Quantifying temperature-equilibrium time using temperature analysis inside a Farmer ionization chamber

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ABSTRACT

In this study, we propose a methodology for temperature determination of the temperature and pressure correction factor, $P_{TP}$, by analyzing the temperature distribution of the modeled ionization chamber taking into account the thermal effect of a water phantom on neighboring materials in the process. Additionally, we present an appropriate temperature-equilibrium time for conducting measurements. The temporal response in the cavity is acquired at 20-s intervals using a Farmer ionization chamber and an electrometer. The initial temperature of the water phantom is 20–25°C with continuous heating/cooling. The temporal response is measured until temperature equilibrium is confirmed, specifically when a temperature difference of 1–5°C is observed between the ionization chamber and the water phantom. Using an ionization-chamber model, temperature distribution is simulated between 20 and 25°C with various parameters set to receive heating and cooling from surrounding media. The results suggest that the temporal response of the ionization chamber essentially coincides with the temperature change at the tip and middle; moreover, the predicted temperature change for temporal response and the simulated temperature of water are different by ~0.16°C at the tip and ~0.79°C at the bottom. Overall, the temperature-equilibration time for absorbed dosimetry is affected by two factors: the cavity wall and the stem side of the cavity; moreover, 400 s is required to obtain complete temperature equilibrium in the water phantom. This analytical study supports the experimental value obtained in previous research. Therefore, analytical representation of the temperature distribution in the ionization chamber is possible.

Keywords: Farmer ionization chamber; temperature-equilibrium time; temperature analysis; temperature distribution; absorbed-dose measurement

INTRODUCTION

The American Association of Physicists in Medicine and International Atomic Energy Agency define the temperature and pressure correction factor, $P_{TP}$, as the coefficient used to correct the effect of mass change in the cavity of a Farmer-type ionization chamber because of the temperature and atmospheric pressure exerted on the ionization quantity [1–3]. $P_{TP}$ has a major effect on the absorbed-dose measurements in a correction factor defined by standard dosimetry protocol. However, it is difficult to measure the difference in temperature between the ionization volume and a water phantom. Therefore, it is generally assumed that water and cavity volume reach temperature equilibrium when users measure the water-absorbed dose in an ionization chamber.

The temperature change in an ionization chamber is often obtained by quantifying electric charge [4–8]. In other methods, temperature changes with respect to time are confirmed with a micro-thermometer located inside the ionization chamber [8–10]. Previous studies have used water [4, 6–10], air [4, 6, 9], plastic phantoms [4, 6, 9] and build-up caps [6, 9]. Among these, the temporal response of several ionization chambers has been acquired at different treatment-room temperatures [4, 6–8]. For instance, the temperature-equilibrium time reported by Tailor was 78 s (10% change of ionization current) in water, as opposed to the intermediate value suggested by Kubo (120–180 s) and van der Giessen (40 s) [4, 6, 9]. Indeed, these results are consistent with existing literature [7, 8, 10]. Often, the temperature-equilibrium
Temperature analysis inside an ionization chamber

MATERIALS AND METHODS

Temporal response measurements

The ionization chamber was a TN30013 Farmer type (PTW Freiburg GmbH, Freiburg, Germany). The temporal response in the cavity with a 10 cm water depth was acquired at 20-s intervals with UNIDOS Webline (PTW Freiburg GmbH, Freiburg, Germany). A 10-MV X-ray with a $10 \times 10$ cm$^2$ field size was used for irradiation sourced from an ELEKTAR Synergy linear accelerator (Elekta AB Stockholm, Sweden). The temperature was recorded using a TL1-R digital thermometer (ThermoProbe Inc., Pearl, MS, USA) with a high resolution of 0.01°C and high accuracy of $\pm 0.05$°C. The measurement apparatus is shown in Fig. 1, which also shows the position of both the thermometer and the temperature-control device. The initial temperature of the water phantom was established at 20–25°C with continuous heating/cooling using the temperature-control device and stirring. Furthermore, the ionization chamber was set to a constant temperature of 20°C inside the desiccator. The temperature of the water phantom was measured up to 15 min after irradiation. Room temperature was set to 20°C, which allowed for uniformity between the temperatures of the treatment room and the ionization chamber. In other words, the temporal response was measured until temperature equilibrium was confirmed when a difference of 1–5°C was obtained between the ionization chamber and the water phantom.

