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**Original Article**
**บทวิทยาการ**

# Tooth deformation in extracted molars in response to thermal stimuli

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## Abstract

***Objective*** This study investigated patterns of tooth deformation in response to immersion in hot and cold water, and attempted to correlate the measured dimensional change with calculated values based on coefficients of thermal expansion.

***Materials and methods*** The extent of cuspal deformation and strains within dentine were assessed in extracted human molars, in response to immersion in hot and cold water. Cuspal displacement was measured using an extensometer attached to the buccal and lingual cusps, and strains on the pulpal dentine surface were measured using strain gauges attached to the occlusal pulpal surface. Temperature change was monitored with thermocouples. Tooth crowns were immersed in hot (80°C) or cold (2°C) water for 5 seconds

***Results*** Cuspal displacement and dentinal strain were greater, and occurred more rapidly, in response to heat than to cold. Thermal strain was detected on the pulpal surface of dentine before any temperature change occurred, and was much greater than calculated values based on thermal expansion or contraction alone.

***Conclusion*** Patterns of deformation of the tooth crown are complex, and involve not only thermal expansion/contraction but also tooth flexure resulting from temperature gradients across tooth structure.

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***Key words:*** *deformation; teeth; thermal contraction; thermal expansion; thermal stimulus*

## Introduction

Teeth are exposed to a wide range of temperatures during the normal functions of eating and drinking, as well as during some restorative procedures and thermal pulp testing. An intraoral temperature range of 0.4-77.4°C has been recorded during consumption of cold and hot drinks[1], but a more commonly accepted range is 5-65°C [2]. Exposure tends to be transient, with only brief temperature fluctuations (approximately 5 seconds during normal function)[1,3,4], at an estimated frequency of 20-50 cycles per day[5]. With clinical pulp testing and restorative procedures the temperature range may be more extreme, but the frequency of exposure is extremely limited.

One consequence of temperature fluctuations in teeth has long been recognized in restorative dentistry: a difference in the coefficients of thermal expansion between tooth structure and restorative materials can lead to marginal gaps and microleakage or to stress at the interface of bonded restorations[2,6]. However, the stress-strain behaviour of teeth, with complex coronal morphology, in response to thermal stimuli is likely to be more complex than simple linear expansion and contraction. The temperature change associated with the ingestion of food or liquids is sudden, of brief duration, and unevenly distributed over the tooth surface, leading to use of the expression "thermal shock"[4]. The short duration of exposure is insufficient for thermal equilibrium, resulting in a temperature gradient across enamel and dentine and an uneven distribution of stresses throughout tooth structure[4,7]. Hence a difference in the coefficients of thermal expansion between a restorative material and tooth structure may provide only a very incomplete picture of marginal gaps or stresses resulting from oral exposure to temperature change.

While numerous investigators have measured (or modeled) temperature changes within teeth in response to thermal stimuli[4,7-11], little attention has been paid to the resultant effect on tooth deformation. Finite element modeling of thermally induced stresses in teeth has been undertaken for more than three decades, but with only limited experimental validation[7,9]. In an early study using finite element analysis (FEA) of a molar tooth[9], simulated immersion of the tooth crown in cold water caused large compressive hoop stresses in dentine, which peaked approximately 1 second after exposure. Thus, a thermal stimulus applied to the enamel surface resulted in large and rapid mechanical stresses in the deeper structure. We have recently demonstrated that heat or cold applied to the labial surface of incisors resulted in a rapid and complex pattern of strain in the tooth, with flexure of the tooth surface as well as thermal expansion or contraction. The greatest strain within tooth structure was located on the underlying pulpal surface of dentine[7]. A similar pattern was noted in an FEA model of a maxillary premolar[4]. In both studies, stresses developed within dentine before any accompanying temperature change.

In this initial study of intact teeth, temperature change, cuspal displacement and strains on the pulpal surface of dentine were measured in extracted third molars when the crown was immersed in hot and cold water. The objectives of the study included: 1) to investigate patterns of tooth deformation, in terms of cuspal displacement and strains at the pulpal surface, in response to heat and cold applied over the entire enamel surface; 2) to correlate tooth deformation with temperature change at the enamel surface, DEJ and pulpal surface. The main hypothesis of the study was that heat or cold applied to the enamel surface of intact teeth will result in deformation of the entire crown, resulting in complex patterns of expansion and contraction.

