

In vitro investigations of the heat transfer phenomena in human tooth

MARIA PREISKORN, STANISŁAW ŻMUDA, JAN TRYKOWSKI

Institute of Dentistry, Military Medical Academy, Szaserów 128, 00-909 Warsaw, Poland

ANDRZEJ PANAS, MAREK PREISKORN

Institute of Aviation Technology, Military University of Technology,
Kaliskiego 2, 00-908 Warsaw, Poland

An experimental stand for in vitro investigations of transient heat transfer phenomena in human teeth is described. The stand has been designed to reproduce thermal conditions of the environment of the oral cavity. In this particular case, special attention was paid to simulation of the heat transfer by the pulp. Appropriate modifications have been introduced into the experimental set-up. The measurements confirmed that they enabled very close replication of real conditions. The paper presents results of test measurements and results of preliminary numerical calculations for the heat conduction in incisor tooth. In this particular case, effects of exposition of the tooth to radiation of two different dental polymerisation lamps have been compared. As a result the methodology of verification of theoretical modelling of heat transfer and heat transmission-related effects in teeth have been developed and described.

Key words: heat transfer, dental pulp, thermal conditions, heat transfer modelling

1. Introduction

There are many reasons to study a problem of thermal stimuli propagation in dental structures – like in the whole medicine, heat effects and heat transfer phenomena are of a great importance in modern dentistry. Firstly, the analysis of the temperature distribution could substantially help in diagnosis of many diseases [1]. Secondly, the temperature and temperature-related effects are major risk factors in destruction of tooth structures [2]. The last concerns both hard and soft tooth tissues and, in addition, the cured tooth with dental filling structures. The thermal loads are responsible for that.

Considering major dental therapy processes one should keep in mind the fact that very often they are accompanied by substantial temperature changes in the cured tooth. As it concerns the risk related to it even the temperature exceeding the limit of 42.5 °C damages the tooth pulp. The critical value of 42.5 °C was reported by POHTO and SCHENIN [3]. Because of the fact that tooth and pulp can transfer outside only limited amount of heat, even exposing the cured tooth to radiation of the dental polymerisation lamp could cause such a temperature increase. Gradual increase in power of commonly utilised halogen polymerisation lamps increases the risk related to the therapy. The risk is lower when semiconductor diode light is utilised. When not the temperature but the temperature gradients are taken into consideration, one should keep in mind that they are connected with significant differences in thermophysical properties of dental structures according to the different properties of restorative materials [4], [5]. Temperature gradients might be caused by draught of liquid or even air during deep breathing. They are extremely intense in cases of sore/deceased tissue removal with a drill or a pulse-laser instrument. In view of lack of detailed knowledge concerning the thermal load on tooth, a proper planning of therapy process and its optimisation are considerably impeded. So, there is a need for experimental data as a basis for theoretical modelling and a need for experimental verification of both analytical and numerical models [2].

Direct, in vivo experimental investigations of heat transfer phenomena in tooth are very difficult because of many instrumental and methodological limitations. There are also very strict limitations due to the health care regulations imposed on them. Even non-invasive measurements are difficult to conduct because that they could not be accepted by a patient due to a time of duration of an average experiment. A numerous research personnel is usually required to service the apparatus, to record the data and to take care of a patient at the same time. But the most important is the fact that results are precisely restricted to the limited range of parameters ensuring safety of experiments. This is why the spectra of the phenomena investigated are very narrow. For instance, many high-power experiments are excluded from studies.

For those reasons most of experiments are carried out under in vitro conditions. There are some literature reports on temperature measurements using thermocouples as temperature sensors. Measurements were done during preparation of the cavity for the tooth restoration [6], [7], grinding the surface for prosthetic crowns [8], preparation pinholes [9] and exposition of the tooth to the polymerisation lamp light [10], [11]. Some investigations were made with use of a thermal imaging camera [12]–[14]. In all these and similar cases, the very important thing is to ensure thermal conditions of the experiment as close as possible to the thermal conditions of the oral cavity and the tooth socket. Based on the available literature on that subject one can drawn conclusion that this demand has been rarely fulfilled. In particular, the existing experimental set-ups do not allow modelling the heat transfer by a pulp due to blood circulation. The blood circulation-related heat effects are neglected. However, there

are some reports proving that heat transfer effects due to a blood circulation in the pulp might be significant [15], [16].

