Thermochimica Acta, 119 (1987) 81–93
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

A WATER CALORIMETRIC DETERMINATION OF ABSORBED DOSE TO WATER

M. ROOS

Physikalisch-Technische Bundesanstalt, 3300 Braunschweig
Federal Republic of Germany

SUMMARY

To realize a more accurate determination of the water absorbed dose, a basic quantity in radiation dosimetry, water absorbed dose calorimeters are being developed. They allow the dose to be measured according to its definition. A calorimeter type is described which permits the application of horizontally directed beams of different types of radiation.

It is shown that the use of water calorimeters for the determination of the dose under reference conditions can cause substantial errors if the results are not corrected for the influence of heat conduction in the water.

INTRODUCTION

In the course of the developement of dosimetric quantities the absorbed dose is now being used universally in radiation dosimetry. It is closely related to biological and chemical effects of radiation and can be determined using physical methods. Whereas biologists and physicians are interested mainly in the correlation of dose and biological effects, it is the task of dosimetry to determine the absorbed dose for given irradiation conditions.

The definition of this quantity itself suggests calorimetric methods:

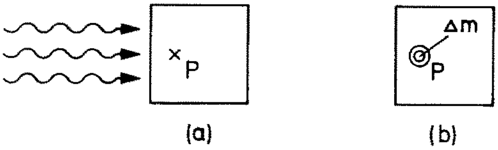

Fig. 1a. Phantom irradiated with ionizing radiation. The dose is to be measured at point P.
b. At the point of measurement P a mass element Δm is thermally isolated from its surroundings.

0040-6031/87/$03.50

The absorbed dose D at point P (Fig. 1a) is the quotient $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm. Depending on the material of dm - the reference material - one is dealing with water absorbed dose, tissue absorbed dose etc..

Since the absorbed dose is defined at a point, the mean energy imparted in a narrow region has to be measured before heat transport can cause error. This means one usually has to thermally isolate a small mass Δm (Fig. 1b) - the absorber - from its surroundings - the phantom.

If the energy imparted to matter by radiation is completely converted to heat, the absorbed dose at the point of measurement is the product of the specific heat capacity c_p of the absorber material and the radiation induced temperature rise. Thus the absorbed dose can be measured by calorimetric methods according to its definition.

A common reference material in radiation therapy and radiation protection is water. The water absorbed dose approximates the tissue absorbed dose and water is available everywhere in appropriate composition. The water absorbed dose therefore is the measurand in radiotherapy and the measurands in radiation protection are based on this quantity.

Whereas hitherto the measurement of the water absorbed dose was based on indirect methods, Domen (refs. 1, 2) in pioneering papers showed recently that a water calorimeter for absorbed dose measurements can in principle easily be constructed. He developed a calorimeter which takes advantage of the low thermal diffusivity of water, which retards a temperature change at the measuring point. He showed that for his irradiation conditions - (i. e. vertically directed, extended ^{60}Co-γ- radiation beam, depth of measurement 5 cm and irradiation times less than 5 minutes) - heat convection and conduction do not falsify the radiation induced temperature rise at the point of measurement. So in this case it is not necessary to isolate an absorber from its surroundings but it is sufficient to measure the temperature rise at the point of measurement and calculate the water absorbed dose by multiplying by the specific heat capacity of water.

There are several copies of the Domen calorimeter currently in operation. They are not only used for γ-radiation but also for high energy electron radiation (refs. 3-5), high energy bremsstrahlung (refs. 3-5), X-rays (refs. 6-7) and neutrons (ref. 8).

At the PTB (Physikalisch-Technische Bundesanstalt, FRG) a water absorbed dose calorimeter is being built for the application of horizontal beams of different types of radiation in surroundings which are not temperature-stabilized. In conjunction with an experimental setup for the determination of that part of the mean energy imparted to water by the radiation which is not changed into heat, this calorimeter is intended for use as a primary standard measuring device for water absorbed dose.

CALORIMETER SET UP

The water absorbed dose calorimeter is built for horizontal beams. It is based on Domen's development (ref. 2) for vertical beams. Fig. 2 shows its main features.

