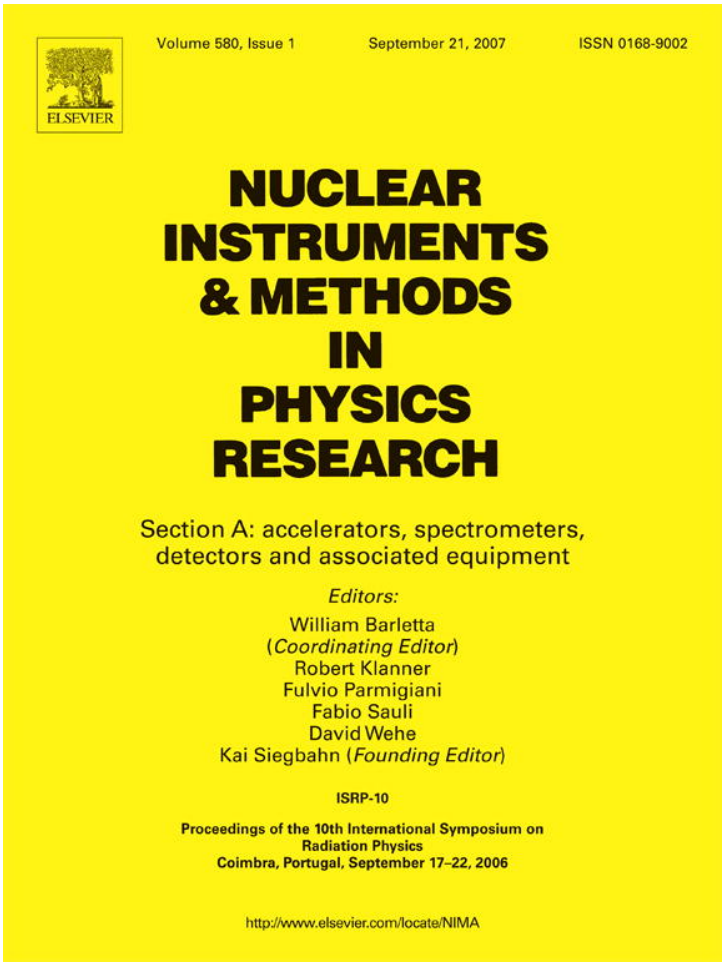

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An optimized Monte Carlo (PENELOPE) code for the characterization of gel-layer detectors in radiotherapy

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Abstract

Monte Carlo (MC) simulation of radiation transport is considered to be one of the most accurate methods of radiation therapy dose calculation. A basic requirement for MC treatment planning is a detailed knowledge of the characteristics of radiation beam generated from medical linear accelerators (LINACs). One of the most important input parameters is the photon fluence of the beam, usually not determinable experimentally. Thus, an MC simulation code based on the PENELOPE package was developed in order to survey the influence of the incident spectrum on the in-phantom dose distributions. Different spectra for the incident photon fluence have been considered in order to establish the most adequate one. The resulting planned dose distributions have been compared with those determined experimentally with ionization chamber measurements and gel dosimeter layers analyzed with optical technique. The specific gel composition has been implemented in the MC simulation code. Comparisons between experimental measurements, approximated simulations (water) and specific simulations (gel composition) have been performed.

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Keywords: Monte Carlo simulation; External radiotherapy; Fricke gel dosimetry

1. Introduction

The assessment of radiation dose distribution in radiotherapy treatment planning should be quite accurate, since the dose delivered to patients must not differ more than 5% from the prescribed dose [1,2]. Although most three-dimensional treatment planning system algorithms usually involve the pencil beam method [3], Monte Carlo (MC) simulation has increasingly become more important since several irradiation configurations can be simulated for dose distribution determinations.

Utilization of MC codes has found an extensive application in radiation transport studies and also for dose distribution determinations in clinical dosimetry. In order to simulate the irradiation situation corresponding to a typical commercial Linac therapy unit, PENELOPE MC package [4] has been employed.

