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Conversion coefficients from fluence and air kerma to personal dose equivalent for monoenergetic photons using analytical fit and Monte Carlo simulation

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Abstract

The present study aims to calculate a new database of conversion coefficients from fluence and air Kerma to personal dose equivalent in two terms: absorbed dose and Kerma-approximations. In this work, we propose a new equation to perform an analytical fit of our Monte Carlo (MC) calculated conversion coefficients for photons for different angles. Also, we have calculated the conversion coefficients using the EGSnrc code. The conversion coefficients have been calculated for beams of monoenergetic photons from 0.015 to 10 MeV, incident on phantom ICRU for angles of incidence from 0° to a 75° in steps of 15°. Our computed values agree well when compared with those published for the ICRU 57 in Kerma-approximations with statistical uncertainties in the calculation around 2%. We can conclude from this work that the analytical approach is successful and powerful such as Monte Carlo methods to calculate the operational quantities.

Key words: operational quantity; personal dose equivalent; conversion coefficients; fluence; air kerma; MC.

Introduction

The protection quantities are defined by the International Commission on Radiological-Protection (ICRP) and operational quantities are defined by the International Commission on Radiation Units and Measurements (ICRU) to protect humans from radiation. The operational quantities and the protection quantities are related to basic physical quantities, it is necessary to use the conversion coefficients [1]. So, the radiation exposure for workers and members of the general public can be evaluated from basic physical quantities values. The relationships between the basic physical quantities, the protection quantities and the operational quantities in **Figure 1** [2]. The difficulty to measure organ dose directly in the field and therefore dose conversion coefficients are needed to convert measurable values such as air Kerma to organ dose [3]. So, the operational quantities have been evaluated from the air Kerma through conversion coefficients calculations from air Kerma to the personal dose equivalent and its value must provide a reasonable estimate for the protection quantities recommended by the (ICRU) [2].

The conversion coefficients for photon radiation published by (ICRP) and by (ICRU) for mono-energetic radiation fields. The protection quantity, equivalent dose in an organ or tissue, H , is then defined by:

$$H = \sum_R w_R D_{T,R} \quad \text{Eq. 1}$$

where $D_{T,R}$ is the main absorbed dose from the radiation of type R in the specified organ or tissue T , and w_R is the radiation weight factor, w_R is assigned to be unity, for photons [4,5]. For assessment of the radiation protection quantity 'effective dose', a depth $d = 10$ mm is selected.

The dose equivalent, H , is the product of quality factor and absorbed dose at a point in tissue at that point, thus [6,7]:

$$H = QD \quad \text{Eq. 2}$$

where D is the absorbed dose and Q is the quality factor, the quality factor Q equal to 1 for photons [8]. Our work can be useful to improve the protection of workers medically, industrially and in research, from potentially external radiation exposures. In ICRU 57 the conversion coefficients calculated use the Kerma-approximation method to approach CPE. The data for the quantities of $H_p(10, \alpha)$ in absorbed dose mode for photons are lacking in that report, owing the numerical value of Kerma approaches that of the absorbed dose, to the degree that CPE exists, that radiative losses are negligible. The aim of this study is to obtain a set of conversion coefficients relating fluence and air Kerma to personal dose equivalent for a set of energy and angular dependent on two terms (absorbed dose and Kerma-approximations) for mono-energetic photons between 0.01 to 10 MeV for angles of incidence between 0° and 75° in steps 15°, in the phantom made of ICRU tissue have been calculated with the analytical approach and MC.

Figure 1. Relationships between the basic physical quantities, the protection quantities and the operational quantities [2].

Materials and methods

Monte Carlo calculations

The conversion-coefficients relating by physical quantities to protection quantities can estimate potential health danger for people in the case of a radiological happening. The majority of published conversion coefficients are derived from different types of Monte Carlo calculations, few are derived from measurements on anthropomorphic phantoms [9].

The Monte Carlo technique is one of the numerical methods that permit to solve complex problems by using pseudo-random numbers made by computers. The EGSnrc code is one of the general codes based on the Monte Carlo method to simulate the particle transport in matter. The calculations were carried out with the default settings, which include modeling the Compton interaction for bound electrons, the effect of any atomic relaxation events, and relativistic spin effects in the multiple scattering theories for charged particles.