## Materials and methods

### Tooth selection

This project was approved by the institutional human research ethics committee. Intact mandibular and maxillary molars with fully formed roots (extracted for oral surgical reasons) were collected, cleaned and stored in 1% chloramine T (Sigma-Aldrich Co., St. Louis, MO, USA) solution in distilled water at 4°C until use within two weeks of extraction.

Approximately equal numbers of maxillary and mandibular teeth were selected, with uniform coronal morphology and an intercuspal distance (mesial cusps) of approximately 7 mm. Teeth were divided into two groups each of eight teeth, for the separate measurement of cuspal displacement and pulpal surface strains.

### Part A: Measurement of linear cuspal displacement

Linear cuspal displacement was measured using an extensometer attached to the mesio-buccal and mesio-palatal or mesio-lingual cusps of each tooth. Eight teeth were mounted vertically in a nylon ring, with dental stone covering the root to a height 2 mm below the cemento-enamel junction (CEJ). A small dimple was prepared on the outer surface of the enamel near both cusp tips to accommodate the measuring rods.

A well to contain hot or cold water during thermal stimulation was placed over the nylon ring (Fig. 1). Two small holes in the well allowed the measuring rods to be positioned in contact with the prepared dimples in the cuspal enamel. A thin latex band was used to cover the opening to prevent leakage,

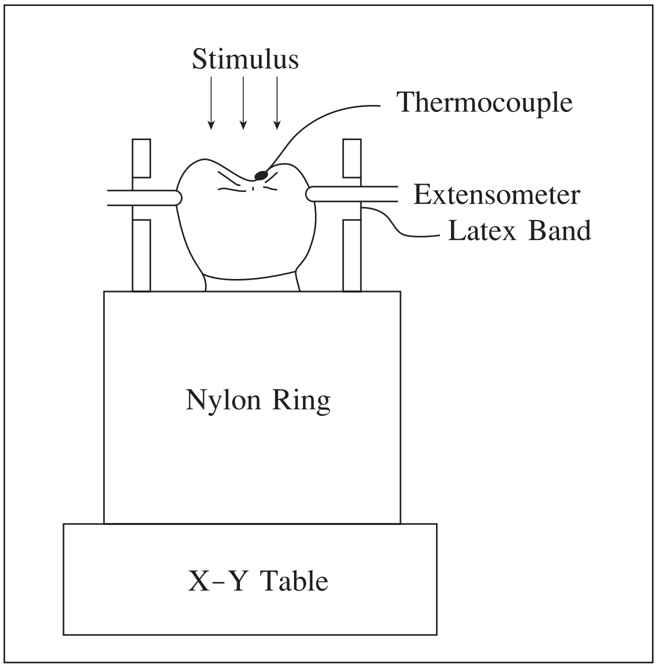

**Fig. 1** Experimental setup for measuring cuspal movement during application of heat or cold to the tooth crown. The tooth was mounted in dental stone and the crown was enclosed within a well to which hot or cold water could be added. Cuspal movement was detected by an extensometer, via invar rods contacting the buccal and palatal/lingual cusps near the cusp tips.

and the rods penetrated the latex band to contact the prepared dimples. The nylon ring with the mounted tooth was attached to an X-Y table, allowing for the precise adjustment of tooth orientation.

An extensometer (Model 632.11-2x, MTS Systems, Eden Prairie, MN, USA) was modified by the addition of a short invar rod to each arm, with the rod tips contacting the buccal and palatal (lingual) cusps at the prepared dimples (Fig. 1). Invar is an alloy of iron (64%) and nickel (36%) with a low coefficient of thermal expansion (less than $1.3 \times 10^{-6}$°$C^{-1}$). Preliminary studies showed almost undetectable dimensional change of this material when subjected to the thermal stimuli used in this study.

A fine J-type thermocouple (serial number 5TC-TT-J-40-36, Omega Engineering INC, Stamford, Connecticut, USA) was attached to the occlusal surface of the tooth to measure temperature change at the enamel surface.

