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Application of Finite Element Method for Thermal Analysis of Esthetic Restorative Materials in Dentistry

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***ABSTRACT:** In this study, the temperature distribution and heat flow patterns of two different restorative dental materials using light-polymerization process are analyzed and compared. An effort is made to demonstrate the application of Finite Element Method (FEM) for thermal analysis in dentistry. Esthetic materials such as composite resin and ceramics are becoming more popular in dentistry due mainly to the esthetic restorations. These materials are exposed to a heat source generated by light-polymerizing equipments and are expected to be polymerized in a short time. The factors effecting the polymerization are the intensity and duration of polymerizing light as well as the thermal characteristics of the materials under consideration. In the present study, mathematical model of bucco-lingual section geometry of the first lower premolar tooth with two different restoration materials are considered to evaluate the FEM results. The results obtained from both FEM and in-vitro measurements are presented and compared. It is shown that FEM offers reliable results so that knowing thermal characteristics of new materials may suffice to determine the duration of polymerizing light.*

Key words: **Finite element analysis, composite resin, ceramic, temperature distribution, light polymerization unit.**

I. INTRODUCTION

In current dentistry practice, composite resins and ceramic restorative materials are widely used especially in esthetic applications due primarily to their low thermal conductivity *(k)*. In parallel to the recent developments and diversification of dental materials, the cementation process came in to prominence. As the use of light polymerizing composite resin cements has expanded over recent years, different light polymerization units (LPUs) are being employed for the process of cementation of esthetic restorative materials. In order to accomplish a successful polymerization, light polymerization units (LPU) should have good specific qualifications such as adequate light intensity, proper wavelength and sufficient polymerization period. The use of high intensity light sources shortens the polymerization time. However, employing such light sources may cause pulp damage due to the infliction of high temperature during the restoration. However, in the intraoral environment, there are many components affecting the distribution of the heat that may arise during the luting procedure with LPUs. Restorative material selected, type of the restoration are also among these as well as the specifications of the LPU used for the procedure.

Heat transfer through solid substances most commonly occurs by means of conduction. Thermal conductivity (k) is a thermo physical measure of how well heat is transferred through a material by conductive flow. Dental restorative materials such as porcelains and composites are known as having low thermal conductivity (Phillips). However, the protection degree of the underlying vital tissues during heat generation intraorally is obscure when these materials are considered. The Finite Element Method (FEM) has been widely used in dental research. The use 2-D and 3-D Finite Element Analysis (FEA) in investigating the mechanical behavior of a maxillary premolar restored with a complete crown is dependent on many interrelated factors. It is concluded that for a single tooth unit, 2-D FEA is helpful for investigating key aspects of a dental restoration while 3-D FEA may offer the better understanding for complex dental structures and tooth units. Although 3-D FE models better represent the complex dental structures of the restored tooth units, 2-D FEM offers high mesh refinement and can predict the inhomogeneity of a structure and may find application in investigating the mechanical and thermal behavior of a dental restoration in a single tooth unit. A 2-D and 3-D FEM can also be used to solve a thermal stress analysis problem because the heat flow starts from the outer surface of the crown and moves toward the center, so the pattern of heat flow and stress generation by temperature gradient will be similar in 2- and 3-D models. In this study, the outcomes of in vitro thermal measurements for composite resin and porcelain dental materials while using LPUs for polymerization process are compared with the FEM results for the same experimental setup and coherencies as well as deviations between the two are discussed.

II. MATERIAL AND METHODS

This study is composed of two parts to offer a complete thermal analysis of restorative materials. First part covers an in-vitro experiment where two restorative materials are tested by exposing to the LPU. The second part is to conduct the thermal analysis on cross section geometry of a restored tooth with Finite Element Method using the same materials.

In vitro test

In the present study, the ceramic (Empress II, Ivoclar-Vivadent, Schaan, Liechtenstein) and the composite resin restorative dental material (Synergy; Coltene, Whaledent, Switzerland) are used for the experiments. A 15ea separate discs having the diameter and thickness of 5mm and 2mm respectively are prepared for the each material to be tested. The samples are not over glazed or polished. Hilux 250 (First Medica) QTH light polymerization device is used as the light polymerization unit (see Table 1).

Table-1: Light Polymerization Unit specifications

Light-polymerization Unit (Manufacturer)	Wave Length (nm)	Maximum Light Output (Mw/cm^2)	Time of Exposure (s)
Quartz-Tungsten Halogen LPU *(Hilux 250;First Medica,Greensboro, USA)*	400-515	600-800	40

The samples are fixed stable as to leave upper and lower surfaces free as shown in Fig.1. A K-type thermocouples are connected to the both surfaces of the disk while the upper surface is exposed to the LPU. The thermocouple is cold junction compensated and connected to a sensitive voltmeter. For each and every disk, temperature data is recorded for 40seconds. This experimental setup allowed us to record the temperatures of both ends of the disks.

