration, the minimum stress and maximum stress were observed in amalgam and glass ionomer cement, respectively. This possible reason may be related to different mechanical and thermal properties of restorative materials.

As a result, to minimum stress in the restorative material and reduce the risk of loss of material, amalgam could be used in class V cavities. Further *in vivo* and *in vitro* studies are required to confirm the findings obtained herein.

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