Finite Element Study on Thermal Effects in Root Canals During Treatment with a Surface-absorbed Laser

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Purpose: Because unwanted thermal damage may occur during laser treatment of root canals, this study was conducted to determine temperature distributions in the tooth and the periapical tissue using a finite elements model.

Materials and Methods: To calculate the temperature distribution, a numerical model of a mandibular molar was developed and edited for use with the finite element (FE) model. For the simulations, density, specific heat, and heat conductivity were included as a set of material constants. Heat deposition was simulated for a surface-absorbing laser system at an average power of 1.5 W whose properties were modeled within the simulation program. This corresponds to the power settings and laser-tissue interaction of an erbium laser with a repetition rate of 20 Hz, pulse energy of 75 mJ, pulse duration of 150 µs, and a full angle of divergence of 25 degrees.

Results: The FE analysis of the tooth showed a heat concentration in the region of the apical root canal wall. The temperatures of ca 100°C in this region drop very quickly during the treatment process and are not conveyed to the neighboring tissue. Temperatures of up to 40 to 52° C were found on the root surface for a period of 8 s.

Conclusion: The rapid decline of the temperatures on the root surface simulated in this finite element study makes it clear that thermal damage of the surrounding tissue can be avoided if treatment instructions – including power settings and treatment time – are followed.

Key words: endodontics, finite element, heat stress, root canal.

J Oral Laser Applications 2005; 5: 31-36. *Submitted for publication: 14.06.04; accepted for publication: 10.11.04.*

For lasting therapy success on a chronically infected tooth, the disinfection of the root canal is of utmost importance. In conventional therapy, the root canal is mechanically enlarged up to 1 mm from the radiographic apex. This is done by hand or by the use of an ultrasonic system.[1] Conventional canal preparation is supported by irrigation, primarily with NaOCl solution, which dissolves organic tissue and acts as a strong disinfection medium.[2] A smear layer is created by the mechanical preparation, which cannot be removed entirely by the NaOCl.[3]

A modern approach to bacterial reduction in the root canal is the application of laser radiation.[4] Numerous studies indicate that the smear layer in the root canal is removed by the laser light. Furthermore, the laser may seal off the root canal wall dentin.[5-9] Gutknecht et al verified a germ reduction of 99.91% in vitro with a pulsed Nd:YAG laser,[10] as did Hardee et al.[11] A large reduction in bacterial count was also found in vitro for the Ho:YAG and the diode laser at 810 nm.[12,13] Using Er:YAG laser, bacteria count reductions of 53% have been reported.[25]

The clinical application of laser in the root canal is only possible if the neighboring periapical tissue does not suffer thermal stress. The critical temperature for irreversible bone necrosis is 47°C, 10°C above the normal body temperature in the mouth.[14] Some of the measured temperatures on the root surface of extracted human teeth were in this vicinity.[15] The aim of this study was to calculate the temperature distribution in the root canal and neighboring tissue during a simulated laser treatment using a finite elements model (FEM). For the calculations, the tooth, periodontal ligament, and mandibular bone were included in the model. The apical third is of specific interest in this region. Furthermore, the temperature influence due to heat conductance to other root canals was included in the model by simulating a tooth with two root canals. The amount of heat deposition per time and the movement of this heat source can be obtained from the guidelines for laser treatment.

MATERIALS AND METHODS

Using data from the literature,[16] a computer model of a human mandibular molar was created and cut into many horizontal slices using a microtome. Slices were made from coronal to apical, starting from slice thicknesses of 1000 µm in the coronal region to 100 µm in the apical region. The final FEM was calculated from these slices in the FE preprocessor of the COSMOS /M software (SRAC, Los Angeles, CA, USA) as seen in Fig 1. COSMOS/M software uses interpolation between the slices to generate a voxel model of the tooth. The created voxels are not uniform in size, but are smaller in the apical area for increased numerical precision. The average length of a voxel is ca 500 µm. The smallest voxels in the apical region are about 10 to 20 µm in length (Fig 1). Material properties of the molar were obtained from the literature[17-20] as shown in Tables 1 to 3.