In analyzing the data, independent t test was used in comparison of groups. Assessments were made based on the 95% confidence interval and by recognizing $p<0.05$ as significant.

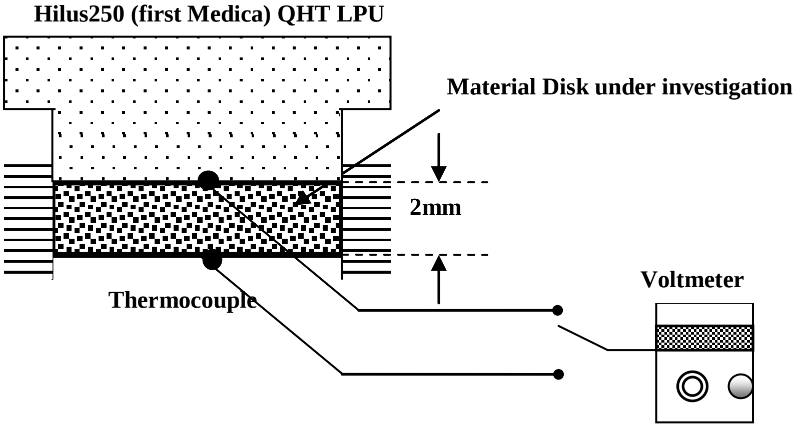

Fig 1: In-vitro experimental setup.

Finite Element Method

Mathematical modeling of buccolingual cross section geometry of restored first lower premolar tooth is considered as shown in Fig.2. Porcelain and composite resin restorative restoration materials are considered for the study. The model is divided into various segments including restoration, cement, dentin and pulp sections. Thermal properties of each section are separately considered as boundaries of thermal conduction. Thermal properties and heat transfer coefficients of restorative materials, dentin and pulp are given in Table 2.

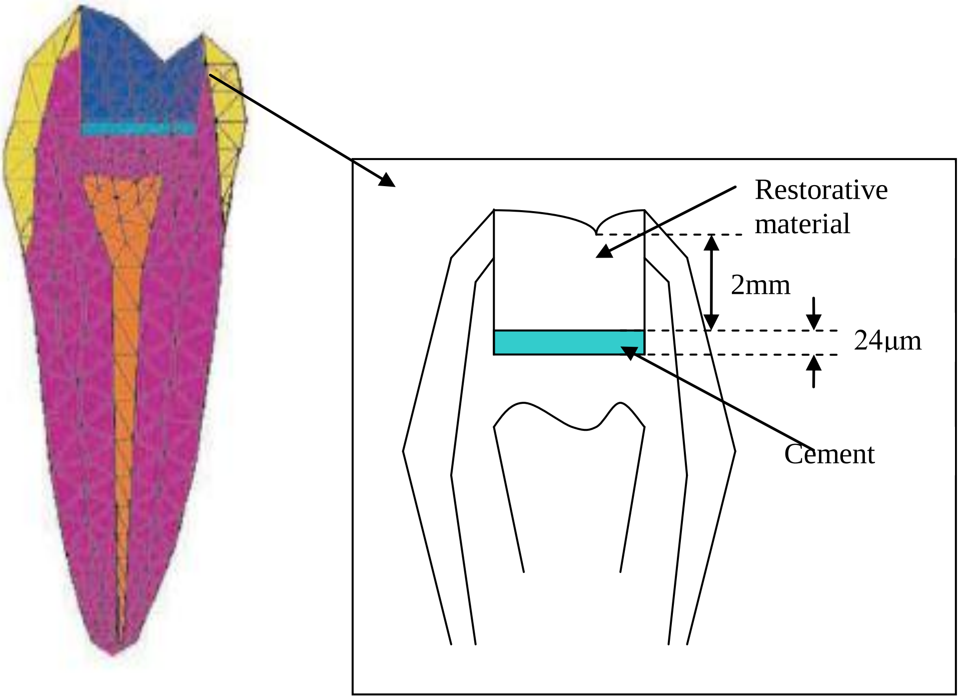

Fig 2: Finite Element Model and restoration-cement details

Table.2 Thermal properties and heat transfer coefficient of modeled materials

Material	Thermal Expansion Coefficient $(1/{}^{0}C)$	Thermal Conductivity $(Cal/mm^{-1}s^{-1}\,{}^{0}C)$	Density *Specific Heat $(Cal/mm^{-3}\,{}^{0}C)$
Porcelain	$13.1\text{x}10^{-6}$	$0.250\text{x}10^{-3}$	$0.754\text{x}10^{-3}$
Composite Resin	$39.4\text{x}10^{-6}$	$0.258\text{x}10^{-3}$	$0.470\text{x}10^{-3}$
Dentin	$11.4\text{x}10^{-6}$	$0.150\text{x}10^{-3}$	$0.588\text{x}10^{-3}$
Pulp	$180\text{x}10^{-6}$	$1.599\text{x}10^{-4}$	$0.238\text{x}10^{-3}$