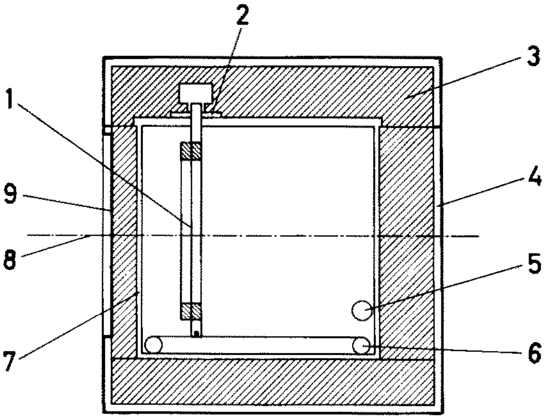

Fig. 2. Schematic diagram of the water calorimeter. (1) exchangeable detector assembly fixed in support (2),(3) expanded polystyrene, (4) outer enclosure, (5) immersion heater, (6) perforated silicon tube, (7) acrylic tank filled with water, (8) beam axis, (9) entrance window.

It consists of an acrylic (polymethylmethacrylate) tank (7) (21 cm length, 30 cm width, 25 cm height) filled with distilled water. This is thermally isolated from its surroundings by polystyrene layers (3) and wooden enclosure (4) covered with aluminium foil.

The rise in temperature at the point of measurement, caused by a broad radiation beam entering through the entrance window (9), is measured using thermistors in the detector assembly (1). The water tank contains an immersion heater (5) as well as a perforated silicon tube (6) around its bottom edges. By bubbling gas (usually nitrogen) through the tube the water can be agitated to remove internal temperature gradients and to saturate it with the gas.

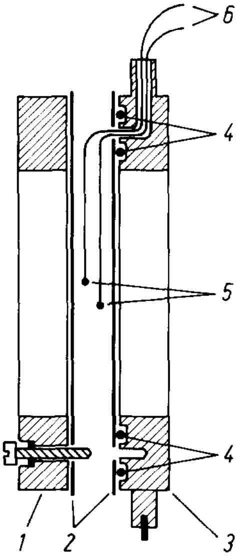

Fig. 3. Schematic diagram of the detector assembly. (1) acrylic ring, (2) polyethylene films, (3) acrylic ring with supports, (4) O-rings, (5) thermistors, (6) electrical connections.

Fig. 3 shows the detector assembly in more detail. The sensor elements are two 0.5 mm diameter bead thermistors (5), connected electrically by two cable pairs (6) to opposite arms of a Wheatstone DC bridge. For support and electrical insulation the thermistors are sandwiched between 20 µm polyethylene films (2). These films are stretched between two acrylic rings (1) and (3). Care is taken to remove the air from between the films, two O-rings (4) are used to provide watertight seals on the acrylic rings.

The rings are held in position inside the tank by a support, facilitating insertion or removal of the detector assembly. The detector assembly can easily be replaced by other dosemeters e. g. ionization chambers or Fricke dosemeters for calibration purposes.

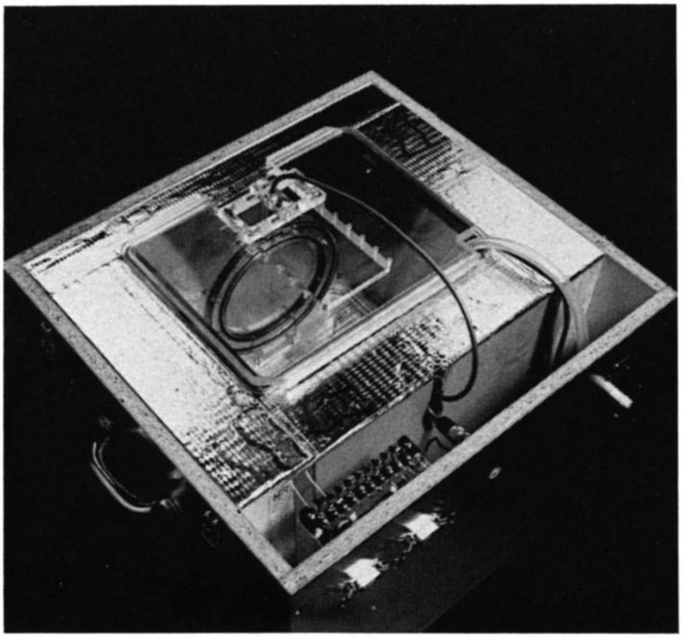

Fig. 4. Top view photograph showing the inner chamber of the calorimeter.

Fig. 4 is a top view of the inner chamber of the calorimeter, with the lid removed. In fact, that part of the calorimeter is surrounded by a temperature stabilized enclosure, permitting operation in rooms without temperature control and at temperatures deviating essentially from room temperature.

