In Vitro investigation of heat transfer in human tooth

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ABSTRACT

The understanding of heat transfer in human teeth is important for optimizing clinical practice protocols and daily intake instructions. However, it is technically challenging to study the in vitro thermal behavior of human tooth due to its small size and complex biological/geometrical structure. The currently widely used method is based on thermocouples, which has several limitations such as low spatial resolution, contact measurement and, in particular, lack of whole-field information. To address these challenges, an experimental system was developed to measure the whole-field temperature distribution in human tooth in vitro. The human tooth sample was heated at the tooth crown with flowing hot water (60 °C) for 10 s and then cooled down by natural convection of air. The temperature of the whole sectioned sample surface was recorded using an infrared camera. The results demonstrate that the developed system is capable of measuring temperature evolution in small human tooth samples. The biological junction of tooth (e.g., dental-enamel junction) is shown to have great influence on its heat transfer behavior. The present study could open the door for several future applications, e.g., systemic investigation of heat transfer in intact/restored tooth heated with clinical methods for treatment optimization, and measurement of thermal properties for different tooth layers.

Keywords: human tooth, heat transfer, whole-field temperature information

1. INTRODUCTION

While responsible for maintaining the viability of tooth, dental pulp is vulnerable to thermal agitation. A rise of 5.5 °C in pulp chamber above normal temperature (37 °C) can result in irreversible pulpal damage [1-3]. Moreover, Trowbridge et al.[4] observed that the sensory response (pain sensation) of teeth to thermal agitation occurred before a temperature change could be detected in the pulpal wall that houses most nerve endings[5]. However, the underlying physical mechanism remains an issue. An entire knowledge of the temperature distribution and heat transfer behavior in thermally agitated teeth will contribute to a better understanding of the mechanism underlying teeth thermal pain and its relief. It could also lead to improved daily substance intake suggestions and dental orthopedic procedures.

It is technically challenging to study the *in vitro* thermal behavior of human tooth due to its small size and complex biological/geometrical structure. The current widely used experimental methods for both *in vivo*[6-11] and *in vitro*[12-14] studies are based on thermocouples, which only offer temperature information at discrete locations rather than whole-field characteristics[15-17]. Intrapulpal temperature rises have recently been successfully accessed with infrared (IR) camera when a tooth sample was subjected to light-curing dental restorative procedures[18]. Leveraging the advantage of this technique, here we develop an experimental approach to characterize the transport of heat throughout a human molar tooth. The validity of the system is checked by mimicking heat transfer in intact human tooth in oral cavity under daily common situations (e.g., drinking hot water). The experimental approach could also be used to study heat transfer in restored tooth, so that different restorative materials can be evaluated and temperature changes in tooth during pulpal vitality testing can be investigated[15].

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2. MATERIAL AND METHODS

2.1 Sample preparation

Intact human third molar tooth was extracted from an adult patient for orthodontic purposes and was preserved in saline solution at 4 °C following the protocol reported in[12]. The tooth was longitudinally sectioned (in half) using a diamond-bladed saw (Buchler Ltd. ISOMET 1000). The sectioned surface was grinded on wet emery paper of grit size 800, 1000 and polished on an automatic polisher (Buchler Ltd.) with a 6-µm-particle-size diamond paste, followed by a 3-µm-particle-size paste. The specimen was then mounted in a thin resin plate (~ 0.5 mm in thickness) to prevent water leakage, Figs. 1(a)-(c). Controlled thermal boundary condition (e.g., mimicking drinking hot water) was achieved by pasting an additional layer of resin on the tooth root section whilst the bare tooth crown was heated by circulating hot water, Fig. 1(b). The resin paste worked as gingival around the tooth root section, providing a thermal conduction environment similar to practical oral conditions.

