ISSN 0027-1349, Moscow University Physics Bulletin, 2015, Vol. 70, No. 5, pp. 416–422. © Allerton Press, Inc., 2015.
Original Russian Text © A.V. Belousov, A.A. Kalachev, G.A. Krusanov, A.P. Chernyaev, 2015, published in Vestnik Moskovskogo Universiteta. Fizika, 2015, No. 5, pp. 86–93.

BIOPHYSICS AND MEDICAL PHYSICS

Estimation of Absorbed and Equivalent Doses of Photon Radiation in Thin Layers

A. V. Belousov, A. A. Kalachev, G. A. Krusanov, and A. P. Chernyaev
Department of Physics, Moscow State University, Moscow, 119991 Russia
e-mail: belousovav@physics.msu.ru, krusanov@physics.msu.ru

Received March 27, 2015; in final form, May 5, 2015

Abstract—This study is devoted to the investigation of the interaction of photon radiation with an energy of up to 30 MeV with thin layers, which simulates the conditions of radiobiological experiments on determination of the relative biological efficiency (RBE). The values of the absorbed dose of all of the produced particles in irradiated layers were determined via computer simulation using Geant4 and the equivalent dose was calculated. Computer experiments were performed in media of different elemental compositions: water and model biological tissue. We demonstrate that starting from the threshold of photonuclear reactions on light elements the equivalent dose of monochromatic radiation differs from the absorbed dose by a factor of 3–15 depending on the layer thickness and composition. Similar calculations for bremsstrahlung spectra also demonstrate a noticeable difference between the absorbed and equivalent doses in a layer.

Keywords: Geant4, thin layers, photonuclear reactions, bremsstrahlung.

DOI: 10.3103/S0027134915050033

INTRODUCTION

The effect of ionizing radiations is determined by the fraction of energy that is absorbed by a substance, i.e., the absorbed radiation dose; this is the dE/dm ratio, where dE is the energy of the ionizing radiation that is absorbed by the substance in the volume dV at the observation point and dm is the mass of the considered volume. The effects (including the biological effects) of the ionizing radiation for the same absorbed dose depend on many factors, such as its spatial distribution in an irradiated volume and its time distribution. The spatial distribution is characterized by the linear energy transfer (LET), i.e., the energy per unit path length transmitted by a particle to the substance, which is closely connected with the linear ionization density. All radiation types can be conditionally divided into two groups: densely ionizing (protons, alpha particles, ions, recoil nuclei and other heavy charged particles, and neutrons) and sparsely ionizing (photons, electrons, and positrons) radiation.

Radiation types with different LET have qualitatively and quantitatively different effects even for the same absorbed dose. For example, the type of radiation defects in a crystalline lattice substantially depends on the masses of the particles that cause these defects; the form of the survival curve also strongly depends on the particle type. If biological objects are considered, the idea of an equivalent dose is introduced to account for differences in the biological actions of radiation types; the equivalent dose is the absorbed dose multiplied by a weighting coefficient (this coefficient is the radiation weighting factor (RWF); previously, the radiation quality coefficient and the quality coefficient were used) depending on the radiation type. It is assumed that the biological effect of different types of radiation (and radiation of one type but different energies) is the same if the values of the equivalent doses of these radiations are the same. The weighting coefficients are estimated from the relative biological efficiency (RBE) that is determined in radiobiological experiments.

The interaction of high-energy photons with matter is mainly accompanied by electron production in inelastic Compton scattering and electron–positron pair production. In the case of light elements ($Z \leqslant 10$), from which biological tissues are mainly formed, the contribution of the photo effect can be neglected if the photon energy is higher than 0.1 MeV. At higher energies photonuclear reactions become possible; the threshold of these reactions is in the ~7 MeV range (see the table). It is mainly the following reactions that take place in biological tissue: (γ, n), (γ, p), (γ, np), and (γ, α); these reactions yield high-LET, and therefore, high-RWF particles (alpha particles, recoil nuclei, etc.). Thus, an object that is irradiated by photons is in a field of mixed radiation, primary photon radiation and secondary radiation, namely, electrons, positrons, products of photonuclear reactions, etc.