MEASUREMENT METHOD

As already pointed out, the absorbed dose at the point of measurement is given by the product of the specific heat capacity c_p of water and the radiation induced temperature rise, if there is no heat defect , i. e. if the energy imparted is wholly converted to heat.

(The heat defect should be zero for pure water and radiation having low LET (refs. 9-10). It is being determined in separate experiments (ref. 11) for photon and electron radiation of different radiation qualities for the water actually used in the absorbed dose calorimeter.)

For small temperature changes and negligible lead resistances and electrical power fluctuations in the thermistors, the absorbe dose is (ref. 2)

$$D = (1/2)(\Delta R/R)(\bar{S})^{-1}(c_p)$$

where D is the absorbed dose to water
$\Delta R/R$ is the fractional change in resistance of the bridge balancing resistor
$\bar{S}$ is the mean fractional change in resistance of the thermistors for unit temperature rise, and
c_p is the specific heat capacity of water

Values of c_p versus temperature are given in ref. 12. The sensitivities S of the thermistors are determined from measurements of the resistances as a function of temperature. Measurements with similar types of calorimeter for vertical beams are described in detail in ref. 2.

The fractional change in resistance of a thermistor is about 4 % per K. The dose rate produced by a typical high activity ^{60}Co source for radiation therapy amounts to 1 Gy/min under reference conditions, leading to a rise in temperature of about 1 mK after 4 minutes irradiation time.

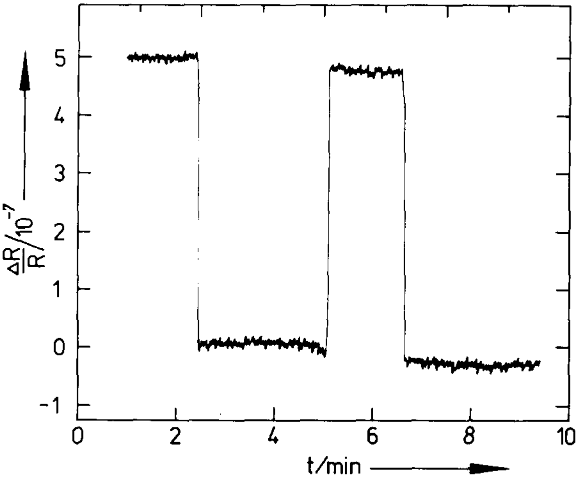

Fig. 5. Recorder trace showing fractional changes in resistance $\Delta R/R$ of about $5 \cdot 10^{-7}$ in each case, corresponding to temperature changes of about $1.25 \cdot 10^{-5}$ K.

Consequently, if a typical temperature rise of 1 mK is to be determined with an uncertainty of less than 1 %, a fractional change in resistance of less than $4 \cdot 10^{-7}$ has to be measured.

Fig. 5 shows that the experimental arrangement fulfils that requirement.

The bridge was balanced and the bridge voltage recorded. The sudden changes were caused by relative changes in resistance of about $5 \cdot 10^{-7}$, corresponding to temperature changes of about $1.25 \cdot 10^{-5}$ K.

IRRADIATION CONDITIONS

In order to measure the true radiation induced temperature rise, the influence of heat transport must be negligible or it must be corrected for. The design of the calorimeter could infer the occurrence of convection. However, Domen showed (ref. 2) that, at least for ^{60}Co radiation beams directed vertically downwards, the use of thin convection barriers does not influence the experiments. Schulz and Weinhous (ref. 13) also proved that for 19 MeV electrons and 25 MeV X-rays there was no evidence of convection when the beams were directed vertically downwards.

In the case of the calorimeter for horizontal beams (Fig. 2) the situation may be more critical. The influence of convection cannot even be excluded for extended radiation fields in every case. The problem may be overcome by the use of thin convection barriers or - as we preferred - by choosing a water temperature of 4 °C (ref. 13). Water will remain motionless, despite the existence of buoyant forces, until the Rayleigh number exceeds a critical value (ref. 2). The Rayleigh number is proportional to the volume coefficient of expansion and the latter is zero at a temperature of 4 °C. To adjust this water temperature the temperature regulated enclosure of the calorimeter is cooled down by Peltier aggregates in conjunction with air heat exchangers.