In order to fill the gap, the program for investigating the heat transfer phenomena and heat-related effects in teeth was started. The investigations are carried out at the Military Medical Academy, Institute of Stomatology, in co-operation with the Military University of Technology, Laboratory of Thermophysical Measurements. The program comprises both experimental and theoretical studies. In the present paper, the results of test measurements and results of preliminary numerical calculations for heat conduction in incisor tooth are described. During investigations the effects of exposition of the tooth surface to radiation of two dental polymerisation lamps have been studied. Experimental investigations have been conducted on experimental stand on extracted tooth with an insert modelling the heat transfer by the pulp. As a result the methodology of verification of theoretical modelling of heat transfer and heat transmission-related effects in teeth have been developed and described.

2. The experimental stand for in vitro investigations of heat effects in teeth

2.1. General description of the experimental stand

The experimental stand consists of three main subsystems, i.e.:

- the chamber of isothermal liquid flowing with a circular socket for placing the tooth investigated;
- the thermostatic system of liquid circulation with a thermostat;
- the data acquisition, processing and visualisation system.

A schematic diagram of the whole system is depicted in figure 1a. Figure 1b shows the isothermal test chamber.

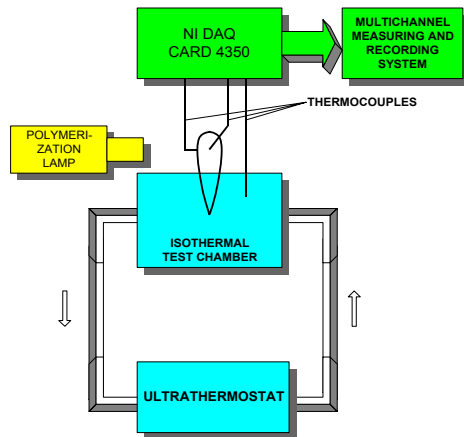


Fig. 1a. Schematic diagram
of the whole portable system

Fig. 1b. Isothermal test chamber

The extracted tooth is mounted on a thin, disk-shape plate. Before being put into the socket of the test chamber the tooth is equipped with tiny thermocouples. Usually thermocouples of type K and a wire diameter equal to 0.05 mm are applied. Thermocouples are placed at certain points inside the tooth and on its surface. Basic dimensions of the tooth investigated, geometric parameters of the temperature measuring points and the basic distances are determined from X-ray images. Due to a small dimension of the thermocouples adopted not only the relaxation time is short, but also the heat conduction through the thermoelectric wire is minor. In such a way the transient temperature measurement errors are minimised. If necessary, some additional thermocouples for the water bath or the ambient air temperature measurements could be used.

In a circulation, distilled water is usually employed. The water is supplied from a thermostat, which stabilises its temperature within the limits of ± 0.1 °C around the fixed temperature.

The signals being measured are handled by a portable PC (laptop) equipped with a NI DAQ Card 4350. This is an interface board for multichannel temperature and low-voltage signal measurement. In this particular case, six-channel measurements are possible. Temperature is measured and recorded in the computer memory. A minimal sampling time is equal to 1 s. A computer program of a virtual multichannel recorder – a data logger, which is supplied with a card, is utilised for visualisation/imaging of the results on a computer screen. This makes the preliminary evaluation of the results possible and enables an on-line control of the experiment. The whole portable system of data acquisition was designed in such a way that it can be used for measurements in dentist surgery room.