For the parameters of variance reduction techniques, the default settings were used. For secondary particle production, the threshold was set to PCUT for photons and ECUT for charged particles, the photon and electron cut-off energies were set to PCUT = 10 keV and ECUT = 521 keV, the photon cross-section packages are available in EGSnrc code for the photoelectric, pair production, triplet production, and coherent scattering cross-sections. The photon interaction cross-sections from the XCOM database were used [10].

The conversion coefficients calculation performed by the EGSnrc algorithm of PRESTA-II (called parameter reduced electron-step transport algorithm) [11], a boundary-crossing algorithm (BCA = EXACT means crossing boundaries in a single scattering mode), maximum fractional energy loss/step (ESTEPE = 0.25), maximum first elastic moment/step (XIMAX = 0.5) and skin-depth for boundary-crossing (MFP = 3) [10,12]. A total of 1×10^7 particles were used in order to obtain statistical uncertainty associated with the EGSnrc code in the calculation may be slim (Tables 7-17).

$H_p(10, \alpha)$ calculations

The EGSnrc code has been used to perform the simulation for beams of mono-energetic photons from 0.015 to 10 MeV for angles of incidence from 0° to a 75° in steps of 15° which incident on phantom a 30-cm-thick slab of ICRU tissues material with a density of 1 g/cm^3 four-element tissue and a weight composition of 76.2% oxygen (O), 11.1% carbon (C), 10.1% hydrogen (H), and 2.6% nitrogen (N) [13,14]. The centers of the scoring volumes are positioned on the midplane at the depth of 10 mm, the thickness is 2 mm along the radius and the height is 2 cm. Two sets of dose conversion coefficients were calculated in terms of absorbed dose and in terms of Kerma approximations, Table 1.

Table 1. The radiation, mode of conversion coefficients, quality factor Q, energies and units by EGSnrcs code.

Radiation	Conversion coefficients	Q	Energies	Units
Photons	$H_p(10, \alpha) / \Phi = Q \times D(10, \alpha) / \Phi$	1	From 0.015 to 10 MeV	pSv·cm ²
	$H_p(10, \alpha) / \Phi = Q \times K(10, \alpha) / \Phi$			pSv·cm ²
	$H_p(10, \alpha) / K_{\text{air}} = Q \times D(10, \alpha) / K_{\text{air}}$			Sv/Gy
	$H_p(10, \alpha) / K_{\text{air}} = Q \times K(10, \alpha) / K_{\text{air}}$			Sv/Gy

The relative differences with is calculated by EGSnrc code and reference ICRU-57 has given by relation in the following:

$$\text{Relative difference} = \frac{\text{Abs}(\text{Calculated Value} - \text{Reference Value})}{\text{Reference Value}} \% \quad \text{Eq. 3}$$

The relative differences between obtained results and the value of ICRU-57 less than 3%, except at the low energy the relative differences more than 3%.

Conversion coefficients by analytical fits

In this work, we suggest a new equation to perform an analytical fit of our Monte Carlo calculated conversion coefficients for photons $H_p(10)$ for different angles. The new analytical fit has been based on non-linear least squares Levenberg-Marquardt algorithm to calculate the parameters. The new analytical Method of a non-linear least squares Levenberg-Marquardt algorithm has been applied for calculating the parameter of **Equation 4**. The **Tables 2-6** show the fitting parameter of the analytical Method a non-linear least square. **Equation 4** has been validated to calculate the conversion coefficients [15].

$$f(x) = \frac{a_1x^5 + a_2x^4 + a_3x^3 + a_4x^2 + a_5x + a_6}{x^5 + b_1x^4 + b_2x^3 + b_3x^2 + b_4x + b_5} \quad \text{Eq. 4}$$

where:

$f(x)$ is the conversion coefficients.

x is energy, with Energy in MeV.

a_i, b_j ($i = 1, 2, \dots, 6$ and $j = 1, 2, \dots, 5$), are the parameter fitting non-linear least squares Levenberg-Marquardt algorithm of conversion coefficients. The parameters of the analytical fit are summarized in **Tables 2-6**.