Whilst convection can be suppressed, one has nevertheless to deal with radiation induced temperature gradients causing heat transfer by conduction. Using extended homogeneous radiation fields, gradients perpendicular to the beam axis can be avoided to a great extent. However, in the direction of the beam axis one obtains a depth dose curve. How large the deviation of the measured temperature rise from the "true" radiation induced temperature rise (i. e. the temperature rise not falsified by heat conduction) actually is, depends - for a given irradiation time - essentially on the dose distribution and on the depth of measurement.

Domen showed that for his irradiation conditions (ref. 2) the influence of conduction heat transfer was negligible as a consequence of the low thermal diffusivity of water. Meanwhile there are several copies of the Domen calorimeter in operation; they are used for different types of radiation under the same conditions as for ionization dosimetry, the influence of conduction heat transfer usually not being discussed.

To study the influence of conduction heat transfer on the measured temperature rise, the disintegration of radiation induced temperature profiles during and after irradiation was calculated. These calculations are necessary to verify that for usual irradiation conditions the extrapolations to sudden heat transfers of pre and post irradiation curves indeed lead to correct results. If that is not the case, one can investigate the conditions which are suitable for the application of water absorbed dose calorimeters.

In the following, two examples for γ- and electron radiation are given. The application of almost homogeneous radiation fields extending over the whole phantom incident surface permits the simplification of the calculations as a numerical solution of the one dimensional unsteady-state heat conduction equation (see for instance ref. 14). It was further assumed that there is no heat transfer through the water surface. Since the radiation induced temperature rise is proportional to the absorbed dose, these temperature distributions in the water were determined by absorbed dose measurements. The calculations were performed for a water temperature of 22 °C.

Fig. 6 shows the results for ^{60}Co-γ-radiation (source to surface distance 100 cm, field dimensions 25 cm x 25 cm).

Depth distributions of temperature are given at several times after starting irradiation . The solid curve shows the "true" temperatures. Obviously the reference depth of 5 cm is also very suitable for application of the calorimeter. The heat transferred to greater depths is almost entirely substituted by heat transferred from shallower regions. This can be inferred quantitatively from Fig. 7.

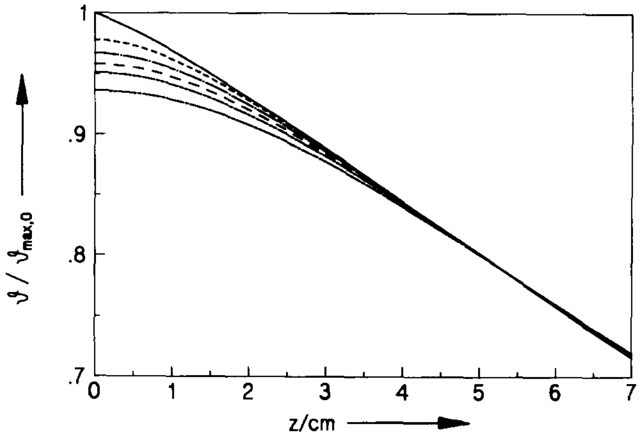

Fig. 6. Calculated depth distributions in time of temperature in the water phantom irradiated with ^{60}Co-γ-radiation for an irradiation time of 40 minutes. The distributions are normalized to the temperatures at the water front surface $\vartheta_{max,0}$ not falsified by heat conduction.

——————— immediately after irradiation commenced
- - - - - - - - after 10 minutes
—·—·— after 20 minutes
— — — — — after 30 minutes
—··—··— after 40 minutes (at the end of the irradiation period)
— — - — - — after 50 minutes

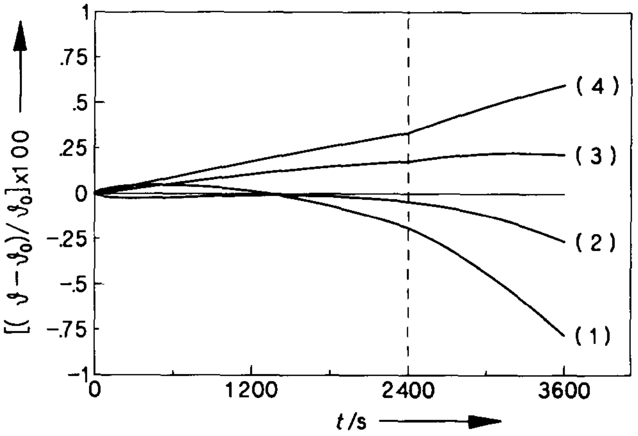

Fig. 7. Calculated deviation of the temperature ϑ from the "true" value ϑ_0 in percent as a function of time t after beginning ^{60}Co-γ-radiation for depths of 4 cm (1), 5 cm (2), 6 cm (3) and 7.5 cm (4). The end of the irradiation period is indicated by a dashed line.