Temperature analysis

Analytical ionization chamber model

It is possible that temperature-equilibrium time and thermal expansion are directly influenced by the heterogeneous temperature distribution of different materials. Temperature distribution due to material differences cannot be clarified according to previous studies and, because of this, they must be calculated theoretically. Therefore, in this paper, taking into account the influence of adjacent materials, the temperature distribution of the ionization chamber is obtained using a finite-element method with heat-transfer analysis.
Fig. 2. Analytical model of the ionization chamber. The cavity wall was constructed using PMMA and graphite, 0.335 mm and 0.09 mm, respectively. Aluminum covered the electrode and stem, while polyethylene covered the bottom of the cavity and the center conductor of the cable. Rubber was set up with a substance similar to elastomer based on our analysis. Each thickness was defined by manufacture specification and/or measured by us.

| Material                        | Heat-conductivity coefficient $k$ (W/mK) at 22 °C [11] |
|---------------------------------|---------------------------------------------------------|
| Cavity wall                     | PMMA 0.21                                              |
|                                 | Carbon 0.21                                            |
| Electrode and stem cover        | Aluminum 236                                           |
| Center and outer conductor      | Copper 398                                             |
| Insulator                       | Rubber (for cable sheath) 1.9                          |
|                                 | Polyethylene 120                                       |

Analyzed temperature acquisition

The temperature simulation was performed with in-house software based on ThermoNet 7 (Mentor Graphics Corporation, Wilsonville, OR, USA,). The following equations were used to determine the heat-transfer rate for the materials used in the analysis, including the Nusselt number $N_u$ with a heat-conductivity coefficient $k$ (W/mK), a heat-transfer coefficient $h$ (W/m²K), and length of subject $L_{ch}$ (mm).

$$N_u = \frac{hL_{ch}}{k}$$

1

The Reilly number $R_e$ can be defined using the Grashof Number $G_r$, and the Prandt number $P_r$, as follows:

$$R_e = G_r P_r$$

2

$$G_r = \frac{g \beta (T_W - T_\infty) L_{ch}^3 \rho^2}{\nu^2}$$

3

$$P_r = \frac{\mu C_p}{k}$$

4

where $g$ denotes gravity, $\beta$ denotes the volume coefficient of expansion, $\rho$ denotes the physical density, $\alpha$ denotes thermal diffusivity, $\mu$ denotes a kinematic-viscosity coefficient and $C_p$ denotes specific heat. The conductivity coefficients of the materials used in the ionization chamber are shown in Table 1, the values of which were provided by the Thermophysical Properties Handbook, Second Edition [11]. A temperature physical property of 20–25°C was adopted for each material. A water phantom was placed around the ionization chamber and temperature distribution was simulated between 20 and 25°C. In simulating the ionization chamber, various parameters were set to
receive heating and cooling from surrounding media; accordingly, the natural-convection temperature was set as 20–25°C for water, which is consistent with existing literature. Simulations were conducted with temperature differences of 1–5°C between the ionization chamber and water phantom at 4-s intervals and at three distinct points: tip, central part (middle) and the stem side (bottom) of a cylinder with a radius and height of 2 mm. To ensure the validity of the simulation, commissioning was confirmed in a tip with simulated temperature and measured average temporal response.

RESULTS

Figure 3 shows the temporal response of the ionization chamber in water at 5°C of temperature difference. In addition, the temperature distribution of the ionization chamber is divided into three locations (tip, middle and bottom), as can be seen in Fig. 3. Here, the temporal response was measured with an accuracy of 0.5%, and the temperature of each location was calculated so that the error was 0.6%. Relative temporal response defined as 1.00 was the average of the measured values after 400 s and was considered to have reached temperature equilibrium. The temporal response of the ionization chamber almost coincides with the temperature change at the tip and middle; moreover, the predicted temperature change for temporal response and the simulated temperature of water are different by ∼0.1°C. In addition, the temperature change begins by ∼0.16°C at the tip and ∼0.79°C at the bottom. Regarding the temporal response, the results suggest that the ionization chamber quickly reaches equilibrium within a few minutes after being submerged in water. However, a temperature change of 0.1°C affects the temporal response by 0.4%.

Figure 4 shows the temperature distribution for the ionization chamber, from which it is evident that the temperature change begins from the tip of the ionization chamber and spreads over the cavity. An insulator at the bottom region of the simulated temperature indicated a suppression in temperature change.