The cross section of photonuclear reactions in biological tissue is rather small and makes up not more than 5% of the total cross section of photon–matter

The parameters of photonuclear reactions on the main elements that form biological tissue [13]

Element	Reaction	Reaction threshold, MeV	Maximum energy, MeV	Maximum cross section, mbarn
O-16	(γ, p)	12	24	3.0
	(γ, n)	16	17	1.0
	(γ, α)	7	22	0.2
	(γ, np)	22	28	1.0
N-14	(γ, p)	7	17	5.1
	(γ, n)	11	18	3.3
	(γ, α)	12	17	0.8
	(γ, np)	12	23	12.1
C-12	(γ, p)	16	23	3.8
	(γ, n)	19	23	2.5
	(γ, α)	7	23	0.7
	(γ, np)	27	36	0.4

interactions. In the case of electron equilibrium, i.e., when sufficiently extended objects are irradiated, the contribution of products of photonuclear reactions to the absorbed dose is small. In the absence of electron equilibrium (in thin and surface layers) the situation is different. Because of the small mean free path of heavy charged particles their contribution to the absorbed, and therefore, to the equivalent dose (due to large RWF values) becomes much larger than the contribution of electrons and positrons, whose mean free path is long. Light particles carry part of the energy beyond the considered volume; this energy is not compensated by the energy that is brought to this volume from the ambient medium.

For example, for a photon energy of ~23 MeV, which corresponds to the maximum cross section of the ${}^{16}_{8}O(\gamma, p){}^{15}_{7}N$ reaction, a proton with an energy of ~8 MeV is produced; the mean free path of this proton in soft tissues is ~0.3 mm, and the energy losses within a 1-mm thick layer are not less than ~6 MeV. Electrons are produced with an average energy of ~10 MeV; the stopping power of such electrons is ~2 MeV/cm; in a 1 mm thick layer they deposit ~100 keV. For a proton production probability of about 1% their contribution to the absorbed dose is $6 \times 0.01/(6 \times 0.01 + 0.99 \times 0.1) \approx 40\%$. Thus, accumulating the absorbed and equivalent doses in thin and surface layers (in the build-up region) can differ substantially from thick absorbers. Without accounting for photonuclear reactions at high photon energies the attenuation coefficient for light elements weakly depends on the atomic number, while the absorbed dose that is determined by photons, electrons, and positrons weakly depends on the particular elemental composition. The cross section of photonuclear reactions, in contrast, strongly depends on the photon energy and elemental composition of the material. The results of the calculation for water, which is a tissue—equivalent material and is often used as a model, can differ from the results for real biological tissues.

The contribution of the products of photonuclear reactions, mainly protons and neutrons, to the absorbed dose has been studied by many authors. In [1], a contribution of photonuclear reaction products equal to 2% of the total absorbed dose was obtained for a 50 MeV scanning bremsstrahlung beam using microdosimetry. In [2], the contribution of secondary heavy particles to the absorbed and equivalent doses for a photon energy of 20 MeV was measured using Kodak LR115 and CR39 track detectors; the following values were obtained: 0.045 and 0.39%, respectively. For an energy of 50 MeV the contributions are 0.245 and 2.13%. In [3], the contribution to the absorbed dose of photonuclear reaction products was estimated as ~0.1% from the evaluation of the total irradiation of a patient by a 24 MeV bremsstrahlung beam. In [4], a contribution of 0.15 ± 0.08% of the maximum photon dose at a depth of 5.5 cm was obtained for soft tissues using a Monte Carlo simulation (MCNP4B [5]). In [6], the contribution of heavy particles to the absorbed dose was also estimated using the Monte Carlo method; the result was 0.3–0.42%, depending on the spectrum. Note that all of these authors performed calculations for extended objects and the condition of electron equilibrium.

The interest in this problem decreased somewhat in the last decade for two reasons: first, estimates that were obtained for extended objects indicate a small contribution (tenth fractions of a percent for the absorbed dose and about 1% for the equivalent dose) of photonuclear reaction products; second, the errors of these estimates are rather high. Nonetheless, it was demonstrated in [7, 8] that the contribution of these products to the absorbed dose in thin layers can be much higher. In this study, we investigate the contributions of reaction products to the absorbed dose, as well as the RWF, in detail; the calculations were performed with large statistics that correspond to an error of the order of ~1% and a finer step with respect to photon energies.

The objectives of the study were to simulate the process of the passage of monochromatic photon radiation through thin layers that model biological tissue, to calculate the energy dependence of the absorbed and equivalent doses in water and a model biological tissue that is irradiated by a monochromatic beam, to simulate photon radiation spectra that correspond to medical linear accelerators, and to estimate the absorbed and equivalent doses of photo bremsstrahlung with different maximum energy. The topical character of this study is determined by the fact that sources of photon radiation, in particular accelerators, are widespread for beam therapy and the values of weighting coefficients and ideas on the radiation safety of the population are regularly revised. The results are useful for estimating the degree of the radiation hazard of sources of photon radiation and reducing the radiation load on the cutaneous covering of patients in convectional beam therapy. Moreover, the results of the estimation of the contributions of different photonuclear reaction products to the absorbed dose are useful in industries that are connected with radiation modification of the properties of crystals, polymer films, etc.