Regarding the quality of the data in literature on the materials, the data for the density are relatively exact (± 2% in the case of jaw bone, ± 5% for the desmodont). The data for heat conductivity, however, show a broad variety. For dentin, it can be from 0.6 to 2.2 W/mK. In our simulations, λ_{Dn} was set to 1.4 W/mK because low heat conductivity means a slow heat transfer to neighboring tissue and therefore high local temperatures. The average value for λ_{Dn} represents the most likely value for clinical treatment. The same consideration applies to the periodontal ligament and the jaw bone.

The FE software COSMOS/M allows setting power-time functions for single knots or groups of knots in the FE grid. The heat deposition during laser treatment of the root canal is typically done with 1.5 W and a fiber-related full divergence cone of 25 degrees (fiber NA 0.20). Laser energy absorption was assumed to take place at the surface of the corresponding finite element. This is justifiable by taking into account that erbium laser radiation at wavelengths of 2.79 to 2.94 µm has absorption constants greater than 10^4 cm^{-1} in wet tissues, which amounts to a radiation penetration depth of less than 1 µm. Since voxel size is 10 µm for the smallest voxels, it can safely be assumed that the absorption takes place in the voxel at the canal surface. Therefore, power transfer from laser light to tissue can be modeled by power-time curves P(t) which are given for each voxel that is irradiated by the calculated light source during the simulation.

Energy deposition was modeled close to the treatment guidelines, which are as follows: The fiber is inserted into the root canal to its full length, which is 15 mm in the FE model. Immediately after switching on the laser, the fiber is retracted from the canal in a steady motion while performing circular movements inside the canal. The time of treatment should be ca 20 s, which yields a lateral fiber velocity of

$$V_L = \frac{15\ \text{mm}}{20\text{s}} = 0.75\ \frac{\text{mm}}{\text{s}}$$

Circular movements of the fiber are simulated and also clinically used, because the diameter of the root canal changes from apical to coronal. In the apex, we have a much smaller canal diameter than in the coronal part, so to ensure that the applied laser energy is distributed as uniformly as possible the fiber has to be moved as described.

Let x_L, y_L, z_L be the Cartesian coordinates for the center of the tip of the fiber. Then the lateral position of the fiber tip is $y_L = y_0 + v^L t$ where (x_0, y_0, z_0) is the coordinate for the deepest point of the root canal. The actual position of the fiber tip in the horizontal plane is then given by

$$x_L = r_y \cos wt + x_0$$
$$z_L = r_y \sin wt + z_0$$

where r_y is the radius of the canal at the lateral position y_L. Therefore, the real movement is equivalent to a trajectory on a helix with increasing radius. Furthermore, it can be assumed that the horizontal spiral motion (angular speed wt) is much faster than the slow withdrawal of the fiber from the root canal, which leads to the simplification that the laser energy is evenly distributed in the treated area. These movement functions of the