DISCUSSION

To estimate the waiting time in using the water phantom, it was essential to allow the ionization chamber and cavity to reach equilibrium temperatures. Previous studies [4–10] have found that 0.7–4.9 min are required for various ionization chambers to reach temperature equilibrium in water. However, in our study, complete temperature equilibrium was successfully achieved within ∼400 s, which is greater compared with previous studies. This difference can be attributed to errors in adjusting the temperature of the treatment room and water phantom, as well as imperfections related to the thermometer having a temperature accuracy ∼5–10 times higher than the thermometer used in the present study [6–8]. Therefore, the error related to temperature measurement could be reduced by up to 20%. These error sources must be further considered when measuring the respective temporal response. In a previous report, the temperature equilibrium time was defined as <10% of the initial temperature difference [6]. In this paper, a temperature-equilibrium time of ∼180–200 s was obtained. This result seems to support previous research.

Figure 4 shows the heterogeneous temperature distribution in the cavity of the ionization chamber. Temperature-equilibrium time at the bottom was reached later than at the other two regions (tip and middle), which was ∼32 s in water. $P_{TP}$ at 100 s after installation in the water phantom was shown to differ by up to 0.2% between tip/middle and bottom regions. Although the cavity tip and its middle have uniform heat conduction, temperature at the bottom was lower compared with the other regions in the interval prior to reaching temperature equilibrium. In the apparatus, the insulator and cable sheath were made of rubber, the heat-conductivity coefficient of which was 1.9 kW/mK [11], a value that is far greater than that of water or polymethyl methacrylate (PMMA)/carbon of the cavity wall. Therefore, the difference in temperature increase influenced the temperature-equilibrium time for the absorbed-dose measurement. Using a mean value of simulated temperature, a fitting curve was obtained for the water phantom (Fig. 5). The fitting curve was generated using equation (5).

$$y = A_1 \left(1 - e^{-\frac{t}{t_1}}\right) + A_2 \left(1 - e^{-\frac{t}{t_2}}\right)$$  \hspace{1cm} (5)$$

where $A_1$ and $A_2$ denote amplitude, and $t_1$ and $t_2$ denote width. Equation (5) comprises two terms that are represented via exponential functions. Table 2 shows the calculated results for each coefficient of the fitting curve. Because the fitting curve is expressed as two exponential functions in one equation, the two exponential functions accounting for temperature-equilibrium time are taken into account. On the one hand, the term provided by $A_1$ and $t_1$ is an element that quickly approaches the temperature equilibrium, representing the heat conduction from the cavity wall. On the other hand, the term provided by $A_2$ and $t_2$ is an element of the cavity bottom that requires a greater amount of time to reach equilibrium. Indeed, an extremely strong correlation exists between the temporal response and the simulated temperature in the tip and the middle of the ionization chamber. Here in water, temperature equilibria of 63 and 90% were obtained in 40 and 92 s, respectively; a time lag exists due to the structure and composition of the ionization chamber.

Fig. 3. Temporal response of the ionization chamber and simulated temperature of three regions in the water phantom at a temperature difference of 5°C.
CONCLUSION
In this study, the temperature distribution of an ionization chamber was acquired using a finite-element method. We have shown that the temperature-equilibrium time for absorbed dosimetry is affected by two factors, namely the cavity wall and the stem side of the cavity. The temperature-equilibrium time at the stem side was reached later than the region surrounded by cavity wall: $\sim 32$ s in water with a temperature difference of 5°C. Temperature-equilibrium times of 40 and 92 s were obtained for temperature equilibria of 63 and 90%. However, to satisfy complete temperature equilibrium in the water phantom, 400 s was required with a temperature difference of 5°C. This analytical study supports the experimental value obtained in previous research. Overall, a temperature change of 0.1°C affected the temporal response by 0.4%. Comparing the temperature distribution with the temporal response, the temperature at the tip of the ionization chamber is important for dosimetry. Therefore, analytical representation of the temperature distribution in the ionization chamber is possible.

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CONFLICT OF INTEREST
The authors have no conflicts of interest directly relevant to the content of this article.

Table 2. Fitting-curve parameters

|        | Water            |
|--------|------------------|
|        | Calculated value | Standard deviation |
| $A_1$  | 0.298            | 0                  |
| $t_1$  | 10.3             | 0.028              |
| $A_2$  | 0.703            | 0                  |
| $t_2$  | 73.1             | 0.04               |

Fig. 4. Temperature distribution at 20-s time intervals in water. The left-hand chamber represents a value of 0 s. Left: the temperature distribution of the entire ionization chamber; right: the neighboring cavity region including the insulator. The calculated area is only considered to be that inside the ionization chamber in order to reduce the calculation time.

Fig. 5. Calculated fitting curve and simulated average temperature of the three regions. The fitting curve was generated from equation (5) comprising two exponential functions.
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