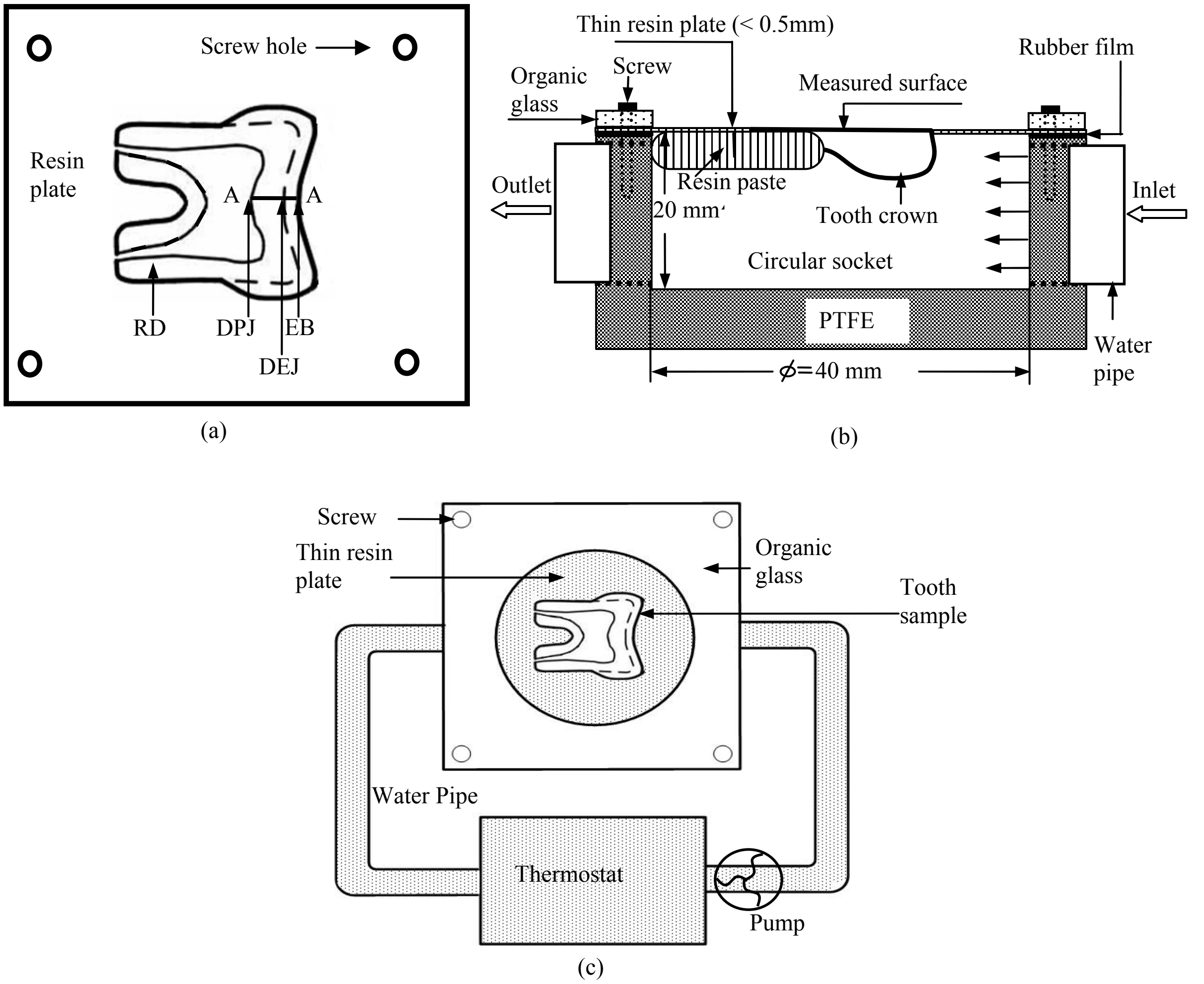


Figure 1. Schematic of as prepared sample and test rig: (a) sectioned tooth mounted in thin resin plate, specific points of interest denoted as EB (enamel border), DEJ (dentine-enamel junction, dashed line), DPJ (dentine-pulp junction), RD (root dentine), and A-A (line); (b) cross-sectional view of test setup, with resin paste mimicking heat transfer through gingival; (c) overview of experimental stand.

2.2 Experimental procedures

The sectioned tooth sample embedded in a thin resin plate was fixed to a polytetrafluoroethylene (PTFE) stand machined with a circular socket (40 mm in diameter), Figs. 1(a)-(c). A thin rubber film, with a 40 mm diameter hole in the center, was inserted between the resin plate and the PTFE stand to prevent water leakage. The PTFE stand was connected with a pipe to the thermostat water tank (with temperature resolution of 0.1 °C).