1. THE METHOD OF THE INVESTIGATION

The Geant4free software package [9], version 9.6, was used for the investigation. This software is a tool for simulating the passage of particles of all types through matter using the Monte Carlo method. Geant4 is written in C++; its libraries present wide possibilities for the user to implement each part of the simulation: the geometry, the elemental composition of the medium, particle properties and beam parameters, models of physical processes, data storage and output at different stages, both for the entire medium and separate regions of interest, as well as visualization of a numerical experiment using other free software tools. Because of its flexibility Geant4 is used for solving a wide variety of problems in nuclear and accelerator physics, as well as medicine.

In this study the calculations are based on the QGSP_BIC built-in physical model which, in addition to standard electromagnetic interactions, describes hadron interactions, i.e., the interactions of protons, neutrons, heavy nuclei, etc., including secondary particles. This model is optimal for medical problems and is recommended for application in this field [10]. The following interactions are taken into account for photons: elastic scattering, Compton scattering, electron–positron pair production in the field of the nucleus and atomic electrons, and photonuclear reactions. Ionization and bremsstrahlung losses, elastic collisions, and multiple scattering are taken into account for electrons and positrons. For positrons, annihilation, including that “in flight,” is also taken into account. For heavy charged particles the same processes as for electrons and inelastic scattering in nuclear reactions are taken into account.

In order to reduce the computer time, the threshold energy was chosen to be equal to 1 keV for photons, electrons, and positrons, and 500 keV for heavy charged particles in this computer experiment; the threshold energy for neutrons corresponds to the thermalization energy. Irradiation of a thin film (water or an average biological tissue, viz., $C_5H_{40}O_{18}N$) that hangs in the air using a broad photon beam was simulated; the cross section of the parallel monochromatic photon beam is larger than the cross section of the irradiated object to provide electron equilibrium in the transverse direction. The radiation source is situated at a distance of 100 cm from the irradiated plate (*SSD* = 100 cm corresponds to the common clinical practice [11]). The object is assumed to be a Sensitive Detector, the number of interactions of particles of all types and the energy that is released in the layer in each of the processes are determined in it. These data are used to estimate the absorbed and equivalent doses with account for all of the induced radiation types, including those that result from photonuclear reactions and the recoil nuclei in the layer.

The plate surface area (S) and its elemental composition did not change within one computer experiment, while the thickness, l, of the irradiated layer varied. The mass of the irradiated object $M = \rho S l$, where ρ is the material density and the plate surface area was chosen in such a way that $\rho S = 1$ g/cm; then the absorbed radiation dose is $D = \sum D_i$, where E_{dep} is the energy that is deposited in the entire layer. Since the object is in a field of mixed radiation, all of the radiation types should be taken into account for calculating the absorbed dose: $D = \sum D_i$, where D_i is the dose that is absorbed as a result of the interaction of a particle of the ith type. The equivalent dose is calculated as $H = \sum H_i = \sum D_i w_i$; the following values of w_i recommended by ICRP [12] are used: 1 for electrons and photons, 2 for protons, and 20 for alpha particles and heavy nuclei. If we denote the number of photons in the spectrum whose energy is in the interval from E_γ to $E_\gamma + dE_\gamma$, the absorbed and equivalent doses can be found as

$$D = \int_0^{E_\gamma^{\max}} \frac{dN_\gamma}{dE_\gamma} D(E_\gamma) dE_\gamma, \quad (1)$$

$$H = \int_0^{E_\gamma^{\max}} \frac{dN_\gamma}{dE_\gamma} H(E_\gamma) dE_\gamma, \quad (2)$$