Results and discussion

Air-Kerma calculations

The conversion coefficients relate protection or operational quantity to radiometric or dosimetric quantities. They are given to the operational quantities from the radiometric and dosimetric quantities fluence or air kerma. The air Kerma in air is calculated as a measurable reference quantity for photon metrology [16]. Air Kerma has been calculated using the analytical method, **Equation 5** and EGSnrc code. The K_{air}/Φ ($\text{pGy}\cdot\text{cm}^2$) values can be calculated from the mass-energy transfer coefficients (μ_{tr}/ρ) by stratifying the following **Equation 5** [16-18]:

$$\frac{K_{\text{air}}}{\Phi} = E \frac{\mu_{\text{tr}}}{\rho} \quad \text{Eq. 5}$$

Where is the mass-energy transfer coefficients in (cm^2/g), E is the photon energy in Joule.

The results obtained by EGSnrc code, Calculation by **Equation 5** and analytical fit are identical with the comparison to those reports CEA-R-6235 [16] and ICRU 57 [14], **Figure 2** and **Table 7**.

Figure 2. K_{air}/Φ ($\text{pGy}\cdot\text{cm}^2$) values calculated with EGSnrc code, ICRU 57, CEA-R-6235, analytical fit and calculation by Equation 5 from 0.015 to 10 MeV.

The statistical uncertainty associated with EGSnrc code for low photon energy less than 0.2%, and for high photon energy less than 0.3%.

Conversion coefficients from fluence to personal dose equivalent $H_p(10, \alpha)/\Phi$

The calculation of the conversion coefficients has been carried out in two modes: absorbed dose Kerma approximation. The values of $H_p(10, \alpha)/\Phi$ in $\text{pSv}\cdot\text{cm}^2$ for energies from 15 keV to 10 MeV angles of incidence from 0° to a 75° in steps of 15° .

The following curves (**Figures 3-8**) represent the data of the conversion coefficients $H_p(10, \alpha)/\Phi$ in $\text{pSv}\cdot\text{cm}^2$, calculated using EGSnrc code, analytical approaches and those published at ICRU 57 in term pf Kerma approximation and in terms of absorbed dose according to the angle incidence. The values of $H_p(10, \alpha)/\Phi$ summarized in **Tables 8-9** in absorbed dose term and in **Tables 10-12** in approximation Kerma (**Appendix**).

$H_p(10, \alpha)/\Phi$ values are increased for photon energies from 15 keV to about 20 keV owing to the decreasing of the transmission factor that the energy increases in this area where the preponderant interaction is photoelectric. At 20 keV, the curve reaches a maximum before bending and decreasing odorant interaction is the Compton type. The energy of the photon incident is strong, the higher the one carried by the electron Compton is on average high, the energy yielded in the medium grows so as the energy increases [16].

For low photons energies, when the angle of incidence α increases, consequently the distance increases to interest point, so it absorbs energy before it reaches the point of interest, the dose absorbed may be under 10 mm the curve of conversion coefficients is low **Figures 3-8** [16]. For high photons energies, this Compton scattering becomes significant and the incident beam attenuation less important. The scattered photon contributes to the increase of the dose at the measurement point under 10 mm and compensates for the attenuation of the primary beam [16].

Figure 3. Conversion coefficients from photon fluence to personal dose equivalent for 0° incident angle.

Figure 6. Conversion coefficients from photon fluence to personal dose equivalent for 45° incident angle.

Figure 4. Conversion coefficients from photon fluence to personal dose equivalent for 15° incident angle.

Figure 7. Conversion coefficients from photon fluence to personal dose equivalent for 60° incident angle.

Figure 5. Conversion coefficients from photon fluence to personal dose equivalent for 30° incident angle.

Figure 8. Conversion coefficients from photon fluence to personal dose equivalent for 75° incident angle.

