Effect of Thermal Stresses on the Mechanism of Tooth Pain

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Abstract

Introduction: Daily hot and cold thermal loadings on teeth may result in structural deformation, mechanical stress, and pain signaling. The aim of this study was to compare the adverse effects of hot and cold beverages on an intact tooth and, then, to provide physical evidence to support the hydrodynamic theory of tooth pain sensation mechanism. **Methods:** Three-dimensional finite element analysis was performed on a premolar model subjected to hot and cold thermal loadings. Elapsed times for heat diffusion and stress detection at the pulp-dentin junction were calculated as measures of the pain sensation. **Results:** Extreme tensile stress within the enamel resulted in damage in cold loadings. Also, extreme values of stress at the pulpal wall occurred 21.6 seconds earlier than extreme temperatures in hot and cold loadings. **Conclusions:** The intact tooth was remarkably vulnerable to cold loading. Earlier changes in mechanical stress rather than temperature at the pulp-dentin junction indicate that the dental pain caused by hot or cold beverages may be based on the hydrodynamic theory. *(J Endod 2014;40:1835–1839)*

Key Words

Finite element, mechanical stress, pain sensation, thermal load, tooth

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The intake of hot and cold foods and drinks is a repetitive daily habit (1–3) that may cause instantaneous and permanent damage to dental and oral tissues (3–9). The severity of such damages warrants discussion, particularly from 2 aspects: (1) pulp tissues are sensitive to temperature rise and an increase of 5.5°C in the pulp-dentin junction (PDJ) results in irreversible injuries in the pulp (3, 5–7) and (2) dental hard tissues, like enamel or dentin, are vulnerable to mechanical stresses. The stresses induced by thermal loads of hot and cold intakes and mechanical loads of chewing may generate cracks followed by pain, damage, and shortened dental lifetime (3, 8, 9).

The tooth pain sensation has been the subject of several studies as a sophisticated and key mechanism involved in dental structural changes. The primarily developed theory of pain sensation has been founded on the thermal excitation of neurons in sensory organs located at the PDJ (10, 11). This neural theory ignores the underlying mechanism of pain generation but insists on the existence of such sensors inside the dental components (10, 11). On the other hand, the hydrodynamic theory of tooth sensation deals with how cold and hot intakes force dentinal intratubular fluid to move and then stimulate the transduction of pain signals (12, 13). Today, this theory is well accepted among researchers (11, 13). A reflection of such recognition may be seen by the treatment of dentinal hypersensitivity using laser therapy to occlude or narrow tubules (14, 15) and also by considering the effects of other mechanical factors such as the hyperosmotic stress of pain sensation (16).

The overriding principle of the hydrodynamic theory has been based on the contraction and expansion of dental components under thermal stimuli (13, 17, 18). Thus, drawing a comparison with neural theory would require further mechanical information of the structure. Finite element (FE) is an appropriate method for analyzing the mechanical behavior of structures with irregular morphology and different materials (3). This method can shed light on the dental response against thermal loads applied by hot and cold intakes. FE analysis can properly predict temperature changes within the dental constituents after the thermal load has been applied (3). Temperature gradients generated by the diffusion of heat cause contraction and expansion in the constrained composite tissues, which, in turn, lead to thermal stresses. Lloyd et al (8) calculated thermal stress in an axisymmetric model of enamel and dentin of a molar tooth besides an *ex vivo* thermal cyclic loading and concluded that the consumption of cold foods and drinks led to cracks in the enamel. By using the 2-dimensional (2D) FE model of restored molar, Arola and Huang (19) showed that 35% of the overall stress within the tooth is attributed to thermal loadings, and the rest are caused by chewing loads. Toparli et al (20) compared the distribution of temperature and subsequent thermal stresses in an intact tooth and one restored by crown materials. Their 3-dimensional (3D) FE model indicated an increased stress magnitude in the restored case during cold and hot ingestions. Cornacchia et al (21) used a precise 3D model of healthy and restored molar teeth simultaneously subjected to thermal and mechanical loads. Based on their results, hot liquids caused compressive stress on the restoration surface and tensile stress at the dentin-restoration interface, and cold loads did the opposite. Similarly, Palka et al (22) investigated the effects of thermal and mechanical stresses and their superposed loading on a 3D model of restored premolar tooth and found the mechanical share in overall stress to be higher than the thermal one.

Because pain signals are sensed immediately after thermal stimulation (5, 23), it was hypothesized that the time taken to detect a stress (strain) change is much shorter than that taken to sense any temperature change at the pulpal wall, an index supporting the hydrodynamic theory. To our knowledge, previous FE studies on restored or intact

TABLE 1. Elastic and Thermal Expansion Properties of Components in the Model (20, 23, 25–28)

Component	Young's modulus (GPa)	Poisson ratio	Expansion coefficient ($\times 10^{-6}$/°C)
Enamel	84.1 (25)	0.3 (25)	11.4 (23)
Dentin	18.3 (25)	0.31 (25)	8.3 (23)
Pulp	0.002 (26)	0.45 (26)	10 (20)
Periodontal ligament	0.069 (26)	0.45 (26)	10 (27)
Cortical bone	14.7 (28)	0.30 (28)	10 (27)
Trabecular bone	0.49 (28)	0.30 (28)	10 (27)

teeth have merely dealt with the reporting of stress values. Furthermore, experimental studies on hydrodynamic theory have not investigated the mechanisms of pain sensation (5, 12, 13, 17). The present study aimed at evaluating thermal stress within an intact mandibular premolar using the FE method to provide physical evidence in accordance with the hydrodynamic theory and to reach a consensus on the 2 different points of view.