For water circulation, water at a specific temperature was pumped out from the thermostat tank. Before heating, the circular socket was first circulated with room temperature water (~24.5 °C) to exclude air bubbles. The circulation was then turned off and the water in the tank was heated to 60 °C by the thermostat. The tooth sample was heated at its crown (Fig. 1(b)) with flowing hot water (60 °C) for 10 s before the circulation was turned off again. The whole system including the sample was then cooled down by natural convection of air. A thermocouple (J type Omega) was inserted into the socket, with its tip located close (~ 0.5 mm) to the tooth occlusal surface, to record the temperature of flowing water, Fig. 2.

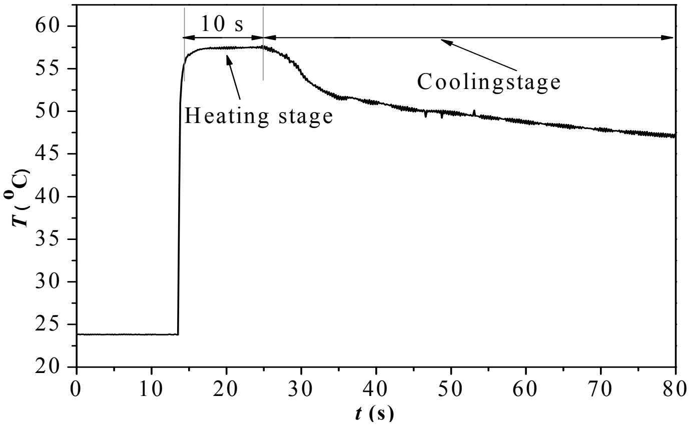


Figure 2. Evolution of temperature in circular socket (heating and cooling protocol) measured with embedded thermocouples during heating and cooling stages. At the end of heating, with circulation turned off, the hot water cools down naturally in the circular socket.

An IR camera (NEC, TH9100 MV) was fixed over the measured surface, controlled by a PC, to map the tooth surface temperature. The camera was set in the range of -20 to 100 °C in temperature and 8 to 14 μm in wavelength, and had a sampling rate of 30 frames per second. Each frame was mapped into 320 by 240 pixels, with each pixel corresponding to a 0.1mm x 0.1mm surface area. The IR camera started capturing the surface temperature before thermal loading was applied to the tooth.

2.3 Calibration of IR camera

Prior to data acquisition, the camera was calibrated in terms of reflectance calibration, non-even calibration and missivity adjustment according to manufacturer's guide. For tooth composes of enamel and dentine, both of which possesses different emissivity with enamel of 0.91 and dentine 0.92[19]. As emissivity adjustment is critical for obtaining precise temperature data, a sensitivity test was carried out. No obvious discrepancy was found when the emissivity was chosen as 0.91 or 0.92, Fig. 3. The temperature (~ 50 °C) at a specific location on the sample surface was measured by the camera and compared with that measured with a thermocouple (J-type, Omega). A slight discrepancy was observed (< 0.5 °C), which is deemed acceptable in view of the large increase in tooth temperature (> 25 °C) in the present experiment.