Fricke (ferrous-sulphate) layered-gel dosimeters imaged with an optical system have demonstrated to be a useful tool for dose distribution measurements in radiotherapy [5,6]. Briefly, the optical method used for Fricke gel dosimeter analysis is based on the imaging of visible light transmittance through the dosimeters, detected before and after irradiation. In order to perform optical transmittance analysis, gel dosimeters are in form of layers and they are placed on a plane and homogeneous illuminator. The images are detected by means of a CCD camera supplied with a suitable optical filter, giving a good spatial resolution for the dose distribution.

A suitable dedicated MC subroutine has been adapted in order to check the tissue-equivalence of the here used Fricke gel dosimeters, for photon and electron beams.

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Therefore, exact knowledge of Fricke gel dosimeter chemical composition and dimensions allowed appropriate target material input, in order to define the dosimeter chemical and geometrical properties for the simulation code.

2. Materials and methods

2.1. Monte Carlo simulations

The MC code used in this work has been adapted from the sample programs distributed with version 2003 of the PENELOPE package. These FORTRAN 77 routines perform MC simulation of coupled electron–photon transport in arbitrary materials. The scattering models included allow the simulation of electron, positron and photon transport in the energy range of 100 eV–1 GeV. Random electron–photon showers are generated in complex material structures consisting of distinct homogeneous regions of different compositions.

The main program has to control the evolution of the simulated tracks and keep score of the relevant quantities. Photon transport is simulated in a detailed way, which means that all the interaction events in a photon history are simulated in chronological succession. On the other hand, electron and positron tracks are simulated by means of a mixed algorithm: individual hard interactions are accounted for in a detailed way, whereas soft collisions are taken into account through condensed simulation, i.e., several interactions are grouped in one single event. This procedure ensures reliable simulation results, while saving simulation CPU time.

The sample program PENCYL provided in the 2003 PENELOPE distribution has been modified according the requirements of the actual situations to be reproduced. In order to allow a divergent rectangular beam, the developed program generates pseudo-random numbers to adequately cover the desired rectangular field area with the corresponding incident photon fluence. For each primary photon generated in this way, a proper incident direction is assigned following the source divergence.

Different energy distributions for the incident photon beam have been considered. With the aim of achieving the most reliable situation, a typical bremsstrahlung spectrum has been taken into account as well as simplified cases, such as combinations of monoenergetic beam components.

The main irradiated materials considered here have been two kinds of phantoms: the first one consisting of homogeneous water, while the second one reproduced the detailed chemical composition and geometry of the Fricke gel layer dosimeters described below.

The simulations were carried out in a cluster facility with 3.0 MHz Pentium processors, each with 10^8 primary particles, which typically implied around 10^6 s of CPU time.

2.2. Experimental dosimeter characterization

The elaboration process of gel dosimeters involves a Fricke (ferrous sulfate) solution infused with Xylenol Orange, which is incorporated to a gel matrix (porcine skin gelatin) as described in [6,7]. The mass chemical composition of the dosimeter sensitive volume is approximately: H, 11.04%; O, 88.42%; C, 0.04%; N, 0.002%; Fe, 0.003%; Na, 0.002% and S, 0.005%.

Simulated and experimental relative dose distributions corresponding to these dosimeters have been compared with ionization chamber reference data for in-water on-axis relative depth dose distributions.

Fricke gel dosimeters have been irradiated with an 18 MV photon beam from the Clinac 2100 C Varian linear accelerator (Linac). The employed beam field size was 10 cm × 10 cm, with an isocentric technique, SSD 100 cm. The dosimeters have been irradiated inside a suitable tissue-equivalent phantom in order to ensure accurate dosimetric conditions.

3. Results and discussion

The simplest incident spectrum considered for the simulations was a monoenergetic beam with half of the maximum of the bremsstrahlung spectrum, i.e. 9 MeV. Other simple incident beams tested have been suitable combinations of monoenergetic components, as the 2-delta example shown in Fig. 1.

