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Observations of crack damage in the tooth structure from in vivo *studies and* in vitro *experimental thermal cycling studies were combined with numerical analysis techniques to identify and isolate the influence of thermal stresses on the creation and propagation of cracks in teeth. The factors considered in this study included: (a) variations in tooth type or geometry (molar, bicuspid, etc.), (b) tooth age, (c) material properties of the tooth, (d) the magnitude of the change in the temperature of the environment surrounding the tooth, and (e) the thermal resistance between the tooth and the medium surrounding the tooth.*

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Careful examination of in vivo teeth with an intense light source often reveals cracks in the enamel. These cracks have generally been attributed to the mastication process, accidents, abnormalities in the maturation process, or to thermal stresses resulting from the ingestion of hot or cold food and drink. Because cracks in the enamel weaken the tooth structure, it is important to develop an understanding of the cause and extent of such damage. The objective of this study was to assess the influence of thermal effects on the formation and growth of cracks in teeth.

Previous in vitro studies at this laboratory have demonstrated that crack initiation and growth occur in the enamel when teeth are subjected to sudden and repeated fluid temperature changes.[1–5] It has also been shown that the magnitude of the damage is not merely dependent on the temperature of the environment but also on the thermal resistance between the medium and the tooth.[6] Thus, the manner in which the environmental temperature change occurs and the heat transfer properties of the medium are also important.

The current study included numerical analysis of the temperature and stress distributions in teeth subject to a sudden change in environment, as well as experimental studies on extracted teeth which were subjected to temperature cycling. Both whole and restored teeth were analyzed, but the results presented here are for whole teeth only. A succeeding paper will discuss the results for restored teeth.

Methods and Procedures

Teeth used in the experimental portion of the study were obtained from local oral surgeons. Sets of small vials, filled with a Minimum Essential Medium (MEM) storage solution were supplied to each surgeon. At the time of extraction, teeth were placed in the vials and the age and sex of the patient, and date of extraction, were recorded. Vials were collected twice a week and teeth were stored at a constant temperature of 4 C until used. Teeth

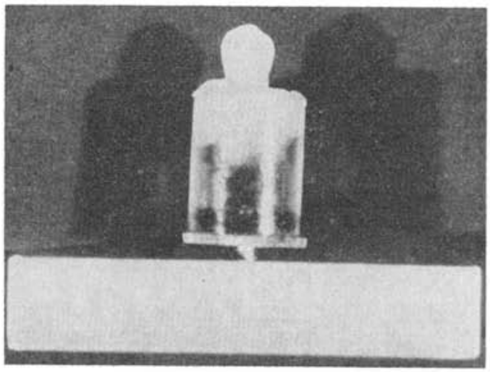

FIG 1.—Bicuspid prepared for thermal cycling tests. Note root portion immersed in MEM solution.

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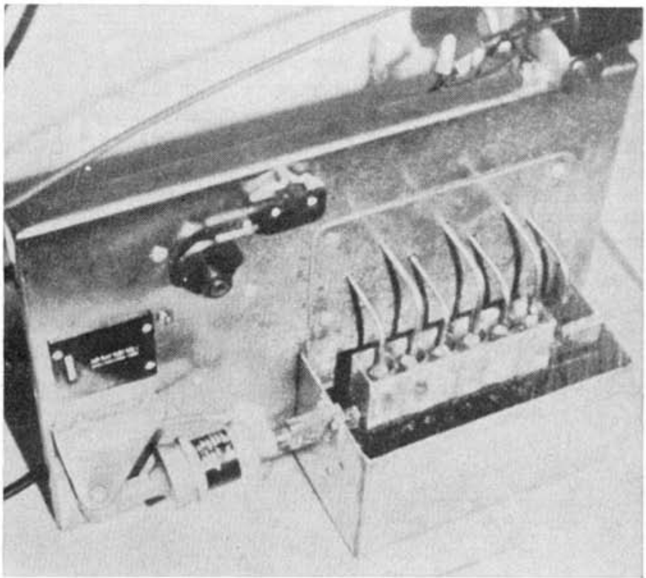


FIG 2.—Thermal cycling apparatus.

were prepared for thermal cycling experiments by mounting them in acrylic holders, as shown in Figure 1. The acrylic mounting devices were constructed so that the root of the tooth was immersed in MEM solution in an attempt to maintain the viability of the tooth to the fullest extent possible. The storage solution was Eagle's Minimum Essential Solution with Hank's Basic Salt Solution plus 5% calf serum. Penicillin and streptomycin, respectively, were added to control bacterial growth.

Cracks, open to the surface of each tooth, were enhanced for visual observation by treating the tooth with a fluorescent dye penetrant.* This dye is used extensively for detection of microscopic surface cracks in metals, ceramics, plastics, and glass. Cracks, lamella, or other defects which were not open to the surface were detected and mapped by use of high intensity translucent lighting techniques. Quantitative measurement of the crack lengths was achieved by use of high magnification photographic techniques. A Nikon F camera and bellows with Micro Nikkor Auto 55 mm f/3.5 lens was used to photograph the surfaces of each tooth under a fluorescent light immediately after treatment with dye. A grid of known size was then superimposed with the resulting photographic slide and the crack length was measured and recorded. Using this technique crack growth could be monitored and recorded at intervals throughout the testing process.