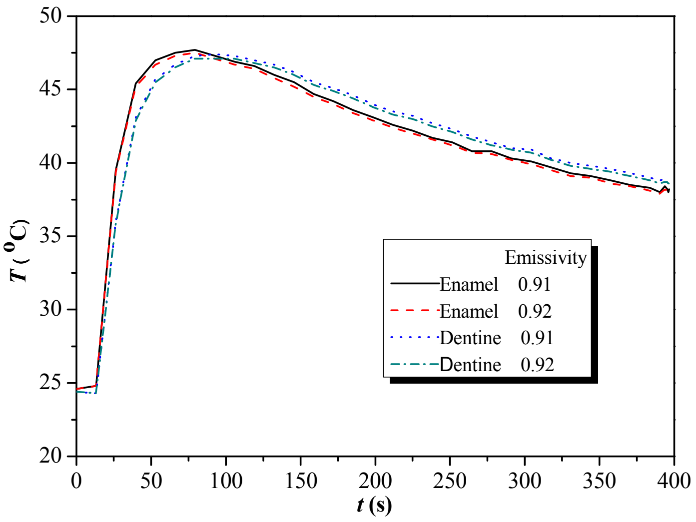
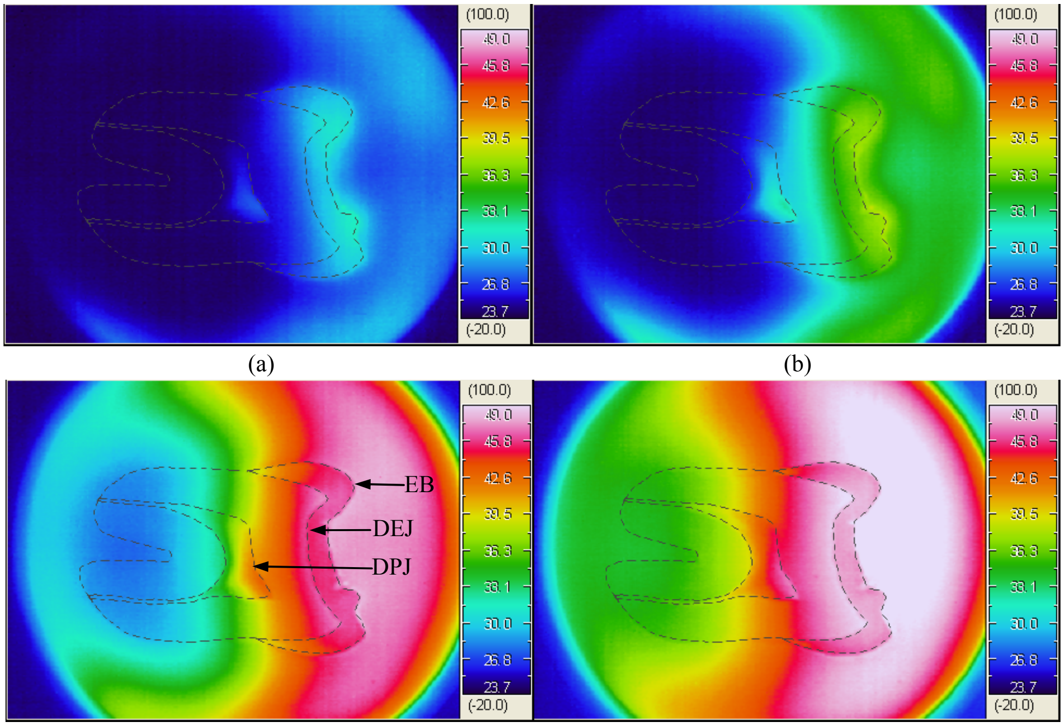


Figure 3. Evolution of temperature in enamel and dentine for selected values of emissivity.

3. RESULTS AND DISCUSSIONS

Figures 4(a)-(d) present the IR images of the sample surface at time t = 5, 10, 30, 60 s after the sample was heated with flowing 60 °C water. The temperature contours show that high temperature gradients on the measured surface, which is attributed to the layer-like composite structure of tooth and the different thermal properties of each layer. As time elapses,



(a)

(b)

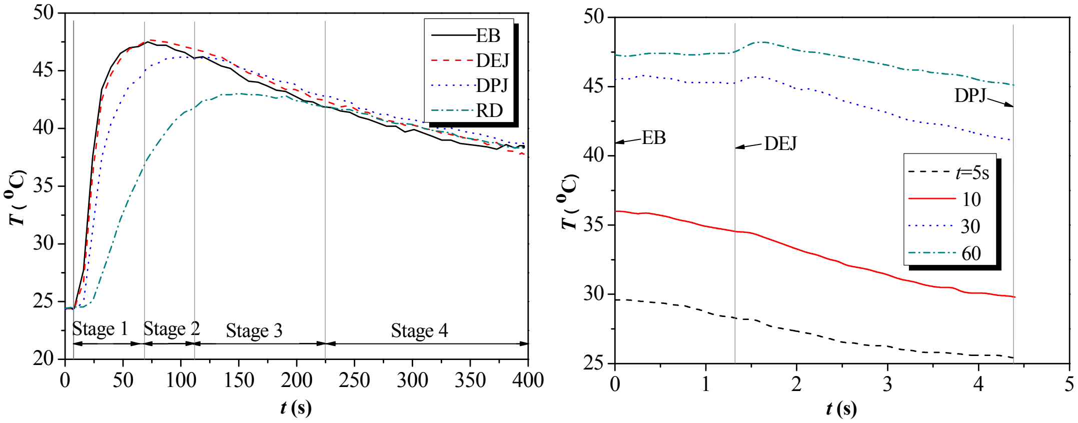
(c)

(d)

Figure 4. Temperature distribution on longitudinally sectioned tooth surface measured with IR camera (unit = °C) at: (a) t = 5s; (b) t = 10s; (c) t = 30s and (d) t = 60s after heating is started. Arrows and dash lines indicate contours of tooth structures: EB (enamel border), DEJ (dentine-enamel junction), DPJ (dentine-pulp junction).

heat propagation from EB (enamel border) to tooth root can be "visualized". The EB, DEJ (dentine-enamel junction), as well as the DPJ (dentine-pulp junction) can be clearly distinguished from the IR images of Figs. 4(c)-(d), marked by dash contour lines. This indicates that the IR camera is capable of capturing the main heat propagation features in small tissues with complex composite structure, like tooth here.