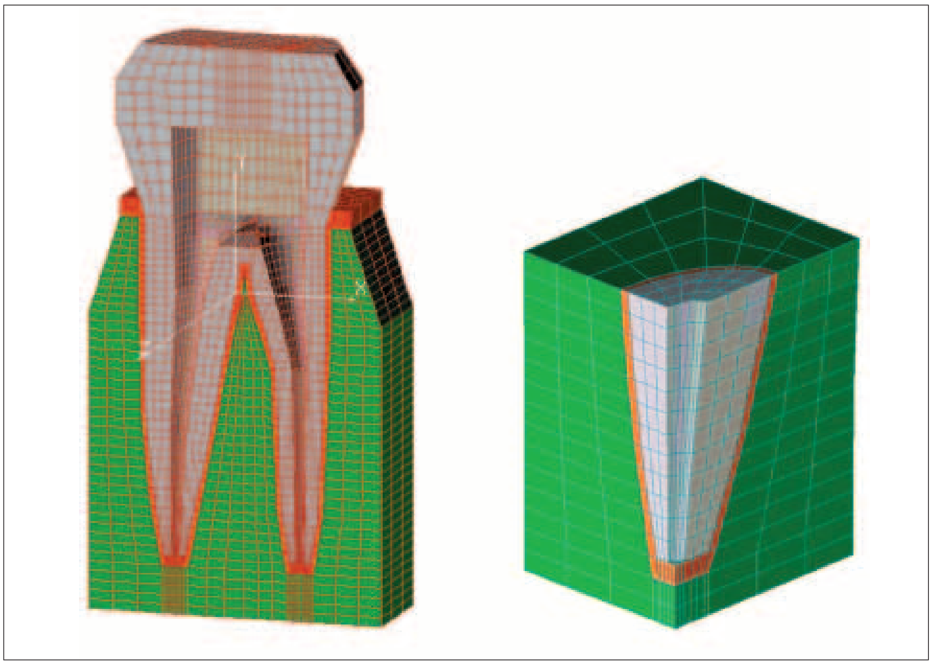

Fig 1 Illustration of the FE model. On the left side, the whole model is shown with the tooth in gray, the periodontal ligament in red, and the jaw bone in green. On the right, the region of the apical third is shown enlarged.

Table 1 Physical properties of dentin

Material data of dentin	
Density	$\pi = 3 \cdot 10^3$ kg/m^3
Specific heat	$C\pi = 1.34 \cdot 10^3$ J/kgK
Heat conductivity	$\lambda = 0.6\text{-}2.2$ W/mK

Table 2 Physical properties of the periodontal ligament

Material data of the periodontal ligament	
Density	$\pi = 0.98 \cdot 10^3$ kg/m^3
Specific heat	$C_\pi = 2.5 - 3.4 \cdot 10^3$ J/kgK
Heat conductivity	$\lambda = 0.49$ W/mK

Table 3 Physical properties of the jaw bone

Material data of the jaw bone	
Density	$\pi = 2.31 \cdot 10^3$ kg/m^3
Specific heat	$C_\pi = 2.65 \cdot 10^3$ J/kgK
Heat conductivity	$\lambda = 0.38 - 2.3$ W/mK

light source (tip) were used to generate power-time curves P(t) for each voxel at the root canal surface for the simulated treatment, which uses the following parameters: pulse energy 75 mJ, pulse duration 150 µs, average power 1.5 W, repetition rate 20 Hz, fiber diameter 200 µm, fiber NA 0.2, which yields a full opening angle of the beam of 25 degrees. Absorption was of course not only considered to take place at the fiber's end but also on lower apical regions as well as on the opposite wall of the root canal, as illustrated in Fig 2.

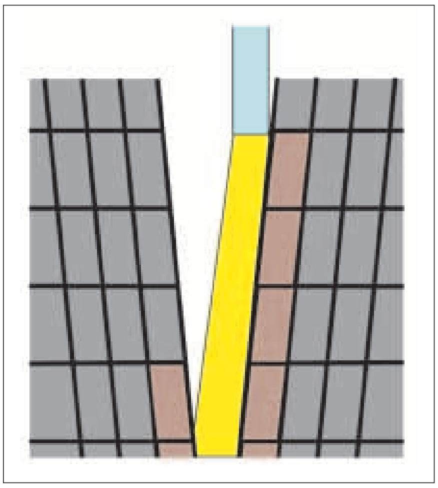

Fig 2 Illustration of the FE model in the root canal region close to the apex. The fiber is shown in blue while the laser light cone is shown in yellow. Voxels are shown in gray, with the voxels absorbing a portion of the laser energy shown with a red overlay. When the fiber moves upwards in its helical movement, the red overlays would change according to the position of the laser light cone.

