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A Model Considering Secondary Particles Contribution in RBE of Primary Bremsstrahlung

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Abstract Passage of ionizing radiation through biological matter, for example during beam therapy, is followed by the production of secondary particles, which change the relative biological effectiveness (RBE) of the beam. The absorbed dose is represented by the sum of two components: the dose delivered by photons and secondary e^+ and e^- and the dose from heavy charged particles. Therefore, in order to assess the overall biological effectiveness of the beam, it is necessary to consider RBE of all kinds of induced radiation. In this work a model theoretically describing the biological effectiveness of various types of ionizing radiation depending on their energies is proposed. A method for estimating the relative biological effectiveness taking into account the contribution of photonuclear reactions with the energy ranging from a threshold of photonuclear reactions on light elements (Z<10) to 50MeV is developed. The results obtained are compared to the experimental and calculated data of the other authors.

Keywords: *bremsstrahlung, relative biological effectiveness, photonuclear particles*

1. Introduction

Passage of the ionizing radiation through biological matter is accompanied by the production of secondary particles (electrons, protons, neutrons, photons, nuclear recoil etc.) which are produced as a result of non-elastic scattering and nuclear reactions in the patient's body. Mechanisms of secondary particles formation vary for different types of ionizing radiation (photons, electrons, neutrons, π-mesons, protons and ions) and depend on their energy. Secondary particles influence the form of dose distribution and change the relative biological effectiveness (RBE) of ionizing radiation [1].

Modern radiation therapy machines generate high-energy radiotherapy beams using bremsstrahlung. High-energy photons create high linear-energy transfer (LET) photonuclear particles in the irradiated tissue. The role of photonuclear reactions in the majority of operating beam therapy planning systems is not considered because their contribution to the whole dose transferred to biological matter is very small. However, at bremsstrahlung energy greater than 10MeV the influence of photonuclear reactions products appears appreciable, and the RBE values of secondary particles (n, p, 2H, 3He, 4He) which are produced in photonuclear reactions, are greater than unity.

We will limit our study to the consideration of photonuclear reactions on ^{12}C, ^{16}O, ^{14}N only, since the share of the other elements in the biological matter (^{18}O, ^{13}C, ^{15}N, ^{23}Na, Cl^{nat}, ^{31}P, ^{32}S, ^{39}K etc) is negligibly small. On these elements the following photonuclear reactions may occur (γ, n), (γ, 2n), (γ, np), (γ, p), (γ, α), (γ, He^3), but the basic contribution is represented by photoneutrons (γ, xn) and photoprotons (γ, xp) reactions - more than 96% of integrated cross-section of nuclear photoabsorption. Their contribution to the full photoabsorption cross-section (taking into account the photoeffect, Compton and pair production) does not exceed 2% for bremsstrahlung energy lower than 50MeV, and in the area of Giant Dipole Resonance (GDR) for quasi-monochromatic photons reaches ~5% [2].

The purpose of the present work is to estimate the RBE of photonuclear reactions products and their contribution to the RBE of bremsstrahlung with energy ranging from 10 to 30MeV.

2. Method of RBE Estimation

In the present work the model of a direct transmission of photons energy to reaction products is used. The energy of particle E_N which has been produced as a result of photonuclear reaction, is described by the following expression:

$$E_N = \left(E_\gamma - E_t - E_l\right)\left(A_r - A_n\right)/A_r \qquad (1)$$

where E_γ – photons energy, E_t – threshold energy for the photonuclear reaction, E_l - excitation energy, A_r – atomic mass of recoil nuclear and A_n–atomic mass of the emitted particle. The factor $\left(A_r - A_n\right)/A_r$ corrects kinetic energy distribution between nucleon and recoil nuclear. The energy spectrum $\Phi_{k,Z}\left(E_k\right)$ of k particle, produced by element Z, can be described by

$$\begin{aligned}\Phi_{k,Z}\left(E_k\right)dE_k \\ = \left(A_r - A_n\right)/A_r \sum_k \sum_j N_Z c_k \sigma_{k,j}\left(E_\gamma\right)\Phi_\gamma\left(E_\gamma\right)dE_\gamma\end{aligned} \qquad (2)$$

where $\Phi_{\gamma}\left(E_{\gamma}\right)$ -photon fluence differential in energy, $\sigma_{k,j}\left(E_{\gamma}\right)$ -cross-section of photonuclear reactions with k particles emission and excitation level j, c_k – number of emission particles, N_z –quantity of nuclei of Z-elements.