Materials and Methods

Model Preparation

A 3D geometry of an intact human premolar tooth, based on precise computed tomographic data, was used. The model included the enamel, dentin, pulp, periodontal ligament, and mandible with 2 regions of cortical and trabecular bone. The employed mandible bone was cut from buccolingual planes in vicinity to the premolar tooth. Specifications of the model have been explained in more detail in Oskui et al (24).

Material Properties

Besides the thermal and physical properties of the model components, which have been pointed out in our earlier work (24), elastic properties and thermal expansion coefficients were required to analyze thermal-induced stresses. Table 1 presents the latter materials' properties. It was assumed that all material properties were homogenous, isotropic, linear, and independent from temperature and time.

Analyses

To evaluate thermal stresses, first, transient thermal FE analysis was performed. Then, based on the temperature distribution of the previous stage, a static elastic linear analysis was done. Both the analyses were accomplished in ABAQUS 6.3 (Dassault Systemes, Velizy-Villacoublay, France).

Thermal Analysis

The model was subjected to 2 thermal conditions including hot and cold loads. The hot loading (HL) case was imposed 60°C to the oral cavity during 1 second (24, 29). Given the similarity with the HL, the cold loading (CL) case was exerted 0°C for 1 second as the oral cavity temperature (30). The initial temperature of the oral cavity and model constituents for both heat loads were considered at 37°C. The heat convection (transfer) coefficient of 500 J $m^{-2}s^{-1}°C^{-1}$ was considered for both types of thermal loading (1, 24). Convection was the only means to transfer heat flux from the oral cavity to the occlusal and lingual surfaces of the enamel. Then, transmitted energy was diffused into the dental components by conduction (24).

Thermal Stress Analysis

The temperature gradients produced within the model led to thermal stresses, which were calculated based on static linear elastic analysis with a relationship of $\sigma_T = K_r \alpha E(\Delta T)$, where σ, α, and E denote thermal stress, linear thermal expansion coefficient, and Young's modulus of elasticity, respectively. Also, K_r represents the effects of geometry, external restraint, and the Poisson ratio. The 2 cutting faces of the mandible were also constrained in all degrees of freedom in space.

The model in both analyses was discretized into 167,003 nodes and 118,435 quadratic tetrahedral elements. Figure 1*A* and *B* shows the tooth components and meshed view of the geometry of the whole model. The modeling excluded the effects of pulpal perfusion, dentinal fluid flow, and the presence of gum and tongue. Moreover, the model disregarded the microstructures of enamel and dentin and did not consider the orthotropic properties of dentin.

Results

Von Mises stress values induced by the temperature gradients within the model are shown in Figure 1*C* for the HL case at 4 time interrupts of 1, 5, 10, and 100 seconds. Buccolingual cut views of the premolar tooth indicated the appearance of maximum amounts of stress in the enamel in earlier times. Pulp tissues clearly received negligible stress compared with dentin and, notably, enamel. With the passage of time, stress values diminished through the model.

The components forming the model incorporated different amounts of stress at different times. Table 2 lists the extreme principal stress within the enamel and at the dentin-enamel junction (DEJ) for both HL and CL and also the associated elapsed time. Extreme values for temperature and their related times were maximum and minimum for the HL and CL cases, respectively. It was determined that the location of extreme stresses would not necessarily coincide with those of corresponding extreme temperatures. Furthermore, negative and positive values for principal stresses represented compressive and tensile stresses, respectively. Regardless of stress directions, enamel and DEJ experienced higher principal stress values in CL than in HL cases. The associated elapsed times for reaching these extremes were about 1.0 second. In contrast, the extreme temperature at the DEJ occurred at 2.6 seconds, about 1.6 second later than that of the extreme principal stress. The trend was similar for both load cases.

Variations of temperature and stress at the pulpal wall over time have been plotted for HL and CL in Figure 1*D* and *E*. Temperature data have been extracted from the point that received extreme values. Stress graphs were also plotted for the dentinal side of the pulpal wall in order to give insight into the compressive or tensile nature of thermal loadings in the dentinal tubules.

In the HL case (Fig. 1*D*), stress rapidly dropped during 1 second to its extremum at 686 kPa (compressive) and then asymptomatically descended after 1 second and rose to become a plateau shape in the tensile direction. On the other hand, temperature increased more slowly to pass its maximum value, (ie, 37.88°C at 22.6 seconds) and then slowly decreased. The same trend was remarkably observed for stress and temperature in the CL case, albeit in reversed nature of cooling (Fig. 1*E*). In the CL case, the pulpal wall experienced a stress of about 1124 kPa (tensile) at 1 second, sharply falling to compressive values.