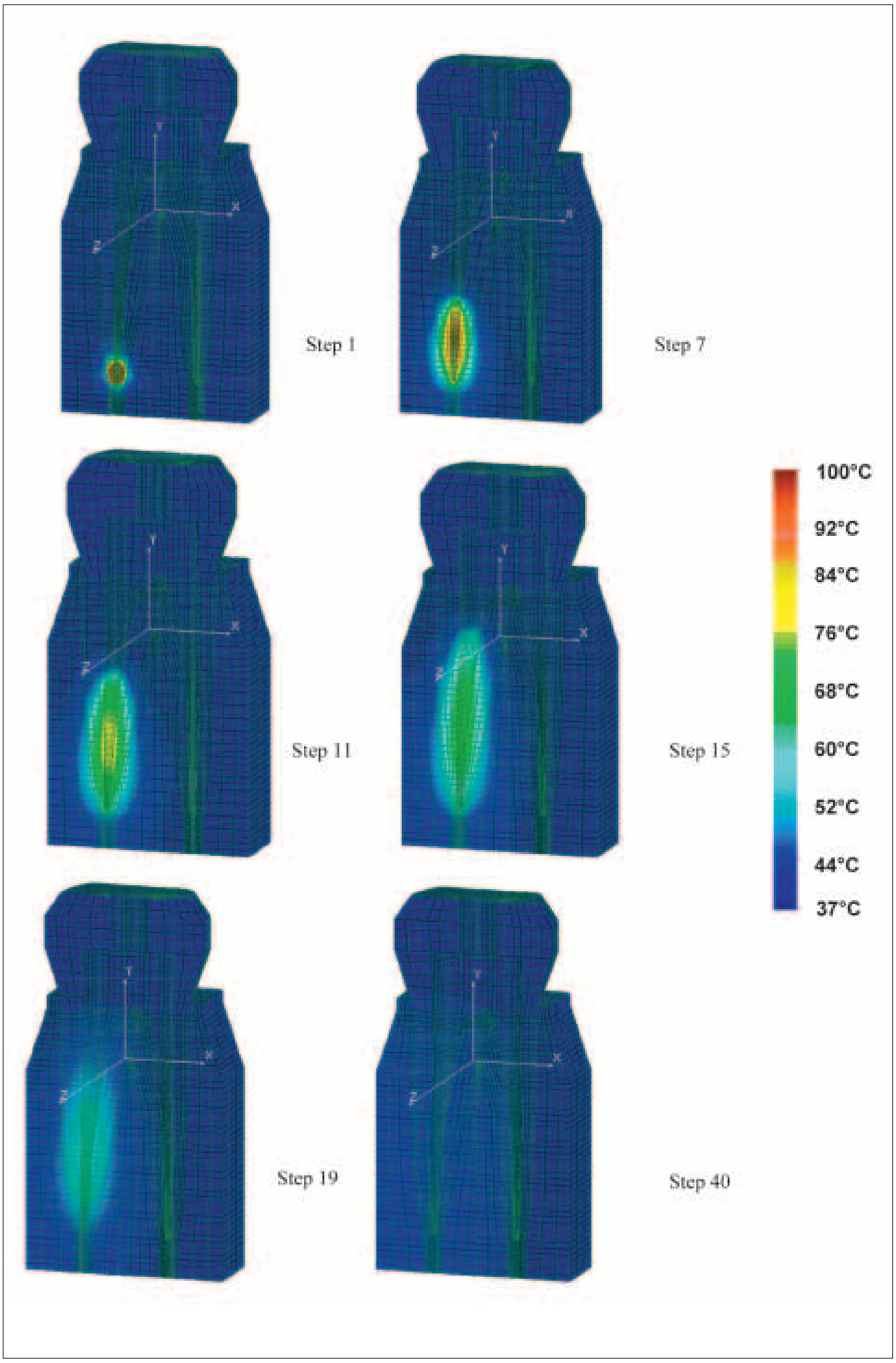

Fig 3 Image sequence of a simulated laser treatment. The temperature is color-coded as indicated on the scale. Each step number in the upper left of the pictures indicate the time index. Each time step shown corredsponds to 0.5 s. The simulation itself was done with an internal time step of 0.05 s, but only every tenth image is displayed in the output.