Fig. 2 shows the on-axis normalized depth dose distribution (PDD) results obtained with several simplified input incident spectra corresponding to a homogeneous water phantom. For the case of the 2-delta incident spectrum, equal intensities have been chosen for the 6 and 12 MeV photon beam components. On the other hand,

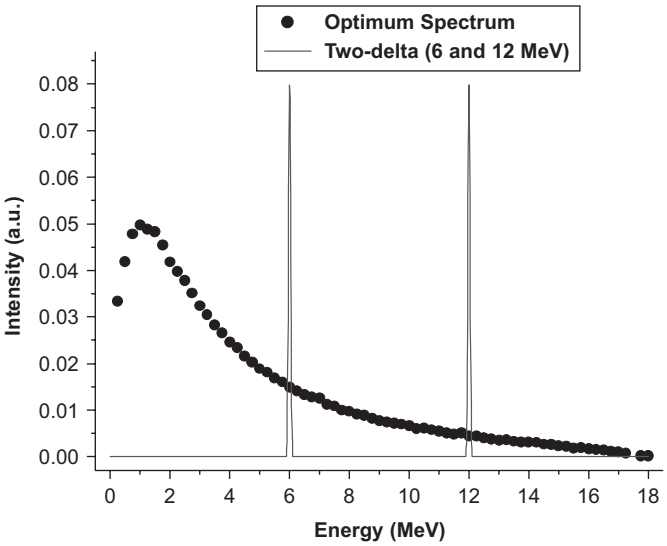

Fig. 1. Optimal bremsstrahlung spectrum and 2-delta simple model for the Clinac 2100 C 18 MV photon beam as input for dose distribution simulations.

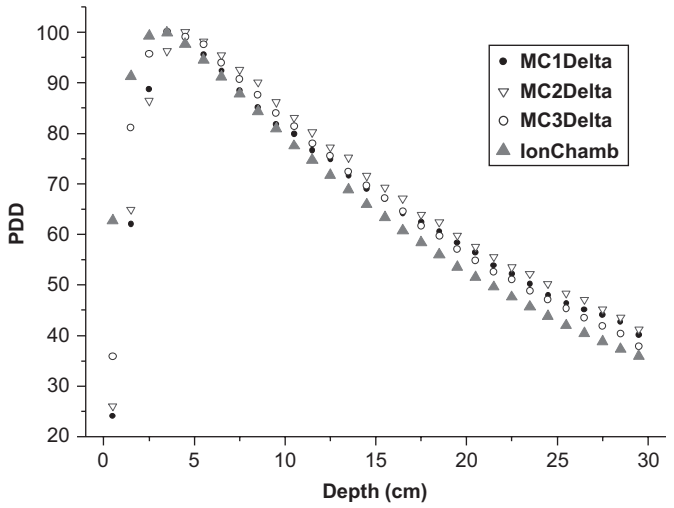

Fig. 2. Monte Carlo simulations for the normalized depth dose (PDD) corresponding to the several simplified delta spectra considered, as compared to the experimental distribution measured with an ionization chamber.

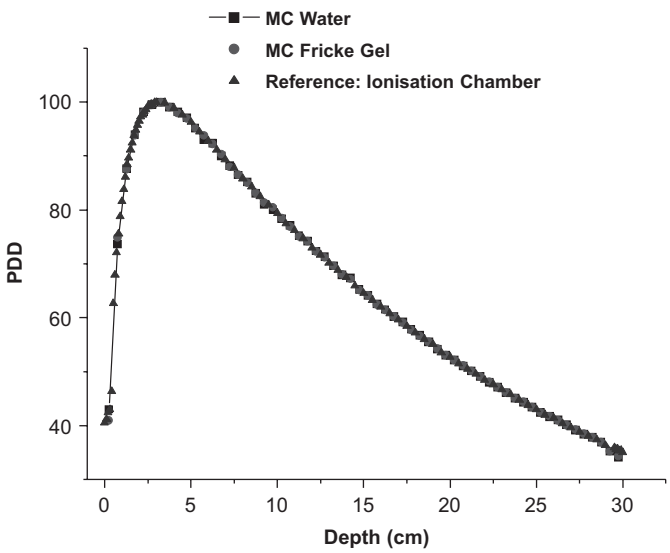

Fig. 3. Comparison of simulated PDD for water and Fricke gel phantoms with reference data.

