Model assessing thermal changes during high temperature root canal irrigation

Analise Bartolo¹, Edmond Koyess², Josette Camilleri³ ✉, Christopher Micallef¹

¹Department of Mechanical Engineering, Faculty of Engineering, University of Malta, Msida, Malta

²Department of Endodontics, Lebanese University, Beirut, Lebanon

³Department of Restorative Dentistry, Faculty of Dental Surgery, University of Malta, Msida, Malta

✉ E-mail: josette.camilleri@um.edu.mt

Published in Healthcare Technology Letters; Received on 3rd March 2016; Revised on 6th July 2016; Accepted on 6th July 2016

The main aim of root canal irrigation is to eliminate micro-organisms. Sodium hypochlorite (NaOCl) is considered to be the ideal material and raising its temperature potentiates the antimicrobial activity. NaOCl may lead to localised tissue necrosis when extruded past the root apex. This study analyses the use of high temperature root canal irrigation as an alternative process for the elimination of microorganisms from the root canal system. An experimental set-up was designed where a constant supply of heat was passed from a heat source through a copper wire inside the root canal. The data acquired together with known constants pertaining to enamel and dentine was used to numerically model the thermal changes in a tooth using a finite element method. Results obtained from the finite element thermal model of the tooth were repeatable and were validated with the experimental results. The thermo-physical properties of the tooth were varied and convergence criteria met. The temperatures reached were below what has been reported to cause irreversible damage to the bone. This was further confirmed from a series of simulations that were undertaken. The temperatures achieved were suitable for the elimination of microorganisms during root canal therapy.

1. Introduction: Teeth consist of a crown and a root, which is embedded in bone. Teeth are made up of an outer layer of enamel in the crown and cementum in the root area, an inner layer of dentine, which encases the dental pulp. The dental pulp is innervated and has a blood circulation system. Any break in enamel and dentine caused by dental caries or trauma poses a risk of pulp infection and the need for root canal treatment. An infected root canal system in a tooth can be considered a niche where certain colonies of microorganisms reside. *Enterococcus faecalis*, the most persistent type of microorganism, is able to live in dentinal tubules and resists extremely harsh environments [1]. Removal of bacteria and their by-products is fundamental in root canal treatment. A major cause of post-treatment disease is claimed to be the incomplete disinfection of the root canal system [2–5]. The most effective way of removing bacteria from the canal is by using an effective irrigating solution [6].

NaOCl is the most common irrigant used due to its antimicrobial activity and tissue solvent properties [7–9]. High concentrations are more effective [6, 10] and at higher temperatures the antimicrobial activity is increased. NaOCl has cytotoxic potential leading to severe pain, swelling, ulceration, haemorrhage from the root canal and necrosis if it is accidentally extruded out of the root canal into the periapical tissues. Long-term exposure of dentine to NaOCl reduces dentine elasticity and flexural strength [11]. Root canal preparation using manual instrumentation and saline as an irrigant has been shown to reduce the number of bacteria in infected canals [12]. Sterile water and saline do not possess tissue-dissolving properties and thus cannot be used as main irrigants. Their use is restricted to in between irrigating solutions [6]. Currently there is insufficient evidence documenting clinically relevant and patient related outcomes to identify a superior irrigant [13]. None of the available irrigation solutions can be regarded as optimal [6].

High temperatures can be effective in elimination of microorganisms. A 100-fold increase in killing efficacy was observed when solutions were heated to 20°C and 45°C [14]. Using a heating device, a 20°C solution reached 45°C and 60°C in 7 and 20 min, respectively [14]. There is little information on the temperature required to heat the inside of the root canal effectively thus eliminating microorganisms present. Furthermore the only reports quantifying the heat dissipation to the surrounding tissues from increases

in temperature inside the root canal are for warm obturation techniques [15–17]. The objectives of this Letter were;

- To investigate whether a simplified mathematical model of a typical tooth is sufficient to predict its thermal behaviour when subjected to high temperature irrigation inside the root canal aiming at microbial elimination during a root canal treatment.
- To numerically assess the most appropriate thermo-physical properties of the various materials forming the tooth.