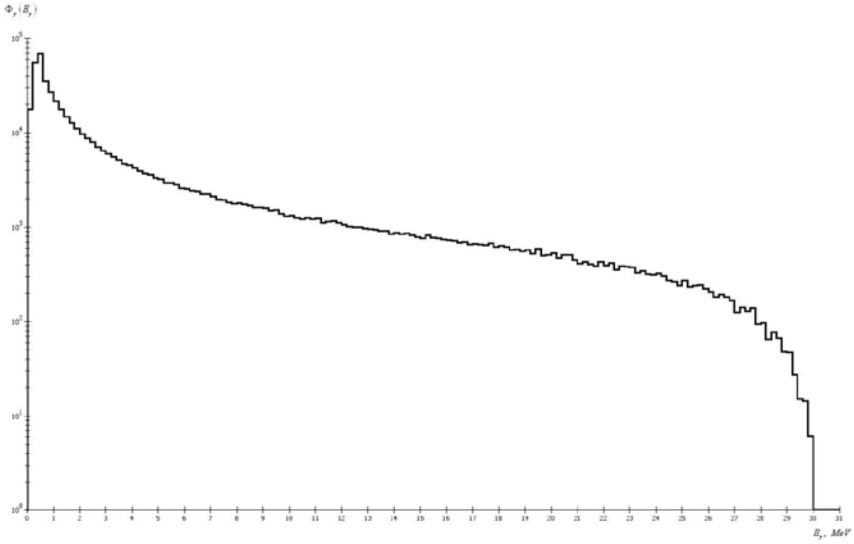

Figure 1. The photon fluence. Simulation: GEANT4, scanned beam of end point 30MeV

Bremsstrahlumg spectra were obtained by Monte Carlo simulations by means of the Monte Carlo code GEANT4. The standard example “Medical Linac advanced” was used. Figure 1 shows the Monte Carlo simulation bremsstrahlung spectrum for $E_{\gamma}^{\max} = 30$ MeV.

Further, we assume that the final nuclei are not excited, therefore the summation in the formula (2) is carried out on one index k:

$$\Phi_{k,Z}\left(E_k\right)dE_k = \left(A_r - A_n\right)/A_r \sum_k N_Z c_k \sigma_k\left(E_{\gamma}\right)\Phi_{\gamma}\left(E_{\gamma}\right)dE_{\gamma} \qquad (3)$$

The full energy spectrum is the summation over all elements present in the biological matter taking into account their weights α_Z:

$$\Phi_k\left(E_k\right)dE_k = \sum_Z \alpha_Z \Phi_{k,Z}\left(E_k\right)dE_k \qquad (4)$$

In the present work, experimental cross-section were taken from database CDFE [3] while, quality factor [1] energy dependence of photoparticles k types are taken from recommendation [4]. The average RBE value for k particles produced via photonuclear reaction may be described by the following expression:

$$\left\langle R_k \right\rangle = \int_0^{E_k^{\max}} \Phi_k\left(E_k\right)R_k\left(E_k\right)dE_k \Bigg/ \int_0^{E_k^{\max}} \Phi_k\left(E_k\right)dE_k \qquad (5)$$

where $R_k\left(E_k\right)$ - energy dependence of RBE value for k particle. The contribution of the channel with products of type k particles in full photoabsorption cross-section is represented as follows:

$$\delta_k\left(E_{\lambda}^{\max}\right) = \int_0^{E_{\gamma}^{\max}} \Phi_{\gamma}\left(E_{\gamma}\right)\sigma_{(\gamma,xk)}\left(E_{\gamma}\right)dE_{\gamma} \Bigg/ \int_0^{E_{\gamma}^{\max}} \Phi_{\gamma}\left(E_{\gamma}\right)\sigma_{(\gamma,abs)}\left(E_{\gamma}\right)dE_{\gamma} \qquad (6)$$

In (6) we assume, that $\sigma_{(\gamma,abs)} = \sigma_{(\gamma,n)} + \sigma_{(\gamma,p)} + \sigma_{(\gamma,p+n)} + \sigma_{(\gamma,\alpha)}$. The average RBE value of all particles of type k produced as a result of photonuclear reactions is calculated using the following formula:

$$\left\langle R\left(E_{\gamma}^{\max}\right)\right\rangle = \sum_k \delta_k\left(E_{\gamma}^{\max}\right)\left\langle R_k\left(E_{\gamma}^{\max}\right)\right\rangle \qquad (7)$$