2.2. Modelling of heat transfer away from the tooth

There are at least two mechanisms of heat transfer away from the tooth to the blood system. The first is the direct heat exchange between the surface of a tooth root and the tissue of a tooth socket. The second is the heat transfer away through the pulp placed inside the tooth chamber. Though both phenomena have not been examined qualitatively so far, the heat transport is so intense that many investigators accept even stabilised boundary conditions imposed on the root part of the tooth. Nevertheless, experiments are usually carried out without precise modelling of heat transfer. There are reports on investigations with the whole tooth in the air [12], [13], [17] and investigations with the tooth placed in a gel of stabilised temperature [6], [7]. In both cases, the conditions of experiments are not adequate and reliability of transient temperature measurements could be disputable. There is lack literature reports on experiments with modelling the heat transport throughout the tooth pulp.

In the present case, it was decided to model the heat transfer away through the pulp by placing the wire inside the tooth-root. A scheme of a typically instrumented tooth is shown in figure 2a. The protruding part of the wire is usually spirally shaped

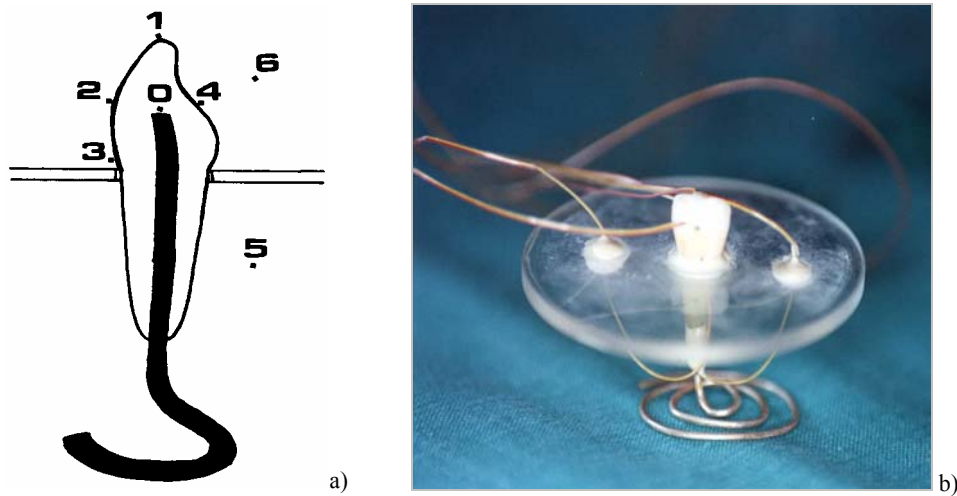


Fig. 2. Schematic diagram (a) and view (b) of the tooth equipped with thermocouples

so it is long enough to intensify the heat exchange between the wire and a water bath. Changing the wire diameter or the wire material one can adjust the amount of heat transferred away. The outside surface of the tooth root is continuously rinsed with running water of stabilised temperature. Figure 2 presents the tooth prepared for measurements.

3. Testing the experimental model of the heat transfer away from the tooth

The above experimental model of the heat transfer away from the tooth was tested. The effect of the metal wire insert on a transient temperature distribution in the tooth investigated was studied. The aim of the tests was to verify the concept and to determine the possibility of adjusting the model to real conditions of the oral cavity. In the present stage of investigations, two kinds of tests were carried out. Firstly, experimental investigations of the extracted central incisor tooth were conducted with use of the experimental stand. Secondly, numerical calculations were done based on a two-dimensional FEM (finite element method) model. In both cases, the changes in tooth temperature after the exposition to the radiation of a dentist polymerisation lamp were studied.

3.1. Experimental test

Test measurements were performed for a tooth equipped with four thermocouples placed on a plane of symmetry of the tooth. Three thermocouples were placed on the labial surface of the tooth at the cutting edge (figure 2a, thermocouple T1), in a central position of a labial surface (T2) and 1 mm from the cementum–enamel junction (T3). The fourth one was positioned inside the tooth chamber, at its end (T0). The tooth was mounted on a plate and then placed into a circular socket of an isostatic test chamber. The 2 mm thick plate was made of polymethacrylate. A temperature of running water bath was stabilised at 36.9 °C which corresponds to the estimated mean subgingival temperature [1].

