Biomedicine and Biotechnology, 2014, Vol. 2, No. 4, 80-84
Available online at http://pubs.sciepub.com/bb/2/4/3

DOI:10.12691/bb-2-4-3

Evaluation of the Average Weighting Factor in Thin Layer Irradiation by Bremsstrahlung

A.V. Belousov[1,*], U.A. Bliznyuk[2], A.P. Chernyaev[1]

[1]Physical department, M.V. Lomonosov Moscow State University, Moscow, Russia
[2]Nuclear research institute named by D.V. Skobeltcin
*Corresponding author: BelousovAV@physics.msu.ru

Received October 04, 2014; Revised November 19, 2014; Accepted November 23, 2014

Abstract Photon radiation passing through biological tissues induces streams of secondary particles. Photonuclear reactions produce radiation with high linear energy transfer values and, consequently, a high value of radiation weighting factor (w_R). When irradiating thin layers, secondary electrons don't have enough time to transfer all of their energy to the matter of the layer, due to their large range. The heavy particles produced in this process transfer their energy to the matter almost at the location of their production. As a result, the secondary heavy particles may greatly contribute in the equivalent dose, despite the low probability of photonuclear reactions. In this article, the average value of w_R is assessed for all types of radiation induced by bremsstrahlung when thin layers are irradiated.

Keywords: *relative biological effectiveness, bremsstrahlung spectra, radiation weighting factor, photonuclear reaction products*

Cite This Article: A.V. Belousov, U.A. Bliznyuk, and A.P. Chernyaev, "Evaluation of the Average Weighting Factor in Thin Layer Irradiation by Bremsstrahlung." *Biomedicine and Biotechnology*, vol. 2, no. 4 (2014): 80-84. doi: 10.12691/bb-2-4-3.

1. Introduction

Contemporary radiotherapy devices generate high-energy bremsstrahlung radiation. In a large number of publications, their authors have come to the conclusion based on an experimental determination of relative biological effectiveness (RBE), the results of microdosimetric experiments and calculations, as well as computer modeling that the RBE of photons is energy dependent. Irradiation of V79 cloned cells by bremsstrahlung photons from a race track microtron with an output energy of 50 MeV showed RBE, defined relative to the 4 MeV bremsstrahlung beam, ranged from 1.12 to 1.14 [1]. Similar experiments on mice intestinal crypt microcolonies resulted in an estimated RBE of 1.06-1.10 for bremsstrahlung with the maximum energy of 50 MeV [2]. Based on the bremsstrahlung spectra obtained by Monte Carlo simulation and numerical estimates for the contribution of photonuclear reactions in the radiation dose absorbed by patient tissues, the RBE values at 50 MeV photons obtained by Gudowskaetal. Were 1.02±0.01 [3]. Similar estimates were obtained by Spurny et al.[4] Based on the experimentally measured microdosimetric characteristics of a 50 MeV bremsstrahlung beam, Tilikidis et al. estimated the RBE relative to ^{60}Co radiation at 1.13. It is important to note that the low values of RBE estimates [4,5] were obtained by calculations in the entire body of a patient, whereas large RBE values in experimental studies were obtained when thin-layer objects were irradiated.

The International Commission on Radiological Protection (ICRP) admits that extensive evidence clearly suggests energy dependence of RBE of high-energy photons [6]. The RBE increase for high-energy photons is related to the formation of heavy charged particles (such as protons, alpha particles, etc.), recoil nuclei, and neutrons with high linear energy transfer (LET) values, as a result of photonuclear reactions. However, the ICRP recommends that the radiation weighting factor (w_R) [1] which characterizes radiobiological effects of ionizing radiation would be considered as being equal to 1 for all photon energies. This recommendation is based on the assumption that radiation weighting factor is introduced to characterize the radiation hazard to the whole body of this type of radiation. The value of 1 is also recommended for electrons and pions; 2 for protons (this value was 5 in previous recommendations); 20 for alpha particles, recoil nuclei, and heavy ions.

