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# The Problem of Convection in the Water Absorbed Dose Calorimeter

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## Abstract

The water absorbed dose calorimeter allows the water absorbed dose, the measurand in radiotherapy, to be measured in accordance with its definition. Its application, however, requires the suppression of convection.

In the present paper we investigate how far the convection problem may be solved by mechanical means, for the case of $^{60}$Co-$\gamma$-radiation.

## 1. Introduction

The quantity water absorbed dose - the measurand in dosimetry for radiation therapy - is defined as the quotient $d\bar{\varepsilon}/dm$, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to water of mass dm at the point of measurement. The absorbed dose calorimeter [1, 2] allows this quantity to be measured according to its definition.

If the energy imparted to matter is completely converted into heat, the absorbed dose can be determined by measuring the temperature rise due to the radiation. Since the absorbed dose is defined at a point, the calorimeter has to be operated such that the radiation induced temperature distribution is not disturbed by heat conduction or by convection during the measurement. It has been shown that the influence of heat conduction in most cases can be kept small or can be taken into account [2, 6].

In the following, a brief description of the underlying physical aspects of convection is given. Further information can be taken from ref. 4.

The existence of a buoyant force in the water does not necessarily mean that convection will occur. Convection will start when the buoyant force overcomes the opposing force, which is the viscous drag of the fluid. The liquid will

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remain motionless until the so-called Rayleigh number exceeds a critical value of about 1000 [3]. The Rayleigh number is the product of the Grashof number (Gr), which is a measure of the relative importance of the buoyant and viscous forces, and the Prandtl number (Pr), which is a measure of the ratio of the molecular diffusivity of momentum to the molecular diffusivity of energy:

$$Gr = g \, \beta \, \Delta\vartheta \, l^3/\nu^2$$

$$Pr = \nu/\alpha$$

where $g$ is the gravitational force per unit mass,
$\beta$ the volumetric expansion coefficient,
$\Delta\vartheta$ the temperature difference between convection barriers,
$l$ the distance between convection barriers,
$\nu$ the dynamic viscosity and
$\alpha$ the thermal diffusivity.

If there is convection in the water during an absorbed dose measurement it will disturb the radiation induced temperature distribution and may transport water of slightly different temperature to the point of measurement. Of course, the situation may vary from run to run in a random manner, resulting in totally unpredictable changes of the temperature drifts during and after a run, not allowing extrapolations of calorimeter pre- and post-irradiation periods. In the following this effect will be called the "instability effect".

Moreover, even a small movement of water near the temperature measuring thermistors will disturb the equilibrium temperature pattern around the thermistors as a result of their electrical power. Depending on the electrical power and the velocity of the moving water, this effect may cause large cooling drifts which go on for some minutes after the radiation beam is switched off ("cooling effect").

Convection can be totally suppressed by reducing the volumetric expansion coefficient ($\beta$) of the water to zero. This will happen when the calorimeter is operated at a water temperature of 4 °C [5]. This method of operation is used at the PTB to overcome the convection problem. At 4 °C the density of water is at a maximum. Its expansion coefficient will therefore remain essentially zero during the small temperature rises produced by irradiation runs.

A second method of suppressing the convection, even at room temperature, is given by the fact that the Rayleigh number depends strongly on the geometry of the calorimeter. When there is a water temperature difference between two mechanical barriers inside the water tank, then the Rayleigh number varies with the cube of the distance between the two barriers.

In the present experiment convection is studied and it is investigated to what extent it can be supressed by practicable mechanical means, for example convection barriers. For $^{60}Co$-$\gamma$-radiation the effectiveness of the barriers is proved by comparing the results with those of the 4 °C measurements without barriers.

## 2. Experimental Setup and Procedure

The water calorimeter previously described [1, 2] was modified [6, 7], as shown in Fig. 1, for measurements of absorbed dose produced with horizontal irradiation beams.

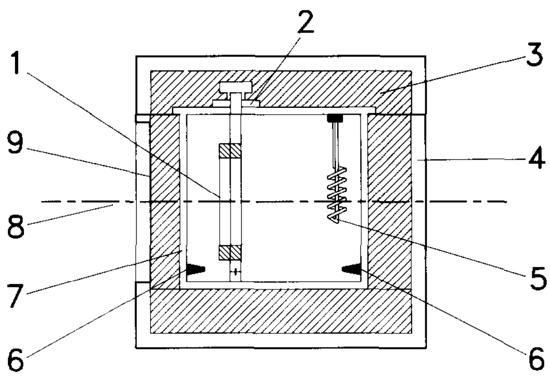


**Fig. 1.** Schematic diagram of the water calorimeter. (1) exchangeable detector assembly fixed in support (2), (3) expanded polystyrene, (4) outer enclosure, (5) combined element for cooling and heating, (6) gas inlet for stirring the water, (7) acrylic tank (21 cm length, 30 cm width, 25 cm height) filled with water, (8) beam axis, (9) entrance window.