Conversion coefficients from air Kerma to personal dose equivalent $H_p(10, \alpha)/K_{air}$

In this part, the **Figures 9-14** represent the values of the conversion coefficients, $H_p(10, \alpha)/K_{air}$ in (Sv/Gy) calculated using, method of analytical, EGSnrc code and compared with

those published at ICRU57 in terms of Kerma approximation and in term of absorbed dose according to the angle incidence from 0° to a 75° in steps of 15° , are summarized in **Tables 13-14** for the term of absorbed dose and **Tables 15-17** for approximation-Kerma (**Appendix**).

Figure 9. Conversion coefficients from photon air Kerma to personal dose equivalent for 0° incident angle.

Figure 12. Conversion coefficients from photon air Kerma to personal dose equivalent for 45° incident angle.

Figure 10. Conversion coefficients from photon air Kerma to personal dose equivalent for 15° incident angle.

Figure 13. Conversion coefficients from photon air Kerma to personal dose equivalent for 60° incident angle.

Figure 11. Conversion coefficients from photon air Kerma to personal dose equivalent for 30° incident angle.

Figure 14. Conversion coefficients from photon air Kerma to personal dose equivalent for 75° incident angle.

In two terms, whenever increasing the angle of incidence, the conversion coefficients values are decreasing up to 3 MeV, due to the long distance between the source and volume interest (depth 10 mm), so, the secondary electron loses energy there before reaching depth 10 mm. Above energies of 3 MeV, there are two cases: The first case, in absorbed dose mode, for low angles incidence and high energies the $H_p(10, \alpha)$ values are decreasing, owing the high energies are not the interactions in volume interest or the secondary electrons are depositing their energy outside the point interest. The second case, in Kerma approximations for low angles incidence and high energies the conversion coefficients stabilize around unity, owing to the achievement of the equilibrium electronic (**Figures 9-14**).

The peak of $H_p(10, \alpha)/K_{air}$ conversion coefficients is found between 60 keV and 100 keV, photon energies that produce the highest quantities of large scattering angles and the dose maximum may be at depth 10 mm [19]. For energies higher than 600 keV the conversion coefficients stabilize around 1 owing to the obtain of the equilibrium electronic [10,20-21]. Generally, as beam angle increases, conversion coefficients decrease in low energies due to the escape of the secondary electrons away at the volume interest. So, the low energies (< 3 MeV) their highest influence on the effective dose (depth 10 mm). Above about 3 MeV, in approximations Kerma the conversion coefficients are quite similar to all angle incidences, and in absorbed dose mode the conversion coefficients decrease more with small-angle at depth 10 mm. We can also say that the Kerma approximation has more effects at high photon energies (> 3 MeV), compared to the absorbed dose, which has no effect at depth 10 mm.

In the report ICRU 57, the conversion coefficients were calculated in Kerma approximations, the numerical value of Kerma approaches that of the absorbed dose, to the degree that charged-particle equilibrium (CPE) exists, that radiative losses are negligible [6]. In this work the simulations to calculate the personal dose equivalent $H_p(10, \alpha)$ consisted of two parts: Kerma approximations and absorbed dose calculation were performed within each volume of interest, on the basis that radiative losses exist in high energy.

It's clear $H_p(10, \alpha)/\Phi$ curves are matched between Dose mode and Kerma from 0° to 75°, up 3 MeV, owing the numerical value of Kerma access that of the absorbed dose, to the degree that charged-particle equilibrium (CPE) exists. Above high energies (> 3 MeV) the difference is large between them in the angles from 0° to 30°, **Figures 7-9**, but the angles from 45° to 75°, **Figures 10-12** are found the variation a low degree because of the lack of electronic equilibrium.

Conclusions

The conversion coefficients have been calculated for mono-energetic photons from 0.015 to 10 MeV in the absorbed dose and Kerma-approximations using analytical fits and MC. Our computed values agree well when compared with those published for the ICRU 57 in Kerma approximations. The $H_p(10, \alpha)$ values for photons have validated by Analytical fit and EGSnrc code. We can conclude a new analytical fit provides a convenient approach for determining conversion coefficients.

