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ROOT SURFACE TEMPERATURE MEASUREMENT DURING ROOT CANAL OBTURATION

Les Hotra[1], Oksana Boyko[2], Igor Helzhynskyy[1], Hryhorii Barylo[1], Pylyp Skoropad[3], Alla Ivanyshyn[3], Olena Basalkevych[2]

[1]Lviv Polytechnic National University, Department of Electronic Engineering, Lviv, Ukraine, [2]Danylo Halytsky Lviv National Medical University, Department of Medical Informatics, Lviv, Ukraine, [3]Lviv Polytechnic National University, Department of Measuring Information Technology, Lviv, Ukraine

Abstract. *Prolonged exposure to elevated temperatures exceeding 47°C, which can occur during root canal obturation, can cause damage of both dental and bone tissues. In order to study the temperature distribution on the surface of the tooth root a temperature measuring device with cold-junction compensation is proposed. For in vitro measurement of the temperature distribution on the surface of the tooth, 8 thermocouples placed in direct contact with the cementum of the tooth were used. In order to eliminate the cold-junction temperature variations, the temperature equilibration device and RTD were used. The suggested linear approximation for the thermocouples' conversion function provides a nonlinearity relative error of less than 0.05% for K-type thermocouples and 0.07% for J-type thermocouples over the temperature range from 20 to 60°C.*

Keywords: temperature measurement, thermocouples, root canal obturation, linearisation

POMIAR TEMPERATURY POWIERZCHNI KORZENIA PODCZAS OBTURACJI KANAŁÓW KORZENIOWYCH

Streszczenie. *Długotrwała ekspozycja na podwyższone temperatury przekraczające 47°C, które mogą wystąpić podczas wypełniania kanałów korzeniowych, może spowodować uszkodzenie zarówno tkanek zęba, jak i kości. W celu zbadania rozkładu temperatury na powierzchni korzenia zęba zaproponowano urządzenie do pomiaru temperatury z kompensacją zimnego złącza. Do pomiaru in vitro rozkładu temperatury na powierzchni zęba wykorzystano 8 termopar umieszczonych w bezpośrednim kontakcie z cementem zęba. W celu wyeliminowania wahania temperatury zimnego złącza zastosowano urządzenie do wyrównania temperatur oraz czujnik rezystancyjny RTD. Proponowana aproksymacja liniowa funkcji przetwarzania termopary zapewnia względny błąd nieliniowości mniejszy niż 0,05% dla termopar typu K i 0,07% dla termopar typu J w zakresie temperatur od 20 do 60°C.*

Słowa kluczowe: pomiar temperatury, termopary, obturacja kanałów korzeniowych, linearyzacja

Introduction

Superior root canal obturation is a crucial prerequisite for the success of endodontic treatment. Incomplete filling can jeopardise the success of root canal treatment. Various methods and materials are employed for root canal obturation [3, 7]. The most popular obturation techniques involves the use of gutta-percha as the core material and an endodontic sealer [22]. During cold lateral compaction gutta-percha cannot fill the lateral and apical canals, and the cavities can be the origin of inflammatory processes in periodontal tissues and destruction of bone tissue [2, 5, 6]. Therefore the softening of gutta-percha by heat is used. However, usage of substantial amount of heat causes potential risks, as the excessive heat may transfer to the adjacent periodontal tissues. Prolonged exposure to elevated temperatures exceeding 47°C can cause damage to both dental and bone tissues. There is a suggestion that exceeding of the temperature by more than 10°C at the external root surface could potentially lead to the damage in cementum, periodontal ligament, and alveolar bone, possibly inducing resorption or ankylosis [17, 23]. If the damage is short-time and the temperature does not exceed 53°C, it may be reversible; however, temperatures beyond this threshold could lead to irreversible bone damage [8]. The danger of excessive temperature increase also occurs during post space preparation, when it is necessary to carry out complete removal of root filling materials to strengthen the adhesive bond with dentin and increase post-retention [19]. During the heated gutta-percha technique of the root canal filling or post space preparation, it is necessary to evaluate the temperature on the root surface.

1. Determination of root surface temperature

To examine the root surface temperature distribution, it is necessary to perform in vitro temperature measurements directly on the root surface.