Figure 5(a) presents the evolution of temperature at locations of particular interest, i.e., EB, DEJ, DPJ and RD (root dentine). The temperature curves may be divided into four stages. Stage 1 shows the delay of temperature response in the inner layers. In stage 2, a higher temperature in DEJ than that in the outer layer (EB) can be observed. This also happens when comparing the temperature rise in DPJ and RD with that of EB in stage 3 and stage 4, respectively. This indicates that when considering heat propagating along the longitudinal direction of the thermally agitated tooth, two opposite heat fluxes (from tooth root to EB and the opposite) contribute to its main heat transfer characteristics. Figure 5(b) shows the spatial distribution of temperature along the A-A line as indicated in Fig. 1(a), where arrows and lines correspond to EB, DEJ and DPJ, with EB set as 0 mm at the enamel border and DPJ as 4.4 mm. Temperature discontinuities across the DEJ interface are observed in Fig. 5(b), due to difference in thermal conductivities between the two adjacent layers. The spatial distribution of temperature at t = 5 and 10 s exhibit a decrease in temperature from EB to DPJ, Fig. 5(b). However, over a prolonged heating time, as implied by temperature gradient curves at t = 30 and 60 s, a sudden increase of temperature near EDJ is observed, suggesting that the biological junction (i.e., DEJ) plays an important role in tooth heat transfer. That is, the heat flux is not only transferred through the DEJ but also accumulates at the DEJ. At nano and microscale level, the enamel layer is consisted of aligned prisms approximately perpendicular to the DEJ towards the tooth surface; these oriented prisms are calcium hydroxyapatite crystals, approximately 200 nm in diameter and 100 mm in length[20]. This nano/micro-structure combined with the presence of tubules in the dentine layer is expected to have significant effect on tooth heat transfer. The study of heat transfer dependence on these microstructures may explain the present data but is out of the range of this article. In a separate study, a computational model using the finite element method will be developed to simulate the discontinuous heat transfer behavior: the interfaces are modeled as a film layer whose thickness is recognized as zero according to energy balance law and heat transfer; the integral principal and integral median theorem will be used for determining the boundary conditions on the thermally discontinuous interfaces.



(a) (b)

Figure 5. (a) Temperature evolution at specific points of interest: EB (enamel border), DEJ (dentine-enamel junction), DPJ (dentine-pulp junction), RD (root dentine); (b) temperature distribution along A-A, at t = 5, 10, 30 and 60s after heating is started.

4. CONCLUSION

To capture the whole-field temperature distribution on the surface of tooth subjected to user-defined thermal agitation, an experimental system based on IR camera has been developed to "visualize" the temperature evolution. The results show that the system is capable of observing temperature evolution on small tooth samples with high temperature and spatial resolutions. It is demonstrated that tooth biological junctions (e.g., DEJ) affect significantly the heat transfer behavior of tooth. This means that measuring tooth thermal properties by destructing its biological structure[21, 22] may affect the obtained results. The present experimental setup can be employed (as we will do in a separate study) to measure the thermal properties (e.g., thermal diffusivity) of individual tooth components (layers) without destructing the biological junctions of tooth. The advantage of the experimental setup is that both the whole-field temperature gradient information and heat propagation characteristics in tooth can be accurately obtained and therefore a better understanding of tooth heat transfer is possible. The developed approach could also be extended to investigate the influence of different restorative materials on the heat transfer behavior of restored tooth subjected to hot fluid intake process. This could improve the selection of better restorative materials.

Acknowledgements

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REFERENCES

[1] Sulieman, M., Rees, J., S. and Addy,M., "Surface and pulp chamber temperature rises during tooth bleaching using a diode laser: a study in vitro," British Dental Journal 200(11), 631-634 (2006).

[2] Pohto, M. and Scheinin, A., "Microscopic Observations on Living Dental Pulp II. The Effect of Thermal Irritants on the Circulation of the Pulp in the Lower Rat Incisor," Acta Odontologica Scandinavica 16(3), 315-327 (1958).