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Appendix

Table 2. Coefficients Fitting non-linear least squares Levenberg-Marquardt algorithm of conversion coefficients for air Kerma.

parameter	Air Kerma
a1	3.7990E+05
a2	8.3140E+05
a3	-2.8900E+06
a4	1.6580E+06
a5	-1.5240E+05
a6	6.1220E+03
b1	2.0280E+05
b2	-1.9440E+05
b3	-2.1920E+05
b4	1.7420E+05
b5	-1.2160E+03

Table 3. Parameter Fitting of conversion coefficients for $H_p(10, \alpha)/\Phi$ for photons from 0° to 75° in terms of absorbed dose.

Angles	Conversion coefficients from photon fluence in terms of absorbed dose.					
Parameter	0°	15°	30°	45°	60°	75°
a1	8.813E+00	9.052E+00	5.220E+00	9.945E+00	-8.519E+06	2.637E+01
a2	-5.664E+01	-4.603E+01	8.184E-01	5.323E+01	3.853E+08	-3.041E+02
a3	1.741E+02	1.400E+02	1.632E+02	1.691E+01	-3.467E+08	2.860E+02
a4	-1.275E+01	-8.938E+00	-1.222E+01	-1.827E+00	2.212E+07	-2.445E+01
a5	7.749E-01	5.496E-01	7.328E-01	9.612E-02	-8.972E+05	1.216E+00
a6	-7.217E-03	-5.238E-03	-7.583E-03	-9.440E-04	7.396E+03	-1.301E-02
b1	-4.815E+00	-3.719E+00	-3.628E+00	1.468E+00	1.329E+07	-7.364E+00
b2	6.683E+00	4.404E+00	1.579E+01	1.135E+01	4.343E+07	-3.660E+01
b3	1.906E+01	1.656E+01	1.730E+01	9.912E-01	-4.855E+07	4.111E+01
b4	-3.068E-01	-2.928E-01	-2.558E-01	-9.538E-03	1.726E+06	-1.261E+00
b5	2.575E-03	2.243E-03	1.674E-03	1.902E-04	-2.358E+04	2.691E-02

Table 4. Parameter Fitting of conversion coefficients for $H_p(10, \alpha)/\Phi$ for photons from 0° to 75° in terms of approximation Kerma.

Angles	Conversion coefficients from photon fluence in terms of approximations Kerma					
Parameter	0°	15°	30°	45°	60°	75°
a1	-8.515E+02	-2.689E+05	7.730E+03	7.430E+05	2.785E+01	6.393E+01
a2	-1.816E+03	-4.767E+05	3.910E+04	1.804E+06	8.920E+01	-1.196E+02
a3	1.235E+04	3.855E+06	-2.227E+02	-6.931E+06	3.221E+03	5.371E+02
a4	-8.162E+02	-2.573E+05	-7.538E+01	5.502E+05	-2.594E+02	-4.956E+01
a5	4.750E+01	1.451E+04	1.320E+01	-3.342E+04	1.433E+01	2.532E+00
a6	-4.473E-01	-1.324E+02	-1.675E-01	3.616E+02	-1.449E-01	-2.798E-02
b1	-4.404E+02	-1.337E+05	3.883E+03	3.700E+05	-9.943E+00	1.161E+01
b2	7.467E+02	2.474E+05	4.928E+03	-3.864E+05	2.199E+02	-2.035E+00
b3	1.428E+03	4.434E+05	9.292E+01	-7.268E+05	3.941E+02	8.316E+01
b4	-2.883E+01	-9.354E+03	2.363E+00	7.501E+03	-8.179E+00	-2.626E+00
b5	2.589E-01	9.009E+01	-5.134E-02	-3.120E+01	1.199E-01	5.770E-02

Table 5. Parameter Fitting of conversion coefficients for $H_p(10, \alpha)/K_{air}$ for photons from 0° to 75° in terms of absorbed dose.