High-energy photons passing through matter transfer their energy primarily via Compton scattering and due to the effect of electron-positron pair production. In the case of light elements—of which biological tissue primarily consists—photoelectric effects maybe neglected at photon energy above 10 MeV. The range of secondary electrons produced as a result of both processes is ~ 5 cm.

When photon radiation passes through a thick absorber, only a small fraction of the absorbed dose is associated with photonuclear reaction products because the electrons produced lose almost all of their energy within the

[1] In previous recommendations, radiationquality factor was used for similar purposes.

absorber and the probability of their production is significantly higher than the probability of photonuclear reactions.

In thin layers, the electrons exit the layer without having lost all of their energy. Heavy charged particles and recoil nuclei resulting from photonuclear reactions have high LET value; they have significantly smaller range than electrons, and all their energy is absorbed almost at the location of their production. Even though the cross section of photonuclear reaction is considerably smaller than the total cross section of other types of photon interaction with matter, the contribution of products (protons, recoil nuclei) may be significant. For example, if the photon energy is ~23 MeV, which corresponds to the maximum cross section of the reaction ${}^{16}_{8}O(\gamma, p)N^{15}_{7}$, a proton is produced with an energy of ~8 MeV (conditional probability[2] of its formationis ~1%). If the range in soft tissues is ~0.3 mm, the energy losses within a layer 0,5 mm thick would be ~6 MeV. 23 MeV photons produce electrons with an average energy of ~10 MeV, the conditional probability of electron production is ~99%, the stopping power of such electrons is ~2 MeV/cm. In a 1 mm layer, such electrons lose ~100 keV of energy. Assuming that the entire absorbed dose is created only by protons and electrons, the contribution of protons to the absorbed dose would be 6×0.01/(6×0.01+0.1×0.99) ~ 40%. Even this very rough estimate shows that, taking into account photonuclear reactions, dose formation in thin layers is very different from the dose formation in greater layer, the contribution of protons to an equivalent dose will be even higher. A similar situation could be noted for recoil nuclei their energy constitutes approximately one 15th to 20th of protons; however, taking into account the value of w_R=20, their contribution to the equivalent dose has the same order of magnitude as the contribution of protons but their contribution to the absorbed dose is extremely small.

This article addresses computer simulation of the passage of high-energy photon radiation through thin layers of biological tissue; determination of the contribution of the heavy particles and recoil nuclei resulting from photonuclear reactions to the absorbed dose; assessment of the average radiation weighting factor of all types of radiation induced by the high-energy photons within the layer; and performance of similar calculations for bremsstrahlung spectra with various maximum energy.

2. Computer Simulation

GEANT4.9.6 [7,8] software was chosen to as a tool for computer simulation using the Monte Carlo algorithm. This software package can simulate transport of all types of particles through the medium of an arbitrary (i.e., user-defined) geometry and arbitrary elemental composition. The following types of photon interactions [9,10] could be simulated: elastic scattering, Compton scattering, electron-positron pair production in the fields of the nucleus and the atomic electrons, photonuclear reactions, production of π-mesons. For electrons and positrons, ionization energy losses and bremsstrahlung losses, elastic collisions and multiple scattering are taken into account. For positrons, annihilation processes are also taken into account, including “on-the-fly” annihilation. The same processes are accounted for heavy charged particles as for electrons plus inelastic scattering in nuclear reactions. Transport of photons and electrons (positrons) is calculated to 250 eV minimum energy, the cut-off energy for a heavy charged particle is 1 keV.

GEANT4 is widely used for radiotherapy units simulation [11,12,13,14]. In this work bremsstrahlung spectra are obtained using the standard Medical Linac Advanced Example included in the GEANT4 package and simulated medical accelerator [15]. Electrons generate bremsstrahlung photons in a tungsten target, radiation is filtered through 9 mm beryllium + 6 mm tungsten.