## Part B: Measurement of strains and temperature changes

Eight extracted third molars were sectioned at the level 2 mm apical to the CEJ. Pulp tissue was removed with tweezers. A small rectangular box was prepared at the bucco-cervical part of the tooth to facilitate the application of strain gauges and thermocouples to the pulpal surface of occlusal dentine (Fig. 2).

Strain gauges (CEA-06-032UW-120, Micro-measurement, Raleigh, NC, USA) were trimmed and bonded to the pulpal wall of the occlusal surface of the teeth using an acid-etch technique and cyanoacrylate adhesive (M-bond 200; Micro-measurement, Raleigh, NC, USA). The orientation of the gauge was in a bucco-lingual direction, which detected strain in the same direction as the cuspal movement from the extensometer experiment described above.

Fine J-type thermocouples were installed on the

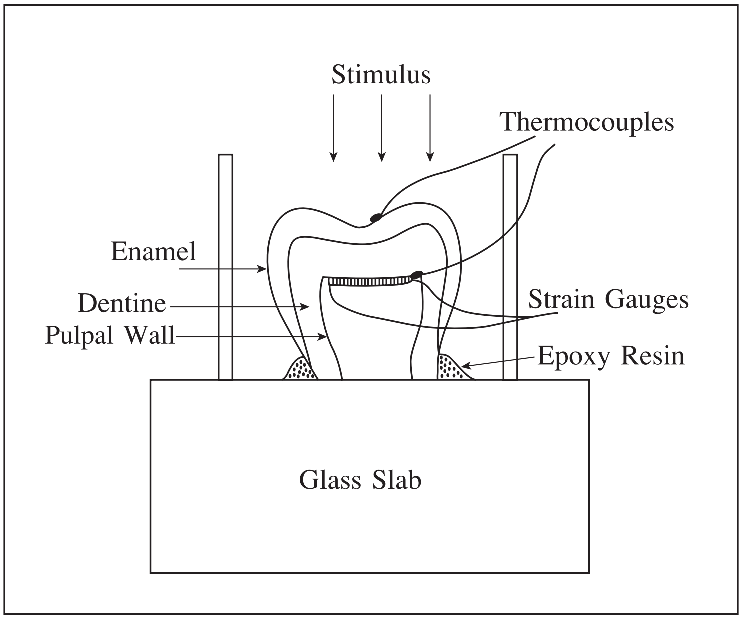

**Fig. 2** Experimental setup for measuring strains on the pulpal surface of dentine. A strain gauge was attached to dentine underlying the occlusal surface, with leads attached via a small aperture cut into the buccal surface. The tooth was mounted on a glass slab and surrounded by a well to contain hot or cold water.

occlusal surface and the pulpal wall (adjacent to the strain gauge). Silicone heat conducting compound (Unick, Unick Chemical Corp, Taipei, Taiwan) was used to enhance the contact between the thermocouples and tooth structure at the pulpal wall. The prepared tooth was then mounted on a thick glass slab. A small well was placed over the tooth, and bonded to the glass block to serve as a container for the thermal stimuli. Epoxy resin (Araldyte, Selleys PTY Limited, NSW, Australia), and rubber dam were placed as an insulator and barrier to prevent thermal stimuli from contacting the cementum and glass slab.

A control tooth, with an attached strain gauge but not subjected to thermal stimulation was mounted adjacent to the test tooth. This compensator gauge was connected with identical lead wires via a half bridge (of a Wheatstone bridge) configuration to minimize asymmetrical resistance changes caused by temperature fluctuations from excitation current or the local environment. The strain gauges were connected to a conditioning module (SCC SG03 National Instruments Corp, Austin, TX, USA) housed in a configurable connector block (SC2345). Similarly, J type thermocouples were connected to appropriate conditioning modules (SCC TC02) in the same connector block. Data were collected using a multifunction I/O card (DAQCARD-6062E*) attached to a computer with LabView 7.0 software.

Tested teeth were reinvestigated for the effect of thermal stimulation on temperature changes at various locations of tooth structure; namely outer enamel surface, dentino-enamel junction (DEJ) and pulpal wall. A small pulp bur was used to drill a hole at the pulpal surface of the pulp chamber reaching the DEJ at the occlusal surface of the tooth crown (confirmed by subsequent sectioning of the teeth). Thermocouples were installed at the three locations, connected to the LabView program, and then the teeth were subjected to thermal stimulation.