This was done by creating a simplified finite element thermal model of a typical tooth which was validated against experimental data.

2. Methodology: The experimental procedure included the collection of temperature data from an experiment on an extracted tooth. A thermal model was then developed and steady state and transient analyses were carried out. The validity of data from the experimentation compared with the thermal model was then worked out.

2.1. Validation of the experimental procedure

2.1.1 Tooth preparation: Single rooted teeth extracted for orthodontic and periodontal purposes were used. The roots were cleaned of soft tissue and calculus using hand instruments. Access cavities were prepared and the root canals were cleaned to working length, which was established by a #10 K file introduced into the canal until it just emerged from the apical foramen. The canals were shaped to #F3 ProTaper file and irrigated with 5 ml of 5% NaOCl solution after insertion of each instrument followed by a final rinse of 5 ml of 17% ethylene diamine tetraacetic acid (EDTA; Calasept; NordiskaDental, Angelholm, Sweden). The canals were then flushed with 2 ml of deionised water and dried with paper points. On each tooth four holes were drilled with size 2 round bur on the labial surface of the tooth. The locations of the holes were in the middle of the crown, at the cement-enamel junction (CEJ), mid-root and in the vicinity of the root apex.

At these four locations, T-type thermocouples (Tolerance Class 2) were attached. These thermocouples were manufactured from PFA coated copper and constantan wires having P/Ns TFCC-003-50 and TFCP-003-50, respectively (OMEGA Engineering, Inc,

Fig. 1 Diagram showing experimental set up of heat supply to the root canal through a soldering iron and copper wire, and thermocouple location with T1: at the root apex, T2: mid-root, T3: at the CEJ, T4: in the middle of the crown and T5: inside the root canal. The thermocouples were connected to a data logger

Atlanta GA, USA). Thermocouple wires were soldered at the tip creating the thermocouple sensor. Such thermocouples had a standard limits of error of 0.75% of the measured temperature or 1°C whichever is the highest. The exposed wires were insulated using plastic spray (Plastik-70, CRC Industries, Europe) to electrically insulate the sensors from their surroundings. Another T-type thermocouple was also placed in the root canal space.

2.1.2 Experimental set-up: Fig. 1 illustrates the experimental set-up. The constant source of heat applied using a soldering iron was conducted from the source to the tooth through a piece of copper wire (diameter of 0.60 ± 0.02 mm). Thermal paste was injected inside the root canal maximising conduction between the copper wire and various parts of the tooth. One end of the copper wire was coiled around the tip of the soldering iron; the other end was inserted in the root canal to working length. Copper wire was selected as the heat transfer medium due to its excellent thermal conductive properties.

Liquid-absorbing foam soaked in water was used to hold the tooth in position and prevent any moisture loss. The tooth was positioned into the liquid-absorbing foam up to the CEJ. This was done since clinically only the crown up to the CEJ is in contact with air while the tooth root is in contact with bone and tissue fluids. The system was then well-lagged using Rockwool™ insulating material (see Fig. 2).

Another two T-type thermocouples were used to measure the temperature of the surrounding liquid and the temperature between the lagging and the tooth. The heat source was set to

Fig. 2 Picture showing experimental setup

provide a temperature of the order of 100°C. All temperature sensors were connected to a thermal probe and all data were logged accordingly. Temperatures at the crown, CEJ, mid-root and in the vicinity of the root apex were recorded at time intervals of 0.5 s until the system reached a steady state. Steady-state condition was deemed to be reached when temperatures did not vary by more than the thermocouple uncertainty band (1°C) over a period of 5 min. The system was then allowed to cool down. This procedure was repeated three times per tooth on six different teeth.

