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The use of recombination chambers at radiation therapy facilities

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ABSTRACT

The paper presents an overview of the applications of recombination chambers for dosimetric measurements at radiotherapy facilities. The chambers were used at electron, proton and heavy ion accelerators, in the beam and in the vicinity of the accelerators at very different dose rates. The examples of measurements discussed in the paper include: the determination of the absorbed dose and radiation quality parameters of a 170 MeV proton beam and BNCT (boron neutron capture therapy) beam, neutron dose measurements at a phantom surface outside the beam of a 15 MV electron medical accelerator, determination of ambient dose equivalent, H* (10) outside the irradiated phantom in the proton therapy treatment room at JINR (Dubna, Russia), and at working places outside the shielding of the heavy ion therapy facility at GSI (Darmstadt, Germany).

1. Introduction

Dosimetry at radiation therapy (RT) facilities involves two aspects: proper RT and radiation protection (RP). For the proper RT, absorbed doses should be precisely determined in the treated organ and in the surrounding tissues. For the RP (of the patient, personnel and other persons) it is necessary to estimate the equivalent dose in the patient's organs or in appropriate phantoms, and the ambient dose equivalent values inside and outside the treatment room. Values of dose rates in the irradiated organ and outside the shielding differ up to nine orders of magnitude. This obviously should be taken into account when selecting an appropriate detector.

RT departments are usually equipped with dosimetric detectors for X-ray and gamma radiations. Mostly, these are free-air ionization chambers (small chambers for in-phantom measurements and large chambers for RP). Sometimes, there are also neutron dose-equivalent-meters (rem-meters) for RP dosimetry, especially at hadron therapy facilities. The additional use of a recombination chamber (RC) can be advantageous, because this chamber is sensitive to all kinds of radiation and provides information on radiation quality.

2. Recombination chambers and recombination methods

RCs are high-pressure ionization chambers, designed in such a way that, for a certain range of gas pressure and dose rates, initial recombination of ions occurs when the chamber operates at polarizing voltages below saturation, and is much greater than volume recombination. This phenomenon is used for the determination of dosimetric quantities dependent on radiation quality, using a relationship between the initial recombination efficiency and local ion density.

Electrodes of RCs are mostly made with a tissue-equivalent (TE) material. Gas in the chamber usually contains hydrocarbons; however, hydrogen-free RCs are also used as detectors with very low sensitivity to high-LET radiation.

Most of in-phantom measurements were performed with an F-1 type chamber, which is a 3.8 cm^3 parallel-plate RC. The chamber has three electrodes with a diameter of 34 mm, a wall thickness of 0.6 g/cm^2 and a distance of 1.75 mm between electrodes. The chamber is designed in such a way that it can be placed inside a water phantom and directly used for the measurements at dose rates from 10^{-5} Gy/min up to 100 Gy/min.

In-beam measurements were also performed with a pair of high-pressure cylindrical RCs: a TE T-5 chamber and a graphite G-5 chamber. Both chambers are 115 mm in length and 18 mm in diameter. The distance between the electrodes is 2 mm. The chambers are enclosed in a 0.3 mm-thick aluminium container.

Measurements of H* (10) were mostly performed with a large recombination chamber of the REM-2 type. This is a cylindrical, parallel-plate ionization chamber with 25 tissue-equivalent electrodes, a volume of 1800 cm^3, a mass of 6 kg and an effective wall thickness of about 2 g/cm^2. The RC of the same design, but with Al electrodes and filled with CO_2 (2.8 MPa), is denoted as GW2. The 1800 cm^3 TE chamber filled with BF_3 is referred to as BOR-3.

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All recombination methods are based on the comparison of ion collection efficiency at a given polarizing voltage U, in the investigated radiation field, and the ion collection efficiency at the same voltage U in the reference gamma radiation field (in our measurements, this is the field created by a ^{137}Cs source). Therefore, either the whole saturation curve should be determined or a number of points on this curve (at least two), depending on the dosimetric quantities to be determined and on the desired accuracy. About 30 types of RCs and about 20 recombination methods have already been developed (Zielczynski and Golnik, 2000; Golnik, 1996; Zielczynski et al., 2007); however, only a few of them were used at RT facilities:

1. The method based on the determination of the recombination index of radiation quality (RIQ, Q_R) (Zielczynski and Golnik, 1994a). In this method, two values of the polarizing voltage should be applied consecutively to the chamber electrodes in order to determine the absorbed dose and to estimate the radiation quality factor. One voltage should be high enough to ensure that the chamber operates in saturation (or close to saturation). At the second voltage, specific for certain chambers, initial recombination occurs and the ion collection efficiency is measured.
2. The extrapolation recombination method (ERM) (Zielczynski, 2004). Measurements of the ionization current at four to seven voltages are needed in order to separately determine the low- and high-LET components of the absorbed dose.
3. The recombination microdosimetry method (RMM) (Golnik, 1995 and Golnik, 1996). Here, about 20 polarizing voltages should be applied in order to obtain a crude distribution of the absorbed dose versus restricted LET. When RMM is used for the determination of only two components of the absorbed dose, associated with low- and high-LET particles, this method becomes similar to ERM.

