ROOT SURFACE TEMPERATURE MEASUREMENT DURING ROOT CANAL OBTURATION

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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

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 involve 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, thermo resistive 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) \((R_\theta)\) 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](image)

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:

\[
\varepsilon = f(t_c) - f(t_l) = f(t_c - t_l)
\]

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

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

\[
\varepsilon = f(t_c) - f(t_l_f) = f(t_c - t_{l_f})
\]

where \(e_{l_f}\) is the value of thermo-emf at \(t = t_l\).

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 thermostating of cold junction at 0°C 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 \(R_\theta\) is determined by the value of the RTT reference current and is described by the following expression:

\[
U_{\varepsilon} = I_c \cdot R_\theta \cdot (1 + \alpha t_c)
\]

where \(I_c\) is the value of the reference current; \(R_\theta\) is the resistance value of the RTD at a temperature of 0°C; \(\alpha\) is the temperature coefficient of resistance.

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

\[
U_t = I_r \cdot R_{\theta \cdot \alpha \cdot t_c} \cdot k_t
\]

where \(k_t\) is the conversion factor of the RTT.

For compensation of the influence of the temperature of cold junctions the equality \(I_r \cdot R_{\theta \cdot \alpha \cdot t_c} = e_{l_f}\) is required. This is achieved by choosing the coefficient \(k_t\).

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 thermo-emf value at the endpoint of the measured temperature range, the nonlinearity error is formulated as follows:

\[
\delta = \left(1 - \frac{e_t}{e_{l_f}}\right) \times 100\%
\]

where \(e_t\) is the output voltage at the measured temperature \(t\); \(e_{l_f}\) is the output voltage at the end point of the temperature range, \(t_{l_f}\) denotes the end point value of the temperature range.

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 \(t_c = 60°C\) (a), \(t_c = 45°C\) (b), \(t_c = 30°C\) (c) for K-type thermocouple (a) and J-type thermocouple (b)](image)

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:

\[
e = a_i \cdot t + b_i
\]

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

\[
N_{av} = \frac{1}{n} \sum_{j=1}^{n} N_{ij}, \quad N_{av} = \frac{1}{n} \sum_{j=1}^{n} N_{avj}
\]  

(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 \( t_0 \):

\[
N_{e} = a N_{avj} + b
\]  

(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 \( t_0 = 0°C \):

\[
N_{e} = N_{av} + N_{e}
\]  

(12)

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

\[
t = \frac{N_{avj} + b}{a}
\]  

(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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