The tooth being investigated was subjected to measurements twice: without the wire insert and after placing the wire into the tooth chamber along the root cavity. A copper wire, 1 mm in diameter, was used. In the second cycle, investigations were carried out with an additional thermocouple installed. It was placed in the central position of the palatal surface of the tooth (figure 2a, T4). The free thermocouples – two in the first cycle, one in the second cycle – were utilised for an ambient air and a running water temperature control.

During the test the effect of two different polymerisation lamps was compared. The popular lamps Visilux 2 (3M) and Elipar Highlight (ESPE) were used. The latter generates a significant temperature rise. In every case, the temperature signals were recorded every 1 s during a short period just before exposition of the tooth to the light, in the courses of a 40 s exposition time and through a 300 s relaxation time. The front surface of the tooth was irradiated. Typical recordings of transient temperature are shown in figures 3a and 3b. Diagrams illustrate the effects of using both lamps. In every of the two cases, the first peak corresponds to the Visilux II lamp, while the second one to the Elipar Highlight lamp.

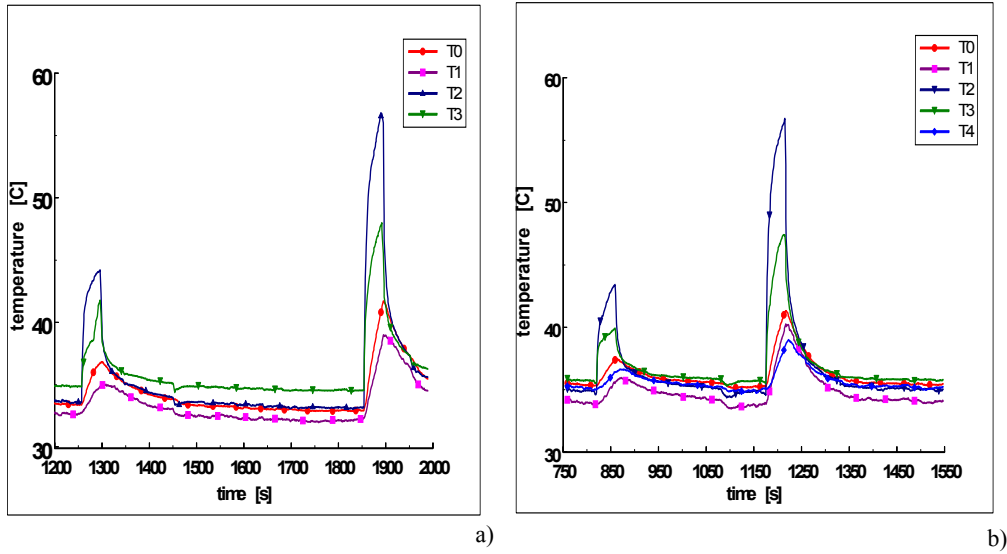


Fig. 3. Typical recordings of transient temperature without (a) and with a model of the pulp (b)

Selected representative values of a temperature in all (four) measurements are listed in table 1.

Table 1. Average values of the temperature measured in all measuring points

	Pulp heat transfer modelling	T0 [°C]	T1 [°C]	T2 [°C]	T3 [°C]	T4 [°C]
Steady state	No	31.6	31.1	31.9	33.5	32.0
	Yes	35.0	33.2	34.3	35.1	34.6
Visilux II	No	35.6	34.3	43.5	42.9	35.9
	Yes	37.0	35.0	43.1	42.7	36.0
Elipar Highlight	No	38.4	38.1	53.7	49.3	37.8
	Yes	39.2	39.6	54.3	49.0	38.1

Comparing the results one can observe that the heat transfer through the pulp model causes homogenisation of the temperature distribution in the tooth being in a steady state. The temperature differences in such a case are similar to those reported from in vivo experiments carried out with an open mouth [18]. The correctness of the idea of the heat transfer through the pulp modelling was proven. As we expected, the copper wire insert caused a distinct decrease in the maximal recorded temperature. The relaxation time of the temperature equilibration was also shorter for those cases.