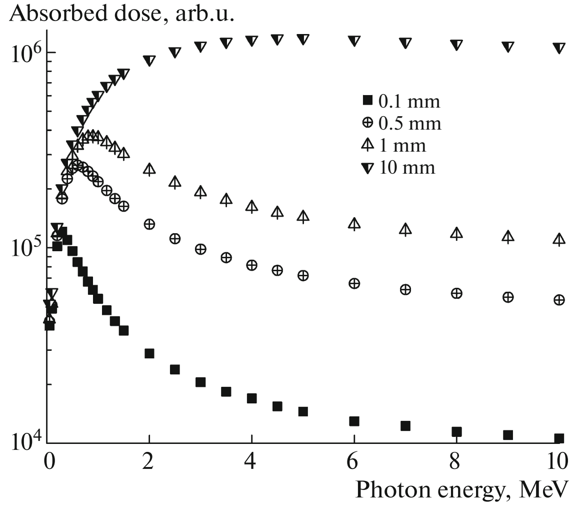

Fig. 1. The absorbed dose as a function of the primary photon energy below 10 MeV for water layers of different thickness.

where $D(E_\gamma)$ and $H(E_\gamma)$ are the absorbed and equivalent doses for the case of irradiation by a monochromatic photon radiation with the energy E_γ, and $E_\gamma^{\max}$ is the maximum photon energy in the spectrum. Integrals were replaced by sums in the calculation. For quantitative description of the difference of the equivalent and absorbed doses for the case of irradiation by bremsstrahlung photons we used δ, the quantity that describes the deviation of the equivalent dose, H, that is calculated using formula (2) from the absorbed dose, D, that is calculated using formula (1),

$$\delta = \frac{H - D}{D}. \tag{3}$$

2. RESULTS AND DISCUSSION

For a photon energy of up to 10 MeV the absorbed (Fig. 1) and equivalent doses in water weakly differ for any thickness of the irradiated layer from 0.1 to 10 mm. However, the character of the variation of the absorbed dose with increasing energy of monochromatic photon radiation depends on the layer thickness. For small thickness (less than 5 mm) the absorbed dose increases sharply with increasing photon energy; pronounced maxima occur whose positions depend on the layer thickness. For a minimal layer thickness of 0.1 mm the maximum corresponds to an energy of ~0.5 MeV, while for 0.5 and 1 mm layers it corresponds to ~1 MeV. For photon energies

