Low-energy photons in high-energy photon fields – Monte Carlo generated spectra and a new descriptive parameter

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Abstract

The varying low-energy contribution to the photon spectra at points within and around radiotherapy photon fields is associated with variations in the responses of non-water equivalent dosimeters and in the water-to-material dose conversion factors for tissues such as the red bone marrow. In addition, the presence of low-energy photons in the photon spectrum enhances the RBE in general and in particular for the induction of second malignancies. The present study discusses the general rules valid for the low-energy spectral component of radiotherapeutic photon beams at points within and in the periphery of the treatment field, taking as an example the Siemens Primus linear accelerator at 6 MV and 15 MV. The photon spectra at these points and their typical variations due to the target system, attenuation, single and multiple Compton scattering, are described by the Monte Carlo method, using the code BEAMnrc/EGSnrc. A survey of the role of low energy photons in the spectra within and around radiotherapy fields is presented.

In addition to the spectra, some data compression has proven useful to support the overview of the behaviour of the low-energy component. A characteristic indicator of the presence of low-energy photons is the dose fraction attributable to photons with energies not exceeding 200 keV, termed $P_D{}^{200keV}$. Its values are calculated for different depths and lateral positions within a water phantom. For a pencil beam of 6 or 15 MV primary photons in water, the radial distribution of $P_D{}^{200keV}$ is bellshaped, with a wide-ranging exponential tail of half value 6 to 7 cm. The $P_D{}^{200keV}$ value obtained on the central axis of a photon

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Zusammenfassung

Der unterschiedliche niederenergetische Anteil der Photonenspektren an Aufpunkten innerhalb und außerhalb von Bestrahlungsfeldern beeinflusst die Ansprechvermögen von nicht wasseräquivalenten Dosimetern sowie die Dosisumrechnungsfaktoren zwischen Wasser und Geweben wie dem roten Knochenmark. Auch eine Erhöhung der RBW, besonders für die Induktion von Zweitkarzinomen, ist auf niederenergetische Photonen zurückzuführen. Diese Arbeit beschäftigt sich mit den Gesetzmäßigkeiten der niederenergetischen Komponente der Spektren von Photonenstrahlungen an Punkten innerhalb und außerhalb des Bestrahlungsfeldes am Beispiel eines Siemens-Primus-Linearbeschleunigers bei 6 MV und 15 MV. Mithilfe des BEAMnrc/EGSnrc Monte-Carlo-Programms werden die Photonenspektren und deren Änderungen durch das Target-System, durch Schwächung sowie durch einfache und mehrfache Comptonstreuung studiert. Die Rolle der niederenergetischen Photonen in Spektren innerhalb oder außerhalb des Feldes wird untersucht.

Zusätzlich zu den Spektren erweist sich eine Datenkompression als nützlich, um die Gesetzmäßigkeiten der niederenergetischen Komponente zu beschreiben. Ein typischer Indikator für niederenergetische Photonen ist der

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field shows an approximately proportional increase with field size. Out-of-field $P_D{}^{200keV}$ values are up to an order of magnitude higher than on the central axis for the same irradiation depth. The 2D pattern of $P_D{}^{200keV}$ for a radiotherapy field visualizes the regions, e.g. at the field margin, where changes of detector responses and dose conversion factors, as well as increases of the RBE have to be anticipated. Parameter $P_D{}^{200keV}$ can also be used as a guidance supporting the selection of a calibration geometry suitable for radiation dosimeters to be used in small radiation fields.

Keywords: Photon spectra, Monte Carlo, low-energy photons, detector responses, RBE

Parameter $P_D{}^{200keV}$, der prozentuale Dosisbeitrag von Photonen mit Energien unter 200 keV. Dieser Parameter wurde für unterschiedliche Tiefen und laterale Positionen in einem Wasserphantom berechnet. Für einen Nadelstrahl bei 6 oder 15 MV ist das radiale Profil von $P_D{}^{200keV}$ glockenförmig, mit einem weiten Ausläufer mit Halbwertsradius 6 bis 7 cm. Auf der Achse eines Photonenfeldes nimmt $P_D{}^{200keV}$ annähernd linear mit dem Feldradius zu. Die Werte von $P_D{}^{200keV}$ außerhalb des Feldes sind um eine Größenordnung höher als innerhalb des Feldes. In zweidimensionalen Darstellungen von $P_D{}^{200keV}$ erkennt man Bereiche, z.B. am Feldrand, wo Änderungen der Ansprechvermögen von Detektoren und der Dosisumrechnungsfaktoren sowie erhöhte RBW-Werte zu erwarten sind. $P_D{}^{200keV}$ ist auch ein nützliches Kriterium für die Auswahl der Kalibrierbedingungen für die Dosimetrie von schmalen Photonenfeldern.

Schlüsselwörter: Photonenspektren, Monte Carlo, niederenergetische Photonen, Detektor Ansprechvermögen, RBW

1 Introduction

Under the aspects of radiotherapy physics, experimental determinations of beam quality parameter Q [1,14] and of incident photon beam spectra [30,38] have been complemented by Monte-Carlo calculated photon spectra for points within the phantom or patient at varying depths and off-axis distances [6,10,15,16,32,33]. Shifts of the photon spectra towards lower energies are resulting from Compton interaction processes within the treatment head and within absorbers in the beam path. The corresponding changes of the energy-dependent responses of non-water-equivalent dosimetric detectors such as ionization chambers [6,10,15], radiographic films [31–33,40,44] and silicon diodes [7,9,11,37] are likely to occur at points within and around the field borders. Edwards and Mountford [9] have shown that diode detectors may overestimate the out-of-field dose by as much as two thirds, whereas thermoluminescence dosimeters (TLD) provide a more invariant response. Even for the in-field-region, Palm *et al* [32,33] observed depth-dependent variations of the film response up to 30% in water phantoms, and Eklund and Ahnesjö [11] demonstrated the influence of the field size upon the depth dependent response of silicon diodes. Detector responses at low photon energies have been systematically studied with synchrotron radiation [27]. The second reason for the interest in the low-energy spectral region is the energy dependence of the water-to-tissue dose conversion factors, e.g. for the red bone marrow, well known from dose calculations for voxel phantoms [26,52].

Thirdly, there are variations of the relative biological effectiveness (RBE) of photon radiations dependent upon the dose contribution by low-energy photons [13,16–18,21,35,39,43]. This phenomenon results from the enhanced linear density of the physical interactions along the tracks of low-energy secondary electrons and Auger electrons [13,16,17]. The low-energy components of the photon spectra inside absorbers such as the human body have gained increasing interest since, in the development of intensity modulated radiotherapy and radiosurgery, it has become necessary to pay attention to the peripheral dose levels around radiotherapy fields [4,28,42,48–51]. A large fraction of the second malignancies attributable to radiotherapeutic treatment [47] occurred near the field border or in the periphery of the treatment field [5,8]. Recently, Kirkby *et al* [25] used Monte Carlo calculated secondary electron spectra to show that the radiation quality in the periphery of a typical radiotherapy field is differing greatly from that within the field limits, due to the spectral shifts towards lower energies via the Compton effect. This may lead to an increase of the potential radiobiological damage in out-of-field regions. In a radiobiological study, Syme *et al* [45] showed that the shift in Monte Carlo computed secondary electron spectra towards low energies in the penumbra region is accompanied by a significant increase in radiobiological damage per unit dose when compared to the region within the open beam.

In consideration of the impact which the shifts in the photon spectrum of a radiation field towards lower energies may have on dosimetry and on relative biological effectiveness, we have undertaken a study focusing upon the general regularities of