Radiation Physics and Chemistry xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Coupling Monte Carlo simulations with thermal analysis for correcting microdosimetric spectra from a novel micro-calorimeter

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ARTICLE INFO

Keywords:
Particle therapy
Calorimetry
Microdosimetry
Monte Carlo Simulations
Thermal analysis

ABSTRACT

The high uncertainty in the Relative Biological Effectiveness (RBE) values of particle therapy beam, which are used in combination with the quantity absorbed dose in radiotherapy, together with the increase in the number of particle therapy centres worldwide necessitate a better understating of the biological effect of such modalities.

The present novel study is part of performance testing and development of a micro-calorimeter based on Superconducting QUantum Interference Devices (SQUIDs). Unlike other microdosimetric detectors that are used for investigating the energy distribution, this detector provides a direct measurement of energy deposition at the micrometre scale, that can be used to improve our understanding of biological effects in particle therapy application, radiation protection and environmental dosimetry. Temperature rises of less than 1μK are detectable and when combined with the low specific heat capacity of the absorber at cryogenic temperature, extremely high energy deposition sensitivity of approximately 0.4 eV can be achieved.

The detector consists of 3 layers: tissue equivalent (TE) absorber, superconducting (SC) absorber and silicon substrate. Ideally all energy would be absorbed in the TE absorber and heat rise in the superconducting layer would arise due to heat conduction from the TE layer. However, in practice direct particle absorption occurs in all 3 layers and must be corrected for.

To investigate the thermal behaviour within the detector, and quantify any possible correction, particle tracks were simulated employing Geant4 (v9.6) Monte Carlo simulations. The track information was then passed to the COMSOL Multiphysics (Finite Element Method) software. The 3D heat transfer within each layer was then evaluated in a time-dependent model. For a statistically reliable outcome, the simulations had to be repeated for a large number of particles. An automated system has been developed that couples Geant4 Monte Carlo output to COMSOL for determining the expected distribution of proton tracks and their thermal contribution within the detector.

The correction factor for a 3.8 MeV proton pencil beam was determined and applied to the expected spectra. The corrected microdosimetric spectra was shown to have a good agreement with the ideal spectra.

1. Introduction

Particle therapy has the advantage of more localised deposition of dose compared to photons and consequently, less complication of the adjacent healthy tissues.

Since the first use of high energy proton beams for treating cancer in the mid-1950s there has been a rise in the number of proton and ion therapy centres and is projected to increase further. Latest statistics published by the Particle Therapy Co-Operative Group (PTCOG) in 2016, show that there are 68 centres in operation worldwide, 31 under construction and 17 in planning stages (Particle Therapy Co-Operative Group, 2016).

The effective dose in particle therapy is determined by multiplying the physical dose by a Relative Biological Effectiveness (RBE) factor (Paganetti et al., 2002). Accurate determination of the RBE value is necessary for utilising particle therapy to its full potential. There have

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http://dx.doi.org/10.1016/j.radphyschem.2017.02.055
Received 27 September 2016; Received in revised form 22 February 2017; Accepted 24 February 2017
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been a number of in-vivo and in-vitro studies suggesting different values for the RBE for equivalent beams (Daşu and Toma-Daşu, 2008; Jones and Dale, 2000; Matsuura et al., 2010; Paganetti et al., 2002; Tilly et al., 2007).

The biological (and other structural) effects of radiation are not only influenced by the average energy deposited per unit mass (i.e. absorbed dose) but also by the number of interactions in a volume of interest (for example nucleus, cell, tissue), their magnitude (amount of energy transferred) and their spatial distribution. Microdosimetry, which defines concepts and quantities to specify the energy concentration in microdosimetric regions, can be employed to improve our understanding of radiation effects at the cellular scale (Kellerer, 1985, 1984; Microdosimetry ICRU Report 36, 1983). The determination of the RBE using microdosimetric spectra for intercomparison of different clinical radiotherapy beams has been demonstrated by Brenner and Zaider (1998).

The experimental methods in microdosimetry often measure ionisations in gases or semiconductors that are not necessarily representative of the energy depositions and ionisations in tissue. Tissue Equivalent Proportional Counters (TEPCs) are the most commonly used microdosimetry devices and have been attractive due to their ability to amplify the ionisation from a single particle passage (event) into a detectable signal. However, their large sensitive volume (usually centimetre scale) and low energy resolution has led to design and development of many other detectors which work on similar principles. These include the miniaturized TEPCs (mini-TEPCs) designed at the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Legnaro (INFN-LNL) with a sensitive volume on the millimetre scale instead of the centimetre scale (De Nardo et al., 2004; Moro et al., 2006). The mini-TEPCs still suffer from large sensitive volumes relative to the scale desired in microdosimetry measurements (micrometre). In addition, only the ionisations, disregarding excitations and local heating, are considered as a representation of the energy deposited in the counter.