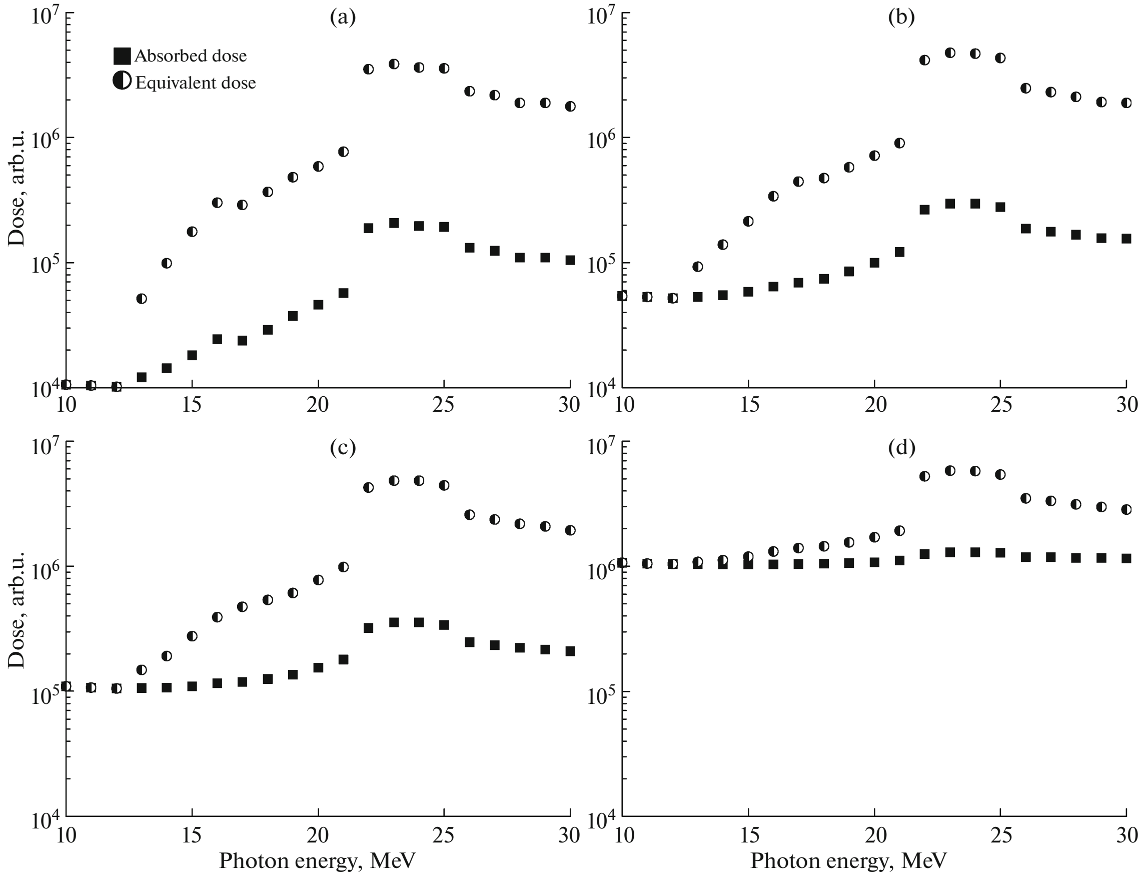

Fig. 2. The absorbed and equivalent doses as functions of the primary photon energy above 10 MeV for water layers of different thickness.

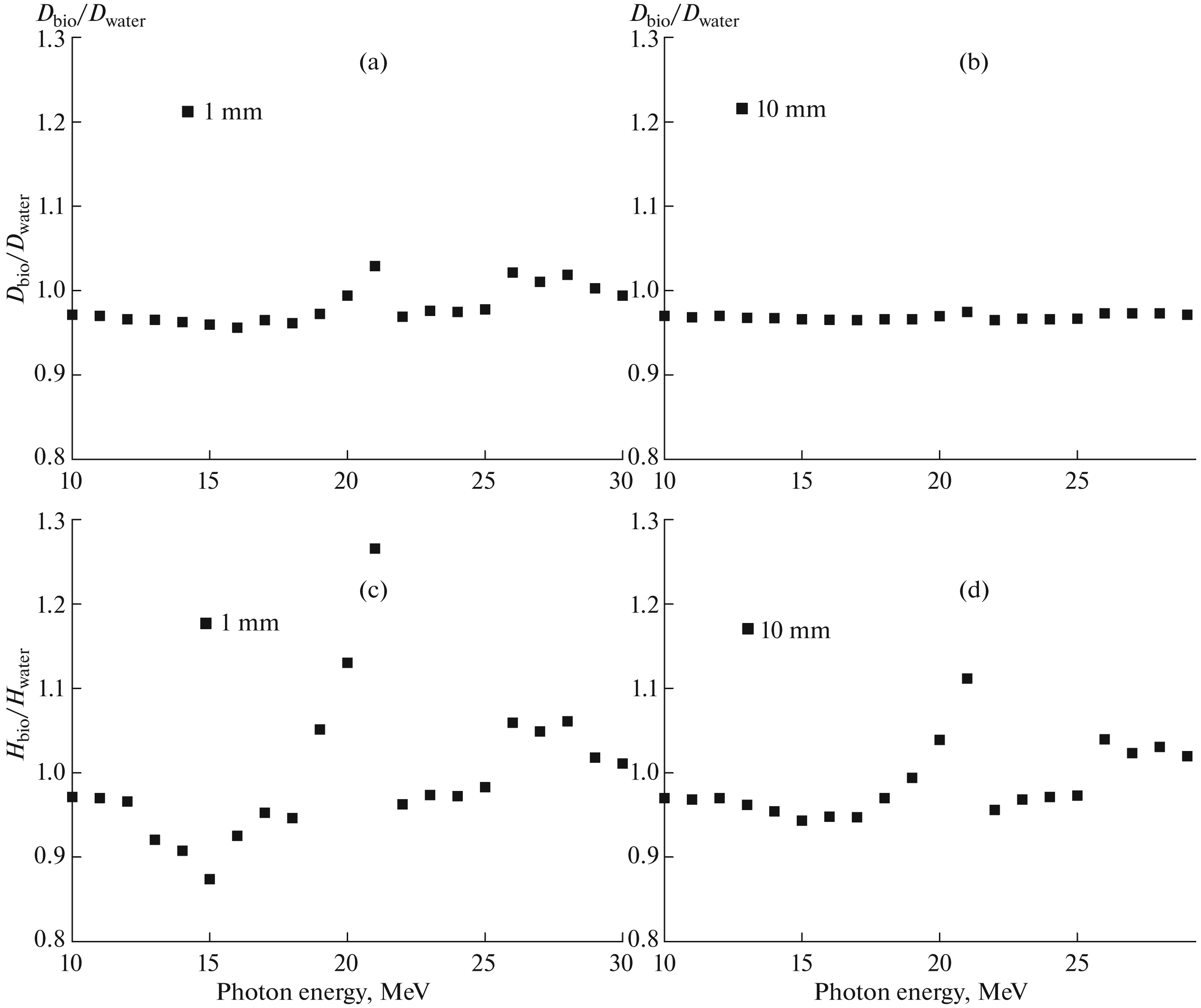

Fig. 3. The ratios of the absorbed and equivalent doses in biological tissue and water as functions of the primary photon energy above 10 MeV for layers of different thickness.