In this approach, the split tooth model is employed [26], in which during obturation the extracted tooth is placed in some medium and fixed in a holder, or manually held by forceps in the hands of the researcher [15].

To measure the temperature range during in vitro root canal obturation, various primary temperature transducers such as thermoelectric, thermoresistive or semiconducting ones can be employed [4, 10–12, 14]. The temperature measurements in separate points on the root surface and inside the root canal can be effectively performed using thermocouples [20, 24]. Compactness, wide temperature range, interchangeability, relatively fast thermal response, long term of operation, reliability and affordable price are the main advantages of thermocouples.

The K type (chromel-alumel) and J type (iron-constantan) are the most prevalent thermocouples, known for their affordability, precision, dependability and wide temperature range [21].

The thermocouples used for measurement were placed in direct contact with the cementum layer on the root surface [9], as shown in Fig. 1. To minimise the impact of external temperature, the thermocouples were housed in thermally and electrically insulating tubes.

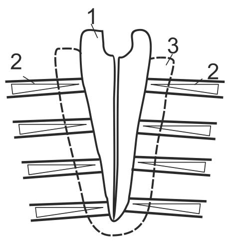

Fig. 1. The arrangement of thermocouples on the root surface: 1 – tooth, 2 – thermocouples, 3 – artificial substitute of periodontal tissues

To prevent heat dissipation loss from the tooth, it is advisable to use thermocouple electrodes with a minimal diameter. It is necessary to ensure tight fit of the measuring junction and electrodes of the thermocouple to the examined tooth surface using a heat-conducting material. The electrodes of the thermocouples are thermally insulated with a coating of thermoisolating lacquer.

The extracted tooth, along with the attached thermocouples, is then positioned in an environment with thermal conductivity similar to that of human tissues.

2. The design of temperature measuring device

For measurements of thermocouple output signals, an 8-channel microprocessor temperature measuring device has been designed. Its structural scheme (Fig. 2) consists of a temperature equalising device (TED), Resistance Temperature Detector (RTD) (R_{t0}) for measuring the temperature of the cold junctions of the thermocouples; a block of resistive temperature transducer (RTT); a 9-channel voltage commutator (VC); an analogue-to-digital converter (ADC); a microprocessor (MP); a digital readout (DR); an output interface (OI) and a supply unit (SU).

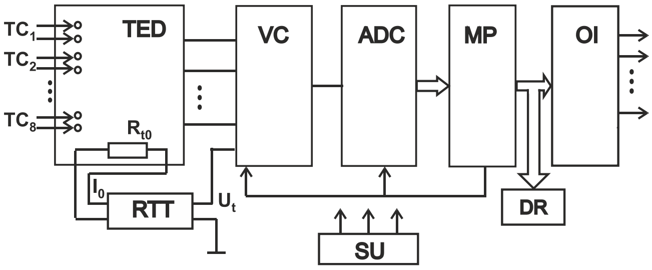

Fig. 2. Structural scheme of the temperature measuring device

The output terminals of the thermocouples are connected to the input terminals of the temperature equalising device. The values of thermo electromotive force (thermo-emf) generated in the thermocouples are a function of the temperature difference between the measuring and cold junctions:

$$e = f(t_h - t_c) = f(t_h) - f(t_c) \quad (1)$$

where t_h is the temperature of measuring (i.e. hot) junction, and t_c is the temperature of cold junction.

If the temperature of cold junction is not equal to 0ºC, the thermo-emf is equal to:

$$e = f(t_h) - e_{tc} \quad (2)$$

where e_{tc} is the value of thermo-emf at $t = t_c$.

The precision of temperature measurement is significantly influenced by the cold junction temperature, particularly in cases of lower measured temperatures [18, 25]. In order to eliminate the cold-junction temperature variations, either thermostatting of cold junction at 0ºC or electrical compensating circuits are used [13].

In the designed measuring device, the temperature equalising device was used for compensation of cold-junction temperature variations. It ensures the uniform temperature of cold junctions of the thermocouples and of the RTD. The long-term thermal stability of the circuit is achieved by placing it in a passive thermostat.

The RTD is connected to the RTT circuit, which is designed to generate a voltage proportional to the temperature of the cold junctions of the thermocouples.

