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Analysis of cyclic thermal stress on restored tooth using finite element analysis

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Abstract

Analysis of cyclic thermal stress on restored tooth using finite element analysis

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Introduction

The intake of hot and cold substance in daily life generates cyclic thermal stress to tooth and this repeated stress may result in fatigue failure. The purpose of this study was to analyze the relationship between cyclic thermal stress and tooth crack formation using finite element analysis**.**

Methods

A maxillary first molar with class I or class II restoration was modeled via CAD-FEM procedure. Thermal load based on in vivo experimental data was applied to class I/II prepared natural tooth without filling material (control) and class I/II gold restored tooth. Stress generated in tooth structure was examined. Predicted fatigue life based on stress analysis was calculated using Basquin's equation.

Results

Calculated fatigue life was shorter in gold restored group than in controlled group and class II restored group showed shorter fatigue life than class I restored group. The shortest fatigue life was shown in class II gold restored tooth (3 X 10^7 years). For all cases, maximum stress was held in cold stimulation.

Conclusions

The cyclic thermal stress is a contributing factor of tooth crack formation and the presence of restoration facilitates the fatigue failure caused by cyclic thermal stress.

Keywords: cyclic thermal stress, fatigue life, tooth crack formation, finite element analysis (FEA), gold restoration, cold sensitivity

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I. Introduction

In daily life, teeth frequently encounter cyclic thermal load as we take foods or drinks which have a various range of temperature. Since tooth is composed of different materials, mechanical stress arises due to the different amount of thermal expansion. A tooth with intracoronal restoration is more vulnerable to thermal stress because of the different mechanical properties between the natural tooth structure and restorative material. It is well investigated that the difference in thermal expansion coefficient between tooth and restorative material may lead to failure of restoration or tooth crack. [1, 2]

Many studies reported that there are some differences in the incidence of tooth crack formation between class I and class II restorations. Cameron reported that class II restorations resulted 2.4 times more cracks than class I restorations did.[3] However, Hiatt and Roh et al. found that class I restorations are more vulnerable to crack than class II restorations.[4, 5] On the other hand, there is a report claiming no difference in crack formation associated with class I or class II restorations.[6]

Fatigue failure occurs when repeated stress is applied for more than a certain cycles which can be described by stress-life relationship. [7] If the stress developed by cyclic thermal load is given, the fatigue life of tooth structure can be predicted by stress-life relationship. However, there are very few investigations about the fatigue failure due to the cyclic thermal loading.

The amount and distribution of stress caused by cyclic thermal stress according to different classification of cavity and restorative material will be investigated using finite element analysis (FEA). Therefore, the factors affecting tooth crack formation by cyclic thermal stress will be discussed.

II. Materials and Methods

1. FE model and simulation

A natural maxillary first molar extracted due to periodontal complication (IRB No. S-D2014004) was scanned with Skyscan 1172 micro-CT (Skyscan, Aartselaar, Belgium). Scanned data was visualized and segmented by medical image control system (MIMICS 10.0, Materialise, Leuven, Belgium). Generation of volumetric mesh and re-establishing of dentio-enamel interface was performed with Rapidform XOR3(INUS technology, Seoul, Korea). Class I and Class II cavity were generated and their morphology is described in Fig.1. Stereolithography files (STL) were imported to ABAQUS (Dassault systemes, Rhodes Island, United States) for further FEA simulation.

Mechanical and thermal properties of each material (enamel, dentin, gold) were assigned to each segment and are shown in Table 1.[9-13]

Table 1 Data of mechanical and thermal properties of the material

Material	Young's modulus (GPa)	Poisson's ratio	Thermal expansion coefficient ($x10^{-6}℃^{-1}$)	Thermal conductivity (W/m.k)	Specific heat (J/kg.℃)	Density (kg/m^3)	Fatigue strength coefficient (MPa)	Fatigue strength exponent
Enamel	84.1	0.30	17.0	0.84	750	2800	310.0	-0.111
Dentin	18.3	0.31	10.6	0.63	1302	2000	247.0	-0.111
Gold	96.6	0.35	14.4	297	125	16400	-	-

To model the effect of cyclic thermal load given by intake of hot and cool substance, in vivo experimental data was obtained by our group's study. In case of the tooth with gold restoration, the initial temperature value of crown surface (37℃) is changed to 44.5℃ for a period of 9s in the first stage and in the next stage, tooth underwent cool down in the initial temperature for 120s. In the third stage, the temperature of crown surface went down to 25.3℃ in 8s and in the final stage, tooth stayed in the initial temperature for 120s again.