2.2. Thermal model: A thermal model was developed where the heat dissipation inside a tooth could be investigated when subjected to various temperatures. The finite element method was used to model the behaviour of a tooth when subjected to high temperatures. ANSYS® Academic Research Release 14.0 (ANSYS, Inc., Canonsburg, PA, USA) was used to develop a finite element model in ANSYS® Workbench™. For such a finite element analysis (FEA), steady state and transient thermal analysis were carried out.

For the purposes of tooth modelling the following assumptions were made:

- heat transfer within the tooth and the surrounding fluid takes place by conduction and convection;
- the thermo-physical properties density (ρ), specific heat capacity (c) and thermal conductivity (k) are isotropic, homogeneous and independent of temperature and time;
- heat transfer between one material and the other is continuous (negligible contact resistance);
- initial temperature is 18°C.

The material properties of enamel, dentine, water and air (Table 1) were assigned to the respective material in the FEA model. The system designed took into account the crown and root portions of the tooth and the root was assumed to be single rooted where the root is symmetrical about the tooth's axis. Fig. 3 illustrates the simplified two-dimensional (2D) axisymmetric full scale geometrical model which was used where the dentine apical region was modelled as an inverted cone, the dentine coronal region was modelled as a cylinder and the enamel coronal region was modelled as a cylindrical inverted cap around the dentine coronal region. This approximation was considered valid as the thermal behaviour was analysed rather than stresses that depend on the exact geometry of the body. The liquid absorbing foam was modelled as a solid having thermal properties of water so that the only mode of heat transfer was constrained to conduction. All dimensions were based on the apparatus (beaker, liquid absorbing foam etc.) and the main dimensions of the teeth used during the experimentation. ANSYS® Mesher™ software was used for grid generation (spatial discretisation). In this 2D analysis, nodes are tightly packed close to the root canal and increase in size away from the root canal ensuring that the grid generated is relatively structured.

A steady state and transient thermal analysis were carried out. For both analyses, all input data was obtained from the experimental results. The assumptions, the material properties, the geometry designed and the generated mesh were the same for both the

Table 1 Thermo-physical properties of materials used in the FEA models

	Thermo-physical properties		
	Density, kg/m ³	Specific heat capacity, J/kgK	Thermal conductivity, W/mK
enamel	2800 [18]	711 [18]	0.81 [19]
dentine	1300 [20]	1420 [21]	0.63 [22]
water	998.37 [23]	4185.4 [23]	0.595 [23]
air	1.203 [24]	1.0068 [24]	0.02556 [24]

Fig. 3 Diagram showing the simplified geometrical model of the FEA model

mentioned analyses. The ANSYS® Mechanical™ solver was used in both cases.

2.2.1 Grid independence and convergence criteria: When solving FEA models, it is important to make sure that the numerical solution does not vary with the grid size (spatial discretisation), that is the solution is tested for grid independence. All models were assessed to be grid independent by comparing the simulation results derived from two different grid densities for each of the simulations. Mesh density was increased in areas close to the root canal as steep temperature gradients occur particularly in such region. Results were deemed to be grid independent when the percentage difference did not vary more than 5% between one grid size and another. The course grid contained 2437 elements while the fine grid contained 6552 elements. The maximum percentage difference between the results derived from the two grids was 2.14%. This translates to a maximum temperature difference of 1.6°C. This shows that additional grid elements do not contribute significantly to more accurate results and consequently the courser grid was employed in all the analyses that followed.

Since the solution methodology is an iterative process, it was important to stop the solution when the results are deemed to be converged, that is the results between one iteration and the next does not vary. Convergence criteria were also essential to ensure accurate results by monitoring the asymptotic convergence of temperatures in key locations identified in Section 2.1, where thermocouples were positioned.