[3] Zach, L. and Cohen, G., "Pulp response to externally applied heat.," Oral Surgery Oral Medicine and Oral Pathology 19(4), 515–530 (1965).

[4] Trowbridge, H. O., Franks, M., Korostoff, E. and Emling, R., "Sensory response to thermal stimulation in human teeth," Journal of Endodontics 6(1), 405-412 (1980).

[5] Graf, W. and Bjorlin, G., "Diameters of Nerve Fibers in Human Tooth Pulps," Journal of the American Dental Association 43(2), 186-193 (1951).

[6] Spierings, T. A., Peters, M. C., Bosman, F. and Plasschaert, A. J., "Verification of theoretical modeling of heat transmission in teeth by in vivo experiments," Journal of Dental Research 66(8), 1336-1339 (1987).

[7] Tibbetts, V. R., Schnell, R. J., Swartz, M. L. and Phillips, R. W., "Thermal Diffusion Through Amalgam and Cement Bases: Comparison of In Vitro and In Vivo Measurements," Journal of Dental Research 55(3), 441-451 (1976).

[8] Jyvasjarvi, E. and Kniffki, K. D., "Cold stimulation of teeth: a comparison between the responses of cat intradental A delta and C fibres and human sensation," Journal of Physiology-London 391, 193-207 (1987).

[9] Vongsavan, N. and Matthews, B., "Fluid-flow through cat dentine invivo," Archives of Oral Biology 37(3), 175-185 (1992).

[10] Vongsavan, N. and Matthews, B., "The relationship between the discharge of intradental nerves and the rate of fluid flow through dentine in the cat," Archives of Oral Biology 52(7), 640-647 (2007).

[11] Rizoiu, I., Kohanghadosh, F., Kimmel, A. I. and Eversole, L. R., "Pulpal thermal responses to an erbium,chromium : YSGG pulsed laser hydrokinetic system," Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics 86(2), 220-223 (1998).

[12] Linsuwanont, P., Palamara, J. E. A. and Messer, H. H., "An investigation of thermal stimulation in intact teeth," Archives of Oral Biology 52(3), 218-227 (2007).

[13] White, J. H. and Cooley, R. L., "A quantitative evaluation of thermal pulp testing" Journal of Endodontics 3, 453-457 (1977).

[14] Fuss, Z., Trowbridge, H. O., Bender, I. B., Rickoff, B. and Sorin, S., "Assessment of reliability of electrical and thermal pulp testing agents," Journal of Endodontics 12, 301-305 (1986).

[15] Linsuwanont, P., Palamara, J. E. and Messer, H. H., "Thermal transfer in extracted incisors during thermal pulp sensitivity testing," International Endodontic Journal 41(3), 204-210 (2008).

[16] Preiskorn, M., Zmuda, S. and Trykowski, J., "In vitro investigations of the heat transfer phenomena in human tooth " Acta of Bioengineering and Biomechanics 5(2), 23-36 (2003).

[17] Hannig, M. and Bott,B., "In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources," Dental Materials 15(4), 275-281 (1999).

[18] Bouillaguet, S., Caillot, G., Forchelet , J., Cattani-Lorente, M., Wataha, J. C. and Krejci, I., "Thermal risks from LED- and high-intensity QTH-curing units during polymerization of dental resins," Journal of Biomedical Materials Research Part B: Applied Biomaterials 72B(2), 260-267 (2005).

[19] da Costa Ribeiro, A., Nogueira, G. E. C., Antoniazzi, J. H., Moritz, A. and Zezell, D. M., "Effects of Diode Laser (810 nm) Irradiation on Root Canal Walls: Thermographic and Morphological Studies," Journal of Endodontics 33(3), 252-255 (2007).

[20] Johansen, E., "Microstructure of Enamel and Dentin," Journal of Dental Research 43 Supply, 1007-1020 (1964).

[21] Panas, A. J., Żmuda, S., Terpiłowski, J. and Preiskorn, M., "Investigation of the Thermal Diffusivity of Human Tooth Hard Tissue" International Journal of Thermophysics 24(3), 837-848 (2003).

[22] Magalhães, M. F., Ferreira, R. A. N., Grossi, P. A. and Andrade, R. M., "Measurement of thermophysical properties of human dentin: Effect of open porosity," Journal of Dentistry 36(8), 588-594(2008).