The above results are considered as preliminary. At the present state of investigations an accurate adaptation of the model used is difficult. This is mostly due to lack of the results of in vivo experiments for model verification. Some appropriate

studies are in progress. Nevertheless, even in this stage of investigations many valuable results are possible to obtain. This concerns mainly comparative analyses of any kind.

3.2. Numerical calculations

The numerical analysis was carried out using two-dimensional FEM model of an incisor tooth. The model was based on a cross-section determined by a vertical plane of symmetry of the tooth. In the co-ordinate system established, it was the Oxz plane (Oz – vertical axis). Modelling (GEOSTAR) and calculations (HSTAR) were based on a professional COSMOS/M software package.

In order to formulate the numerical problem, an assumption was accepted that the heat transfer inside the tooth is exclusively conductive in character and that there are no internal heat sources. The governing equation is as follows

$$\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right), \quad (1)$$

where ρ is the density, c_p – the specific heat, τ – the time, T – the temperature, k_x and k_z – the thermal conductivity in the x and z directions, respectively.

Boundary conditions of two types, i.e. of the second order (Neumann type) and of the third order (Fourier type) [19], were assumed. Boundary conditions were differentiated both with respect to time and space. For the front tooth surface, at the time corresponding to its exposition to the polymerisation lamp light, the second-order boundary condition of the heat flux was accepted, i.e.

$$q_{S1} = -K \frac{\partial T}{\partial n}, \quad (2)$$

where K is the resultant thermal conductivity and $\partial T / \partial n$ is the normal temperature gradient. During relaxation time a convective heat flux from this surface was assumed to be

$$q_{S1} = h_{S1}(T - T_a), \quad (3)$$

where h_{S1} is a corresponding heat transfer coefficient and T_a is the ambient air temperature.

For the back surface and the surface of the root (the metal insert as well) convective heat fluxes were assumed to be:

$$q_{S2} = h_{S2}(T - T_a), \quad (4)$$

$$q_{S3} = h_{S3}(T - T_w), \quad (5)$$

where h_{S2} and h_{S3} are corresponding heat transfer coefficients and T_w is the water bath temperature.

It was also assumed that under initial conditions a temperature distribution was uniform. The values of parameters of the initial and boundary conditions are listed in table 2.

Table 2. Parameters of initial and boundary conditions of the numerical model

	Designation	Time limits	Heat flux q [W m ⁻²]	Heat transfer coefficient h [W m ⁻² K ⁻¹]	Ambient temperature T [°C]
Front (irradiated) surface	S_1	exposition time $0 \text{ s} < \tau < 40 \text{ s}$	2000		
		relaxation time $40 \text{ s} < \tau$		10	20
Back surface	S_2	$0 \text{ s} < \tau$		10	20
Root outer surface	S_3	$0 \text{ s} < \tau$		500	36.6
Initial condition		$\tau = 0 \text{ s}$	$T(x, y) = 36.6 \text{ °C}$		

The values of the heat transfer coefficient were estimated based on a criterial formula reported in [19], [20]. The heat flux represented by equation (2) was fitted to results of experimental investigations. Due to complexity of the physical problem an attempt of its derivation from parameters of the lamp and the light guide was unsuccessful. Other thermophysical properties such as specific heat and thermal conductivity were found in [21], [22] and in our articles [4], [5], [23]. They were spatially differentiated according to the model tooth structure. The zones of enamel, dentine, dentine cement, epoxy resin and copper insert were indicated. Basic calculations were performed for isotropic, temperature-independent properties. Nevertheless, the model is constructed in such a way that both time and temperature-dependent orthotropic parameters can be used. Values of parameters taken for calculations are listed in table 3.

Table 3. Values of thermophysical parameters taken for numerical calculations

Material	Thermal conductivity $k_x=k_y$ [W m ⁻¹ K ⁻¹]	Specific heat c_p [J kg ⁻¹ K ⁻¹]	Density ρ [kg m ⁻³]
Enamel	0.933	754	2950
Dentine	0.570	1380	2140
Cement	0.628	1670	2030
Copper (pulp model)	395	390	8900
Air	0.025	1010	1.2

In the model discretisation, 4-node plane quadrilateral elements were employed. The division of the cross-section of the tooth is shown in figure 4.