A 2-dimensional FEM (FlexPDE 4.2; PDE Solutions Inc, Sunol, Calif) software is used to determine the temperature distribution in time. The FEM model divided into 327 cells and 700 nodal points. The temperature values are measured at the surface of the 2 different sections: restoration surface (a), cement surface (b).In applying the FEM, the physical problem is formulated through the use of a 2-dimensional and time-dependent heat conduction equation,

$$\rho c\frac{\partial T(x,y,t)}{\partial t}=k\left(\frac{\partial^2 T(x,y,t)}{\partial x^2}+\frac{\partial^2 T(x,y,t)}{\partial y^2}\right) \qquad (1)$$

where ρ is the density, c is the specific heat and k is the thermal conductivity (literature).

III. RESULTS AND DISCUSSION

In vitro test results

The temperatures measured at the lower side of the ceramic and composite resin restorative materials are shown in Table 3. The temperature differences between upper and lower side of the materials are given in Table 4. According to the results of the in vitro test, while the temperature of the cement surface of the composite material was 45.99 ^{o}C (±3.39 ^{o}C) at the first 10 seconds following the activation of the LPU, it reached up to 75.08 ^{o}C (±7.58) at the end of 40 seconds. Similarly, while the temperature of the cement surface of the ceramic material was 47.57 ^{o}C (±0.68 ^{o}C) at the first 10 seconds following activation of the LPU, it reached up to 64.03 °C (±2.20) at the end of 40 seconds. While the statistical evaluation revealed no significant difference in terms of temperature increase on material surface within the first 10 seconds ($p>0.05$), a highly significant temperature change was determined on surface of the composite material at the end of 40 seconds compared to ceramic material ($p<0.0001$). Also temperature differences evaluated between the upper and the lower side of the materials (Table 4) showed that the heat conduction was significantly lower in porcelain than in composite resin.

Table3: Temperatures at the lower end of the materials

Time (s)	Composite(°C)	Porcelain(°C)	t	p
10	45,99±3,39	47,57±0,68	-1,77	>0,05
20	59,11±5,46	54,53±1,24	3,16	<0,01
30	68,28±6,70	59,65±1,34	4,89	<0,0001
40	75,08±7,58	64,03±2,20	5,42	<0,0001

Table 4: Temperature difference between upper and lower ends of the materials

Time (s)	Composite(°C)	Porcelain(°C)	t	p
10	11,59±4,97	20,14±7,01	3,85	<0,0001
20	13,93±5,11	20,30±7,40	2,74	<0,01
30	14,61±3,45	19,59±8,62	2,08	<0,05
40	14,15±3,89	19,97±9,68	2,16	<0,05

Finite Element Analysis Results

Results are obtained using thermal conductivity equation (Eq.1) and two dimentional FlexPDE 4.2 PDE Solutions Inc., Finite Element Software package. $T(x,y,t)$ is the temperature of the heat conducting medium and depends on both the time and space variables x and y. The initial condition was $T(x,0) = 35.2°C$. At the occlusal surface of the tooth, a constant heat flux q (W/ m2) boundary condition was applied. Overall, external boundaries were assumed to be at a constant temperature of 37°C. The model was divided into 4 separate sections: crown, cement, dentin, and pulp. The material properties ρ, c, and k were assumed to be independent of both dependent and independent variables (temperature, time, and space variables).