The design concept of a novel Superconductive Quantum Interference Device (SQUID) based micro-calorimeter for the determination of microdosimeteric spectra was previously presented by Galer et al. (2011). A typical image of the device is shown in Fig. 1. To convert the signal obtained from the micro-calorimeter accurately to the microdosimetric spectrum, correction factors are required, which are the focus of this work. During irradiation, energy is deposited along the path of the particle passing through a dual absorber located within the SQUID loop. This dual absorber consists of a superconducting (SC) and a tissue-equivalent (TE) absorber as shown in Fig. 1.

The energy deposited and its distribution in the TE absorber provides the microdosimetric information directly relevant for the comparison of different treatment modalities for radiotherapy. The quantity of interest is the energy deposited in the TE absorber by a traversing particle which is then converted to lineal energy. In an ideal situation, the traversing particle will deposit energy in the TE absorber alone leading to a temperature rise within its volume. The temperature is then conducted from the TE absorber to the SC absorber. This will cause a change in the effective area of the SC absorber which will be detected as a voltage change to the SQUID response to an applied magnetic field. The amount of temperature rise causing the voltage change can be derived as shown by Hao et al. (2003) in their work on Inductive superconducting transition-edge detectors for single-photon or macro-molecule detection. The SQUID's response to temperature changes in the SC absorber is given by Eq. (1):

$$\frac{dV}{dT} \approx \frac{6\pi R_{dyn} i_c \mu_0^2 a}{L^2} \frac{\lambda(0) T^3}{\left(1-\left(\frac{T}{T_c}\right)^4\right)^{2/3}} \tag{1}$$

Where.

V is the voltage.

T is the temperature of the superconducting absorber.

R_{dyn} is the dynamic resistance of the SQUID at the bias point.

I_c is the critical current of the SQUID.

T_c is the transition temperature of the superconducting absorber.

$\lambda(0)$ is the penetration depth at T=0 K.

a is the radius of the SQUID loop.

L is the inductance of the SQUID loop.

μ_O is permeability of free space.

However, the ideal situation described above cannot be realized since not all heat from the TE absorber will flow to the SC absorber. If the particle is not stopped in the TE absorber, heat will also be generated in the SC absorber and heat from the SC absorber can flow to the silicon substrate.

The method of determining those corrections for a 3.8 MeV proton pencil beam are described here. Furthermore, the thermal relaxation behaviour of the novel micro-calorimeter is investigated. A model was created employing Monte Carlo (MC) simulations to determine the energy deposition in the micro-calorimeter. The outcome of the MC simulations were used in a heat transfer model to investigate the thermal response of the micro-calorimeter caused by individual incident particles. The process of coupling the two models was automated enabling the analysis of a large number of incident particles at various energies.

2. Method

2.1. Monte Carlo simulations

For the first part of the work, Geant4 version 9.6 patch-02 (Agostinelli et al., 2003) was employed to simulate a 3.8 MeV mono-energetic proton pencil beam interacting with the micro-calorimeter. The positional information of individual energy transfers (called interactions in Geant4) and the amount of energy deposited in each layer was recorded for input into the heat transfer model. In addition, the model was used to produce the expected microdosimetric spectra of the incident particle. The micro-calorimeter model built for this

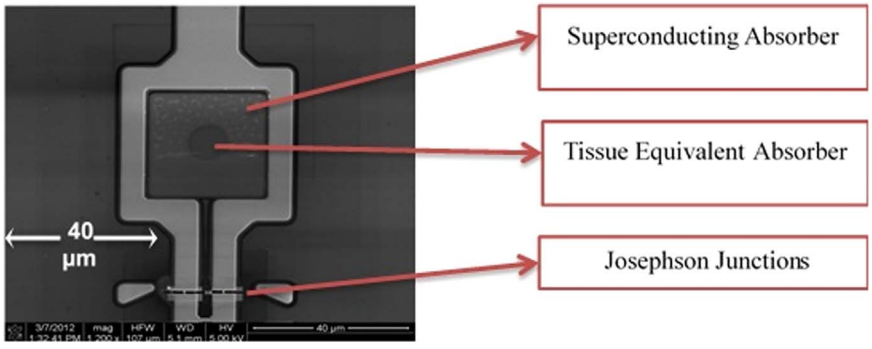

Fig. 1. Scanning electron microscope image of the micro-calorimeter.

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