In addition, the class I and class II prepared natural teeth without filling material used as a controlled group. It also used the experimental data as above. In the first stage, temperature of crown surface is changed to 40.4℃ for a period of 16s then underwent to cool down for 120s. After that, the temperature is changed to 31.7℃ in 9s then the tooth stayed in initial temperature for 120s. This heat transfer cycle is held to obtain the nodal temperature variation of each node. (Figure 1)

Using the result of heat transfer analysis, direct cyclic analysis was performed to obtain stabilized response of the thermal cyclic stress. In this stage, stabilized Von mises stress around the restoration was examined.

2. Fatigue life prediction

The fatigue life of tooth structure was calculated using Basquin's formulation, as stated into equation (1): [14, 15]

$$\sigma_a = (\sigma_f - \sigma_m) \cdot (2N_f)^b \quad (1)$$

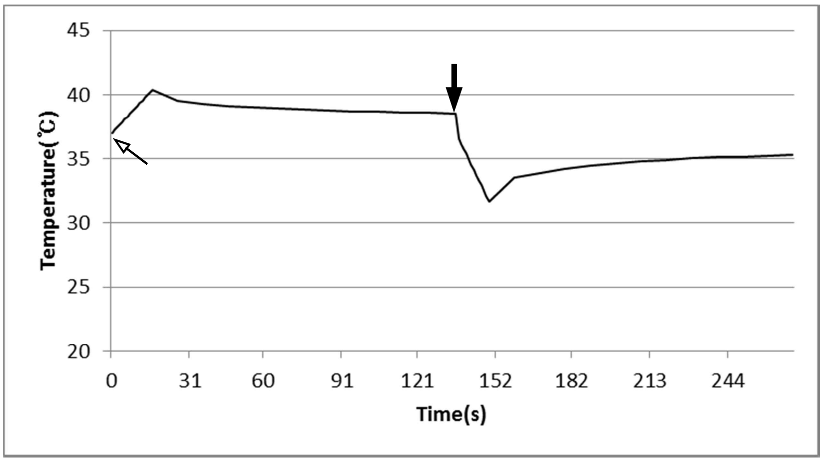
Where "σ_f" is the fatigue strength coefficient and "b" is the fatigue strength exponent. "σ_m" is the main stress and "σ_a" is the stress failure whereas "N_f" is the numbers of cycles to failure. In this study, stress between each cycle almost becomes zero so the main stress can be ignored ($\sigma_a = 0$). With the result of previous direct cyclic analysis, numbers of cycles to failure was obtained for each type of restorations and restorative materials.

III. Results

The nodal temperature by heat transfer analysis is shown in Fig 1. Note that the temperature variation and its velocity are lower in controlled group than in gold restored group. In addition, temperature variation in the intake of cold substance is greater than in the intake of hot substance. The time-stress relation (Von mises stress) of each material is shown in Fig.2. This relationship was recorded at the element which showed the highest stress. The maximum stress was higher in the gold restoration than controlled group and in class II restoration than class I restoration. In addition, maximum stress was held at the intake of cold substance in all cases.

Fig.1 Nodal temperature during one cycle is shown. The temperature variation and its velocity are lower in controlled group (a) than in gold restored group (b). Cold loading (black arrow) showed greater temperature variation than hot loading (white arrow).

(a)



(b)

