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Original article

Low dose out-of-field radiotherapy, part 2: Calculating the mean photon energy values for the out-of-field photon energy spectrum from scattered radiation using Monte Carlo methods

Radiothérapie hors-faisceau de faible dose, deuxième partie : calcul des valeurs énergétiques moyennes de photons pour le spectre d'énergie de photons hors-faisceau à partir de rayonnement diffusé en utilisant des méthodes de Monte-Carlo

A. Skrobala[a,b,*], S. Adamczyk[b], M. Kruszyna-Mochalska[a,b], M. Skórska[b], A. Konefał[c], W. Suchorska[d], K. Zaleska[d], A. Kowalik[b], W. Jackowiak[e], J. Malicki[a,b]

[a] *Electroradiology Department, University of Medical Sciences, Poznan, Poland*
[b] *Medical Physics Department, Greater Poland Cancer Centre, Poznan, Poland*
[c] *Department of Nuclear Physics and its Applications, Institute of Physics, Silesian University, Katowice, Poland*
[d] *Radiobiology Laboratories, Medical Physics Department, Greater Poland Cancer Centre, Poznan, Poland*
[e] *Ist Radiotherapy Department, Greater Poland Cancer Centre, Poznan, Poland*

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ABSTRACT

Purpose. – During radiotherapy, leakage from the machine head and collimator expose patients to out-of-field irradiation doses, which may cause secondary cancers. To quantify the risks of secondary cancers due to out-of-field doses, it is first necessary to measure these doses. Since most dosimeters are energy-dependent, it is essential to first determine the type of photon energy spectrum in the out-of-field area. The aim of this study was to determine the mean photon energy values for the out-of-field photon energy spectrum for a 6 MV photon beam using the GEANT 4–Monte Carlo method.
Material and methods. – A specially-designed large water phantom was simulated with a static field at gantry 0°. The source-to-surface distance was 92 cm for an open field size of 10 × 10 cm2. The photon energy spectra were calculated at five unique positions (at depths of 0.5, 1.6, 4, 6, 8, and 10 cm) along the central beam axis and at six different off-axis distances.
Results. – Monte Carlo simulations showed that mean radiation energy levels drop rapidly beyond the edge of the 6 MV photon beam field: at a distance of 10 cm, the mean energy level is close to 0.3 MeV versus 1.5 MeV at the central beam axis. In some cases, the energy level actually increased even as the distance from the field edge increased: at a depth of 1.6 cm and 15 cm off-axis, the mean energy level was 0.205 MeV versus 0.252 MeV at 20 cm off-axis.
Conclusion. – The out-of-field energy spectra and dose distribution data obtained in this study with Monte Carlo methods can be used to calibrate dosimeters to measure out-of-field radiation from 6 MV photons.

Mots clés :
Simulations
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RÉSUMÉ

Objectif de l'étude. – Au cours d'une radiothérapie, des doses d'irradiation reçues hors faisceau peuvent provoquer des cancers secondaires chez les patients. Il est donc nécessaire de mesurer ces doses de rayonnement en dehors des faisceaux, afin d'évaluer le risque de cancer secondaire. Étant donné que la

* Corresponding author. Department of Medical Physics, Greater Poland Cancer Centre, Garbary 15st., 61-866 Poznan, Poland.
E-mail address: agnieszka.skrobala@wco.pl (A. Skrobala).

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plupart des dosimètres dépendent de l'énergie, il est essentiel de déterminer d'abord le type de spectre d'énergie photonique dans la zone hors faisceau. L'objectif de cette étude était de déterminer les valeurs moyennes d'énergie photonique pour le spectre d'énergie photonique en dehors d'un faisceau de photons de 6 MV en utilisant la méthode GEANT 4–Monte Carlo.

Matériel et méthodes. – Un fantôme spécialement conçu pour l'eau a été simulé avec un faisceau fixe à 0°. La distance entre la source et la surface était de 92 cm pour un faisceau ouvert de $10 \times 10\,cm^2$. Les spectres d'énergie des photons ont été calculés à cinq positions uniques (à des profondeurs de 0,5, 1,6, 4, 6, 8 et 10 cm) le long de l'axe du faisceau et à six distances différentes en dehors de l'axe.