The irradiation geometry for the present experiment and the previous ones [7] are identical. The same $^{60}Co$ - source was used and the beam diameter corresponding to the 50 % and 95 % dose values was 259 mm and 207 mm respectively.

The detector consists of two small bead thermistors sandwiched between 20 µm polyethylene films. These films provide high electrical resistance between the thermistors and the surrounding water. Each thermistor is located in opposite arms of a Wheatstone bridge to double the measuring sensitivity. In the present experiment the thermistors had a diameter of 0,25 mm and were mostly used at a power level of 10 µW. A few irradiation runs were also made at power levels up to 100 µW. Fig. 2 illustrates the method intended to fix the additional convection barriers on both sides of the detector. A support ring (1), 12 cm inner diameter, clamps two stretched polyethylene films (2), enclosing two thermistors (only one is indicated). Horizontal acrylic convection barriers (6), 0,25 mm thick and 11 cm long, were mounted on rings (not shown) and separated by a distance of 30 mm.

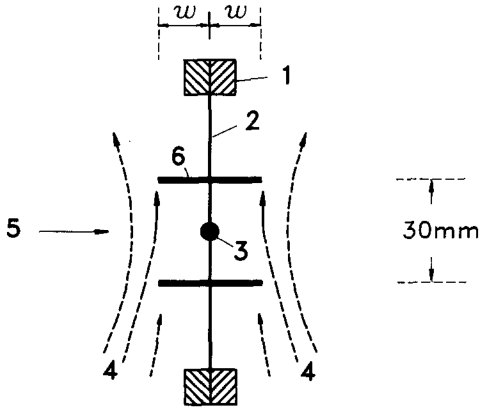


**Fig. 2.** Schematic drawing of the detector ((1) support rings, (2) polyethylene films, (3) thermistors) in a convective stream of water (4). (6) indicates the arrangement of the horizontal convection barriers; (5) is the beam axis.

Three sets of barriers were made with barrier widths (w) of 10 mm, 20 mm and 30 mm.

First, calorimeter measurements were made at room temperature (20,7 °C) without additional convection barriers and at 4 °C. Then the different barriers were placed in position and measurements were made at room temperature. The time for one irradiation was about 450 s, producing a temperature rise of about 0,57 mK, which corresponds to an absorbed dose of about 2,4 Gy. After a series of eight irradiation runs the temperature gradients built up in the water were eliminated by stirring the water for about 15 minutes.

## 3. Results and Discussion

The calorimeter post-irradiation periods at room temperature, with 0,5 mm diameter thermistors operated at a power level of 15 µW [7], showed pronounced cooling drifts caused by the cooling effect of convection. Fig. 3 shows the temperature response for a typical recorder tracing of such a run, clearly demonstrating this effect. By using the measured response of these cooling drifts and information on studies of convective velocity effects on a thermistor in water [8], it is estimated that the observed cooling effect corresponds to a convective velocity of about 2,5 mm/min. Under the same irradiation conditions, a reduced power level of 10 µW would reduce the cooling effect by a factor of bout 2 [8].

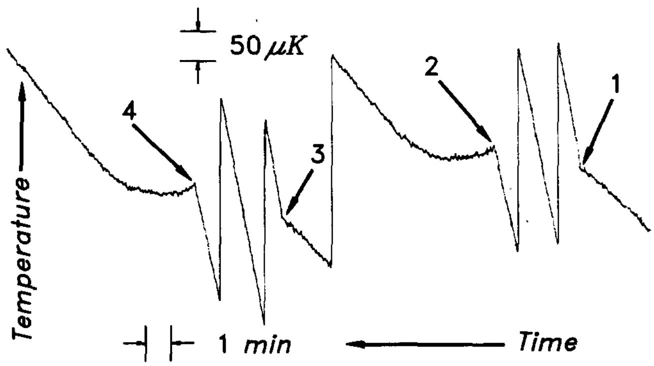


**Fig. 3.** Time dependence of temperature for a calorimeter run at room temperature with 0,5 mm diameter thermistors and without convection barriers, showing the cooling effect of convection. Time 1 and 3: start of irradiation, time 2 and 4: end of irradiation; the abrupt changes inbetween are caused by manual resistance changes in the bridge balancing arm.

In the present investigation it turned out that the cooling effect - even at power levels up to 100 µW - can be avoided by reducing the thermistor diameter to 0,25 mm.