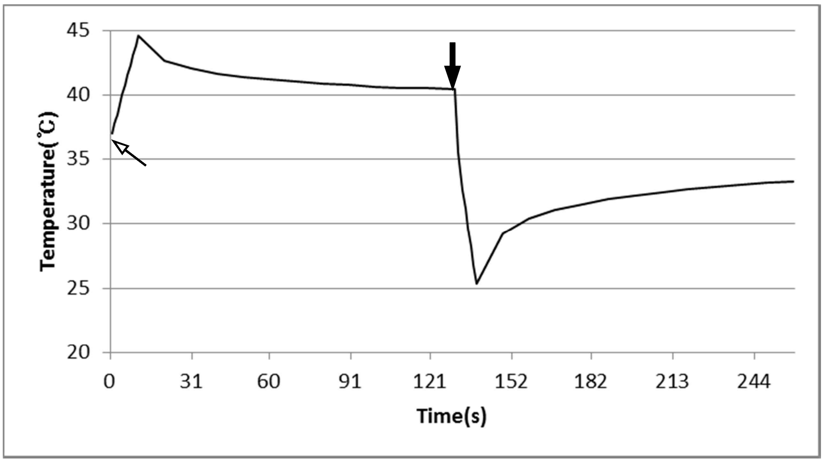
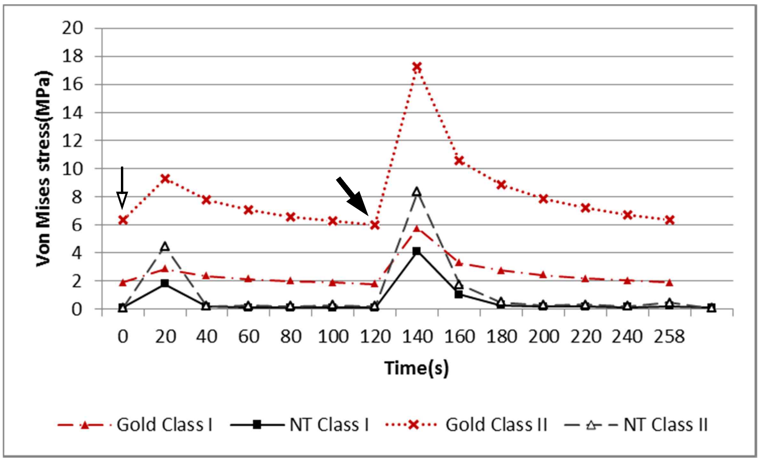
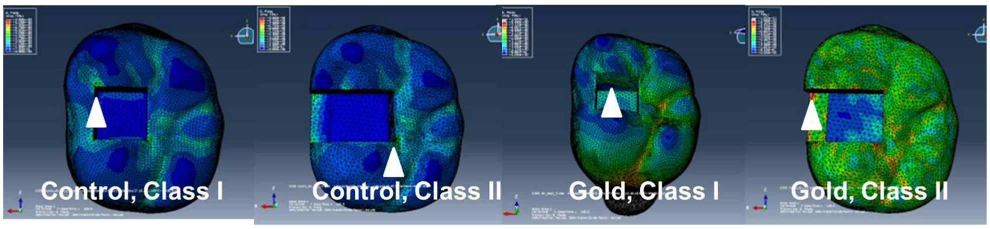


Fig. 2 The time-stress relation of the element which showed maximum stress (a) and its location (b), Cold loading (black arrow) generated more stress than hot loading (white arrow).

(a)



(b)



Based on the maximum stress in previous procedure, predicted fatigue life was calculated. The calculated fatigue life based on the Basquin's formula is shown in Table 2. Gold restored group and class II restoration group showed shorter fatigue life than natural tooth group and class I restoration group respectively. The shortest fatigue life was 2.48 X 10^{11} cycles in class II gold restored tooth.

Table 2 Maximum stress and numbers of cycles to failure

Restorative material	Type of restoration	Maximum stress (MPa)	Numbers of cycles to failure
Control (Natural tooth)	Class I	4.07	4.49×10^{16}
	Class II	8.32	7.15×10^{13}
Gold	Class I	5.05	6.42×10^{15}
	Class II	15.6	2.48×10^{11}

IV. Discussion

The shortest fatigue life was obtained in case of class II gold restoration (2.48×10^{11} cycles). If we assume 20 intakes of hot and cold substance for a day, it takes about 3×10^{7} years to failure. It implies that only with cyclic thermal stress, fatigue failure cannot occur during lifetime. However, the increase in stress due to the temperature variation means that thermal stress can be a contributing factor of fatigue failure. In addition, compared to control group, the restored group showed shorter fatigue life. Therefore the presence of restoration can facilitate fatigue failure caused by cyclic thermal stress. It can be due to the variation of temperature which is greater in gold restored group and also can be due to the difference in thermal expansion coefficient. It is consistent with the previous study that the presence of restoration increases the risk of tooth crack formation.[16-18]

For all groups, class II restoration showed higher maximum stress and shorter fatigue life than class I restoration. It might be due to the amount of expansion which is greater in class II restoration because of the size of restoration. Bader et al. stated that the increase in the volume proportion of a restoration associated with the increase in the odds of the fracture.[19] They claimed that remaining tooth structure(remaining dentinal support) plays a major role in the increasing risk of tooth fracture associated with the increase in the size of restoration. However, in this study, the size of restoration itself can be a contributing factor of tooth crack formation in the view of cyclic thermal fatigue because the restored group was compared with prepared group which has the same amount of remaining tooth structure.