Résultats. – Les simulations de Monte-Carlo ont montré que les niveaux moyens d'énergie de rayonnement décroissaient rapidement au-delà du bord du faisceau de photons de 6 MV : à une distance de 10 cm, le niveau d'énergie moyen était proche de 0,3 MeV contre 1,5 MeV dans l'axe. Dans certains cas, le niveau d'énergie a même augmenté alors même que la distance du bord du faisceau augmentait : à une profondeur de 1,6 cm et à 15 cm de l'axe, le niveau d'énergie moyen était de 0,205 MeV contre 0,252 MeV à 20 cm de l'axe.

Conclusion. – Les spectres d'énergie hors faisceau et les données de la distribution de dose obtenue dans cette étude avec des méthodes Monte Carlo peuvent être utilisés pour étalonner les dosimètres afin de mesurer le rayonnement en dehors d'un faisceau de photons de 6 MV.

1. Introduction

Continuous technological improvements have made radiation therapy an increasingly accurate and effective treatment for cancer [1–3]. However, these more advanced technologies require longer beam-on time to achieve highly-conformal, precise doses, thus exposing patients to more irradiation due to increased leakage from the machine head and collimator [4–6]. As a consequence, the out-of-field dose may be greater than desirable [4]. This is an important drawback, as these out-of-field doses can increase the risk of late secondary cancers.

To quantify the risks of secondary cancers due to out-of-field doses, it is first necessary to measure these doses. However, accurate dose measurement requires energy-dependent dosimeters and the use of such dosimeters poses an important challenge: before the dosimeters can be calibrated properly–a necessary step before out-of-field doses can be reliably measured–the type of photon energy spectrum in the out-of-field area must first be determined. This is a highly complex undertaking because the energy spectrum outside the primary beam changes as a function of both distance and depth. To overcome this challenge, most researchers have opted to use Monte Carlo methods because they methods have already been proven effective and accurate in simulating in-field doses [5,7,8]. However, relatively few studies have used Monte Carlo methods to determine the out-of-field photon dose spectrum [9–12]. In any case, regardless of the calculation method used, data on out-of-field doses measured with well-calibrated dosimeters are scant [7].

To address this knowledge gap, we carried out the study presented here. The main aim was to determine the energy spectrum and out-of-field dose distribution from 6 MV photons at open beam using the GEANT 4 platform and Monte Carlo methods. Secondarily, we also sought to determine the mean photon energy values for the out-of-field 6 MV photon energy spectrum.

2. Material and methods

2.1. Study concept

The study presented here is the second of three interrelated papers that together form a three-part study whose primary aims were to determine (a) the out-of-field radiation doses at varying distances from the primary beam (Part I) [13], (b) the properties of the scattered radiation responsible for these out-of-field doses (Part II), and (c) the impact of these doses on biological response of in vitro cells (Part III) [14]. Each segment of this three-part study contains an experiment that uses a specific technology (dosimetry, calculation algorithms, or cell studies, respectively). Given the wide scope of this project, it was not feasible to present all the data in a single paper as it would exceed typical manuscript volume and would compromise the clarity. However, the three studies are highly interdependent given that the data obtained in the first study was needed to conduct the second study, and these data were needed, in turn, to conduct the third study. Therefore, we have opted to present each study separately, along with this brief description to explain the relationship between the studies. The current paper presents the energy and dose evaluation of out-of-field photon energy spectra using Monte Carlo calculations based on the GEANT 4 code [10,15,16]. The outcomes obtained in the present study are used to propose an energy-dependent co-efficient used to recalculate measured values based on the energy spectrum of the scattered irradiation and then to assess the radiobiological response of irradiated in vitro cells [13,14].

Photon spectra were calculated using the Monte Carlo model in the GEANT4 code [10,15,16]. The accelerator head was simulated based on information provided by the manufacturer (Varian Oncology Systems, CA, USA). The linear accelerator head was represented in model geometry by the target, flattening filter and primary collimators with the dimensions and materials as specified by the vendor. The shape, composition and density of each component were introduced into the model.

2.2. Validation of the Monte Carlo code using dose measurements at the central beam axis

The GEANT4 Monte Carlo simulation toolkit (version 4.7.1) with the low-energy extension module was applied to calculate the 6 MV X-ray beam energy spectra. This software is often used for such calculations because it has the ability to simulate all important physical processes that take place during X-ray beam emission [5,6,15], including the following:

- bremsstrahlung production, ionization, multiple scattering for electrons and positrons, and positron annihilation;