The thermal cycling apparatus is shown in Figure 2. This apparatus allowed six teeth to by cycled between hot and cold streams of water. A pneumatic solenoid, actuated by a rotating cam and microswitch, shifted a given tooth from the hot to the cold stream of water at a constant frequency. A digital counter recorded the number of cycles. The cycling apparatus and temperature control valves were designed so that precision control of a variety of water temperatures, water flow rates, and cycling frequencies could be achieved.

Thermal Stress Analysis

In general, the thermal stress in a structure in which the temperature changes from T_0 to T is given by $\sigma = K \alpha E(T - T_0)$ where σ is the thermal stress, α is the linear coefficient of expansion, E is the modulus of elasticity and K is a restraint coefficient, dependent on geometry, external restraints and Poisson's ratio for the material. The temperature, T, can be determined as a function of time, t, from the heat conduction equation,

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

where α is the thermal diffusivity, a physical property obtained by dividing the thermal con-

* Zyglo Penetrant ZL-22A, Magnaflux Corporation, Chicago, Il.

ductivity by the product of density and specific heat, and x, y, and z are space coordinates. Convection is the dominant heat transfer mechanism between surrounding fluids, such as air or water, and the tooth. A convective heat transfer boundary condition is appropriate for the exposed portion of a tooth when solving the conduction equation. Convective heat transfer is governed by the relation $q = h_c A(T_f - T)$, where q is the rate of heat transfer, A represents area, T_f is the fluid temperature and h_c is the convective heat transfer coefficient.

A tooth is a complicated structure containing regions with marked differences in physical properties. For a composite material structure with a geometry as complex as a tooth, it is impossible to obtain meaningful solutions to the conduction and thermal stress equations by exact analytical means. However, numerical solutions utilizing finite difference techniques for temperature and finite element techniques for stress are quite feasible. By subdividing the problem into small regions, where analytical characterization is feasible, and matching the boundary conditions between regions, the equations can be solved simultaneously by a computer. This results in discrete values for the temperature and stress throughout the tooth as a function of time.

This study utilized two-dimensional, axisymmetric, finite difference and finite element codes to calculate the transient temperature and stress distributions in the tooth. The rather sophisticated computer codes used in this study were developed by Thiokol Chemical Company for aerospace applications and are well suited to this application. References 7 and 8 provide further details of the governing equations and numerical solution techniques. Values of physical properties used in the numerical calculations were generally obtained from the literature and are shown in the Table.

Because the geometry of a tooth is irregular, it was necessary to develop an idealized representation of a tooth for use in the numerical analyses. An axisymmetric model of a mandibular second molar was developed for this purpose. It was reasoned that the three-dimensional model could be typified by an axi-

TABLE

MATERIAL PROPERTIES OF ENAMEL AND DENTIN

Material	Modulus of Elasticity, "E" (× 10^6 psi)			Poisson's Ratio, "ν"	Coefficient of Thermal Erpansion "α" (× 10^{-6}/°C)	
	Compressive	Tensile	*	*		*
Enamel	1.8–8.2 1.4–9.1 11.3–12.2		6.7	0.25	12.0	12.0
Dentin	2.2 2.4–2.7 1.7–2.4	2.8 0.55–3.15	1.7	0.25	7.5	7.5

Material	Thermal Conductivity, "k" (× 10^{-3} cal/sec cm°C)		Density, "ρ" (gm/cm³)		Specific Heat, "C" (cal/gm°C)		Thermal Diffusivity, $\frac{k}{\rho c}$ (× 10^{-3} cm²/sec)	
		*		*		*		*
Enamel	2.23 1.56 2.2	2.23	2.8 2.84–2.87 2.96	2.8	0.17 0.18	0.17	4.69 4.20	4.69
Dentin	1.36–1.39 0.96–1.07 0.257 1.5 2.29	1.36	1.96 2.11	1.96	0.38 0.28	0.38	1.83–1.87 2.60	1.83

* Base values used for this study.

symmetric configuration which could be obtained by revolving the half section of the tooth about the Z–Z axis. Although a cross section of an actual tooth would not really be circular, this model does offer a reasonable approximation and permits solution with a two-dimensional computer code. Figures 3 and 4 display the tooth geometry and the grids used in the finite difference temperature and finite element stress analysis. The grids shown were developed by comparing the numerical techniques with experimental results and exact analytical solutions for a number of simplified problems.

Results and Discussion

The temperature and thermal stress distributions were calculated for a tooth suddenly immersed in a stream of water 28 C below the tooth temperature. The calculation model was designed to simulate conditions resulting from drinking cold liquids. Figure 5a shows the calculated temperature pattern which devel-

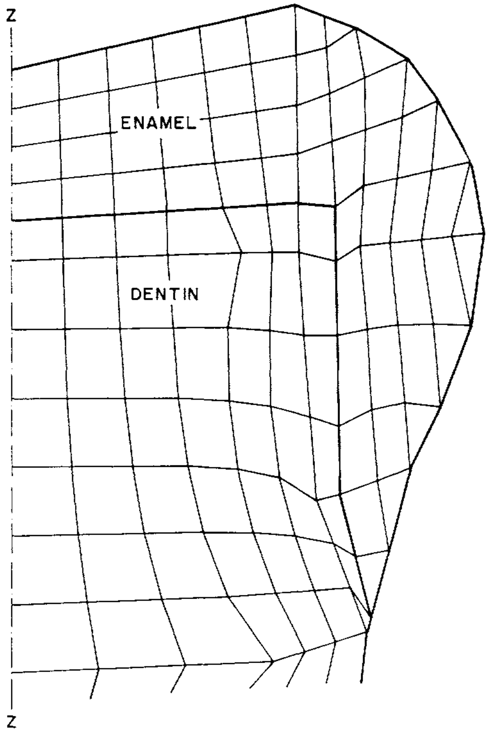


FIG 3.—Mandibular second molar (half section), standard grid for heat transfer analysis.