Since the influence of heat conduction is rather small as a consequence of the small temperature gradient induced, the irradiation time (40 min) was chosen untypically large to make the trend more obvious.

After one hour the deviations are smaller than one percent. It is obvious that care must in general be taken when extrapolating the post periods. For typical irradiation times of 4 minutes however, the deviation at a depth of 5 cm is negligible.

The situation in the case of electron beams is quite different, as can be seen in Fig. 8.

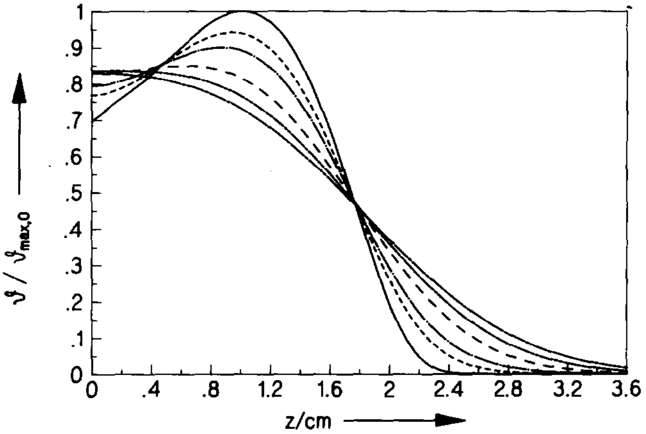

Fig. 8. Calculated depth distributions of temperature in the water phantom irradiated with 4.3 MeV electrons for various times after starting the irradiation. The distributions are normalized to the "true" temperatures for maximum dose.

————————	immediately after irradiation commenced
- - - - - - - - -	after 60 s
—·—·—·—	after 120 s (at the end of the irradiation period)
— — — — —	after 180 s
—··—··—	after 240 s
—·——·——	after 300 s

The figure shows depth distributions of temperature for the absorption of 4.3 MeV electrons. They are normalized to the temperatures for maximum dose without falsification by heat conduction. The irradiation time of 120 s was chosen to achieve a temperature rise of about 1 mK in the dose maximum by irradiation with a linear accelerator.

The reference depth for dosimetry in radiation therapy is the depth of the dose maximum, i. e. about 1 cm in this case. It can be seen that this depth is unsuitable for the application of water absorbed dose calorimeters, since the error in the measured temperature rise is particularly large. But once more there exists a depth (1.76 cm) where the heat transferred to greater depths is roughly compensated by the heat transferred from shallower regions.

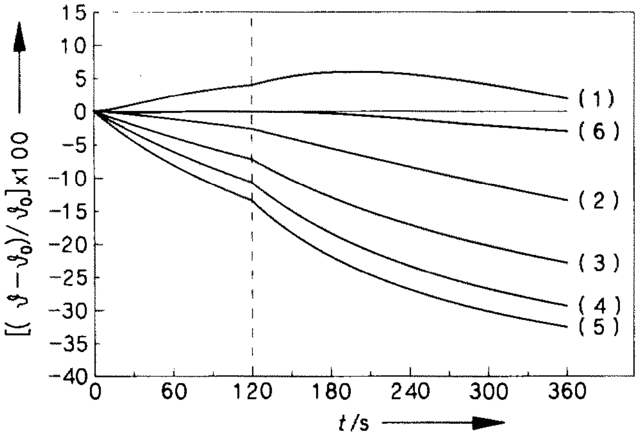

Fig. 9. Calculated deviation of the temperature ϑ from the "true" value ϑ_0 in percent as a function of time t after starting 4.3 MeV electron irradiation for depths of 0.3 cm (1), 0.6 cm (2), 0.8 cm (3), 1 cm (4), 1.3 cm (5) and 1.76 cm (6). The end of the irradiation period is indicated by a dashed line.

Fig. 9 shows the deviation of the measured temperature from the "true" temperature for several depths. At the depth of the dose maximum (4) the deviation is more than 10 % at the end of the irradiation period, increasing to about 30 % after 4 further minutes. At 1.76 cm depth ((6)) the deviation at the end of the irradiation period is smaller than 0.1 % and it amounts to about 3 % after 6 minutes.

The time dependence, however, is critically dependent on the depth, as can be seen from Fig. 10.