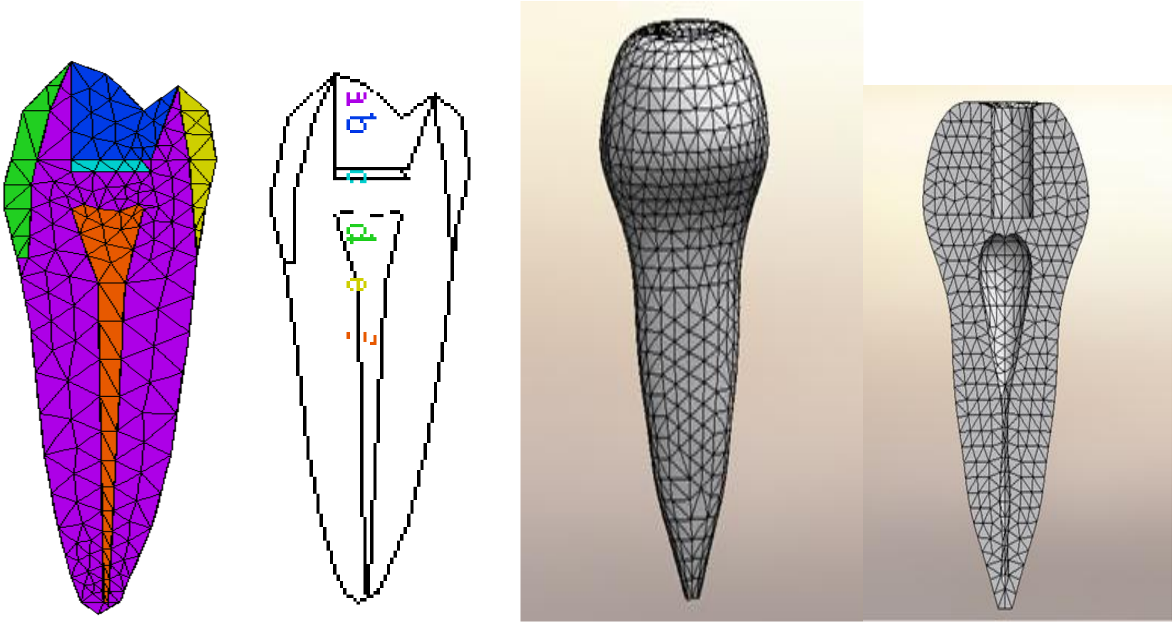

Fig 3: 2D and 3D FEM models and reference points (nodes) indicating the thermal measurements

Time-related heat distribution and thermal conductivity determined by finite element analysis on the pre-defined points of composite and resin restoration materials on the tooth model are shown in Figure 4 and 5. According to those results, the simulation in which composite restoration had been cemented; the temperature reached 60°C in the first 10 sec. and went over 78 °C at the end of 40 secs, whereas it reached 72 °C on the cement surface (b) of the restoration. The temperature on the surface of ceramic restoration (a) reached to 50 °C in the first 10 sec. and exceeded 66 °C at the end of 40 secs. On cement surface (b) of the restoration, heat reached 60 °C at the end of 40 secs.

For porcelain restorative material, temperature values at node a increased during the first 10 seconds up to 40°C and reached 50°C in 40 seconds. Also at node b temperature increased to 38.5°C during the first 10 seconds and 47°C for the following 40 seconds. The values obtained from analysis employing finite element method, showed consistency with the results of in vitro test.