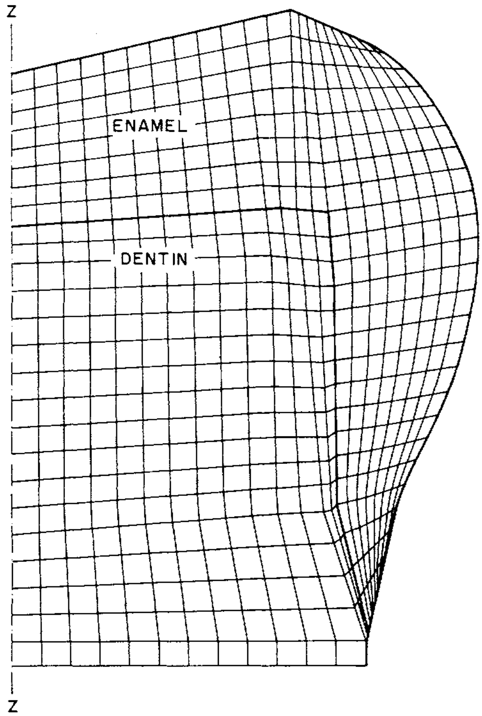


FIG 4.—Mandibular second molar (half section), standard grid stress analysis.

oped in a molar one second after exposure to the cold fluid. Figure 5b shows the variation of calculated temperature with time for three locations: (1) in the enamel adjacent to the tooth surface, (2) adjacent to the dentin-enamel junction, and (3) in the dentin near the pulp region. Two important observations can be made from these data. First, because both enamel and dentin are good thermal insulators, the pulp tissue is well protected from thermal shock. Even after 10 seconds of exposure in a flowing fluid medium 28 C below the temperature of the pulp tissue, the dentin temperature adjacent to the pulp changed only 11.5 C. Solid foods at the same temperature as the fluid would result in smaller temperature changes due to their poor heat transfer characteristics.[6] Figure 5 also illustrates that the temperature gradient in the outer portion of the enamel is extremely high. The thermal diffusivity of enamel is two and one-half times that of dentin which indicates that enamel has a much greater ability than dentin to dissipate energy. As a tooth is subjected to a stream of cold water, the outer layer of enamel

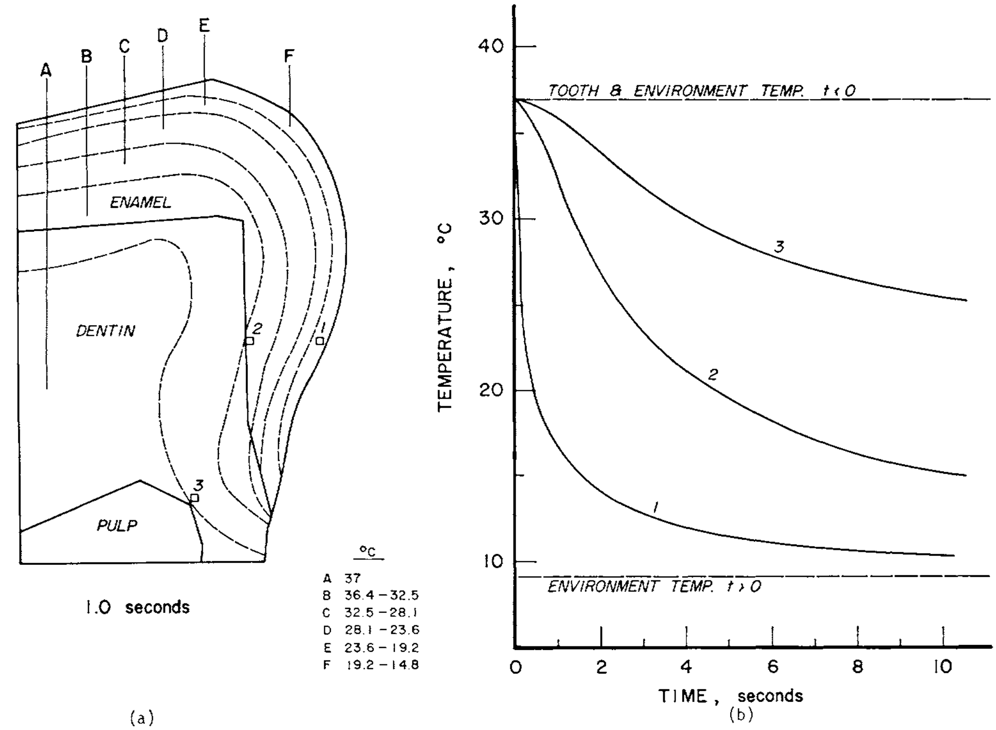


FIG 5.—Temperature pattern in a molar as a function of location and time when exposed to water 28 C lower in temperature than the original tooth temperature of 37 C. Figure 5a shows temperature pattern after 1.0 second; Figure 5b shows temperature patterns at locations 1, 2, and 3 as a function of time ($h_c = 7.1 \times 10^{-2}$ cal/sec cm^2 C).