In these simulation conditions, a plate of an average biological tissue shaped as a parallelepiped of user-defined thickness, which elemental composition corresponds to the formula $(C_5H_{40}O_{18}N)_x$, is irradiated with a monochromatic photon beam emitted by a plane circular source with a radius of 10 cm. The cross-section of the parallelepiped is a square inscribed in the circle from which the particles are emitted, if viewed along the beam. The amount of interactions of all types of particles is determined in the layer of the biological tissue, as well as the energy released in the entire layer as a result of such interactions. Based on this data, the contribution of photonuclear reactions to the total cross-section of photon interactions and the contribution of particles including recoil nuclei produced as a result of the photonuclear reactions in the layer to the absorbed dose, are determined.

3. Results and Discussion

In this part of work GEANT4 was used to simulate the bremsstrahlung spectra in the linear medical accelerator. A geometrical model (Figure 1) was simulated with GEANT4 representing the linac head components, including the target and primary collimator (tungsten), flattening filter (stainless steel) and secondary collimator jaws (tungsten). The distribution of the electron energy and the electron radial intensity was assumed to have Gaussian shape.

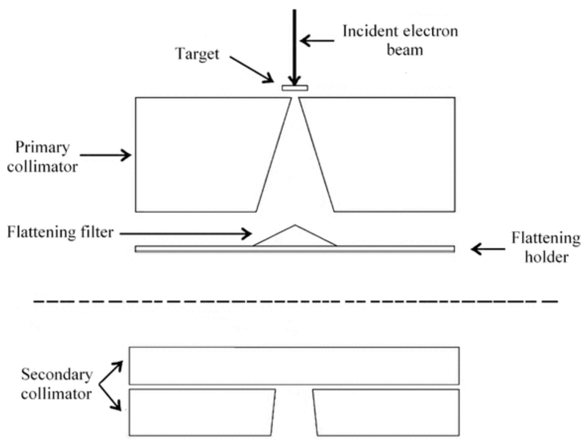

Figure 1. Geometrical model of medical accelerator simulated with GEANT4

[2]The conditional probability is the probability of this processgiven that the photoninteracted with the matter in any way.

Figure 2 shows examples of bremsstrahlung spectra with the maximum energy of 20 and 30 MeV calculated by GEANT4. The field size was 10×10 cm^2 and the source-surface distance (SSD) was 100 cm. The spectra are normalized so that the value $N\left(E_\gamma\right)dE_\gamma$ represents the fraction of photons whose energy is within the range $\left(E_\gamma, E_\gamma + dE_\gamma\right)$. That is, $N\left(E_\gamma\right)dE_\gamma$ can be considered as a probability density.

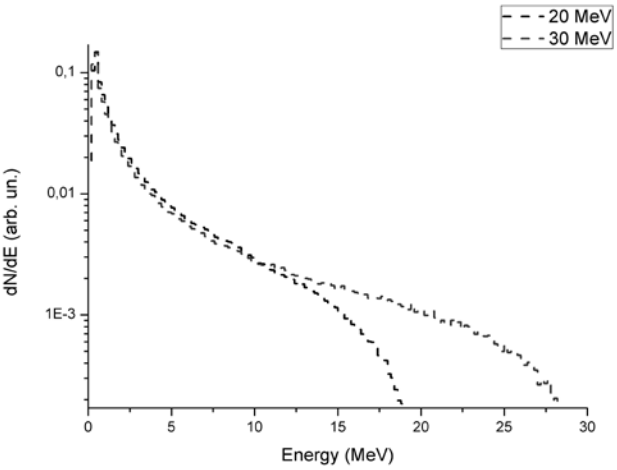

Figure 2. Bremsstrahlung spectra with the maximum energy of 20 and 30 MeV calculated by GEANT4