## Thermal stimulation

All experiments were conducted at room temperature (20°C). Two different thermal stimuli were used, namely; hot water (80°C) and cold water (2°C). Baseline data were collected for 30 seconds. Hot or cold water was added to the well to cover the entire tooth crown. The temperature of the hot water was slightly higher than is usually encountered during normal function. Thermal stimuli were applied for 5 seconds, and the water was removed by high speed suction. Each thermal stimulus was applied twice to each tooth in a random sequence, with a one hour interval between tests.

## Data collection

Data from the extensometer, strain gauges, and thermocouples were recorded simultaneously at a sampling rate of 20 points per second on a computer using the Labview program (National Instruments, Austin, TX, USA). The extensometer measured the combined displacement of both cusps, with a positive value when both cusps moved outward (away from each other) in a bucco-lingual direction, and negative values with the reverse. The strain gauge recorded strains as compressive (negative value) with contraction of dentin at the pulpal wall, and tensile (positive value) with expansion of dentin.

## Data analysis

Analysis of variance (ANOVA) was conducted to compare the times to detect initial cuspal movement, initial strain changes at the pulpal dentin, and temperature changes at the DEJ and pulpal wall for each stimulus. All paired comparisons between means were performed at the 0.05 level of significance, using the least significance difference (LSD). In cases where the variances were unequal, a logarithmic transformation was applied to the data before the ANOVA was performed.

## Results

Both thermal stimuli caused substantial temperature change within tooth structure, and also rapid, transient tooth deformation. As expected, temperature change was greater and occurred more rapidly at the DEJ than at the pulpal surface (Table 1). Hot and cold water resulted in similar response times ($p > 0.05$) at both the DEJ and pulpal surface, and heat caused a greater temperature change at the two locations ($p < 0.001$).

Part A: Cusp displacement. Heat caused the tooth crown to expand, while cold caused it to contract. The typical pattern of cuspal movement during the first 60 seconds in response to the two stimuli is shown for one tooth in Fig. 3. Immersion in hot water resulted in rapid cuspal expansion, reaching a maximum displacement of approximately 5 µm, followed by a sharp drop after removal of the hot water, followed by slow recovery toward baseline position. Cold water resulted in much smaller cusp displacement (contraction

**Table 1.** Time (sec) required for a detectable temperature change at the DEJ and pulpal surface of dentin to thermal stimuli applied to the tooth, and the maximum temperature change [mean (SD), n = 8].

| Stimulus | DEJ | | Pulp | |
|---|---|---|---|---|
| | Response time (sec) | Maximum temp change (°C) | Response time (sec) | Maximum temp change (°C) |
| Hot water | 1.1 (0.3) | 23.6 (3.0)[a] | 3.1 (0.7) | 17.2 (4.2)[a] |
| Cold water | 1.4 (0.4) | 8.2 (0.8) | 3.9 (0.8) | 6.1 (1.3) |

[a]Significantly greater than cold water ($p < 0.001$)

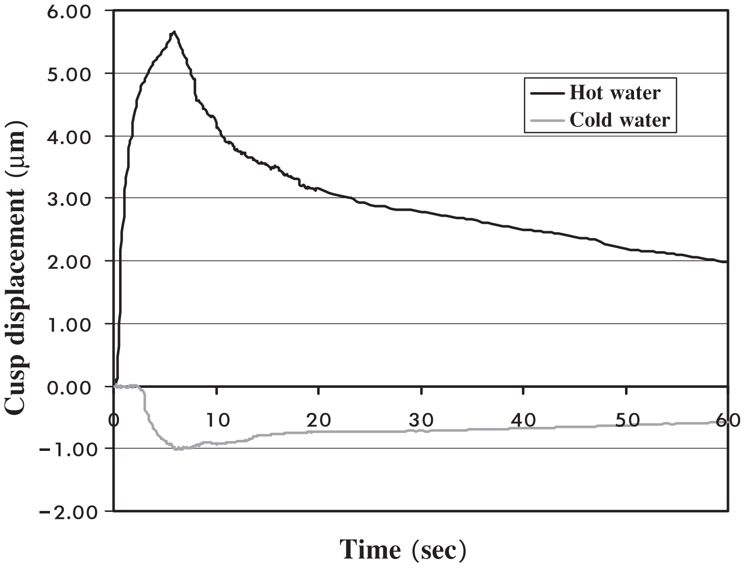

**Fig. 3** Cuspal movement over 60 seconds in response to immersion of the tooth in hot or cold water for 5 seconds. Heat caused cuspal expansion (cusps moving further apart) and cold resulted in smaller and slower cuspal contraction.

of 1-2 μm), with an initial delay of approximately 2.5 seconds in measurable response (Table 2).