2.2.2 Steady-state thermal analysis: The steady-state thermal analysis was simulated first. This analysis was used to obtain the temperature distribution within the tooth when the applied thermal load did not vary over time. The boundary conditions were the temperatures of the water, air and the heat source in the root canal. The heat source temperature boundary condition in the root canal was applied along the edges representing dentine and enamel in the coronal region and dentine in the apical region. The water temperature boundary condition was applied along the edges representing water. Stepped loads were applied such that the load value will be constant for the entire load step. Between one simulation and another, boundary conditions were modified to correspond to those present in the experiments carried out on the tooth described in Section 2.1. As the system was lagged, the edges that represent the surrounding air were insulated in the simulation. The convective heat transfer coefficient (h) between the enamel and the surrounding air was set to 15 W/m²K. Moreover, the material's thermal conductivity (k) was set as constant.

All steady-state models were validated against experimental results by calculating the percentage error between the experimental data and the simulation results of the temperatures at the crown, CEJ, mid-root and root apex areas. A sensitivity analysis of the thermo-physical properties k and h was also performed. The simulation was repeated with different values of thermo-physical properties obtained from literature; assessing the influence these parameters have on the final result. This steady-state thermal analysis confirmed the correct modelling technique, any assumptions taken, the material's thermal conductivity (k), the convective heat transfer coefficient (h) and the geometry.

2.2.3 Transient thermal analysis: The time dependence of the temperature within the model for the first 1000 s was analysed in the transient thermal simulation. For such analysis, a similar procedure as the steady-state thermal analysis was followed but this time performed as a function of time. The thermal load's magnitude and their corresponding time were specified through a table. The temperature of the root canal and the water at transient conditions were set. The heat source temperature boundary condition in the root canal and the water temperature boundary condition were applied as the steady-state analysis. The set values inputted were obtained from the experimental results for the time period between 0 and 1000 s. For this analysis, the initial time step was set equal to 0.001 s based on the Fourier number; larger values were found to produce errors while solving the simulation. The time step sizes used were found to be adequate to capture the transient phenomenon. The initial temperature was set to 18°C. The system was insulated and the same value of h was applied. The thermo-physical properties (h , k , c and ρ) were set as constant. Between one simulation and the other the boundary conditions were changed; corresponding to the experiments performed in Section 2.1. Similar to the steady-state models, all transient models were validated against experimental results.

2.3. Sensitivity analysis: A sensitivity analysis of the thermo-physical properties (k , h , c and ρ) was also performed such that the parameters' influence on the final result will be assessed. The values used were obtained from literature.

3. Results

3.1. Validation of experimental procedure: Experimental results showed that the highest temperatures were measured at the crown, followed by the CEJ, mid-root and apex. Typical results obtained are shown in graphical form in Fig. 4. characterised by a

Fig. 4 Plot of temperature (°C) against time (s)

Table 2 Comparison between experimental and simulation results for the steady-state thermal analysis

Test	Location	T_{exp} , °C	T_{sim} , °C	% Error
1	CEJ	67.6	69.5	2.8
	crown	77.0	74.6	3.0
2	CEJ	72.0	71.5	0.6
	crown	74.2	76.3	2.8
3	CEJ	95.0	100.3	5.5
	crown	113.1	106.6	5.7
4	CEJ	80.2	81.2	1.3
	crown	96.6	85.4	11.5
5	CEJ	69.6	68.7	1.3
	crown	79.5	73.6	7.5
6	CEJ	77.8	75.8	2.5
	crown	83.2	80.0	3.9

CEJ: cement-enamel junction; T_{exp} : experimental temperature; T_{sim} : simulated temperature

transient state until the system reached equilibrium. The uncertainty bars correspond to the uncertainty introduced by the thermocouples plotted at time intervals of 200 s.

3.2. Thermal model: Tables 2 and 3 give a summary of the results. Table 2 shows the percentage difference between the experimental data and simulation results when the system was in equilibrium (steady-state condition) while Table 3 shows the maximum percentage difference between the experimental data and simulation results under transient conditions. Since the percentage error for the transient state analyses was continuously changing with time, the temperatures at the time when the maximum percentage error in each of the temperatures was used to compare the two sets of data and Table 3 reflects this. The steady-state analyses error comparing the actual results obtained from the experiments carried out and the data from FEA was lower than the error for the transient state assessment.