The voltage drop across the resistor R_{t0} is determined by the value of the RTT reference current and is described by the following expression:

$$U_{Rt} = I_0 R_{t0}(1 + \alpha t_c) \quad (3)$$

where I_0 is the value of the reference current; R_{t0} is the resistance value of the RTD at a temperature of 0ºC, α is the temperature coefficient of resistance.

The output voltage of the RTT is described by the expression:

$$U_t = I_0 R_{t0} \alpha t_c k_1 \quad (4)$$

where k_1 is the conversion factor of the RTT.

For compensation of the influence of the temperature of cold junctions the equality $I_0 R_{t0} \alpha t_c k_1 = e_{tc}$ is required. This is achieved by choosing the coefficient k_1.

Compensation can be done in analogue or digital form (hardware or software compensations) [16]. In the first case, the RTT output is connected in series to the thermocouple outputs using a switch. In the second case it is connected to the ADC input.

The output voltage of a thermocouple exhibits a nonlinear relationship with the temperature difference between its hot and cold junctions [1]. To determine the corresponding temperature for a given measured voltage, tabulated values related to thermo-emf or approximating functions must be used. Utilising calibration charts as lookup tables demands significant memory capacity for saving the table content. Conversely, applying higher-degree polynomials for this purpose results in slower measurement rates. Therefore, the optimal approach is a linear approximation, with the accuracy of the approximation depending on the thermocouple type and the temperature range being measured.

Linearisation can be achieved by analogue or digital means. When the linear approximation function includes the coordinate origin and the termo-emf value at the endpoint of the measured temperature range, the nonlinearity error is formulated as follows:

$$\delta = \left(1 - \frac{e_k t}{e_t t_k}\right) \cdot 100\% \quad (5)$$

where e_t is the output voltage at the measured temperature t; e_k is the output voltage at the end point of the temperature range, t_k denotes the end point value of the temperature range.

Fig. 3 illustrates the correlation between the relative nonlinearity error and temperature for linear approximation functions of the K-type thermocouple at different values of t_k.

From the analysis of graphical dependencies, it is clear that each linear function provides a minimum error in separate temperature ranges. The required linearisation error can be provided when different functions, depending on the measurement range, are used to approximate.

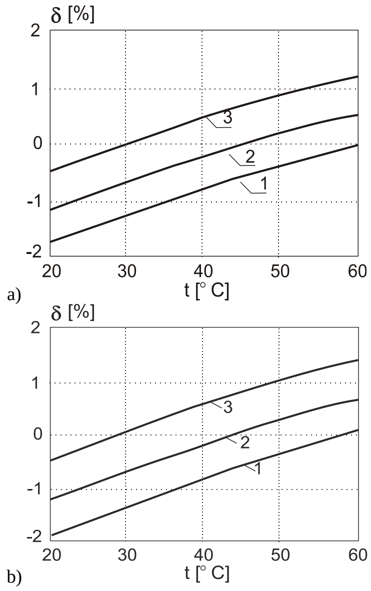

Fig. 3. The relative nonlinearity error vs. temperature at t_k = 60°C (1), t_k = 45°C (2), t_k = 30°C (3) for K-type thermocouple (a) and J-type thermocouple (b)

Fig. 4 illustrates the correlation between linearisation error and temperature for a piecewise-linear approximation function with temperature spline points set at 30°, 40°, 50°, and 60°. The approximation error at the midpoint of each spline interval is zero.

Accuracy improvement and reducing the number of measuring ranges can be provided by employing an approximation function that passes through both the starting and ending points of each measuring range (Fig. 5). In this case, the relative approximation error does not exceed 0.05% for K-type thermocouple and 0.07% for J-type thermocouple (b).

Thus the comprehensive expression of approximation function for the thermo-emf of a thermocouple can be described by the function

$$e = a_i t + b_i \quad (6)$$

where a_i is the scale factor, and b_i is the constant term for the i-th range.