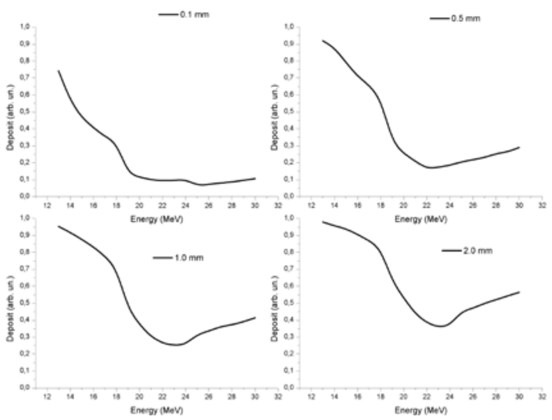

Figure 3. Dependence of the contribution to the absorbed dose from photons, electrons, and positrons on the energy of the primary photons for layers of different thicknesses

When photon radiation passes through a biological tissue, photonuclear reactions which occur are primarily of these types (γ, n), (γ, p), (γ, np) and (γ, α). The average value of the radiation weighting factor (as well as the quality factor) of all types of radiation (protons, alpha particles, recoil nuclei, electrons and positrons, photons) induced in the layer of the biological tissue by primary photons, can be estimated according to the following expression,

$$w_R\left(E_\gamma\right) = \delta_{e,\gamma}\left(E_\gamma\right)\times 1 + \delta_{\alpha,NR}\left(E_\gamma\right)\times 20 + +\delta_p\left(E_\gamma\right)\times 2 \quad (1)$$

Where $\delta_{e,\gamma}\left(E_\gamma\right)$ is the total contribution of photons, electrons, and positrons in the absorbed dose upon irradiation by a monochromatic photon beam with the energy of E_γ; $\delta_{\alpha,NR}\left(E_\gamma\right)$ is the total contribution of alpha particles and recoil nuclei; $\delta_p\left(E_\gamma\right)$ is the contribution of protons. Since alpha particles and recoil nuclei have the same value of w_R, their contribution is combined. Taking into account the minor thickness of the layer and the large mean free path of the photo neutrons being produced, their contribution to the absorbed dose is negligible. The energy dependence of the contribution of different particles to the absorbed dose $\delta_{e,\gamma}\left(E_\gamma\right)$, $\delta_{\alpha,NR}\left(E_\gamma\right)$ and $\delta_p\left(E_\gamma\right)$ or layers of different thicknesses is shown in Figure 3 - Figure 5.

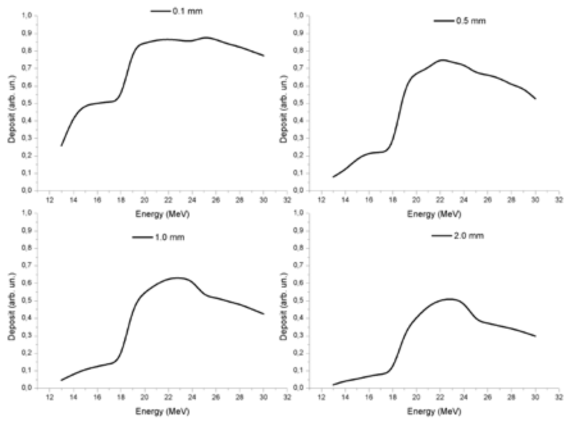

Figure 4. Dependence of the contribution to the absorbed dose from alpha particles and recoil nuclei on the energy of the primary photons for the layers of different thicknesses

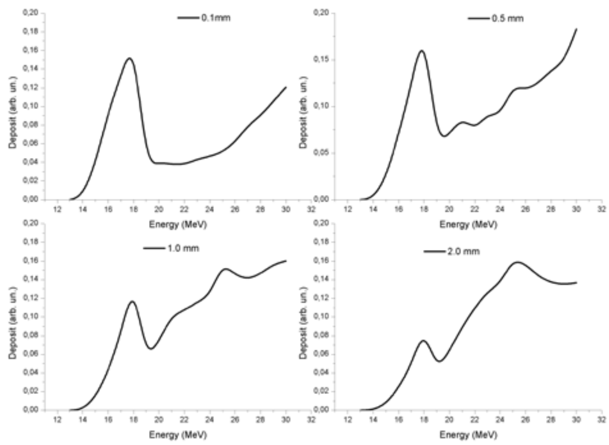

Figure 5. Dependence of the contribution to the absorbed dose from protons on the energy of the primary photons for the layers of different thicknesses