above 2 MeV the curves decrease due to the change of the linear photon-energy absorption coefficient in this interval. The dose in biological tissue is somewhat lower than the dose in water, while for photon energies above 200 keV it differs by less than 2%. In spite of the fact that the threshold energy of photonuclear reactions on oxygen is near ~7 MeV, the cross section of photonuclear reactions becomes sufficiently large such that products noticeably influence the absorbed and equivalent doses in water (Fig. 2) only beginning at ~12 MeV. The maximum dose is that for photon energies of 22–25 MeV, which corresponds to the maximum cross sections of photonuclear reactions. For a 0.1-mm layer the maximum is observed for a photon energy of 16 MeV; this maximum is most probably connected with the growing contribution of recoil nuclei due to the opening of a new channel of photonuclear reactions when the (γ, n) reaction threshold for oxygen is overcome. The sharp boundaries at 22 and 25 MeV (Fig. 2) are determined by the resonance character of photonuclear cross sections; it is necessary to increase the statistics and reduce the energy step for a detailed examination. For biological tissue, the dependence is similar.

Figure 3 shows the ratio of the absorbed and equivalent doses in biological tissue and water. The most noticeable difference for all of the plots is observed at a photon energy of 21 MeV; for a layer thickness of 1 mm the absorbed doses differ by ~5% and the equivalent doses differ by ~25%. A less-pronounced maximum of the dose ratio is observed at ~26 MeV; the difference of the absorbed doses is 2% for a thickness of 1 mm, while for equivalent doses it is ~5%. In other words, the difference is most pronounced in the energy range of the cross-section maxima for photonuclear reactions on carbon.

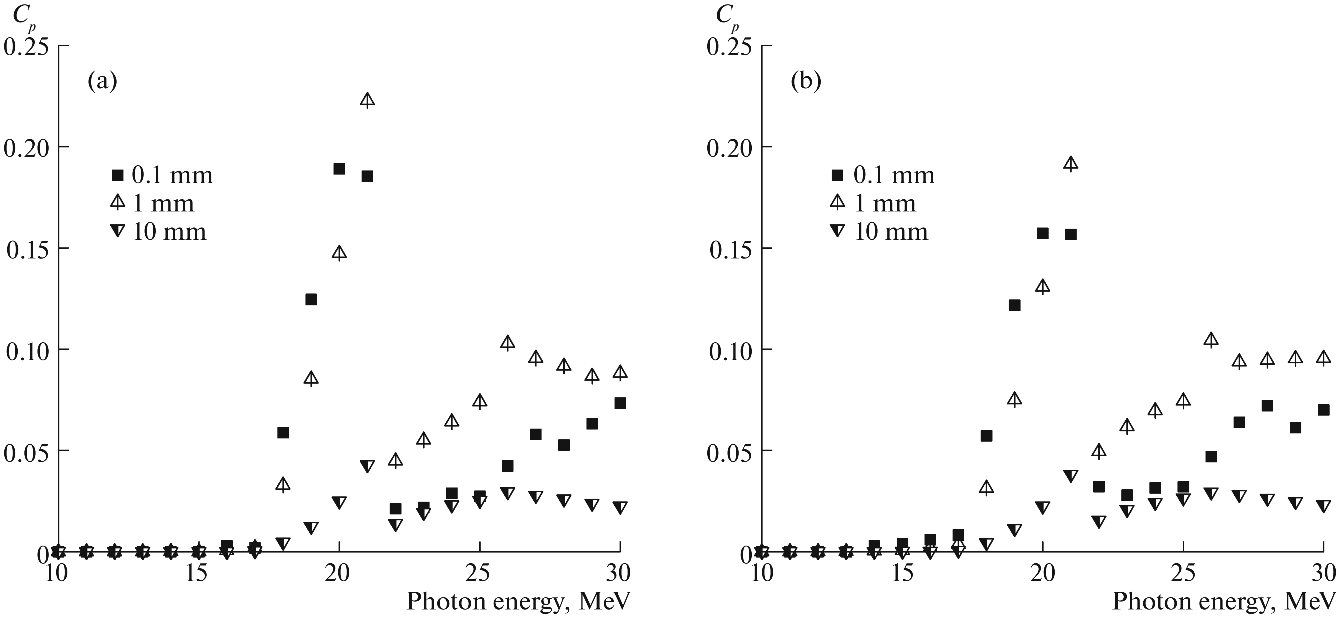

Fig. 4. The contribution of p, d, t to the absorbed dose as a function of the primary photon energy above 10 MeV for (a) water and (b) biological tissue of different thickness.