This can be understood if one takes into account that the detector itself acts as a convection barrier (Fig. 4). The

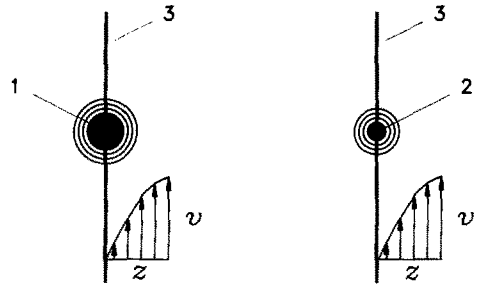


**Fig. 4.** Illustrative convective velocity distribution (v: velocity, z: distance from film) near a vertical film (3) and temperature patterns around thermistors (1, 2) of different sizes.

vertical film is a barrier to an infinitesimal thin water layer adjacent to the film. The velocity of this water is zero, and the velocity distribution is approximately parabolic with the distance from the film. Thermistor 1 in Fig. 4 indicates the 0,5 mm diameter thermistor. The illustrated surrounding temperature pattern extends further away from the film than for the case of the 0,25 mm diameter thermistor 2. Therefore, the temperature pattern around thermistor 1 is in a water layer with greater velocity. If the convective velocity were zero or were essentially constant, the temperature of the thermistors would be at equilibrium; but when the irradiation period causes a velocity increase, thermistor 1 would sense more cooling than thermistor 2.

Although the cooling effect of convection could be avoided by using smaller thermistors, the absorbed dose measurements at room temperature without additional horizontal convection barriers still showed the instability effect of convection. As an example of this, Fig. 5 shows that the pre-irradiation period of the calorimeter is almost constant whereas the post-irradiation period has changed to a slightly increasing signal.

In principle, it is not possible to get an accurate dose measurement out of the extrapolation of such unpredictable changing temperature drifts. To obtain information on how much the instability effect might be affected by convection barriers, we took the standard deviation of the rate of temperature response of a large number of runs as a measure of the random error introduced by the instability effect.

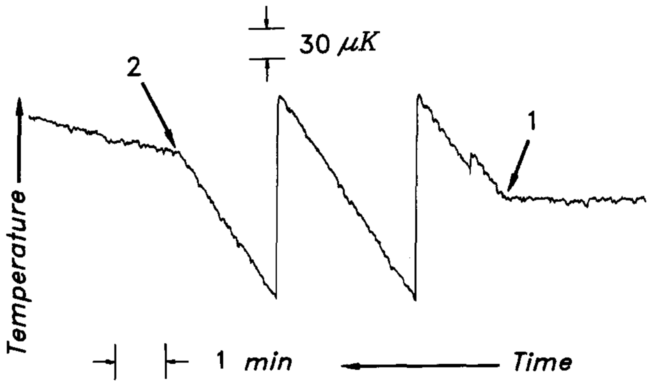


**Fig. 5.** Time dependence of temperature for a calorimeter run at room temperature with 0,25 mm diameter thermistors and without convection barriers, showing an example for the instability effect of convection. The irradiation period is between time 1 and 2.

To investigate the instability effect of convection, runs were made with additional horizontal convection barriers of width (w) equal to 20 mm and 30 mm. The results of the measurements are given in table 1. The relative standard deviation of the measurements without barriers is 3 %, about the same as that with the 20 mm barrier in position. With the 30 mm barrier in position the result shows that the uncertainty of measurements is improved by a factor of two, with a relative standard deviation of 1,5 %.

**Table 1.**

Relative standard deviation (s) of calorimetric measurements at different water temperatures ($\vartheta$) with different convection barrier widths (w). N is the number of measurements.

| $\vartheta$/°C | w/mm | N | s/% |
|---|---|---|---|
| 20,7 | 0 | 78 | 3,0 |
| 20,7 | 20 | 63 | 3,1 |
| 20,7 | 30 | 95 | 1,5 |
| 4 | 0 | 85 | 1,0 |

Even with the barriers in position, however, the measurements were still affected by a combined convection and conduction effect. Fig. 2 illustrates the upward flow of a convective stream, which would flow partly within the barrier region. The stream could carry water at different temperatures within this region; and even though the edges of the stream may not have reached the thermistors, heat conduction would have an effect on them. The precision of the measurements remained unchanged when the 20 mm barriers were in position, but this may partly be because the velocity stream extended significantly toward the thermistors. As expected, the wider 30 mm barriers improved the situation, as indicated by the lower relative standard deviation of 1,5 %.

## 4. Conclusion

The present investigation shows that the effects of convection on room temperature absorbed dose measurements can be reduced by using mechanical convection barriers. The convective effects will then be of reduced importance, especially for irradiation conditions where higher absorbed dose rates are available and shorter irradiation times are sufficient.

A further improvement might be expected using a closed system similar to that of the latest calorimetric development [9, 10]. Such a system could be realized by placing a pair of thin vertical convection barriers against the outer edges of the barriers shown in Fig. 2. Under this condition, the enclosed volume of water will be shielded from external convection currents which would cause water at different temperatures to move mainly to the front and rear of the vertical barriers. Conductive effects would then be significantly smaller because of the longer time it would take for a temperature change to reach the thermistors (the time it takes for a temperature change at a position varies as the square of the distance the heat has to be conducted to reach that position).

This investigation only dealt with the problem of convection in water. In any case however, one has to take into account that additional materials like glass or lucite inside the water tank may also influence the calorimeter signal by creating "excess heat" (because of deviating specific heat capacities and densities) and by perturbing the radiation field.

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