Finite Element Study on thermal effects in root canals

Lasertreatment with a surface absorbed laser

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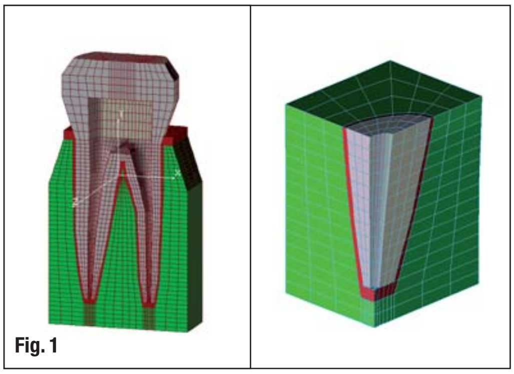


Fig. 1

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

_Introduction

For lasting therapy success on a chronically infected tooth the disinfection of the root canal is of utmost importance. In the conventional therapy the root canal is mechanically enlarged up to 1 mm close to up the physiological apex as can be seen on X-rays pictures. This is done by hand or by the use of an ultrasonic system.[1] The conventional canal preparation is supported by a lavage, primary by a 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 germ reduction in the root canal is the application of laser irradiance.[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. could verify a germ reduction of about 99.91 % in vitro with a pulsed Nd:YAG laser[10] as did Hardee et. al.[11] Also for the Ho:YAG laser and the diode laser at 810 nm a large reduction of the germs could be found in vitro.[12,13]

The clinical application of a laser in the root canal is only possible if the neighboring periapical tissue does not suffer from thermal stress. The critical temperature for irreversible bone necrosis is 47 °C, 10 °C above the normal body temperature in the mouth.[14] The measured temperatures on the root surface of extracted human teeth were partially in this vicinity.[15] Aim of this study was to calculate the temperature distribution in the root canal and its neighboring tissue during a simulated laser treatment using a Finite-Elements-Model. For the calculations the tooth, the periodontal ligament, and the jaw bone were included in the model. The apical third is of specific interest in this region. Furthermore, the temperature influence due to heat conductance on 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 rules for laser treatment.

Material data of dentin	
Density	$\rho_{Dn} = 3 \times 10^3$ kg/m³
Specific heat	$c_{Dn} = 1.34 \times 10^3$ J/kgK
Heat conductivity	$\lambda_{Dn} = 0.6\text{-}2.2$ W/mK

Table 1

Material data of the periodontal ligament	
Density	$\rho_{Dn} = 0.98 \times 103$ kg/m³
Specific heat	$c_{Dn} = 2.5\text{-}3.4 \times 10^3$ J/kgK
Heat conductivity	$\lambda_{Dn} = 0.49$ W/mK

Table 2

Material data of the jaw bone	
Density	$\rho_{Dn} = 2.31 \times 103$ kg/m³
Specific heat	$c_{Dn} = 2.65 \times 103$ J/kgK
Heat conductivity	$\lambda_{Dn} = 0.38\text{-}2.3$ W/mK

Table 3

Table 1_Physical properties of dentin.
Table 2_Physical properties of the periodontal ligament.
Table 3_Physical properties of the jaw bone.