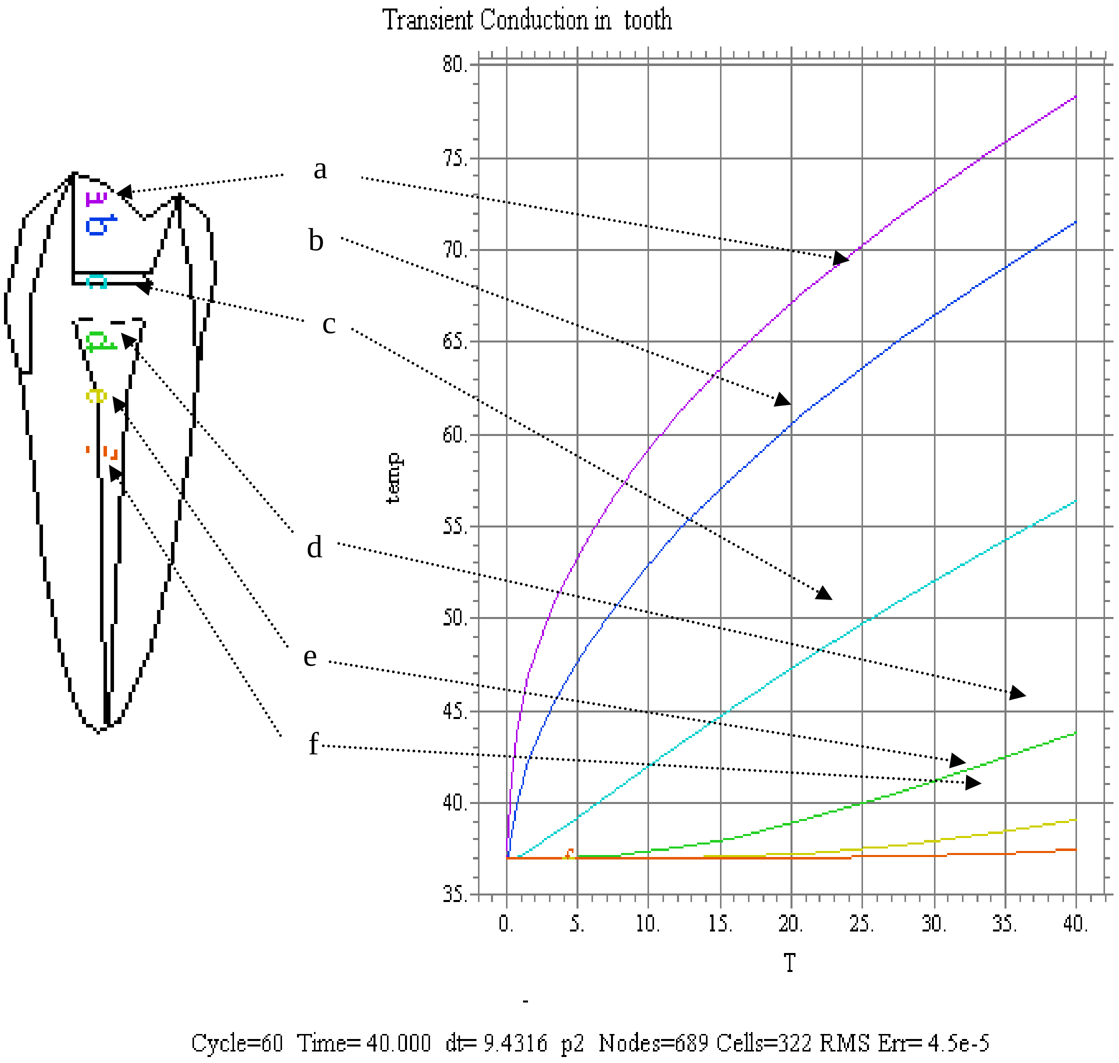

Fig 4: Temperature response of the reference points using FEM including composite material

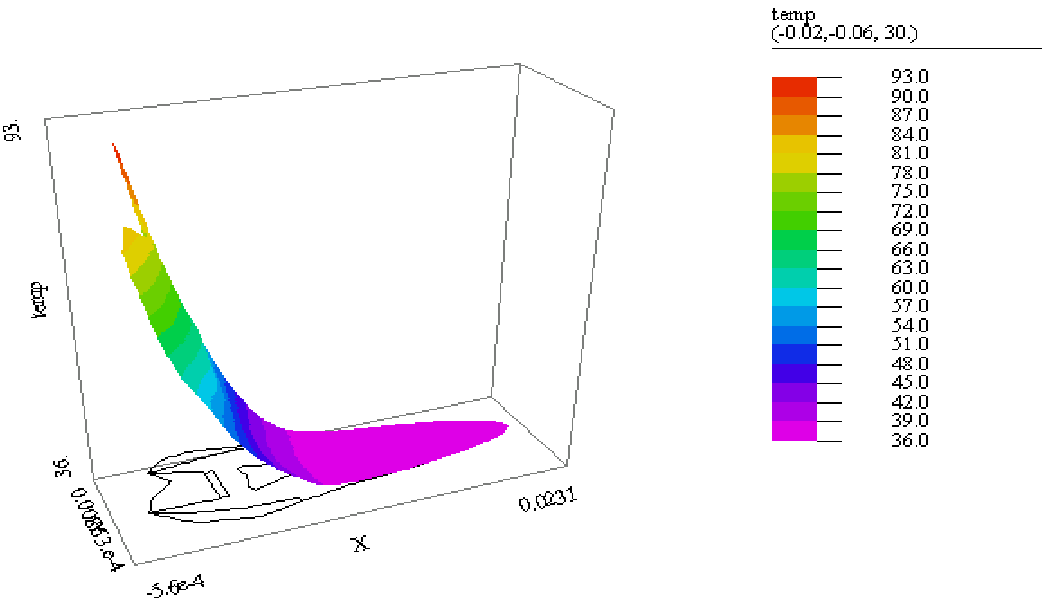

Fig 5: Final temperature values in tooth at the end of 40s. Composite restoration material in use.

