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A MEASUREMENT OF THE HEAT DEFECT OF WATER CAUSED BY HIGH ENERGY ELECTRONS

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SUMMARY

The definition of the quantity water absorbed dose itself suggests its unit be established directly by means of a water calorimeter. This requires the knowledge of the heat defect of water for the radiation applied.

A method is being developed which allows the heat defect for high energy electrons to be measured without involving dose measurements. The method is based on the total absorption of an electron beam in a water absorber, the energy and number of electrons being known. The mean energy imparted to the absorber by the radiation is compared with the energy transferred by electrical heating to achieve the same rise in temperature within the absorber. The difference of both energies is the heat defect of the water.

The method is outlined, the necessary corrections are discussed.

INTRODUCTION

The quantity water absorbed dose is the measurand in dosimetry for radiation therapy and the quantity dose equivalent used in radiation protection is also closely related to water absorbed dose. The absorbed dose can be measured by water calorimeters according to its definition (refs. 1-2). However, in the case of high energy photon and electron radiation (refs. 1, 3-6) the dose values determined by the calorimeters are about 3.5 % larger than the values obtained by other methods. The current assumption is that this discrepancy is caused by a heat defect of water. This means the heat measured and the radiation energy imparted are not equal but 3.5 % excess heat is caused by radiation induced chemical reactions.

To examine the validity of this assumption, model calculations were performed for the radiolysis of pure water and for water saturated with various gases (refs. 7-8). It transpires that for pure water - at least for ionizing radiation with low linear

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energy transfer - the energy imparted must be completely converted to heat. In the case of O_2-saturated water, an overall endothermicity of 1.8 % was calculated whereas the calorimetric results (ref. 1) are independent of whether the water is O_2-saturated or not. Consequently a discrepancy of more than 5 % is revealed. Nevertheless, a heat defect for pure water cannot definitely be excluded. It could be caused, for instance, by the influence of unavoidable impurities. Therefore, the establishment of the water absorbed dose calorimeter as a primary measurement standard requires the determination of the heat defect for the water actually used in the calorimeter by a method which does not involve absorbed dose measurement.

EXPERIMENTAL METHOD

The method presented is based on the total absorption in a water absorber of an electron beam of known electron energy and known current. Fig. 1 shows the experimental arrangement.

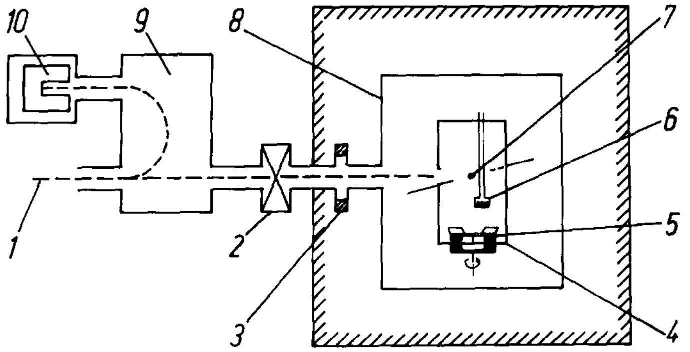

Fig. 1. Schematical illustration of the experimental arrangement for the determination of the heat defect.

1	electron beam from a 5 MeV microtron
2	quadrupole lenses of a beam guiding system
3	beam monitor (current transformer)
4	total absorption vessel (stainless steel, filled with water)
5	magnetically coupled stirrer
6	electrical heater
7	thermistors
8	vacuum container in an air-conditioned enclosure
9	180° deflection chamber
10	Faraday cup

The radiation source is a microtron for electron energies from 1 MeV up to 5 MeV and a mean current of 10^{-7} A. The acceleration principle yields electrons with a narrow energy spread and a high energy stability. A bending magnet (9) in conjunction with a Faraday cup (10) acts as an electron spectrometer, permitting an electron energy determination with 0.2 % uncertainty. When the magnet is turned on the beam is deflected by 180° into the Faraday cup. The magnetic flux density necessary for a given deflection radius is measured using the nuclear magnetic resonance method. The Faraday cup is also be used for the calibration of a current monitor (3) in terms of the charge carried to the absorber. The uncertainty of the charge measurement is 0.3 %.

When the bending magnet is switched off the beam is focussed onto the entrance window of the absorption vessel (4) by a beam guiding system (2). The dimensions of the vessel ensure that all the electrons are stopped completely in the water. So the total energy imparted to the absorber is known.