3.3. Sensitivity analysis: In the steady-state analysis, when analysing the variations introduced by changing the thermal conductivity (k) of the enamel and dentine and convective heat transfer coefficient (h) between the tooth and the air to extreme values shown in Table 4 it was noticed that the values presented in Table 1 gave the most accurate overall results when compared with the experimental data.

Table 3 Comparison between experimental and simulation results for the transient thermal analysis at the time of corresponding temperature maximum error

Test	Location	T_{exp} , °C	T_{sim} , °C	Max. % error
1	CEJ	50.47	43.5	13.7
	crown	61.42	52.4	14.7
2	CEJ	52.8	49.4	6.4
	crown	33.4	41.4	23.7
3	CEJ	69.1	55.6	19.6
	crown	90.9	74.3	18.2
4	CEJ	68.1	49.4	27.5
	crown	82.1	60.1	26.8
5	CEJ	28.6	36.5	27.3
	crown	37.1	45.0	21.2
6	CEJ	59.2	48.8	17.6
	crown	67.0	46.3	30.9

CEJ: cement-enamel junction; T_{exp} : experimental temperature; T_{sim} : simulated temperature

Table 4 Extreme values of thermo-physical properties used for the sensitivity analysis study at steady-state conditions

thermal conductivity, W/mK			
dentine	0.48 [19]	0.88 [25]	
enamel	0.71 [18]	0.93 [26]	
convective heat transfer coefficient, W/m ² K			
natural convection – gases	10 [24]	20 [24]	

Table 5 Extreme values of thermo-physical properties used for the sensitivity analysis study in transient mode

density, kg/m ³	enamel	2500	2980 [27]
	dentine	1170 [28]	2400 [21]
specific heat capacity, J/kgK	enamel	600	800
	dentine	1300	1590 [27]

Similarly in the transient thermal conditions, the same procedure as for steady-state analysis was adopted. When analysing the variations introduced by changing the density (ρ) and specific heat capacity (c) of enamel and dentine to extreme values shown in Table 5 it was noticed that the values presented in Table 1 gave the most accurate overall results when compared with the experimental data.

4. Discussion: *E. faecalis*, the most resistant microorganism present in the root canal is denatured at 60°C [1]. Thus, a set temperature of around 100°C was chosen in the current research. This temperature of 100°C was also investigated in experimental work on the heat transfer from sources used to thermo-plasticised gutta-percha [15–17]. These studies showed that when applying a temperature of 100°C the temperature on the root surface was raised by a few degrees. Therefore, below the limit that can cause bone necrosis and other deleterious effects [29, 30].

It has been shown that a rise in temperature of sodium hypochlorite solutions from 20 to 45°C resulted in a 100-fold increase in killing efficacy of *E. faecalis* [14]. In the current Letter, the effect of high temperatures without the chemical action of sodium hypochlorite was investigated. The heat transfer and dissipation in the tooth experimentally was first investigated and then the data was used to validate a thermal model that predicts changes in temperature inside a tooth in various locations when heat is applied inside the root canal. Preliminary studies carried out showed that injecting water at various temperatures in the root canal did not achieve a constant supply of heat and data was unpredictable. To counteract this, a soldering iron was used to generate constant temperatures and thermal paste was used to maintain these temperatures in the root canal. A device that can act as a constant heat source needs to be devised as the use of a liquid with high temperature is unreliable.

When a tooth is exposed to high temperatures for prolonged periods of time, the heat must be dissipated to the various parts of the tooth mainly by the different modes of heat transfer. The most significant heat transfer mode presented in this Letter was conduction. The highest temperatures recorded were in the crown and at the CEJ. This indicates that the air does not dissipate the heat as fast as the fluid, which was in contact with the root of the tooth. Hence, higher temperatures were recorded at these locations.