The contribution of photoabsorption to full cross-section of photon interaction with matter can be calculated as:

$$m\left(E_{\gamma}^{\max}\right) = \int_0^{E_{\gamma}^{\max}} \Phi_k\left(E_{\gamma}\right)\sigma_{(\gamma,abs)}\left(E_{\gamma}\right)dE_{\gamma} \Bigg/ \int_0^{E_{\gamma}^{\max}} \Phi_k\left(E_{\gamma}\right)\sigma_{(\gamma,tot)}\left(E_{\gamma}\right)dE_{\gamma} \qquad (8)$$

The absorbed dose is represented by the sum of two components: the dose delivered by photons and secondary e^+ and e^- and the dose from heavy charged particles. The absorbed dose is represented by the sum of two components: the dose delivered by primary and secondary photons and secondary electrons and positrons and the dose from photonuclear particles (protons, neutrons, nucleus recoil etc.) Full RBE value for bremsstrahlung $R\left(E_{\gamma}^{\max}\right)$ is defined as sum of RBE of photons and electrons $R_{\gamma}=R_e=1$ and particles formed as a result of photonuclear reactions, the contribution of each part is accordingly $1-m\left(E_{\gamma}^{\max}\right)$ and $m\left(E_{\gamma}^{\max}\right)$. Then:

$$R\left(E_{\gamma}^{\max}\right) = \left[1-m\left(E_{\gamma}^{\max}\right)\right] + m\left(E_{\gamma}^{\max}\right)\left\langle R\left(E_{\gamma}^{\max}\right)\right\rangle \qquad (9)$$

The obtained dependence is in good agreement with data of work [5,6]. In Figure 2 the energy dependence of

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[1] In this work as average value of RBE the value of the quality factor of corresponding radiation will be used

average RBE value of all particles of type k $\left\langle R\left(E_\gamma^{\max}\right)\right\rangle$ produced as a result of photonuclear reactions (proton, neutron and nuclear recoil) is presented. The curve describing the contribution of photonuclear reactions has the form of the giant dipole resonance cross section. At energy of bremsstrahlung end point 30MeV contribution of photonuclear reaction it makes 1.8%. The latter value is in agreement with experimental data [7,8].

Our model and the analysis of available experimental data [9,10,11,12,13] show that the RBE value of photons depends on their energy. Energy reduction of photons under 50keV as well as its increase to more than 10MeV leads to change in the RBE value. Whereas in the first case the most probable reason is the increase in cross-section of photons interaction with the matter (in particular photoeffect and Auger-electron), in the second case it is the contribution of photonuclear products.

According to works [9,10,11,12,13], from which the experimental measurement or modelling calculation were taken, the average RBE value obtained in the present study (on the basis of statistical criteria used) for bremsstrahlung with the end-point energy 50MeV gives a RBE value of 1.08±0.06. This value is in a good agreement with the data of work [14] where the result of modelling calculation gave 1.02±0.01. Within the limits of the technique described above the total RBE $R\left(E_\gamma^{\max}\right)$ dependence on bremsstrahlung energy from threshold of photonuclear reaction on light nuclei up to 50MeV is presented on Figure 3.

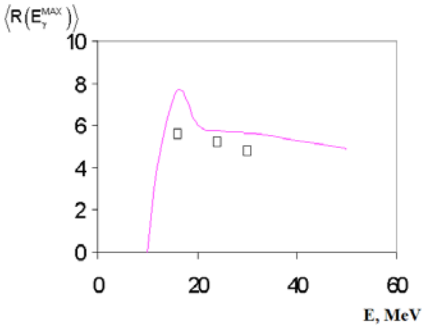

Figure 2. Average value of RBE of all photoparticles formed as a result of bremsstrahlung passage through biological matter. Squares note the values calculated according [10]

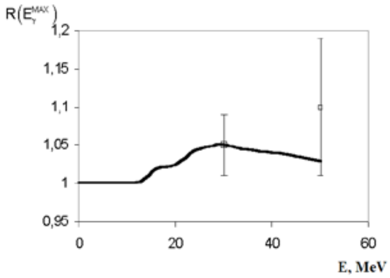

Figure 3. Energy dependence of bremsstrahlung RBE value. Squares note the values calculated according [6]

3. Conclusions

Energy dependence of the average RBE of photo-products was calculated. A Maximum value ~7.5 is reached at energy 20MeV, approximately. The contribution products of photonuclear reactions to the whole absorbed dose has a complicated form with a maximum approximately at 20MeV, similar to the cross-section of photonuclear reaction on light elements in the area of GDR. Its value varies from 4% to 1% in the bremsstrahlung energy 20-30MeV. For the first time energy dependence of bremsstrahlung RBE in the range 20-30MeV was obtained. The calculated dependence is in a good agreement with data of the other works and in the discussed energy region gives 1.02-1.05.

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