These dependencies clearly show that the contribution of secondary electrons and positrons to the absorbed dose increases with increasing thickness (the contribution of the primary photons is small). On the contrary, the contribution of alpha particles and recoil nuclei decreases with increasing thickness of the irradiated layer. The contribution patterns of protons in this range of thicknesses and of the primary beam energy are more complicated. At very small thicknesses, the protons don't have enough time to lose all their energy in the layer; when the layer thickness increases, the larger fraction of their energy is absorbed within the layer and their contribution to the absorbed dose increases. With the further increase of the layer's thickness, the proton energy losses become approximately constant due to the shortness of their range; at the same time, the secondary electrons pass an increasing fraction of their energy to the irradiated volume, and the contribution of protons begins to decrease. The curves which describe energy dependence of the contributions of the various particles to the absorbed dose have multiple local maxima and minima due to large number of possible channels for photonuclear reactions. Another reason relates to the fact that the number of channels grows with the increase of energy, and the probability of each of them greatly changes because the cross-sections in this energy region are described by relatively narrow maxima of giant nuclear resonances.

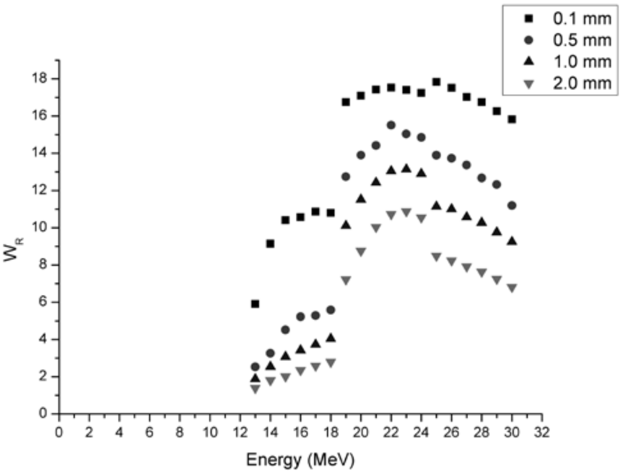

Figure 6. Dependence of the averaged radiation weighting factor for all types of radiation on the energy of the primary photons for the layers of different thicknesses

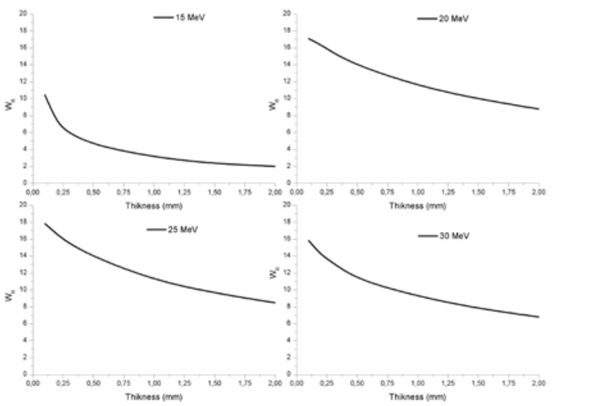

Figure 7. Dependence of the averaged radiation weighting factor for all types of radiation on the the layer thickness for different energies of primary photons

The radiation weighting factors (w_R) calculated by formula (1) for all types of radiation induced in a thin layer irradiated by monochromatic high-energy photons are shown in Figure 6 and Figure 7. Figure 6 shows dependence of the radiation weighting factor on the energy for the layers of different thicknesses; Figure 7 shows dependence of w_R on the layer thickness for a fixed photon energy. In the energy dependence graphs related to the averaged values of w_R for all types of radiation induced by primary photons in a thin layer, some local maxima and minima are also observed, as described above, but they are much less pronounced. As the thickness of the layer increases, w_R tends to decrease. The shape of the curves demonstrating energy dependence is weakly dependent on the thickness of the irradiated layer.