In the steady-state thermal model, the percentage error between experiment and simulation ranged from 0.6 to 11.5% as noted in Table 2. Meanwhile, in the transient thermal analysis the maximum percentage error was higher and a bigger range was noted shown in Table 3. In a simulation, the ideal case is modelled and perfect heat conduction is assumed between the root canal and the various parts of the tooth. These percentage errors may be attributed to the difference that exists between the thermal model having ideal temperature sensing and the non-ideal experimental setup.

The results of this experiment show that a source that can generate constant heat inside the root canal is necessary. The FEA can be then used to predict the temperatures generated inside the root canal and the temperatures dissipated through the tooth and to the external surface of the root, which may affect the periodontium and adjacent bone. The ideal temperatures, which eliminate the microorganisms inside the root canal and are considered safe to be used *in vivo* can thus be predicted.

5. Conclusions: The finite element method can be used to predict temperatures associated with the tooth when high temperatures meant to eliminate microorganisms are used in the root canal.

6. Acknowledgments: The authors thank technical staff particularly Mr. Andrew Briffa of the Department of Mechanical Engineering, Faculty of Engineering, University of Malta and Dr. Raqueli Viapiana from the Araraquara Dental School, Sao Paulo State, Brazil for their assistance.

7. Funding and declaration of interests: Conflict of interest: none declared.

8 References

- [1] Stuart C.H., Schwartz S.A., Beeson T.J., *ET AL.*: 'Enterococcus faecalis: its role in root canal treatment failure and current concepts in retreatment', *J. Endod.*, 2006, **32**, pp. 93–98
- [2] Seltzer S., Bender I.B., Smith J., *ET AL.*: 'Endodontic failures-an analysis bases on clinical, roentgenographic, and histologic findings I & II', *Oral Surg. Oral Med. Oral Pathol.*, 1967, **23**, pp. 500–530
- [3] Lin L.M., Skribner J.E., Gaengler P.: 'Factors associated with endodontic treatment failures', *J. Endod.*, 1992, **18**, pp. 625–627
- [4] van der Waal S.V., Jiang L.M., de Soet J.J., *ET AL.*: 'Sodium chloride and potassium sorbate: a synergistic combination against Enterococcus faecalis biofilms: an in vitro study', *Eur. J. Oral Sci.*, 2012, **120**, pp. 452–457
- [5] van der Waal S.V., van der Sluis L.W., Özok A.R., *ET AL.*: 'The effects of hyperosmosis or high pH on a dual-species biofilm of Enterococcus faecalis and Pseudomonas aeruginosa: an in vitro study', *Int. Endod. J.*, 2011, **44**, pp. 1110–1117
- [6] Haapasalo M., Shen Y., Wang Z., *ET AL.*: 'Irrigation in endodontics', *Br. Dent. J.*, 2014, **216**, pp. 299–303
- [7] Kishen A., Sum C.P., Mathew S., *ET AL.*: 'Influence of irrigation regimens on the adherence of Enterococcus faecalis to root canal dentin', *J. Endod.*, 2008, **34**, pp. 850–854
- [8] Valera M.C., da Silva K.C.G., Lilian Eiko Maekawa L.E., *ET AL.*: 'Antimicrobial activity of sodium hypochlorite associated with intracanal medication for Candida albicans and Enterococcus faecalis inoculated in root canals', *J. Appl. Oral Sci.*, 2009, **17**, pp. 555–559
- [9] Retamozo B., Shabahang S., Johnson N., *ET AL.*: 'Minimum contact time and concentration of sodium hypochlorite required to eliminate Enterococcus faecalis', *J. Endod.*, 2010, **36**, pp. 520–523