In all cases, maximum stress was held in cold stimulation. It is mainly due to the greater range of temperature variation in cold stimulation. However it implies that, in daily life, oral environment undergoes greater amount of temperature variation during the intake of cold substance since the temperature range of tolerance is wider in cold stimulation than in hot stimulation. It also suggests that it can be a contributing factor of cold sensitivity in tooth crack. The cold sensitivity is a common symptom associated with tooth crack but its etiology is still unclear.[20] However, a recent study of tooth pain in intact tooth resulted by thermal stress stated that cold loading generates more tensile stress and more temperature gradient than hot loading and it produces more pain which can be explained by hydrodynamic theory. [21] Same conclusion can be made in restored tooth because the positive principal stress (tensile stress) was resulted in cold loading in present study.

The effect of adhesive layer was ignored in this study. Seo et al. claimed that, the low modulus of adhesive layer roles in compensation of thermal and occlusal surface.[8] Gold inlay should be bonded with adhesive layer in order to gain proper retention. Thus it may give different result if we consider the adhesive layer. However, the statements that only with thermal stress, fatigue failure cannot be formed and the thermal stress is a contributing factor of tooth crack formation will still be consistent.

V. Conclusion

The cyclic thermal stress is a contributing factor of tooth crack formation and the presence of restoration facilitates the fatigue failure caused by cyclic thermal stress**.**

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초 록

1. 목 적

일상생활에서 다양한 온도를 가지는 음식물의 섭취는 치아와 그 수복물에 반복적인 열응력(thermal stress)을 가하게 된다. 본 연구는 수복물의 형태 및 수복재료에 따라 주기적인 열응력에 의한 치아 피로수명을 분석함으로써, 이에 영향을 미치는 요소들을 분석하고자 한다.

2. 대 상 및 방 법

발치된 상악 제1대구치의 microCT scan data를 이용하여 다양한 재료의 제 1급, 2급 수복치아 모델을 형성하였다. 우리 연구 그룹의 생체 내 실험을 통해 얻어진 찬 물과 뜨거운 물 섭취에 의한 수복치아의 온도변화 결과를 토대로 주기적인 열부하(thermal load)를 모델 상에 가한 뒤, 이에 의한 응력양상을 유한요소분석법을 통해 해석하였다. 해석을 통해 얻어진 응력값을 이용하여 Basquin’s formula에 의한 치아의 피로수명을 계산하였다.

3. 결 과

계산된 피로수명은 모두 최소 2×10^{11} 주기 이상으로 나타났으며, 자연치아보다는 수복치아의 피로수명이 짧았고 2급 수복물이 1급 수복물보다 짧은 수명을 나타내었다. 따라서, 하루 20회의 열부하를 가정했을 때 예상되는 피로수명은 모두 3×10^{7}년 이상으로 열부하 자체만으로는 피로파괴가 발생하지 않는다는 것을 알 수 있다. 그러나 대조군인 자연치아와 비교해보았을 때 증가된 응력값은 반복적인 열부하가 피로파괴의 기여요인이 될 수 있다는 것을 의미하며 이는 수복물의 존재 시 더 큰 영향을 나타내는 것으로 해석된다.

모든 경우에 대해서 2급 수복물의 수명이 1급 수복물의 수명보다 짧게 나타났는데 이는 수복물의 크기 차이로 인한 팽창량의 차이에서 비롯된 것이라고 생각된다.

또한 모든 수복물의 형태에 대해서 찬 물을 마셨을 때의 최대 응력이 뜨거운 물을 마셨을 때보다 더 크게 나타났다. 이는 파절된 치아의 냉감수성(cold sensitivity)에 기여요인이 될 수 있을 것이라 생각된다.

4. 결 론

주기적인 열응력은 치아 파절 형성의 기여요인이며 수복물의 존재는 이로 인한 피로 파절을 촉진한다.

주요어: 주기적 열응력, 피로 수명, 치아 파절, 유한요소분석, 금수복물, 냉감수성

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