weighted values have been used in the case of the 3-delta example with energies of 4.5, 9 and 13.5 MeV, with ratio 6:2:1, respectively. Clearly the depth dose distribution cannot be satisfactorily simulated with these simplified spectra. Particularly, when considering several energy components with appropriate intensities, the in-phantom simulated absorbed dose distribution becomes closer to the experimental one.

With the aim of assessing the quality of the most adequate incident beam spectrum, a large number of different energy distributions, employing weighted mono-energetic lines combinations as well as continuous parameterized spectra, have been considered. Minimal squares were the adopted optimization procedure. When approaching the optimal incident spectrum differences are not distinguishable at first sight. Therefore, the measure chosen for quantifying the suitability of the obtained results has been a chi-square test, defining

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\frac{(y_i - \tilde{y}_i)^2}{\sigma_i^2} \quad (1)$$

where y_i and $\tilde{y}_i$ are the measured and simulated values, respectively, and σ_i represents the uncertainty of each of the N simulated values. By means of this tool, the optimal spectrum plotted in Fig. 1 has been achieved. Henceforth, in order to obtain accurate results, the simulations corresponding to the tissue-equivalence tests have been performed including the obtained optimal incident spectrum.

The adapted MC code has been employed to the Fricke gel dosimeter tissue-equivalence study. The obtained on-axis depth dose distributions corresponding to Fricke gel dosimeter and homogeneous water phantoms are compared with ionization chamber measurements in Fig. 3. The obtained results evidence an on-axis tissue-equivalence

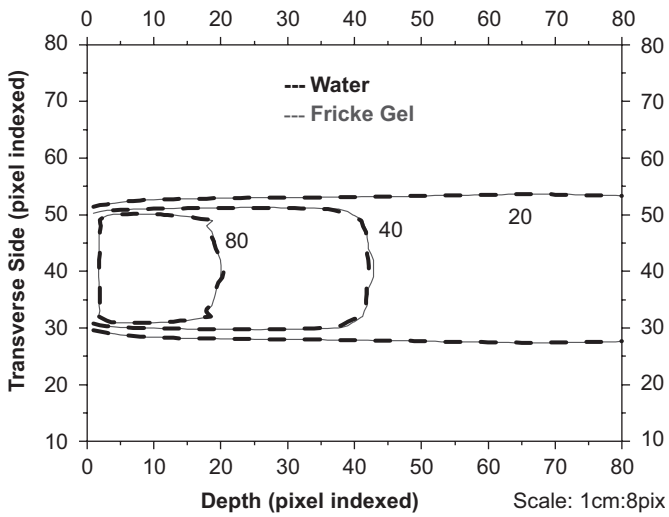

Fig. 4. In-phantom MC central plane isodose curves for water and Fricke gel.

between these materials. However, it is necessary to survey the entire in-phantom dose distributions for achieving a more reliable comparison. To this aim, central plane isodose curves have been determined for both materials, some of which are displayed in Fig. 4. Remarkable coincidences have been obtained for all isodose values.

4. Conclusion

The adapted code has shown to be a suitable tool for simulating in-phantom dose distribution in water and Fricke gel. The obtained results for the on-axis normalized depth dose distribution and the isodose curves may be considered as a first confirmation of the Fricke gel dosimeter tissue-equivalence.

Further developments will focus attention on variance reduction technique in order to save CPU time, as well as details of the accelerator components.

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