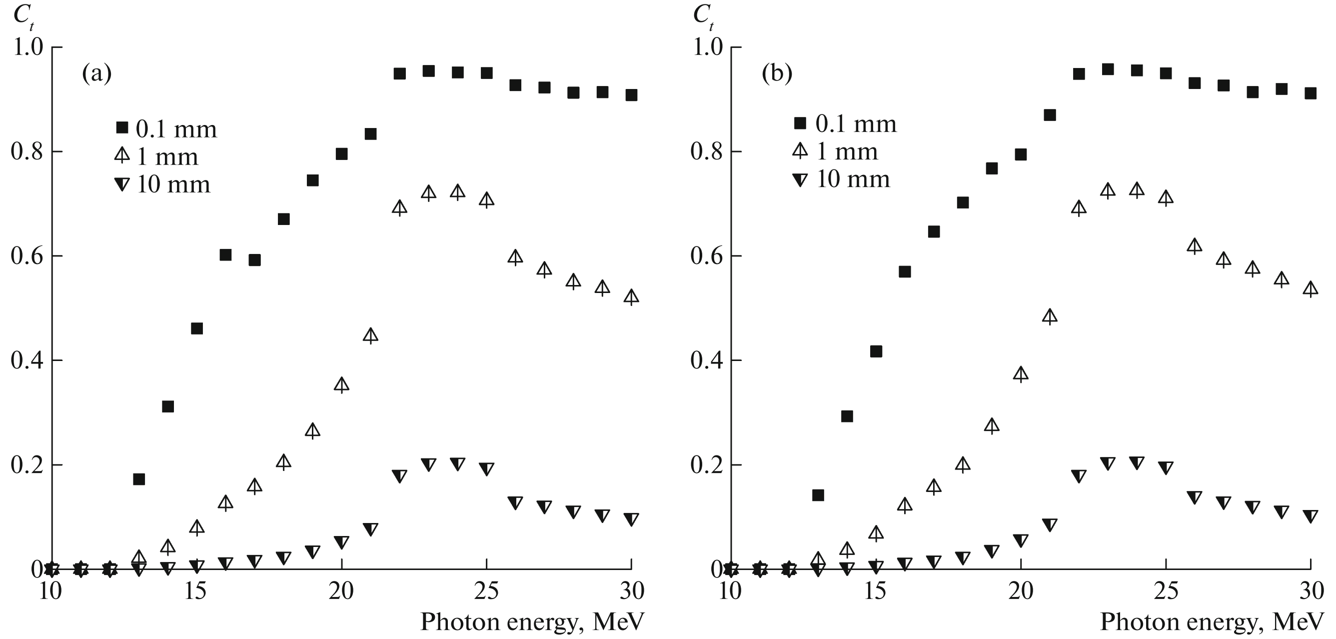

Fig. 5. The contribution of all of the photonuclear reaction products to the absorbed dose as a function of the primary photon energy above 10 MeV for (a) water and (b) biological tissue of different thickness.

Figure 4 presents the energy dependence of the proton contribution (C_p) (with account for the contributions from deuterium and tritium due to their low production) to the absorbed dose in water (Fig. 4a) and biological tissue (Fig. 4b). A pronounced maximum can be observed for a photon energy of 21 MeV (for a layer thickness of 1 mm) which is ~20% for both targets. A less-pronounced maximum (~10%) is observed for 26 MeV. The total contribution (C_t) of all of the products of photonuclear reactions is shown in Fig. 5. The form of the curve is mainly determined by alpha particles and recoil nuclei due to the large contribution of these products. In the interval of 22–25 MeV the contribution of photonuclear reaction