Figure 8 shows the values of the radiation weighting factor for the layers of different thicknesses averaged over the bremsstrahlung spectra depending on the spectrum's maximum energy. The curves gradually increase with increasing maximum energy and reach a flat local maximum at the energy level of approximately 30 MeV. The general tendency of an increasing w_R with a decreasing thickness of the irradiated layer remains. For example, the radiation weighting factor takes the value of ~2.0 for a 0.1 mm thick layer and ~1.3 for a 2.0 mm thick layer.

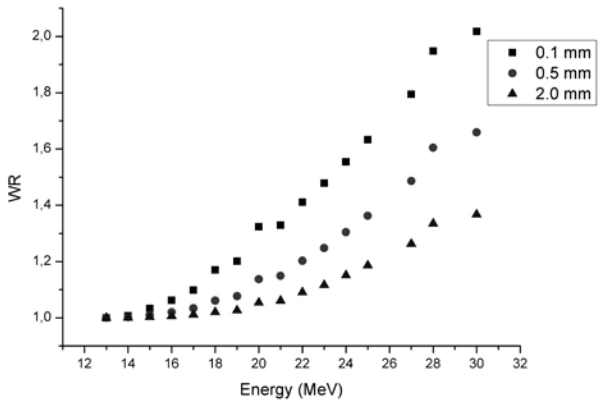

Figure 8. Dependence of w_R of bremsstrahlung radiation on the spectrum's maximum energy

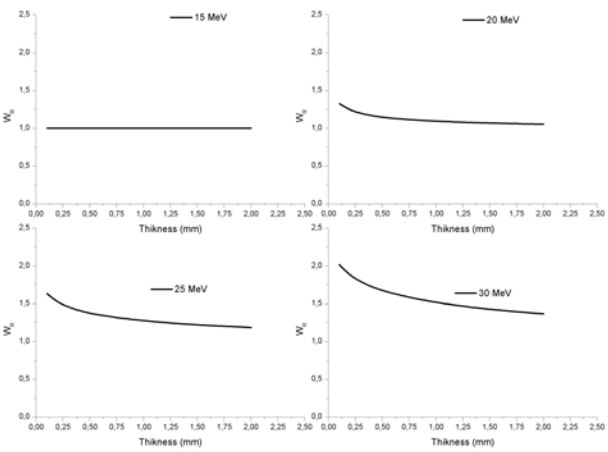

Figure 9. Dependence of w_R of bremsstrahlung radiation on the layer thickness for spectra of different maximum energy

Figure 9 shows the dependence of the radiation weighting factor for all types of radiation induced by bremsstrahlung photons on the thickness of the irradiated volume for different values of maximum energy of the bremsstrahlung spectrum E_γ^{max}. When the maximum energy of bremsstrahlung is 15 MeV, the fraction of photons which can participate in photonuclear reactions is small. The cross-section of photonuclear reactions at such photon energy is also small. As a result, the value of w_R differs little from 1 for the entire range of the thicknesses studied. The higher the upper limit of the energy, the more greatly the radiation weighting factor differs from 1. At the same time, the values of w_R gradually decrease with an increase in the thickness of the irradiated layer. In the studied energy range of bremsstrahlung (up to 30 MeV), the radiation weighting factor increases with increasing photon energy for all layer thicknesses.

Figure 9 shows the dependence of the radiation weighting factor for all types of radiation induced by bremsstrahlung photons on the thickness of the irradiated volume for different values of maximum energy of the bremsstrahlung spectrum $E_\gamma^{\max}$. When the maximum energy of bremsstrahlung is 15 MeV, the fraction of photons which can participate in photonuclear reactions is small. The cross-section of photonuclear reactions at such photon energy is also small. As a result, the value of w_R differs little from 1 for the entire range of the thicknesses studied. The higher the upper limit of the energy, the more greatly the radiation weighting factor differs from 1. At the same time, the values of w_R gradually decrease with an increase in the thickness of the irradiated layer. In the studied energy range of bremsstrahlung (up to 30 MeV), the radiation weighting factor increases with increasing photon energy for all layer thicknesses.