cools quickly, resulting in a large temperature gradient. Figure 5b indicates that the temperature difference between surface enamel and enamel at the d-e junction is 9.9 C at 0.1 second after exposure, 15.2 C after 1 second, and 12.7 C after 2 seconds, and 4.8 C after 10 seconds. The maximum thermal gradient in the enamel develops within the first second after exposure. Since the thermal stress is essentially proportional to the temperature gradient, the relatively large temperature gradients shown in Figure 5a, coupled with the complex geometry and relatively low thermal conductivity of enamel, should cause significant thermal stresses in the enamel. Figure 6a displays the distribution of the thermal stress in a circumferential direction around the tooth, as calculated by the finite element computer code for the temperature distribution shown in Figure 5a.

The numerical solution confirms physical reasoning concerning thermal stress. As the exterior of the tooth is subjected to a cold liquid, the outer layer of enamel attempts to contract. The dentin does not sense the low temperature immediately and, therefore, has no tendency to contract. Since the dentin structure is significantly larger than the thin outer shell of enamel which is cooled, the enamel shell is prevented from contracting. This condition creates tensile stresses in the circumferential or hoop direction at the surface of the enamel, and compressive hoop stresses in the dentin and in portions of the enamel near the d-e junction. Figure 6b illustrates that the thermal stress peaks approximately one second after exposure to the cold fluid and then recedes as the tooth temperature approaches the temperature of the liquid.

Several studies have been reported in which strength and modulus of elasticity have been measured for dentin and enamel. Enamel has a compressive strength in the range of 40,000 to 50,000 psi, a tensile strength in the range of 1,500 to 5,000 psi, and an elastic modulus in the range of 6 to 12 + 10^6 psi.[9–14]

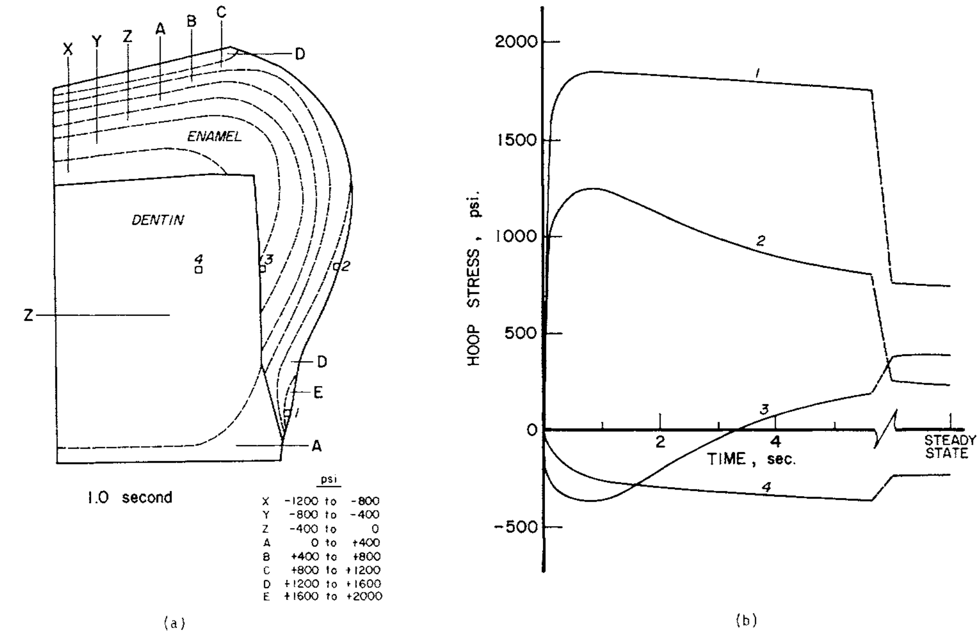


FIG 6.—Stress pattern in a molar as a function of location and time when exposed to water 28 C lower than its original temperature as shown in Figure 5. Figure 6a shows the stress pattern after 1.0 second; Figure 6b shows the stress values at locations 1, 2, and 3 as a function of time.

Dentin has approximately the same compressive strength, 40,000 to 50,000 psi, a higher tensile strength, 4,000 to 8,000 psi, and a lower elastic modulus 1.7 to 3.0×10^6 psi.[10–16] The wide range of values reported for the elastic modulus is especially significant to the thermal stress calculations since thermal stress is linearly dependent on the elastic modulus. Thus, the calculated values can vary significantly, depending on the elastic modulus values used in the analysis. For most of the calculations, an enamel elastic modulus of 6.7×10^6 psi was used; however, some of the calculations were repeated using a value of 12×10^6 psi.

Comparison of the calculated stresses, using the lower elastic modulus, with strength values reported in the literature indicates that at most locations the thermal stresses are significantly below the fracture level. However, the tensile stress in the gingival region exceeds the lowest strength values reported. This suggests the possibility of vertical tensile cracks forming in this region. Because the enamel is very thin in this region, not only is the immediate transient stress large, but it remains large during the environmental temperature change. Furthermore, teeth are subjected to temperature cycles in the mouth as the result of breathing and ingesting food and liquids. Consequently, the teeth will experience corresponding cycles of thermal stress which may cause the tooth material to fatigue, resulting in the initiation and propagation of cracks over a period of time.