Part B: Pulpal surface strain. Hot water resulted in more rapid detection of strain and the larger strain than cold water (Fig. 4, Table 2). Heat caused tensile strain while cold caused compressive strain. Pulpal strain was detected before any temperature change was recorded at the pulpal surface. A second phase of increasing strain occurred after the temperature change reached the pulpal surface, which was more gradual, longer lasting and greater in magnitude than the initial response (Fig. 4).

The extent of cuspal displacement and strain were compared with notional values based purely on coefficients of thermal expansion for enamel and dentine (Table 3). The measured cuspal displacement in response to hot and cold water was similar to the calculated values. However, the pulpal surface strain was approximately double the calculated strain based on simple expansion or contraction of dentine.

## Discussion

The thermal stimuli used in this study were approximately within the range of ingested fluids,

**Table 2.** Response time (sec) and magnitude of cuspal displacement (μm) and dentinal strain at the pulpal surface (μstrain) in response to thermal stimuli. [mean (SD), n = 8]

| **Stimulus** | **Cuspal displacement** | | **Pulpal surface strain** | |
|---|---|---|---|---|
| | **Response time (sec)** | **Displacement (μm)** | **Response time (sec)** | **Strain (μstrain)** |
| Hot water | 0.46 (0.15)$^a$ | 4.72 (0.64)$^a$ | 0.55 (0.23) | 364 (25)$^a$ |
| Cold water | 2.52 (1.31) | 1.18 (0.43) | 1.47 (0.72) | 134 (25) |

$^a$Significantly greater than cold water ($p < 0.001$)

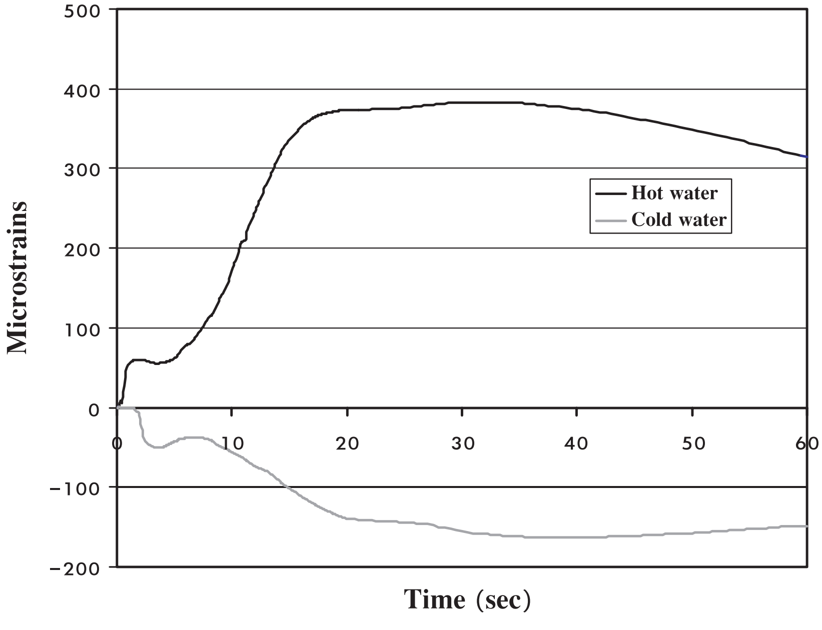

**Fig. 4** Strain on the pulpal dentine surface in response to hot or cold water. The first 60 seconds of strain in response to a 5 second application of heat or cold is shown. A positive value indicates tensile strain and a negative value compressive strain.