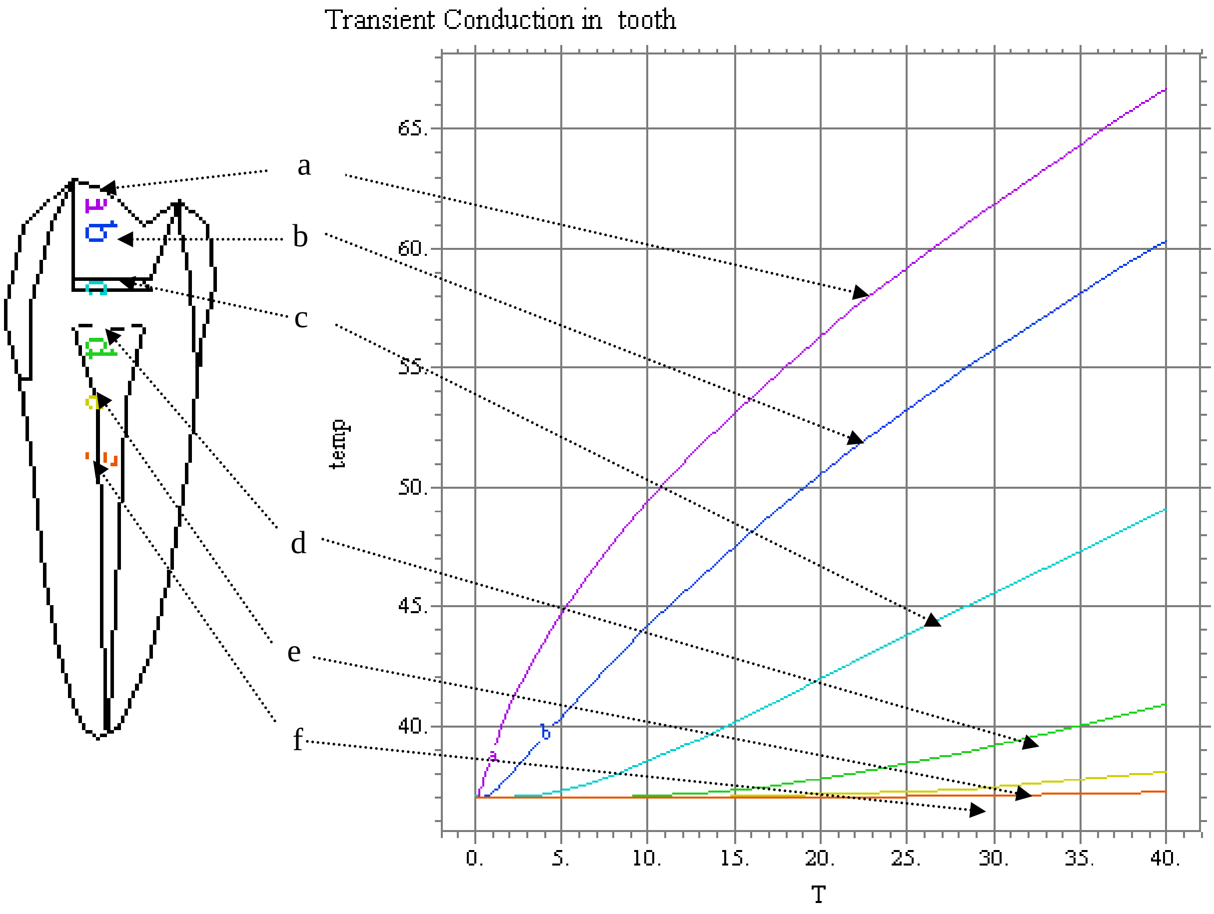

Fig 6: Temperature response of the reference points using FEM including ceramic material