Verification of this analysis was obtained from both in vivo and in vitro observations. Almost without exception, all freshly extracted teeth exhibited some cracks or fractures in the enamel at the gingival margin, extending in length toward the occlusal surface. An example of the crack damage observed at the time of extraction is shown in Figure 7a. The number and length of these cracks varied with tooth type, tooth age, and even within teeth of the same type and age.

The amount of crack initiation and growth resulting from in vitro thermal cycling are presented in Figure 7b. The term crack length is used to represent the sum of the lengths of all cracks in a tooth. An average value is used to represent each set of teeth. The conditions of the in vitro tests closely matched the condi-

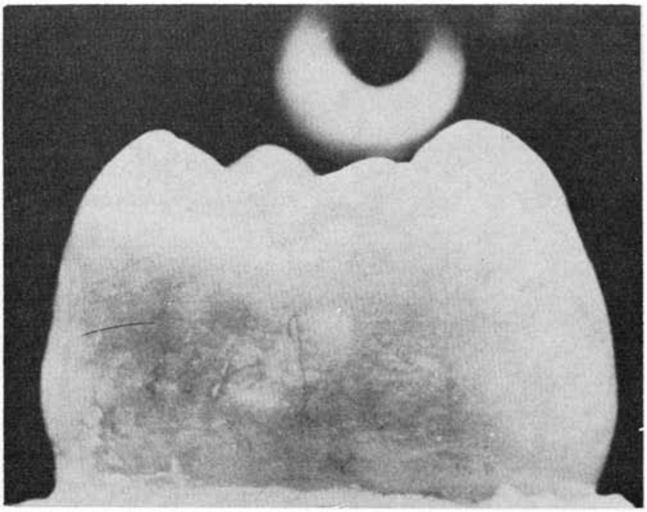


FIG 7a.

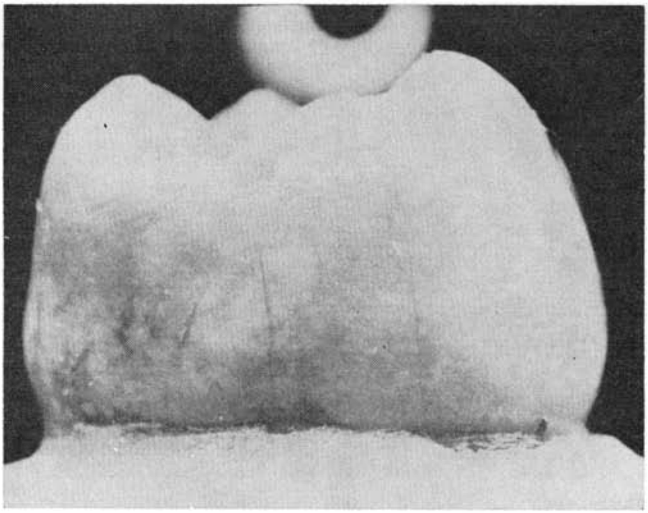


FIG 7b.

FIG 7.—Crack patterns in a third molar from a 24-year-old donor before and after thermal cycling with a 28 C temperature differential. (a) Before cycling; (b) after 3,160 cycles.

tions of the numerical analysis previously discussed (see Figs 6a and 6b). All cracks penetrated only the enamel portion of the tooth structure, as shown in Figure 8, and were on the order of a micron in width.[17]

The average crack growth patterns for third molars and bicuspids cycled under these conditions are plotted in Figure 9. Analysis of these data indicates the crack damage appears to occur in two stages. The first stage is a rapid growth rate occurring within approximately 2,000 thermal cycles. The extent of this first stage crack growth is determined by the inherent strength of the enamel, the tooth geometry and the magnitude of the stress produced by the cycling. The end of the first stage will occur when the number of existing cracks is sufficient to relieve the stress on the surrounding tooth structure. This stress relief is provided as the cracks open and close during the alternating load cycle periods. After this point is reached, a second stage, marked by a much slower rate of crack growth, occurs. This crack growth is the result of fatigue caused by continued cycling.

A comparison of bicuspids and third molars approximately the same age from eruption reveals that greater crack growth occurs in third molars when subjected to the same cycling conditions (third molars ~ 7½ mm in 2,000 cycles; bicuspids ~5 mm in 2,000 cycles.) Part of this difference can be accounted for by

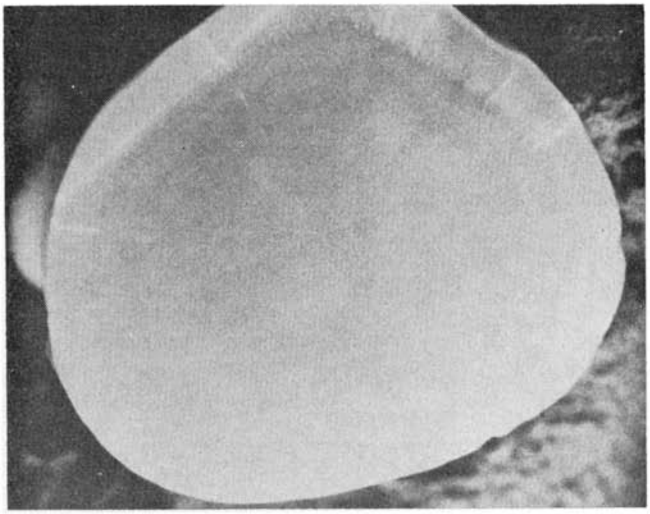


FIG 8.—Crack patterns in a transverse section of a third molar after being subjected to 4,000 thermal cycles of a 28 C temperature differential.