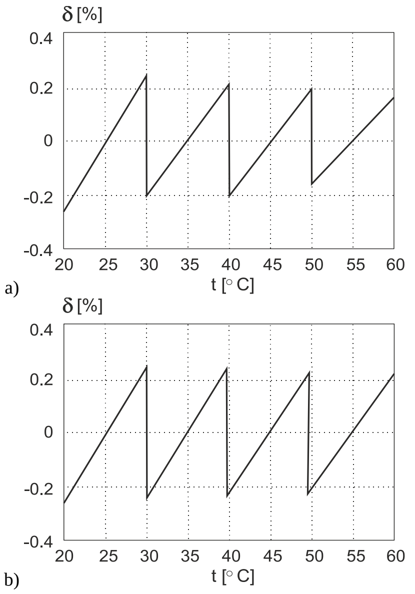

Fig. 4. The relationship between the linearisation error and temperature for piecewise-linear approximation function for K-type thermocouple (a) and J-type thermocouple (b)

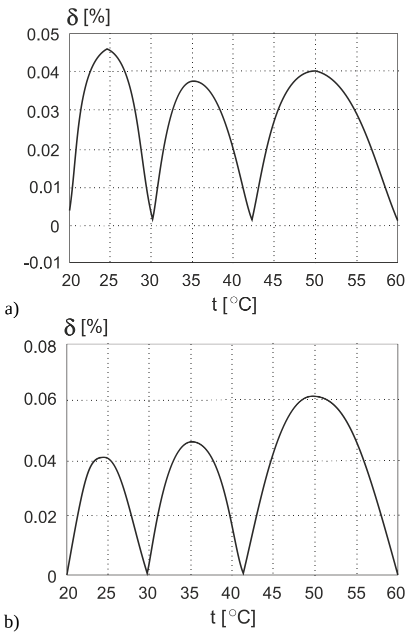

Fig. 5. The relationship between the relative approximation error and temperature for K-type thermocouple (a) and J-type thermocouple (b) in three intervals of piecewise-linear approximation

In this case, the temperature is expressed as:

$$t = \frac{e - b_i}{a_i} \tag{7}$$

The output voltage e_i of the i-th thermocouple and the output voltage of the RTT ΔU_i are passed to the input of ADC through the commutator controlled by the microprocessor. Thus, the voltage values of the thermocouples are converted into the output code of the ADC:

$$N_i = k_2 e_i \tag{8}$$

where k_2 is the conversion factor of the ADC. If $k_2 = 1$, the output code output code of the ADC is equal to the thermo-emf of the thermocouple.

When the output voltage of the RTT is converted, the output code of the ADC is equal to:

$$N_{Rt} = k_1 k_2 t_c \tag{9}$$

With the appropriate choosing the value of k_1, the output code is equal to the equivalent value of the thermo-emf at the temperature of cold junction.

The ADC output codes are passed into the MP input which performs the mathematical computation of ADC results. To decrease normal mode errors, the MP calculates the average of n voltage measurement results for each thermocouple and RTT:

$$N_{avi} = \frac{1}{n}\sum_{j=1}^{n} N_{ij}\ ,\ N_{avRt} = \frac{1}{n}\sum_{j=1}^{n} N_{Rt_j} \tag{10}$$

where n is the number of the measured values at every channel.

After this, the MP calculates the equivalent values of thermo-emf of thermocouples at the temperature of cold junctions t_c:

$$N_{ec} = aN_{avRt} + b \tag{11}$$

where a and b are chosen according to the measured value of the cold-junction temperature.

Then, the MP calculates the equivalent values of thermo-emf of the thermocouples at $t_c = 0$°C:

$$N_{ei} = N_{avi} + N_{ec} \tag{12}$$

The value of the measured temperature is calculated using the formula:

$$t_i = \frac{N_{ei} + b_i}{a_i} \tag{13}$$

where the values of a and b are calculated for the corresponding range of the temperature measured value for the i-th channel.

Following the completion of the mathematical computation, the outcomes are transmitted from the microprocessor (MP) to a digital readout for all corresponding measuring channels, or for a single measuring channel. The microprocessor temperature measuring device can be connected through the output interface to a personal computer for additional processing of the measurement results during the given time period. In this case the investigation of the temperature fluctuations on the surface of the tooth root during endodontic treatment can be conducted.