A magnetically coupled stirrer (5) provides a homogeneous distribution of temperature throughout the absorber. The temperature rise is measured using two thermistors (7) in opposite arms of a Wheatstone AC bridge. The bridge voltage caused by the temperature change is amplified by a lock-in amplifier and then recorded.

To determine that portion of the energy imparted which is converted to heat, the same temperature rise is then produced without a heat defect by electrical heating. The heater (6) is supplied by a constant current generator, the voltage drop is measured by counting the pulses of a calibrated voltage frequency converter. Consequently the difference of the total energy imparted by radiation and the electrical energy for the same temperature rise yields the heat defect.

Fig. 2 shows the central part of the calorimeter for total absorption from the opposite side of the beam entrance.

The absorption vessel (stainless steel) is supported by thin nylon wires to minimize the heat conduction to the supporting ring in the vacuum enclosure. Below the absorber a steel plate support for a synchronous motor can be seen; the latter drives a rotor coupled magnetically to a stirrer inside the absorber. On the beam entrance side there is a diaphragm electrically connected to an electrometer to ensure that all electrons detected by the beam monitor actually enter the absorber by its entrance window.

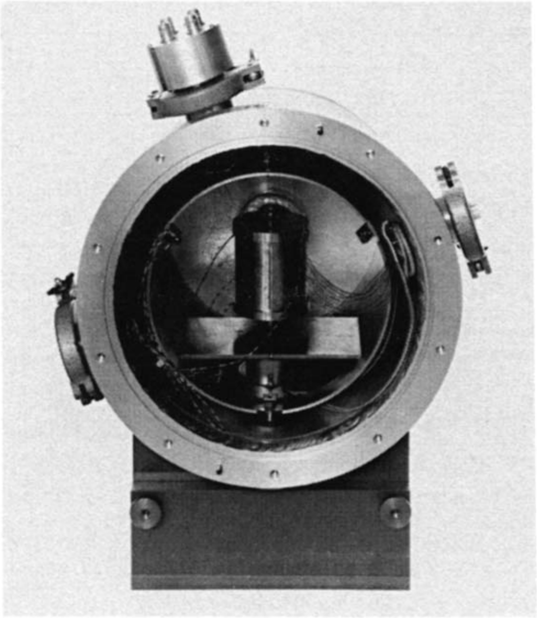

Fig. 2. View into the inner chamber of the calorimeter from the opposite side of the beam entrance, showing the total absorption vessel and the vacuum enclosure.

In Fig. 3 an absorption vessel for 2 MeV electrons (left) is shown. The choice of vessel dimensions (diameter 2 cm, height 3 cm, diameter of the entrance window 7 mm) are based on Monte Carlo

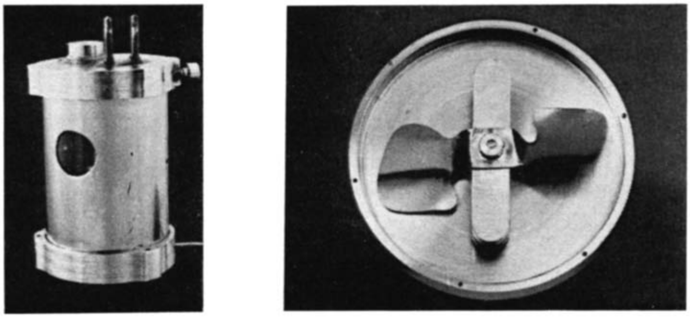

Fig. 3. Stainless steel vessel for total absorption of 2 MeV electrons in water (left) and the bottom of an absorption vessel with a magnetically coupled stirrer (right).

calculations to ensure that the electrons which enter through the window (20 μm polyethylene foil) are stopped completely in water, i. e. they do not reach the walls, the stirrer or the thermistors etc.

The right hand part of fig. 3 shows the bottom of an absorber containing the stirrer magnetically coupled to the synchronous motor. The magnets are covered with polyethylene foil to avoid rusting.

The power transferred to the absorber by stirring is below 1 % of the radiation power and the electrical power.

Several hours before beginning the irradiation the water is stirred with constant power to obtain steady state conditions, i. e. a constant temperature in the absorber. Then a cycle of measurements is performed as schematically illustrated in fig. 4.