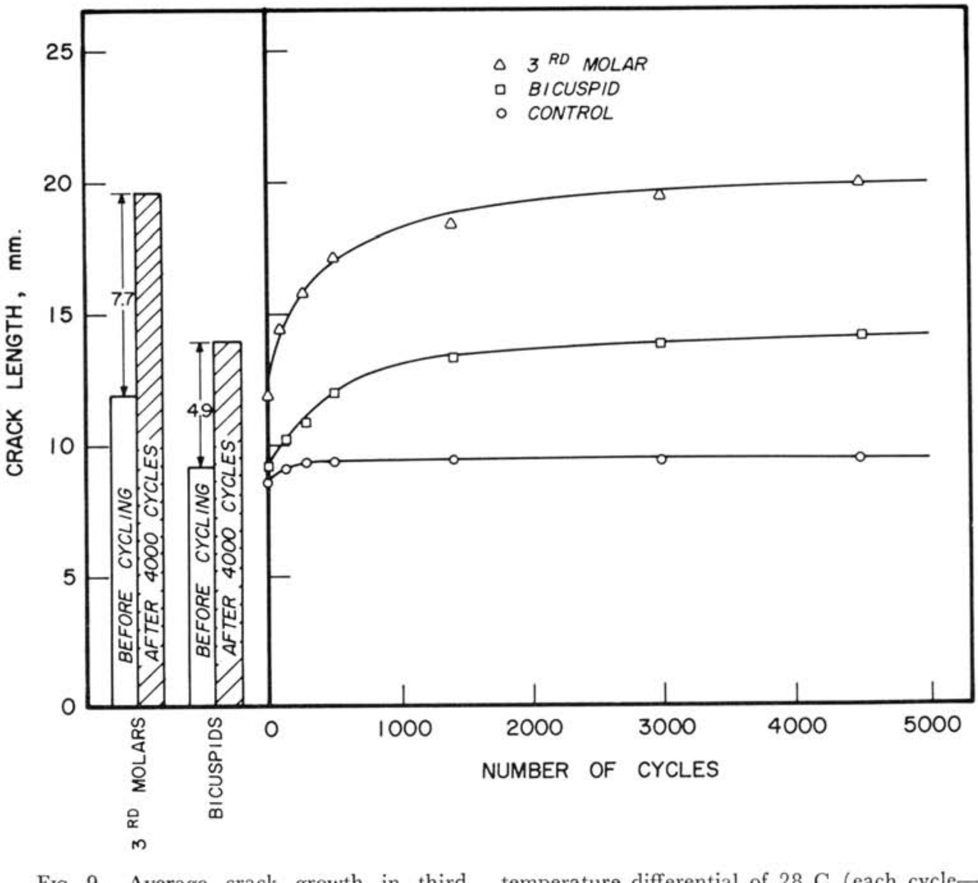


FIG 9.—Average crack growth in third molars (average age 20.4 years—24 samples) and bicuspids (average age 13.2 years—43 samples) subjected to thermal cycling with a temperature differential of 28 C (each cycle—30 seconds at 52 C and 30 seconds at 24 C). Control sample is shown for bicuspid (no thermal cycling for same time period).