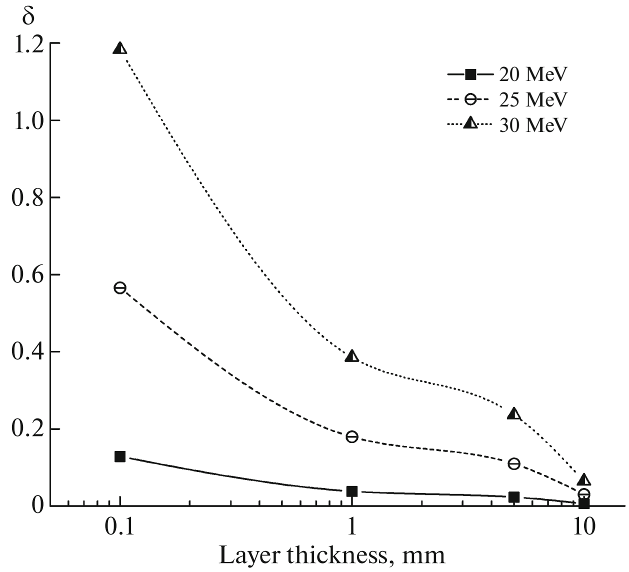

Fig. 6. δ as a function of the water-layer thickness for different bremsstrahlung spectra.

products exceeds 90% for the 0.1 mm layer and reaches ~20% for the 10 mm layer. The curves for biological tissue and water are qualitatively similar.

The absorbed and equivalent doses that form in thin water layers with a thickness from 0.1 to 10 mm were estimated using formulas (1), (2) for the spectra of bremsstrahlung photons with a maximum energy of 20, 25, and 30 MeV. Figure 6 shows the curves that characterize the deviation of the equivalent dose from the absorbed one depending on the thickness of the irradiated layer. The deviation is the largest for the thinnest layers and is qualitatively similar for different spectra. The value of δ is ~1.2 for 30 MeV, approximately 0.6 for 25 MeV, and much smaller, viz., 0.1, for 20 MeV, in a 0.1 mm layer. For a layer thickness of 1 cm the dose difference does not exceed 10% for a maximum energy of 30 MeV.

CONCLUSIONS

The impacts of monoenergetic photon radiation with an energy up to 30 MeV on thin (0.1 – 10 mm) layers of water and a model biological tissue were studied using Geant4.9.6. The values of the absorbed and equivalent doses in irradiated layers were determined. It was demonstrated that in the case of monochromatic photon radiation the equivalent and absorbed doses weakly differ up to a photon energy of approximately 10 MeV. With further growth of the photon energy the decisive role in forming the absorbed and equivalent doses is played by products of photonuclear reactions; their contribution to the absorbed dose is from 20 to 90% depending on the layer thickness in the energy interval of 20–30 MeV. The influence of the elemental composition on the absorbed and equivalent doses in irradiated layers was demonstrated. The results of calculations for bremsstrahlung spectra with different boundary energies also demonstrate substantial (up to a factor of two) deviation between the absorbed and equivalent doses.

These results can be used in the field of radiation safety, radiobiology, and areas connected with the radiation modification of the properties of materials. In particular, in order to reduce the radiation load on the cutaneous covering of a patient in the course of beam therapy it is recommended to limit the maximum photon radiation energy to 20 MeV. Further studies require calculations with larger statistics and a finer energy step. Our goal is to study the contributions of photonuclear reactions in more detail for biological tissues with different elemental compositions and to estimate the RWF based on the LET of all of the particles. The issue of the thickness of the surface layer in which the RWF that is due to photonuclear reaction products is much larger than unity is not quite clear but probably important.

REFERENCES

1. A. Tilikidis, P. Nafstadius, and A. Brahme, Phys. Med. Biol. **41**, 55 (1996).
2. F. Spumy, L. Johansson, A. Satherberg, et al., Phys. Med. Biol. **41**, 2643 (1996).
3. P. D. Allen and M. A. Chaudhri, Med. Phys. **9**, 904 (1982).
4. L. Gudowska, A. Brahme, P. Andreo, et al., Phys. Med. Biol. **44**, 2099 (1999).
5. J. Briesmeister, Los Alamos National Laboratory Report LA-12625-M (1997).
6. A. Satherberg and L. Johansson, Med. Phys. **25**, 683 (1998).
7. A. V. Belousov, A. S. Osipov, and A. P. Chernyaev, Med. Fiz., No. 3, 37 (2013).
8. A. V. Belousov, U. A. Bliznyuk, and A. P. Chernyaev, Biomed. Biotechnol. **2**, 80 (2014).
9. J. Valentin, Ann. ICRP **33** (4), 1 (2003).
10. http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/useCases.shtml
11. *Radiation Oncology Physics: A Handbook for Teachers and Students* (IAEA, Vienna, 2005).
12. *ICRP Publication 92. Ann. ICRP,* 2003, Vol. **33**.
13. http://cdfe.sinp.msu.ru/services/calc_thr/calc_thr.html

Translated by E. G. Baldina