**Table 3**. Measured vs calculated cuspal displacement and pulpal surface strain in response to thermal stimuli.

| Stimulus | Cuspal displacement (µm) | | | Pulpal dentin strain (µstrain) | | |
|---|---|---|---|---|---|---|
| | ΔT (°C)[*] | Measured | Notional[#] | ΔT (°C)[*] | Measured | Notional[#] |
| Hot water | +62°C | +4.72 (0.64) | +4.9 | +17.2 | +364 (25)[ϕ] | +143 |
| Cold water | -19°C | -1.18 (0.43) | -1.5 | -6.1 | -134 (25) | -51 |

[*] Maximum temperature change recorded at the enamel surface (cusp displacement) or pulpal dentin surface (strain) (from Table 1).

[#] Notional cuspal expansion or contraction is calculated based on the coefficient of thermal expansion of enamel ($\alpha$ = 11.4 x $10^{-6}$/°C) and an intercuspal distance of 7 mm. Notional pulpal surface strain is based on the coefficient of thermal expansion of dentin ($\alpha$ = 8.3 x $10^{-6}$/°C).

[ϕ] A positive value indicates tensile strain, and a negative value compressive strain.

although immersion of the entire crown in hot or cold water, is more extreme than occurs during normal function. Temperature changes within the tooth depend on tooth location and the protective effect of the tongue and cheeks[5]. In one clinical study, approximal sites experienced a range of only 24-44°C[12], while the buccal surfaces of maxillary second molars and lingual surfaces of mandibular second molars registered almost no change during consumption of hot and cold drinks[3]. Such asymmetric exposure is not realistic in an experimental setup, but can be simulated using finite element analysis[4]. However, numerical models require experimental validation, and probably the best approach is a combination of the two methods.

In terms of tooth deformation, a faster response to heat than to cold was observed, and the magnitude of cusp displacement and pulpal strain was also greater. The difference can be explained by the direction of the temperature gradient across enamel and dentine. With a cold stimulus, the tendency for enamel to contract is opposed by the underlying warmer dentine. Contraction of the crown occurs only as dentine is also cooled, and hence occurs more slowly. Because the temperature decrease within dentine is less than in the overlying enamel, the extent of contraction is also less. The resultant tensile stress in enamel from the temperature gradient from the tooth surface to the pulp can be high enough to result in cracking, as is observed clinically or experimentally after repeated exposure of the tooth to cold[9]. On the other hand, with a hot stimulus expansion of enamel is not constrained by the underlying dentine. The cuspal expansion observed in this study in response to hot water (approximately 5 µm) is close to the calculated thermal expansion (Table 3).

The pattern of strains within dentine was different from that in incisors as reported previously[7], reflecting the more complex anatomy of molars and the application of stimuli over a wider surface area. Immersing the entire tooth crown in hot water resulted in cuspal expansion (cusps moved further apart); the extent of deformation was consistent with thermal expansion of enamel (and to a lesser extent of dentine) as discussed above. Heating also led to tensile strain on the pulpal surface of dentine. The magnitude of the strain was more than double that predicted from the coefficient of thermal expansion of dentine, reflecting both expansion of the entire crown and flexure within the crown. The response to cold water included inward cuspal movement, similar to what would be predicted by the temperature change and the coefficient of thermal expansion of enamel. Contraction was delayed by approximately 2.5 seconds, until the cooling effect reached underlying dentine. Strain on the pulpal surface was always compressive when the entire crown was immersed in cold water.

The significance of these observations for restorative dentistry should be noted. The crowns of teeth do not simply expand or contract on exposure to heat or cold. While this early study was limited to intact teeth, even more complex patterns of flexure are likely to occur in restored teeth. Fenner *et al*[4] attempted to map the stress distribution in restored maxillary premolars, in response to clinically realistic temperature change on the tooth surface in association with consumption of hot fluid. Their 3-dimensional FEA model demonstrated large maximum principal stresses within both enamel and dentine, including high tensile stress on the pulpal surface of dentine before any temperature change had reached the DEJ. The pattern of stresses also changed with time after the stimulus was removed and the tooth slowly returned to baseline temperature. Thus their model produced similar results to our experimental measurements in intact teeth. Linsuwanont *et al*[7] correlated experimental measurements in bovine incisors with simple geometric models, and demonstrated that the initial strain response was flexure of tooth structure, resulting from the steep thermal gradient across enamel and dentine.