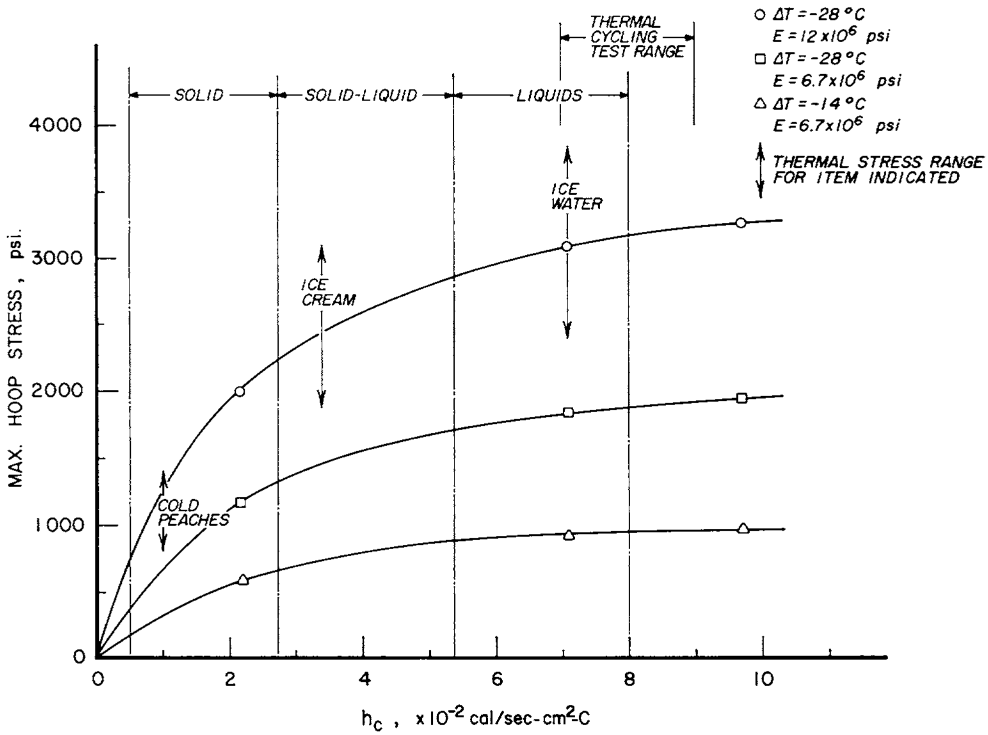
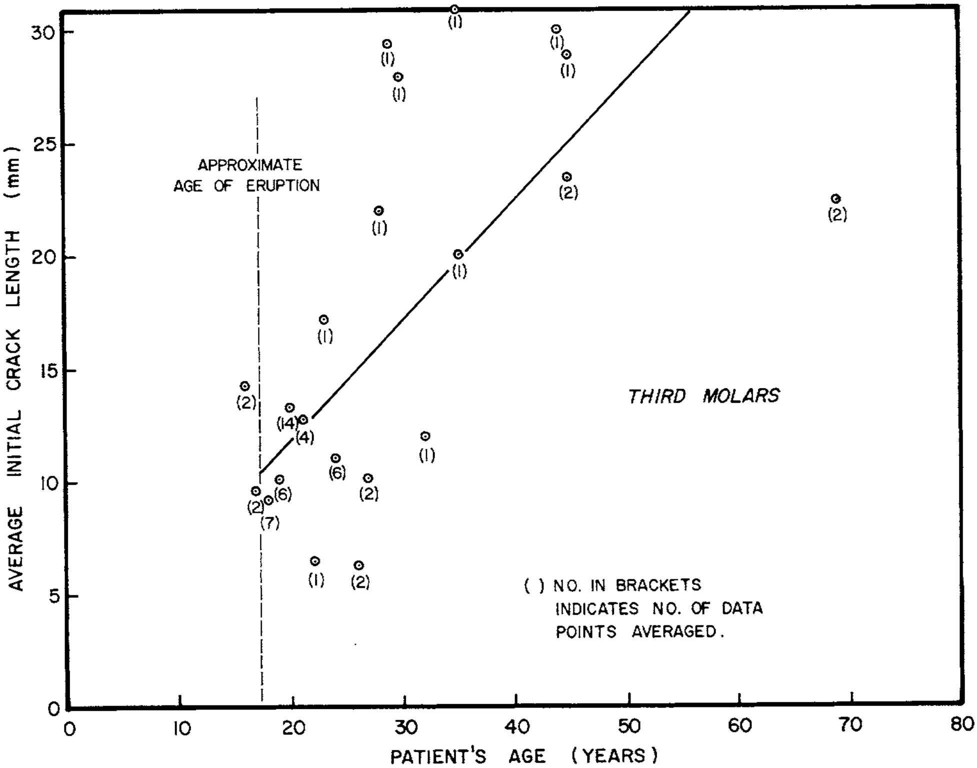


FIG 10.—Comparison of tensile stress levels in enamel at the gingival margin (for computer code analysis) as a function of connective heat transfer coefficient (h_c), enamel modulus of elasticity (E), and food and liquid temperature differential.

the larger initial crack damage in molars. The stress required to propagate an existing crack is much less than that required to initiate a new crack and in this study approximately 75% of the crack growth resulted from the propagation of existing cracks. However, normalizing the crack growth with respect to the initial crack length still indicates a 64% increase in crack growth in molars and only a 54% increase in crack growth in bicuspids.

The effects of other thermal environment changes were examined numerically with some experimental verification. Figure 10 combines results of this study and a previous study[6] to indicate the maximum stress levels that might be expected in the gingival enamel region. The two most significant factors influencing thermal stresses in whole teeth are the temperature difference between the tooth and the ambient media, and the convective heat transfer coefficient between the tooth and the media. Calculations were performed with different values of these parameters and also the modulus of elasticity. The results are shown in Figure 10 where, for a temperature difference of 28 C, a heat transfer coefficient of 7.1×10^{-2} cal/(sec-cm^2 C) and an elastic modulus of 12×10^6 psi, the stress in the gingival enamel is 3,100 psi, compared to 1,800 psi for a modulus of 6.7×10^6 psi. Even the lower modulus value predicts a tensile stress above the lower range of strength values in the literature. Thus, cracks in human teeth should not be uncommon.