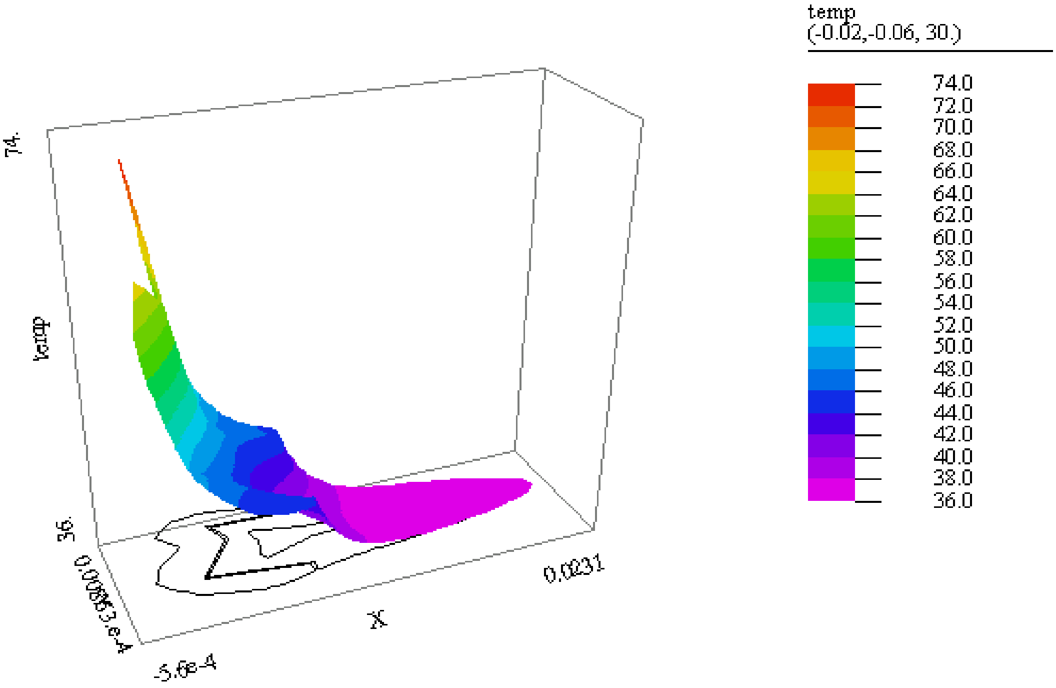

Fig 7: Final temperature values in tooth at the end of 40s. Ceramic restoration material in use.

The mathematical modeling applied by finite element method, is an effective way for solving mechanical and thermal problems of restored teeth (17,18). The investigators verified the safety of this method by comparing it with the in vivo results (19). In the present study, the analysis results obtained by employing finite element method, showed similarity with in vitro study results. However, values of finite element analysis were found to be lower than those of the in vitro study. The failure to reflect environmental conditions which are supposed to encircle the restorative material during in vitro tests, may be the underlying reason for this difference. Heat flow advances from crown surface towards central area, therefore, because the heat flow and the stress associated with temperature will be similar in 2D and 3D models (26), employing 2D modelling in our study was thought to be appropriate. Since high intensity polymerization devices have the power of big energy output, despite reducing the required time for polymerization, they may lead to considerable heat increases on the surface they are applied to (8,9). In the present study, applied QTH light source was observed to cause significant heat changes both in finite element analysis and in the in vitro study results.

IV. RESULTS AND DISCUSSION

Time-related heat distribution and thermal conductivity determined by finite element analysis on defined points of composite and resin restoration materials and tooth, are shown in Figure 4 and 5. According to those results, the simulation in which composite restoration had been cemented, the temperature reached 60°C in the first 10 secs and went over 78 °C at the end of 40 secs, whereas it reached 72 °C on the cement surface (b) of the restoration. The temperature on the surface of ceramic restoration (a) reached to 50 °C in the first 10 secs and exceeded 66 °C at the end of 40 secs. On cement surface (b) of the restoration, heat reached 60 °C at the end of 40 secs. According to the results of the in vitro test, while the temperature of the cement surface of the composite material was 45.99 °C (±3.39 °C) in the first 10 secs following activation of the light device, it reached 75.08 °C (±7.58) at the end of 40 secs. Similarly, while the temperature of the cement surface of the ceramic material was 47.57 °C (±0.68 °C) in the first 10 secs following activation of the light device, it reached 64.03 °C (±2.20) at the end of 40 secs. While the statistical evaluation revealed no significant difference in terms of temperature increase on material surface within the first 10 secs ($p>0.05$), a highly significant temperature change was determined on surface of the composite material at the end of 40 secs compared to ceramic material ($p<0.0001$). The values obtained from analyses employing finite element method, showed consistency with the results of in vitro test. Nonmetals display a weaker thermal conductivity than metals. Although heat transfer coefficients of composite resin and ceramic restorative materials are close to each other, composite resin has a higher heat transfer coefficient (1,4-7). In vitro test results showed a considerably significant difference between composite resin restorative material and ceramic restorative material in terms of heat transfer ($p<0.0001$). Heat rise is a complicated problem in which many components play a role (22,23). While the reason behind heat rise in the present study can be explained with the energy absorbed by the material during lighting process; color, type and light conductivity of the restorative material along with depth of the restoration, influence the results, as well (8,9,24). Moreover, oral environment which houses the blood flow in pulp and fluid movements in dentin canals, affect the management of heat rise, as well (9,25). Because the aim of the present study was to determine heat transfer alterations associated with material change; the color, light transparency, and thickness parameters of the materials were kept the same and only material types were changed. However, because possible effects of vital tissues were not reflected in the test design, the same study may yield different results at in vivo conditions. The mathematical modelling applied by finite element method, is an effective way for solving mechanical and thermal problems of restored teeth (17,18). The investigators verified the safety of this method by comparing it with the in vivo results (19). In the present study, the analysis results obtained by employing finite element method, showed similarity with in vitro study results. However, values of finite element analysis were found to be lower than those of the in vitro study. The failure to reflect environmental conditions which are supposed to encircle the restorative material during in vitro tests, may be the underlying reason for this difference. Heat flow advances from crown surface towards central area, therefore, because the heat flow and the stress associated with temperature will be similar in 2D and 3D models (26), employing 2D modelling in our study was thought to be appropriate. Since high intensity polymerization devices have the power of big energy output, despite reducing the required time for polymerization, they may lead to considerable heat increases on the surface they are applied to (8,9). In the present study, applied QTH light source was observed to cause significant heat changes both in finite element analysis and in the in vitro study results. The calibration of the effects of thermal changes on restored teeth presents experimental difficulties. Mathematical modelling of the process using a finite element method (FEM) offers an alternative approach. In the finite-element method, a distributed physical system to be analysed is divided into a number (often large) of discrete elements. The complete system may be complex and irregularly shaped, but the individual elements are easy to analyse. de Vree et al developed a simulation model to study heat transport problems, and the authors concluded that the described model was a reliable and valuable tool in fundamental studies on thermal behavior of restored teeth. Spierings et al34 reported the lack of any empirical validation for the theoretical model to calculate the temperature distribution within teeth and tested their theoretical model by comparing it with an in vivo experiment under thermal conditions. The authors concluded that the heat transfer coefficient (HTC) was an important parameter in the process of energy transport into teeth and the simulated FEM model was demonstrated to be a good approximation of the physical reality concerning the HTC. However, blood circulation in the pulp chamber and fluid motion in the dentinal tubules are also important in heat conduction in teeth. The lack of modelling for the effect of blood flow on the pulpal response may limit a finite element analysis (FEA) study to directly apply the measured temperature values to the temperature changes that would occur in vivo.