The surface absorption of erbium lasers was modeled by an absorption coefficient of $\alpha=\infty$, where α is the Lambert-Beer coefficient for an irradiated medium according to $I(x)=I(x-0)e^{-\alpha x}$, where I denotes the intensity of the beam. Reflections, transmission, and scattering effects are not modeled in this case.

Surface absorption with $\alpha=\infty$ is justified for modeling erbium lasers, since the penetration depth α^{-1} for real absorption values (α for water is $>10^4$ cm^{-1} and a for hydroxyapatite is >100 cm^{-1}) is smaller than the smallest voxel size used in the model. This assumption is true for all erbium lasers (Er:YAG, Er,Cr:YSGG, Er:GGG and others) which emit in the wavelength region close to 3 µm. Therefore we do not distinguish between erbium laser types in the following. Other lasers and wavelengths, such as Nd:YAG, cannot be modeled by this model, since a considerable amount of scattering would take place, which would require additional numerical methods. Furthermore, Nd:YAG does not have high absorption in water/hydroxyapatite tissues, so the assumption that the voxel size is larger than the penetration depth would be false, and consequently, the power-time curves P(t) of the COSMOS/M software could not be derived in the same way as for surface-absorbed, nonscattering radiation.

RESULTS

The FE analysis of the numerical tooth model showed a strong heat concentration in the area of the apical third, especially on the root canal wall. However, the high temperatures diminished quickly as the fiber was retracted slowly from the root canal and did not move into the neighboring tissue. Solely in the area of the apical third, the heat overlapped to the periodontal ligament. The temperatures of about 100°C found in this region cool off very fast during the treatment process and are not conveyed to the neighboring tissue. Temperatures of up to 40°C to 52°C were found on the root surface for a period of 8 s. The results are shown in the image sequence in Fig 3.

DISCUSSION

In this study, the temperature formation during laser irradiation in a root canal was calculated. No previous clinical studies could be used to study the interaction of the tooth, periodontal ligament, and the jaw bone because the real temperature formation cannot be measured at a sufficient spatial and temporal resolution. At best, animal experiments can supply histological cuts, which can be investigated for thermal damage zones.

The FE model showed temperatures of up to 100°C in the apical third – these temperatures are not high enough to melt the root canal wall dentin and cause recrystallization, but can be assumed to be hazardous to microorganisms in this area. Other studies showed proof of microorganisms down to a depth of as much as 1.150 µm in the tubules of the root canal wall dentin.[21] In contrast to conventional irrigation, it is assumed that laser treatment with its high temperature concentration in this area can eliminate bacteria much more effectively. NaOCl lavages can disinfect the tubules to a depth of 100 µm,[22] while bacterial reduction to a depth of 1 mm was verifiable after Nd:YAG laser treatment.[23] Furthermore, high temperatures ensure a germ reduction in the branches of the root canal, which cannot be achieved with the conventional preparation methods.[24] Microbiological studies with a highly surface-absorbed laser (Er:YAG laser) showed a bacterial reduction of 53% at a depth of 500 µm.[25] This agrees with the findings of this study, where we calculated temperatures of 100°C, reached for a few seconds at these depths, with a subsequent temperature drop to 40°C to 52°C for the next 8 s.

The quick temperature diminishment at the root canal wall with proceeding treatment lets us expect that the neighboring tissue is not or not significantly affected by the heat. Furthermore, because of the good blood supply to the periodontal ligament, an additional cooling factor is present, meaning that critical temperatures are not expected to occur in clinical application. Our simulation of surface-absorbed erbium laser irradiation thus provides strong support for in vitro studies, where elimination of microorganisms in human root canals by Er:YAG or Er,Cr:YSGG lasers are investigated.[25]

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