The depths are varied in 0.1 mm steps from 1.74 cm to 1.79 cm. The resultant temperature deviations after 120 s vary from -1.8 % to +2.8 %. So the use of the calorimeter at depths of about 1.76 cm seems possible but it demands high mechanical accuracy.

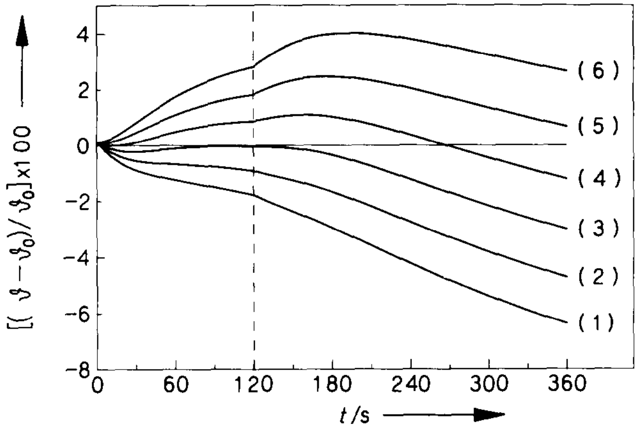

Fig. 10. Calculated deviation of the temperature ϑ from the "true" temperature ϑ_0 in percent as a function of the time t after starting 4.3 MeV electron irradiation, for depths of 1.74 cm (1), 1.75 cm (2), 1.76 cm (3), 1.77 cm (4), 1.78 cm (5) and 1.79 cm (6). The dashed line indicates the end of the irradiation period.

CONCLUSION

The absorbed dose water calorimeter is a very useful energy-independent dosemeter for radiation of different types and quality. When the heat defect is known the calorimeter may be established as a primary standard for water absorbed dose. Problems arising through convection in the use of horizontal beams may be overcome by choosing a water temperature of 4 °C.

Whereas for ^{60}Co-γ-radiation at the reference depth the influence of heat conduction is negligible, it is shown that for other types of radiation neglecting the influence of heat conduction may introduce large errors. In the case of electron dosimetry the reference depth is not really suitable for the application of the water calorimeter, particularly at energies below about 10 MeV. It is shown, however, that there are other depths which allow a water calorimetric determination of the absorbed dose.

In any case the influence of heat conduction has to be determined and it should be taken into account when calorimetric post periods are extrapolated.

REFERENCES

1 S. R. Domen, Absorbed dose water calorimeter, Med. Phys. 7 (1980) 157-159.

2 S. R. Domen, An absorbed dose water calorimeter: theory, design and performance, Journal of Research of the NBS 87 (1982) 211-235.

3 A. E. M. Marles, Comparison of measurements of absorbed dose to water using a water calorimeter and ionization chamber for clinical radiotherapy, photon and electron beams, Thesis; University of Texas Health Science Center (1981).

4 Kubo, Absorbed dose determination with a water calorimeter in comparison with an ionization chamber, Phys. Med. Biol. 28 (1983) 1391-1399.

5 L. O. Mattsson, Application of the water calorimeter, Fricke dosimeter and ionization chamber in clinical dosimetry, Thesis, University of Göteborg (1984).

6 L. O. Mattsson, Comparison of water calorimetry and ionization chamber dosimetry in 100 und 200 kV X-ray beams, CCEMRI(I)/85-15.

7 H. Kubo, Water calorimetric determination of absorbed dose by 280 kVp orthovoltage X-rays, Radiotherapy and Oncology 4 (1985) 275-281.

8 G. Galloway, J. R. Greening and J. R. Williams, A water calorimeter for neutron dosimetry, Phys. Med. Biol., 31(4) (1986) 397-406.

9 J. W. Fletcher, Radiation chemistry of water at low dose rates - emphasis on the energy balance: a computer study, AECL-7834 (Chalk River Nuclear Laboratories, Ontario, Canada) (1982).

10 C. K. Ross, N. V. Klassen and G. D. Smith, The effects of various dissolved gases on the heat defect of water, Med. Phys. 11 (1984) 653-658.

11 M. Roos and K. Hohlfeld, A measurement of the heat defect of water caused by high energy electrons, in this volume.

12 Handbook of chemistry and physics, Cleveland: Chemical Rubber Publishing Co..

13 R. J. Schulz and M. S. Weinhous, Convection currents in a water calorimeter, Phys. Med. Biol. 30 (1985) 1093-1099.

14 J. P. Holman, Heat Transfer, McGraw-Hill, New York (1981).