3. Specific difficulties associated with in-beam measurements

There are several reasons why the measurements with RC in radiation therapy beams are relatively difficult:

(1) Large corrections for volume recombination in the chamber have to be introduced when the measurements are performed in beams, because of high dose rates and an usually pulsed mode of radiation. Another possible approach is to use only high polarizing voltages, but then the accuracy of the low-LET dose determination is limited. In order to avoid these shortcomings, the RCs with a very small gap between electrodes should be used.
(2) Parameters describing the radiation quality (e.g. the distribution of the absorbed dose versus restricted LET) are usually strongly dependent on the depth in a phantom and the human body. The difference can be very large at the end of the Bragg peak, where also the dose rate changes very steeply with the depth in the phantom. This makes it necessary to perform a number of measurements at different, precisely established positions of the RC relative to the Bragg peak. Obviously, the measurements become time-consuming, especially in the case of methods which involve the determination of the whole saturation curve.
(3) The required accuracy of the absorbed dose determination in RT beams is much higher than that needed for radiation protection. Therefore, the gas pressure, the electrical field in the chamber and the active volume of the chamber have to be very stable. Over a longer time scale, this also involves gas composition.
(4) The chambers may exhibit a charge memory, i.e. the measured ionization current at the lowest polarizing voltages (of several volts) and the high absorbed doses may depend on the history of the chamber's operation (Zielczynski and Golnik, 2000). The parameters of the charge memory should first be investigated for the specific type of the chamber used prior to measurements.
(5) The cables connecting the chamber with registration units are usually long. This is, above all, inconvenient; but also, long electrometric cables can cause additional noise therefore diminishing the accuracy of the measurements.
(6) Precise monitoring of the beam intensity is needed, especially when sequential measurements of the ionization current at different voltages are performed.

4. Examples of measurements performed with recombination chambers at RT facilities

The examples shown here were selected mainly with the intention to present the measurements of such parameters which could be determined with RCs while they were not measurable neither with free-air ionization chambers nor with standard neutron rem-meters.

4.1. Proton therapy facility of the Joint Institute for Nuclear Research in Dubna (Russia)

The measurements were performed at the Dubna phasotron using a 170 MeV proton beam with an intensity of 1.7 μA. The beam was directed onto a water phantom, and the Bragg peak was slightly broadened (2 cm at 90% of the maximum absorbed dose). The F1 and REM-2 chambers were used for in-phantom measurements and for the determination of $H^*(10)$ in the treatment room (Gryzinski et al., 2009).

Fig. 1 shows saturation curves determined with an F1 chamber in the Bragg peak and in the reference gamma radiation field of ^{137}Cs. The measurements were performed during 3 h, at two values of the beam intensity. The data were analysed using the RMM. It was found that the contribution of high-LET particles ($L > 50$ keV/μm) to the absorbed dose was equal to 0.1 (10% of the total dose). The contribution of low-LET particles (the mean restricted LET of all particles including delta electrons – below 20 keV/μm) was determined using both RMM and ERM, both methods resulting in a value of 0.7 ± 0.05. This is over 20% more comparing with the low-LET component ($L < 10$ keV/micron) determined using CR-39 track detector.

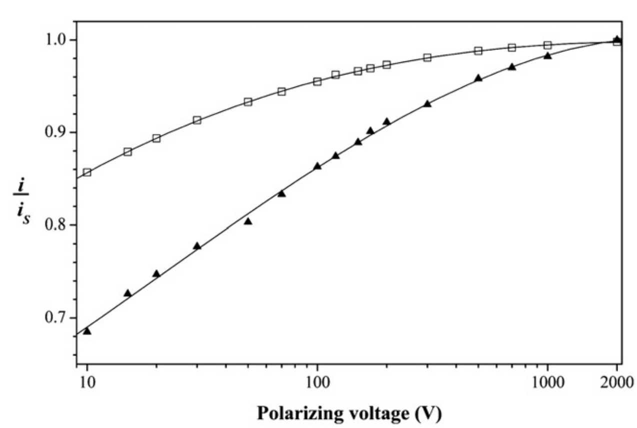

Fig. 1. Saturation curves of RC F1 type (the relative ion collection efficiency i_M/i_S). □ – gamma radiation of ^{137}Cs; ▲ – 170 MeV protons at a broadened Bragg peak.