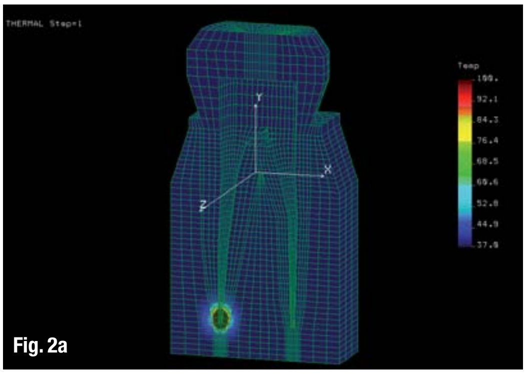


Fig. 2a

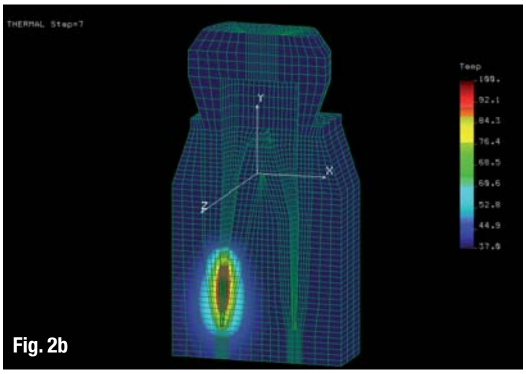


Fig. 2b

_Materials and Methods

Using data from literature[16] a computer model of a human lower molar was created and separated in many horizontal slices. The final FE-model was calculated from these slices in the FE-preprocessor of the COSMOS/M software as seen in Fig. 1. Material properties for the molar were also obtained from literature[17-20] as can be seen in Tables 1-3.

Regarding the quality of the literature data for the materials it can be said, that the data for the density is relatively exact (+/- 2% in the case of jaw bone, +/-5% for the desmondont). 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 c_{Dn} was set to 1.4 W/mK because a small heat conductivity means a slow heat transfer to neighboring tissue and therefore high local temperatures. This means choosing the average value for c_{Dn} represents the most supposable value for the a 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 resp. 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 divergence cone of 25°. Laser energy absorption was assumed to take place at the surface of the corresponding finite element. Energy deposition was modeled close to the rules of treatment, 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-going motion while performing circular movements inside the canal. The time of treatment should be approx. 20 seconds, which yields a lateral fiber velocity of

$$v_L = \frac{15\,\mathrm{mm}}{20\,\mathrm{s}} = 0.75\,\frac{\mathrm{mm}}{\mathrm{s}}\,.$$

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

$$x_L = r_y \cos\omega t + x_0$$

$$z_L = r_y \sin\omega t + z_0$$

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 vt) 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 into the corresponding area. The surface absorption was modeled by an absorption coefficient of a= `, where a is the Lambert-Beer coefficient for an irradiated medium according to

$$P(x) = P(x=0)e^{-\alpha x}.$$

Reflections, transmission, and scattering effects are not modeled in this case.