3. Conclusions

A temperature-measuring device for dentistry investigations has been designed. The accuracy of a thermocouple's measurements, particularly at lower temperatures, is significantly influenced by the temperature of its cold junction and nonlinearity of the output characteristics of the thermocouple. The proposed piecewise-linear approximation of the conversion function of the thermocouple ensures the relative error of nonlinearity less than 0.05% for K-type thermocouples and 0.07% for J-type thermocouples for 3 approximation intervals over the temperature range from 20 to 60°C.

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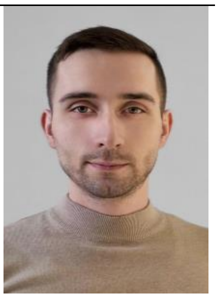
M.Sc. Les Hotra
e-mail: les.m.hotra@lpnu.ua



Les Hotra graduated from Department of Applied Mathematics, Lviv Polytechnic National University. He is currently a postgraduate student at Lviv Polytechnic National University.
His areas of scientific interest cover mathematical modelling and electronics including biomedical devices.

https://orcid.org/0009-0005-1351-1883

Prof. Oksana Boyko
e-mail: oxana_bojko@ukr.net

Oksana Boyko is currently a Head of the Medical Informatics Department of Danylo Halytsky Lviv National Medical University.
Her areas of scientific interest cover mathematical modelling, biomedical devices and medical information systems including elements of artificial intelligence. She is the author of over 200 scientific and methodological works.

https://orcid.org/0000-0002-8810-8969

Prof. Igor Helzhynskyy
e-mail: iigorg@ukr.net

Igor Helzhynskyy is a doctor of solid-state electronics, professor in the Department of Electronic Engineering of Lviv Polytechnic National University. He has been participated in numerous Ukrainian and international projects related to materials science, engineering, in particular organic and gibrid light-emitting devices for organic electronics. His research area focuses on WOLED, PhOLED, QLED and electronics.

https://orcid.org/0000-0002-1931-6991

Prof. Hryhorii Barylo
e-mail: gbarylo@polynet.lviv.ua

Hryhorii Barylo has worked for many companies and institutions. He was the Head of the Microprylad production enterprise in Lviv. Since 2008 he has been working at the Department of Electronic Engineering of Lviv Polytechnic National University. His research activity is focused on the problem of the use of impedance spectrometry in sensor technology, materials science, biological and medical research. His scientific approaches are based on the results of mathematical modelling, elements of artificial intelligence, systems and achievements of Internet technologies.

https://orcid.org/0000-0001-5749-9242

Prof. Pylyp Skoropad
e-mail: pylyp.i.skoropad@lpnu.ua

Pylyp Skoropad is currently a professor in the Department of Measuring Information Technologies of Lviv Polytechnic National University. His areas of scientific interest cover contact and contactless thermometry (from low to high temperatures) and materials science.
He is an author of more than 200 scientific publications, including 2 monographs and 10 patents of Ukraine.

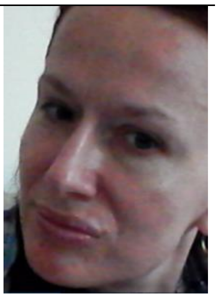
https://orcid.org/0000-0003-3559-6580

Ph.D. Alla Ivanyshyn
e-mail: alla.v.hunkalo@lpnu.ua

Alla Ivanyshyn is currently an Associate Professor in the Department of Measuring Information Technologies of Lviv Polytechnic National University (Ukraine). Her areas of scientific research include expert systems, fuzzy logic, quality monitoring, and management. She is an author of more than 60 scientific publications, including over 30 articles. She is the coordinator of the international educational project Erasmus + Jean Mone 101085516 – QMSEEI (2022-2025). She has 15 years of experience in scientific and pedagogical work.

https://orcid.org/0000-0002-3302-7889

Ph.D. Olena Basalkevych
e-mail: olena.basalkevych@gmail.com



Olena Basalkevych is currently an Assistant in the Medical Informatics Department of Danylo Halytsky Lviv National Medical University.
Ph.D. in Philology, Modelling of the Thesaurus of Qualitative Adjectives in Older Scots (Mathlinguistics)
Her areas of scientific research include expert systems, artificial intelligence and mathematical modelling.
She is the author of 30 publications, 11 in Scopus, 5 reviews.

https://orcid.org/0000-0001-5886-6374