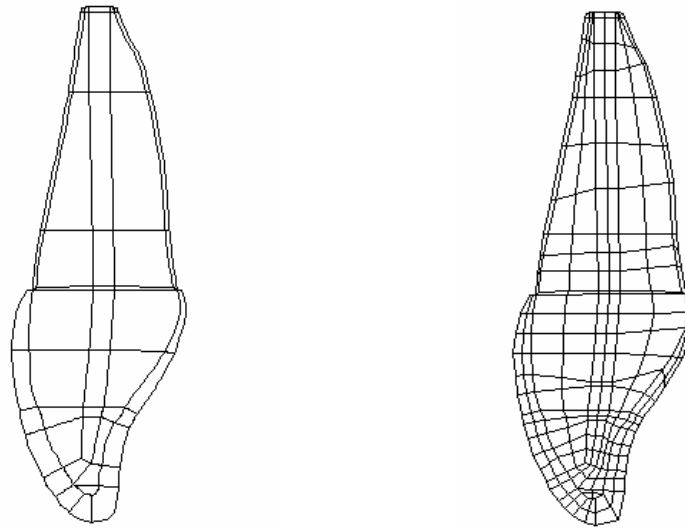


Fig. 4. Division of the tooth into surface elements

The initial conditions for transient analysis were obtained from preliminary calculations for a steady heat transfer with the same boundary conditions as those assumed for the 40 s relaxation period of transient calculations.

In the analysis, the effects of the metal insert dimension and its positioning on the temperature distribution were studied. Three widths of the 2-D metal insert were considered. They were respectively 0.8 mm, 1 mm and 1.2 mm. Also three depths of the insert positioning inside the tooth cavity were investigated. The calculations testified to a substantial influence of the investigated parameters of the model pulp on the temperature distribution in the tooth. It concerns both steady state and transient analysis. The numerical results were compared with the results of experimental investigations of the extracted incisor tooth. This comparison allows us to arrive to optimal parameters of the metal insert modelling the heat transfer through the pulp. A 1 mm width of the metal being inserted to the end part of the pulp cavity of the tooth was selected as the proper one. In such a case, the results of calculations (if the maximal temperatures are concerned) are in agreement with the results of experiments described in the previous paragraph.

Typical results of numerical calculations are depicted in figures 5 and 6. In figure 5, there are compared steady-state temperature distributions with and without modelling of the heat transfer by the pulp. Diagrams depicted in figure 6 show the transient temperature courses for both cases. The courses were taken for the nodes corresponding to the temperature measurement points of experimental investigations.

Analysing the results one can observe the effects of the heat transfer away from the tooth by the model pulp.