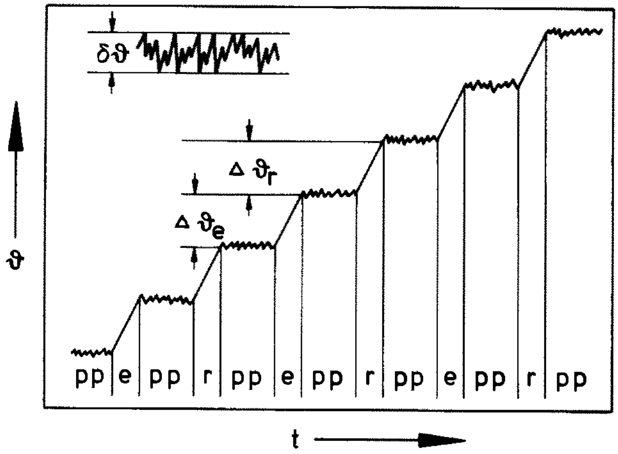

Fig. 4. Illustration of the time dependence of temperature ϑ in the absorber during a cycle of measurements, comprising calorimetric pre- and post periods (pp) respectively, periods of electrical heating (e) with temperature rises $\Delta\vartheta_e$ and periods of heating by irradiation (r), causing rises in temperature $\Delta\vartheta_r$.

The measurements start with the recording of the calorimeter pre period (pp), the amplitude of the signal fluctuations $\delta\vartheta$ being less than 100 μK. Then a rise in temperature $\Delta\vartheta_e \approx 100$ mK is effected in the electrical heating period (e). After a post period (pp) which is the pre-period of the next heating stage, the temperature in the absorber is raised through irradiation (r), again by $\Delta\vartheta_r \approx 100$ mK.

Fig. 5 shows a recorder trace of the time dependence of the temperature in the absorber for 5 MeV electrons during the period of electrical heating.

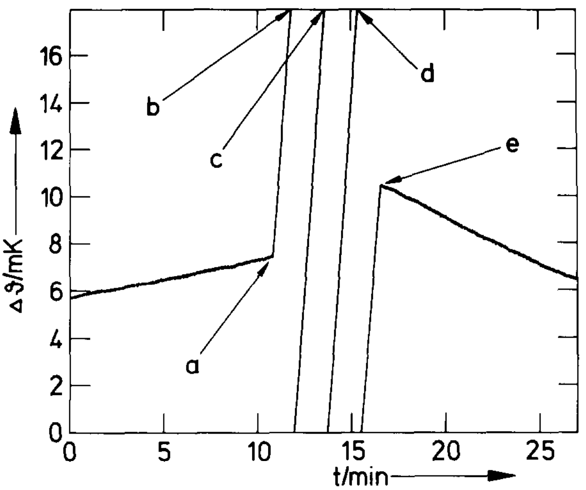

Fig. 5. Recorder trace of the absorber temperature $\Delta\vartheta$ as a function of time t around the period of electrical heating. At time **a** heating commenced, at time **e** it ended, at times **b**, **c**, **d** the bridge resistance was changed manually.

At times (a) and (e) the heating started and ended respectively. At times b, c, and d the bridge resistance was changed manually. The electrical power was 200 mW, the maximum power available in the 5 MeV electron beam of the microtron. The warming-up drift in the pre-period and the large cooling drift during the post period occurred whilst the vacuum enclosure was not evacuated.

For 2 MeV electrons the dimensions of the absorber could be reduced which results in a heat capacity of only about 10 % of that of the 5 MeV absorber. Consequently, even for a reduced power level of the beam, the resolution of the temperature rise is far better than for the 5 MeV vessel (fig. 5).

To calculate the heat defect from the experimentally determined parameters corrections have to be made for backscattering of electrons at the entrance window of the absorber and production of bremsstrahlung during the deceleration of the electrons, as well as reabsorption of bremsstrahlung. The correction factors differ only by a few percent from 1 and are determined using a Monte Carlo code (ref. 9).

CONCLUSION

The experiment presented here enables the heat defect of water to be measured for electron radiation in the energy range from 1 MeV up to 5 MeV. The development of an experimental method for soft X-rays is underway (ref. 10). Thus the heat defect can be studied systematically for low LET radiation, preparing the way for the application of the water calorimeter as a primary measurement standard of absorbed dose for these types of radiation.

Moreover, the water calorimetric determination of the absorbed dose to water is not restricted to low LET radiation. It is, for instance, well suited for neutron beams as well. Therefore, the heat defect should also be known for high LET radiation.

Indeed the method outlined here can also be applied to other types of radiation - e. g. proton radiation - under the presumptions that the ranges are not too small, the dose rate is high enough, the beam can be focussed sufficiently and that the radiant energy can be measured.

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