Considering the thermal specifications in Table2 and using assuming QTH light polymerization unit characteristics, we used 2D Flex PDE 4.2; PDE Solutions Inc, Sunol, Calif, software. Figure 3 shows schematic view of the model which comprises 700 nodes and 327 cells and the reference points selected on the model ; occlusive and cement surfaces of the restoration (a and b), in cement (c), and tooth, were determined (Figure 3). The problem is solved by using this 2D heat transfer partial differential equation dependent on time as given in Eq.1. Nonmetals display a weaker thermal conductivity than metals. Although heat transfer coefficients of composite resin and ceramic restorative materials are close to each other, composite resin has a higher heat transfer coefficient (1,4-7). In vitro test results showed a considerably significant difference between composite resin restorative material and ceramic restorative material in terms of heat transfer ($p<0.0001$). Heat rise is a complicated problem in which many components play a role (22, 23). While the reason behind heat rise in the present study can be explained with the energy absorbed by the material during lighting process; color, type and light conductivity of the restorative material along with depth of the restoration, influence the results, as well (8,9,24). Moreover, oral environment which houses the blood flow in pulp and fluid movements in dentin canals, affect the management of heat rise, as well (9, 25). Because the aim of the present study was to determine heat transfer alterations associated with material change; the color, light transparency, and thickness parameters of the materials were kept the same and only material types were changed. However, because possible effects of vital tissues were not reflected in the test design, the same study may yield different results at in vivo conditions. According to the results of the in vitro test, while the temperature of the cement surface of the composite material was 45.99 ^{o}C (±3.39 ^{o}C) in the first 10 secs following activation of the light device, it reached 75.08 ^{o}C (±7.58) at the end of 40 secs. Similarly, while the temperature of the cement surface of the ceramic material was 47.57 °C (±0.68 °C) in the first 10 secs following activation of the light device, it reached 64.03 °C (±2.20) at the end of 40 secs. While the statistical evaluation revealed no significant difference in terms of temperature increase on material surface within the first 10 secs ($p>0.05$), a highly significant temperature change was determined on surface of the composite material at the end of 40 secs compared to ceramic material ($p<0.0001$). The values obtained from analyses employing finite element method, showed consistency with the results of in vitro test.

V. CONCLUSION

Finite element analysis is an effective method which can be benefited for solving the mechanical and thermal problems of complicated dental structures in studies investigating the properties of complicated dental structures. While generally composite resins and ceramic restorative materials are materials with poor thermal conductivity, in the present study, composite resin was found to be have a higher thermal conductivity than ceramic material. High intensity light sources may lead to significant heat rises in the polymerization field.

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