4. Conclusion

In this paper, a passage of monoenergetic photon radiation through thin layers of biological tissue with an average elemental composition was studied by computer simulation using GEANT4.9.6 software which implements the Monte Carlo method. The spectra of bremsstrahlung, emulation spectra obtained on medical linear accelerators, were simulated.

It was shown that the average radiation weighting factor for all types of radiation induced in a thin layer irradiated by monochromatic photons can reach values which exceed the value of 1 recommended by the ICRP by an order of magnitude. In the case of thin layers irradiated by bremsstrahlung photons, the average value of w_R reaches ~2.0 and ~1.3 at the thicknesses of 0.1 mm and 2.0 mm, respectively.

This work was supported by the Russian Foundation for Basic Research (RFBR), grant 12-02-31390_mol_a.

References

[1] Zackrisson B., Johansson B. and Ostbergh P. Relative biological effectiveness of high-energy photons (upto 50 MV) and electrons (50 MeV), Rad. Res., 1991,128.192-196.

[2] Zackrisson B., Karlsson M. Relative biological effectiveness of 50 MV X-rayson jejuna crypt survival in vivo, Rad. Res., 1992,113. 112-114.

[3] Gudowska I., Brahme A., Andreo P. ttal. Calculation of absorbed dose and biological effectiveness from photonuclear reactions in a bremsstrahlung beams of end point 50 MeV, Physical Medical Biology, 1999. 2099-2125.

[4] Spurny F., Johansson L., Satherberg A. et al.The contribution of secondary heavy particles ti the absorbed dose from high-energy photons beams. Physical Medical Biology, 1996, 41. 2643-2656.

[5] Tilikidis A., Lind B., Nafstadius P., Brahme A. An estimation of the relative biological effectiveness of 50 MV bremsstrahlung beams by microdosimetric techniques, Physical Medical Biology, 1996, 41. 55-69.

[6] ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures, ICRP Publication 116, Annuals 40 (2-5).

[7] Agostinelli S., Allison J., Amako K. et al. GEANT4 – a simulation toolkit, Nulcear Instruments and Methods in Physics Research A, 2003, 506. 250-303.

[8] Allison J., Amako K., Apostolakis J. GEANT4 developments and applications, IEEE Transactions in Nuclear Science, 2006, 53 (1). 270-278.

[9] Cirrone C.A.P., Guttone G., Di Rosa F. et al. Validation of the GEANT4 electromagnetic photon cross-sections for elements and compounds, Nulcear Instruments and Methods in Physics Research A, 2010, 608. 315-322.

[10] Poon E., Verhaegen F. Accuracy of the photon and electron physics in GEANT4 for radiotherapy applications, Medical Physics, 2005, 32. 1696-1711.

[11] Cortes-Giraldo M.A., Quesada J.M., Gallardo M.I., Capote R. GEANT4 application for the simulation of the head of a Siemens Primus linac, AIP Conference Proceedings Series, 2009, 1231. 209-210.

[12] Faddegon B.A., Kawrakow I., Kubyshin Y. et al. The accuracy of EGSnrc, GEANT4 and PENELOPE Monte Carlo systems for the simulation of electron scatter in external beam radiotherapy, Physics in Medicine and Biology, 2009, 54 (20). 6151-6163.

[13] Larsson S., Svensson R., Godowska I., Ivanchenko V., Brahme A. Radiation transport calculations for 50 MV photon therapy beam using the Monte Carlo code GEANT4, Radiation Protection Dosimetry, 115 (1-4). 503-507.

[14] http://www.ge.infn.it/geant4/examples/medical_linac/