- [10] Dornelles-Morgental R., Guerreiro-Tanomaru J.M., de Faria-Júnior N.B., *ET AL.*: 'Antibacterial efficacy of endodontic irrigating solutions and their combinations in root canals contaminated with Enterococcus faecalis', *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, 2011, **112**, pp. 396–400
- [11] Haapasalo M., Shen Y., Qian W., *ET AL.*: 'Irrigation in endodontics', *Dent. Clin. North Am.*, 2010, **54**, pp. 291–312
- [12] Figdor D., Sundqvist G.: 'A big role for the very small — understanding the endodontic microbial flora', *Aust. Dent. J. Suppl.*, 2007, **52**, pp. 38–51
- [13] Keenan A.V.: 'No evidence favouring one irrigant versus another in root canal treatments', *Evid. Based Dent.*, 2012, **13**, (4), p. 107
- [14] Sirtes G., Waltimo T., Schaetzle M., *ET AL.*: 'The effects of temperature on sodium hypochlorite short-term stability, pulp dissolution capacity, and antimicrobial efficacy', *J. Endod.*, 2005, **31**, pp. 669–671
- [15] Venturi M., Pasquantonio G., Falconi M., *ET AL.*: 'Temperature change within gutta-percha induced by the system-B heat source', *Int. Endod. J.*, 2002, **35**, (9), pp. 740–746
- [16] Viapiana R., Baluci C.A., Tanomaru-Filho M., *ET AL.*: 'Investigation of chemical changes in sealers during application of the warm vertical compaction technique', *Int. Endod. J.*, 2015, **48**, pp. 16–27
- [17] Viapiana R., Guerreiro-Tanomaru J.M., Tanomaru-Filho M., *ET AL.*: 'Investigation of the effect of sealer use on the heat generated at the external root surface during root canal obturation using warm vertical compaction technique with System B heat source', *J. Endod.*, 2014, **40**, pp. 555–561
- [18] Brown W.S., Dewey W.A., Jacobs H.R.: 'Thermal Properties of Teeth', *J. Dent. Res.*, 1970, **49**, p. 4
- [19] Lin M., Liu Q.D., Kim T., *ET AL.*: 'A new method for characterization of thermal properties of human enamel and dentine: influence of microstructure', *Infrared Phy. Technol.*, 2010, **53**, p. 7
- [20] Fukase Y., Saitoh M., Kaketani M., *ET AL.*: 'Thermal coefficients of paste-paste type pulp capping cements', *Dent. Mater. J.*, 1992, **11**, pp. 189–196
- [21] Figueiredo de Magalhães M., Neto Ferreira R.A., Grossi P.A., *ET AL.*: 'Measurement of thermophysical properties of human dentin: effect of open porosity', *J. Dent.*, 2008, **36**, pp. 588–594
- [22] Braden M.: 'Heat conduction in normal human teeth', *Arch. Oral Biol.*, 1964, **9**, p. 8
- [23] Cruz UCS: 'Water properties'. Available at: <http://www.people.ucsc.edu/~bkdanil/WaterProperties.html>
- [24] Incropera F.P.: 'Fundamentals of mass and heat transfer' (John Wiley & Sons, USA, 2007, 6th edn.)
- [25] Little P.A., Wood D.J., Bubbs N.L., *ET AL.*: 'Thermal conductivity through various restorative lining materials', *J. Dent.*, 2004, **33**, p. 6
- [26] Craig R.G., Peyton F.A.: 'Thermal conductivity of tooth structure, dental cements, and amalgam', *J. Dent. Res.*, 1961, **40**, pp. 8
- [27] I. I. Foundation. Tissue Properties. Available at: <http://www.itis.ethz.ch/itis-for-health/tissue-properties/database/density/>
- [28] Peyton F.P., Simeral W.G.: 'Specific heat of tooth structure' (University of Michigan School of Dentistry, Alumni Bull, 1954, **33**), p. 56
- [29] Eriksson A., Albrektsson T., Grane B., *ET AL.*: 'Thermal injury to bone. A vital-microscopic description of heat effects', *Int. J. Oral Surg.*, 1982, **11**, pp. 115–121
- [30] Eriksson A.R., Albrektsson T.: 'Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit', *J. Prosthet. Dent.*, 1983, **50**, pp. 101–107