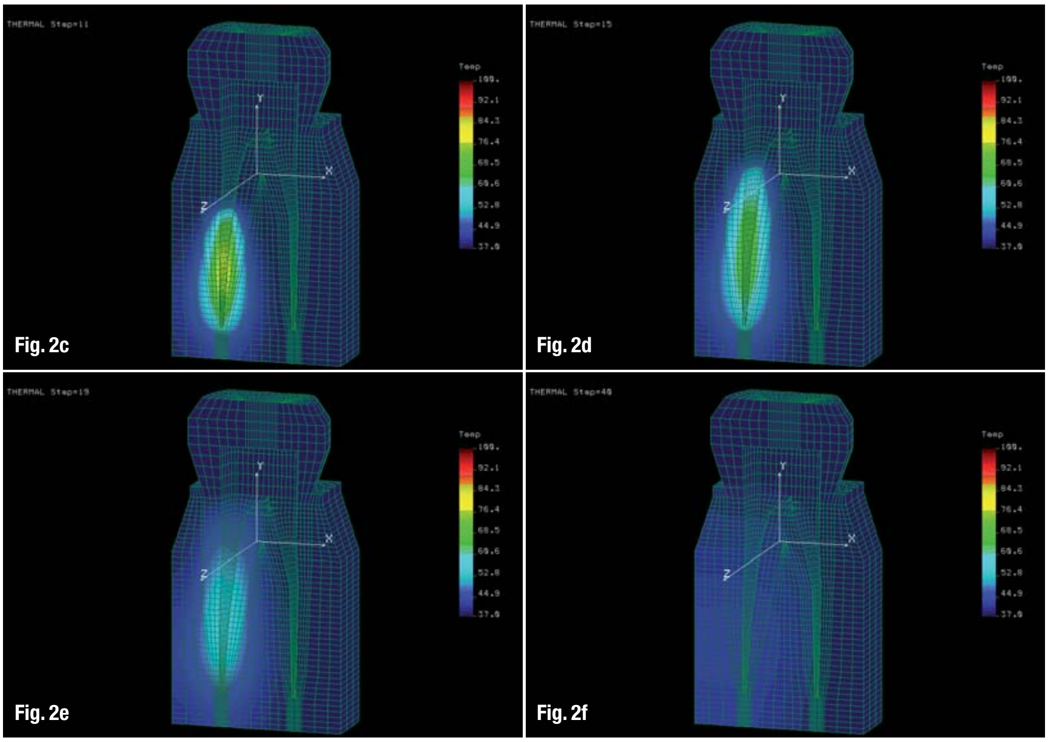
_Results

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 found temperatures of about 100 °C in this region wear off very fast during the treatment process and are not conveyed to the neighboring tissue. Temperatures of up to 40–52 °C were found on the root surface for a period of 8 seconds. The results are shown in the image sequence in Fig. 2.

_Discussion

In this study the temperature formation during a laser irradiation in a root canal was calculated. All previous clinical studies could not be used to study the interaction of the tooth, periodontal lig-

Fig. 2_Image sequence of a simulated laser treatment. The time after the beginning of the treatment is shown. The temperature is color-coded as indicated on the scale. The simulation itself was done with an internal time step of 0.05.
a_after 1 second
b_after 7 seconds
c_after 11 seconds
d_after 15 seconds
e_after 19 seconds
f_after 40 seconds



ament, and the jaw bone because the real temperature formation cannot be measured in a sufficient spatial and temporal resolution. At the utmost, animal experiments can supply histological cuts, which can be investigated for thermal damage zones.

The FE-model showed temperatures up to 100 °C in the apical third—these temperatures are not high enough to melt the root canal wall dentin and enforce a recrystallization. This does not correspond to the results of an electron microscope based study of the root canal wall dentin after Nd:YAG laser irradiation (1,064 nm) by Gutknecht et. al.[6] Microorganisms could be evidenced up to a depth of up to 1,150 µm in the tubules of the root canal wall dentin.[21] In contrast to the conventional lavage, the laser treatment with its high temperature concentration in this area can eliminate the germs much more effectively. NaOCl lavages can disinfect the tubules up to a depth of 100 µm[22] while for a laser treatment with a Nd:YAG-laser a germ reduction could be verified in a depth of 1,000 µm[23]. Furthermore, the high temperature ensures a germ reduction in the ramifications of the root canal, which cannot be achieved with the conventional preparation methods.[24] Microbiologic studies with a high surface absorbed laser (Er:YAG laser) showed a germ reduction of 53 % in a depth of 500 µm.[25]

The quick temperature diminishment at the root canal wall with proceeding treatment lets us anticipate that the neighboring tissue is not or not significantly affected by the heat. Behrens et. al. showed in a in vitro study a rise in temperature of 17 °C on the root canal surface on extracted teeth after 90 s of Nd:YAG laser irradiation (1,064 nm, 150 µs pulse length, 15 Hz repetition rate, 1.5 W, 25° divergence angle).[13] The length of the treatment in vivo is much shorter, namely 20 s. Furthermore, because of the good supply with blood of the periodontal ligament an additional cooling factor is present so that in clinical application it is not anticipated that critical temperatures may occur. For the root canal treatment with Nd:YAG lasers, a long term study by Gutknecht et. al.[4] has proven the above statement. For the simulated Er,Cr:YSGG laser we estimate out of our findings to get similar clinical results as they have been seen after Nd:YAG laser treatment._

The literature list can be requested from the editorial office.

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