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Temperature excursions at the pulp–dentin junction during the curing of light-activated dental restorations

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ABSTRACT

Objectives. Excessive heat produced during the curing of light-activated dental restorations may injure the dental pulp. The maximum temperature excursion at the pulp–dentin junction provides a means to assess the risk of thermal injury. In this investigation we develop and evaluate a model to simulate temperature increases during light-curing of dental restorations and use it to investigate the influence of several factors on the maximum temperature excursion along the pulp–dentin junction.

Methods. Finite element method modeling, using COMSOL 3.3a, was employed to simulate temperature distributions in a 2D, axisymmetric model tooth. The necessary parameters were determined from a combination of literature reports and our measurements of enthalpy of polymerization, heat capacity, density, thermal conductivity and reflectance for several dental composites. Results of the model were validated using *in vitro* experiments.

Results. Comparisons with *in vitro* experiments indicate that the model provides a good approximation of the actual temperature increases. The intensity of the curing light, the curing time and the enthalpy of polymerization of the resin composite were the most important factors. The composite is a good insulator and the greatest risk occurs when using the light to cure the thin layer of bonding resin or in deep restorations that do not have a liner to act as a thermal barrier.

Significance. The results show the importance of considering temperature increases when developing curing protocols. Furthermore, we suggest methods to minimize the temperature increase and hence the risk of thermal injury. The physical properties measured for several commercial composites may be useful in other studies.

1. Introduction

Thermal irritation of teeth can cause pulpitis or even pulp death. While the range of safe temperatures is not accurately known, it is often stated, based on Zach and Cohen's work on rhesus monkeys [1], that temperatures higher than 42.5 °C can cause irreversible damage to the pulp. Photopolymerizing dental resin composites can produce a considerable

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amount of heat, both because of the light energy from the curing lights and because the polymerization is exothermic. Many researchers (*e.g.* [2–9]) have experimentally investigated the temperatures produced during the light-curing of dental restorations, including effects of light intensity, irradiation time, composite and light selection, and residual dentin thickness. The results show temperature increases that might be sufficient to cause thermal injury. This risk is enhanced by the general trend to use very high power curing lights in an attempt to reduce curing time.

Given the prevalence of composite restorations and the clinical importance of avoiding injury to the pulp, efforts should be made to minimize the temperature increase that occurs at the pulp–dentin junction (PDJ) during light-curing. Finite element method (FEM) modeling is a useful tool to advance understanding of the factors that affect the temperature increase in the pulp. In principle, the temperature increase depends on many factors including the curing light intensity, curing time, composite properties (enthalpy of polymerization, thermal conductivity, density, heat capacity, reflectance, and light penetration depth), restoration size, amount of remaining dentin, presence of thermal barrier layers, and convective heat loss. FEM, which previously has been used to model temperature and stress distributions in teeth resulting from hot and cold liquids in the mouth [10–15], is an ideal tool to investigate this problem as multiple parameters can be varied independently and a large number of cases can be studied in a fraction of the time required to perform experimental measurements.

Our hypothesis is that a FEM model, based on simple assumptions, will accurately simulate the temperature excursion at the PDJ during the photocuring of a dental restoration. It is expected that the material properties and energy input from the curing light, which depends on the curing time and light intensity, will affect the magnitude of the temperature increase. The FEM model is applied to determine the most important factors in causing potentially dangerous temperature increases in the pulp.

2. Materials and methods

2.1. *Determination of material properties*

To obtain useful results from FEM simulations of the temperature increase at the pulp–dentin junction, it was necessary to determine typical properties for light-cured dental composites. The required material properties, heat capacity (C_p), density (ρ), enthalpy of polymerization (ΔH_{polym}), thermal conductivity (κ), reflectance (R), and light penetration depth (α), were determined from a combination of literature results and new experiments. The experimental methods are described briefly here.

Heat capacity density and enthalpy of polymerization were measured for five composites: Filtek™ Flow (3M/ESPE, shade: A2), Filtek™ Z250 (3M/ESPE, shade: A2), PermaFlo® (Ultradent, shade: dentin opaquer), Point 4™ (Kerr, shade: A2), and Revolution® Formula 2 (Kerr, shade: A2). Heat capacities of the fully cured materials were measured by relaxation calorimetry using a Physical Property Measurement System (PPMS; Quantum Design, San Diego, CA) with heat capacity option. Three measurements were performed at each temperature. Density was calculated from measurements of mass and volume for samples of cured materials at room temperature. Although no special procedures were taken to eliminate voids, the resulting densities reflect what would be obtained for a carefully placed restoration in the mouth.

Enthalpy of polymerization was measured using a Pyris 1 Differential Scanning Calorimeter (PerkinElmer, Waltham, MA). A small amount (~30 mg) of composite was placed in an uncovered DSC pan on the sample heater of the DSC. A cover was used to isolate the sample and reference heaters and minimize influence of ambient air fluctuations while still allowing a curing light (Virtuoso, Den-Mat Corporation, Santa Maria, CA) to be positioned over the composite. The light, which delivers approximately 0.66 W of radiant power for a duration of 5 s, was clamped into place and activated remotely to avoid movement. Two experiments were required to determine ΔH_{polym}. In the first exposure, the light was activated causing the resin composite to polymerize. A second exposure with the cured composite was done immediately. The second exposure included only the heat from the light; therefore ΔH_{polym} was determined as the difference between the two experiments. A third light exposure was carried out and compared to the second exposure and confirmed that additional polymerization during the second exposure was negligible. The DSC experiments were done in isothermal mode at 35 °C. The accuracy of the results is affected by the assumption that the uncured and cured materials have the same thermal properties and is addressed in the discussion.

Thermal conductivity and reflectance were measured for four cured composites: Filtek™ Supreme (3M/ESPE, shade: A2), Heliomolar® (Ivoclar Vivadent, shade: A2), PermaFlo® (Ultradent, shade: A2), and Vit-l-esence™ (Ultradent, shade: A2). Thermal conductivity measurements were conducted using a Physical Property Measurement System (PPMS) with thermal transport option (Quantum Design, San Diego, CA). The PPMS employs a transient technique and curve fitting to determine thermal conductivity from measurements of the temperature difference across a sample as a function of time resulting from a known heating power, as described by Dilley et al. [16]. Reflectance was measured using a USB4000 Miniature Fiber Optic Spectrometer (Ocean Optics, Dunedin, FL) at normal incidence. Reflectance was measured relative to a highly reflecting PTFE reference (Ocean Optics) that reflects greater than 98% of light from 400 to 1500 nm. Multiple measurements were made on flat, 2 mm thick samples of composite.

2.2. *Finite element method modeling*

Time-dependent FEM modeling was performed using COMSOL 3.3a (COMSOL Inc., Burlington, MA). 2D axisymmetric geometries were used and results were checked for convergence to ensure there was no significant