Clearly the results of the present study must be extended to restored teeth, and FEA modeling in association with experimental measurement will allow a more detailed mapping of stress patterns. Fenner *et al*[4] demonstrated that heat-related stress across the tooth-restoration interface (with an MOD resin composite bonded restoration) varied extensively with location and depth, as well as time. It is evident, however, that teeth do not simply expand or contract linearly following exposure to heat or cold, and that a difference in the coefficients of thermal expansion of enamel and restorative material provides a very incomplete explanation for the behaviour of teeth subjected to temperature variations.

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# การเปลี่ยนรูปของฟันกรามที่ถูกถอนในการตอบสนองต่อสิ่งกระตุ้นชนิดอุณหภูมิ

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## บทคัดย่อ

***วัตถุประสงค์*** เพื่อศึกษารูปแบบการเปลี่ยนแปลงขนาดและรูปร่างของฟันเมื่อแช่ลงในน้ำร้อนและน้ำเย็น และเปรียบเทียบค่าการเปลี่ยนแปลงขนาดของฟันที่วัดได้กับค่าที่คำนวณจากค่าสัมประสิทธิ์การหดและขยายตัวของฟันต่อการเปลี่ยนแปลงของอุณหภูมิ

***วัสดุและวิธีการ*** ระยะการเคลื่อนของปุ่มฟันและแรงเค้นภายในเนื้อฟันถูกวัดในฟันกรามที่ถูกถอนในการตอบสนองต่อการจุ่มฟันลงในน้ำร้อนและน้ำเย็น การเคลื่อนของปุ่มฟันถูกวัดโดยใช้เอ็กเท็นโซมิเตอร์ที่ยึดติดกับปุ่มฟันด้านแก้มและด้านลิ้น แรงเค้นบนเนื้อฟันด้านที่ติดกับเนื้อเยื่อในถูกวัดด้วยเครื่องวัดแรงเค้นที่ยึดติดกับเนื้อฟันด้านที่ติดกับเนื้อเยื่อในด้านบดเคี้ยว การเปลี่ยนแปลงของอุณหภูมิถูกวัดด้วยเทอร์โมคัพเพิล ตัวฟันถูกแช่ลงในน้ำร้อนที่ 80 องศาเซลเซียส หรือน้ำเย็นที่ 2 องศาเซลเซียสเป็นเวลา 5 วินาที

***ผลการศึกษา*** การเคลื่อนของปุ่มฟันและแรงเค้นบนเนื้อฟันมีปริมาณมากกว่าและเกิดขึ้นเร็วกว่าในการตอบสนองต่อน้ำร้อนเปรียบเทียบกับน้ำเย็น แรงเค้นบนเนื้อฟันถูกตรวจพบบนเนื้อฟันด้านที่ติดกับเนื้อเยื่อในก่อนที่การเปลี่ยนแปลงของอุณหภูมิที่บริเวณนั้นเกิดขึ้น และมีค่ามากกว่าค่าที่คำนวณได้จากค่าสัมประสิทธิ์การหดและขยายตัวของฟันต่อการเปลี่ยนแปลงของอุณหภูมิที่วัดได้

***สรุป*** การเปลี่ยนแปลงขนาดและรูปร่างของตัวฟันมีรูปแบบที่ซับซ้อน ไม่เพียงแต่เกี่ยวข้องกับการหดและขยายตัวของฟันเนื่องจากการเปลี่ยนแปลงของอุณหภูมิเท่านั้น แต่ยังรวมถึงการหดหรืองอตัวของฟัน ซึ่งเป็นผลจากการเปลี่ยนแปลงอุณหภูมิผ่านชั้นต่าง ๆ ของฟัน

(ว ทันต จุฬาฯ 2555;35:39-48)

***คำสำคัญ:*** *การขยายตัวเนื่องจากการเปลี่ยนแปลงของอุณหภูมิ; การเปลี่ยนแปลงรูปร่างและขนาด; การหดตัวเนื่องจากการเปลี่ยนแปลงของอุณหภูมิ; ฟัน; สิ่งกระตุ้นในรูปแบบของอุณหภูมิ*