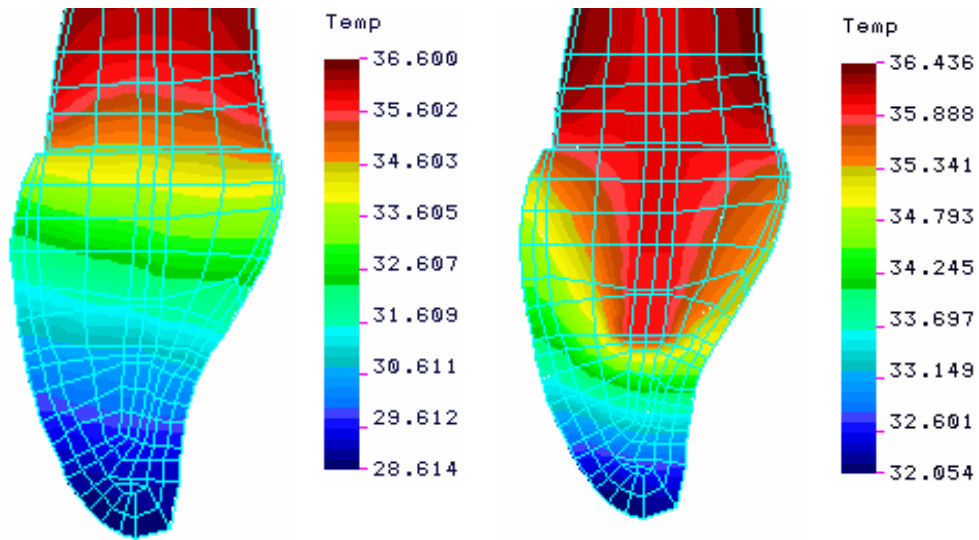


Fig. 5. Steady-state temperature distribution without and with modelling of the heat transfer by the pulp. The temperature indicated is in Celsius degrees

In general, the two-dimensional numerical analysis proved correctness of the idea of modelling the heat transfer away by the pulp. The results obtained are closer to those few reported based on in vivo investigations. The methodology invented will be used for the development of a three-dimensional numerical model of the tooth; the work is in progress.

As regards the details, it should be stated that the model developed needs individual adapting for every single case. When we deal with other mechanisms of heat transport, for instance the radiative heat transfer, the thermal conductivity components should be replaced by effective thermal conductivity in three main directions [24]. Moreover, a proper modelling of heat transport in such a case requires introducing internal heat sources. Due to flexibility of a model developed such changes are easy to introduce. This concerns both two- and three-dimensional modelling.

3.3. Comparison between the results of experimental and numerical tests

In order to facilitate the analysis, time-constants of a temperature-relaxation process were derived from the measured and calculated temperature histories. The temperature relaxation, beginning from the moment of taking away the polymerisation lamp ($\square \square 40$ s), was taken into consideration. The values of time-constants are listed in table 4.

Table 4. Values of time-constants of the temperature-relaxation processes in the tooth from experimental and numerical investigations

	Pulp heat transfer modelling	Point (see figure 2a)			
		$T0$ [s]	$T1$ [s]	$T2$ [s]	$T4$ [s]
Experiments	No	74	84	14	–
	Yes	52	53	10	58
Numerical calculations	No	101	101	57	132
	Yes	48	49	17	59

The comparison revealed that:

- a satisfactory agreement between the results was obtained in the case of test points $T0$, $T1$ and $T4$;
- the differences obtained in the case of point $T2$ exceeded admissible limits;
- in the case of taking into account the heat transfer through the pulp, lower values of time-constants were reported from numerical calculations.

It seems most probably that the differences observed arise because two-dimensional numerical model is inconsistent with real three-dimensional investigated object. This concerns the test points $T0$, $T1$ and $T4$. In numerical calculation, the heat conduction through the model of the pulp is overestimated. In the case of the test point

T2 placed in a central position of the irradiated region, the differences are due to improper modelling of the heat exchange between the surface and the surroundings. As it has been stated before, an appropriate improvement of the model can be made. In particular, this needs taking into account other heat transfer phenomena, e.g. radiative heat transfer from a thin surface layer. Nevertheless, the transient heat exchange in the short period after removing the heat source from the surface examined did not influence much the transient heat exchange in the bulk.

At present stage only qualitative analysis is possible to perform. A detailed quantitative comparative analysis will be possible after developing a three-dimensional numerical model.

4. Conclusions

Experimental stand for in vitro investigations of the heat transfer phenomena in teeth was designed and built. Such a stand has to reproduce thermal conditions of the oral cavity. Another, numerical model complemented the experimental one. It was two-dimensional model of the tooth. Test investigations carried out for the tooth irradiated by a dental polymerisation lamp revealed the advantages of complex studies with utilisation of both models. In particular, they confirmed the necessity of modelling the heat transfer through the pulp. A satisfactory agreement between the two models was achieved. The results also agree with available results obtained in vivo experiments. It is very important to realize that a methodology of investigating heat exchange in teeth was developed.

The work is still in progress. A three-dimensional, more adequate in real situation, model of the tooth is being developed now.

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