From both the numerical analysis and experimental observations it appears that the enamel is quite susceptible to fracture if exposed to abrupt cooling. Such damage, if not repaired, would accumulate over the years and appear to make teeth more brittle with age. To evaluate this effect 66 bicuspids from donors ranging in age from 9 years to 65 years, and 59 molars from donors age 16 through 69 years were examined at the time of extraction for crack damage. Figure 11 shows these results for third molars and bicuspids. Once



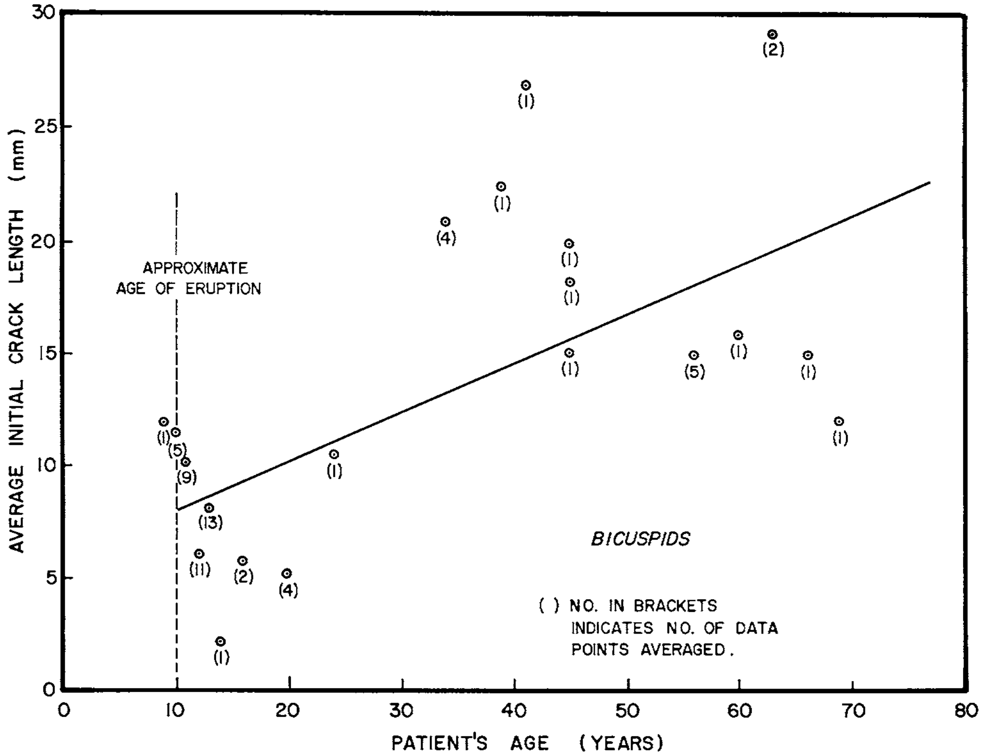
11b.

FIG 11.—Crack damage in third molars (11a) and bicuspids (11b) at the time of extraction from donors of various ages.

again, there appears to be a two-stage crack growth pattern, where either prior to eruption or shortly after eruption, an initial crack level is developed in the tooth followed by a slow fatigue growth pattern for the life of the tooth. As previously observed in the cycling tests, third molars exhibit greater initial crack damage (molars ~ 10 mm, bicuspids ~ 8 mm) and a greater fatigue growth rate (molars ~ ½ mm per year, bicuspids ~ ¼ mm per year) than bicuspids.

As seen in Figures 11a and 11b, the extent of crack damage may vary greatly between teeth of the same age. However, the amount of crack damage generally increases with age. Certainly variations in material properties of teeth and differences in the oral environment are major contributors to this fact.

As a final note, it is interesting to observe that the in vitro thermal cycling tests cause as much damage within a few thousand cycles as appears to occur in in vivo observations over several years. The authors believe the differences can be explained by two factors: (a) individuals generally (perhaps because of response to pain) prevent abrupt temperature changes from occurring around the tooth through selective direction and placement of fluids and solids, and (b) the tongue, cheek and gingival tissues help to shield the enamel in the critical gingival region from abrupt temperature changes. Both of these factors would effectively reduce in vivo thermal stress levels experienced by the tooth. However, even with such shielding, stress levels apparently are great enough to cause cumulative crack damage over a period of years. A recent study indicates that these cracks may become sealed or filled by a soft organic substance in vivo, but they apparently are never structurally repaired.[17] Further details of this work can be found in reference 18.



11b

Fig. 11—(Continued)

Conclusions

It is evident from this analysis that ingestion of cold food or drink can create thermal stress in the tooth of sufficient magnitude to cause cracks in the enamel. The magnitude of the stress depends on the temperature difference between the tooth and the environment, the heat transfer coefficient, the geometry of the tooth and its physical properties. Cracks induced in the teeth by thermal stress may grow in length as they are subjected to further thermal stress or to mechanical stress due to the mastication process or other forms of mechanical loading. Similarly, thermal stress may cause crack growth in cracks initially caused by mechanical stress.

Drinking ice water can certainly cause excessive thermal stresses, and related exposure of the tooth to cold water can eventually result in crack damage. It is not clear that cracks always result in deleterious effects but such cracks clearly weaken the tooth structure. The most effective steps in retarding this damage are to avoid food and drink of extremely low temperature and/or to prevent sudden exposure of the tooth to extreme temperature changes by selectively directing the fluids or solids away from the teeth until their temperatures tend to equilibrate to mouth temperature.

Appreciation is expressed to oral surgeons, Dr. E. H. White and Dr. D. S. Judd, of Salt Lake City, who supplied the extracted teeth, R. Sluder and R. Packer for obtaining much of the experimental data, computer consultants Garron Anderson and Thomas Charlton for their assistance with the numerical analysis and Thiokol Chemical Corporation for the use of the computer codes.

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