Angles	Conversion coefficients from photon Air Kerma in terms of absorbed dose.					
Parameter	0°	15°	30°	45°	60°	75°
a1	6.87E-01	8.79E-01	-1.54E+04	-1.06E+05	3.93E+00	8.93E-01
a2	-9.56E+00	-1.33E+01	3.01E+05	2.43E+06	-8.26E+01	-1.04E+01
a3	3.85E+01	5.15E+01	-1.21E+06	-9.24E+06	2.18E+02	5.04E+01
a4	1.26E+00	1.41E+00	1.36E+06	8.24E+06	7.44E+00	-1.14E+00
a5	-3.55E-02	4.57E-02	5.60E+04	4.56E+05	1.89E+00	8.45E-02
a6	1.58E-04	-7.16E-04	-6.50E+02	-6.23E+03	-2.81E-02	-1.17E-03
b1	-1.04E+01	-1.29E+01	2.02E+05	1.75E+06	-6.18E+01	-1.03E+01
b2	3.74E+01	4.84E+01	-1.01E+06	-8.01E+06	1.82E+02	4.64E+01
b3	-1.91E+00	-2.11E+00	1.27E+06	8.03E+06	4.74E+00	-7.55E-01
b4	9.38E-02	1.12E-01	-4.09E+04	-2.11E+05	2.84E-01	-2.93E-02
b5	-9.63E-04	2.67E-04	2.14E+03	1.38E+04	3.08E-02	3.96E-03

Table 6. Parameter Fitting of conversion coefficients for $H_p(10, \alpha)/K_{air}$ for photons from 0° to 75° in terms of approximation Kerma.

Angles	Conversion coefficients from photon Air Kerma in terms of approximations Kerma.					
Parameter	0°	15°	30°	45°	60°	75°
a1	1.11E+00	1.11E+00	1.11E+00	4.93E+01	1.10E+00	1.08E+00
a2	1.78E+00	-2.58E-01	3.08E-01	3.12E+04	4.97E+00	9.81E-01
a3	3.94E-01	2.31E-01	1.83E-01	3.78E+03	8.03E-01	-1.44E-01
a4	-2.34E-02	-1.13E-02	-1.42E-02	-5.42E+02	-3.50E-02	7.22E-03
a5	1.38E-03	7.73E-04	8.83E-04	4.58E+01	6.81E-03	-1.28E-04
a6	-1.43E-05	-8.19E-06	-9.18E-06	-5.12E-01	-8.92E-05	7.37E-07
b1	1.64E+00	-2.65E-01	2.64E-01	2.91E+04	4.54E+00	9.58E-01
b2	1.71E-01	1.92E-01	1.03E-01	2.86E+02	3.60E-01	-1.50E-01
b3	-1.66E-02	-1.37E-02	-8.73E-03	-9.59E+01	7.30E-03	8.40E-03
b4	8.27E-04	5.75E-04	3.74E-04	7.07E+00	2.12E-04	-2.05E-04
b5	6.10E-07	9.27E-08	2.83E-06	3.59E-01	1.12E-04	2.54E-06

Table 7. Air-Kerma calculations by EGSnrc code, Calculation by Equation 4 and analytical fit in this work are identical with the comparison for those reports CEA-R-6235 and ICRU 57, in unit (pGy·cm²).

Energy (MeV)	EGSnrc	Analytical fits in this work	ICRU 57	CEA-R-6235	Calculation by Eq. 5	Relative differences%
0.015	3.11±0.02	3.12	3.11	3.11	3.2	0.00%
0.02	1.73±0.014	1.70	1.73	1.73	1.73	0.00%
0.03	0.74±0.013	0.78	0.74	0.74	0.74	0.00%
0.04	0.44±0.012	0.46	0.44	0.44	0.44	0.00%
0.05	0.33±0.011	0.33	0.33	0.33	0.33	0.00%
0.06	0.29±0.010	0.28	0.29	0.29	0.29	0.00%
0.08	0.30±0.019	0.28	0.31	0.31	0.31	0.00%
0.1	0.37±0.018	0.34	0.37	0.37	0.37	0.00%
0.15	0.59±0.017	0.58	0.6	0.6	0.6	1.67%
0.2	0.85±0.016	0.86	0.86	0.85	0.86	1.16%
0.3	1.38±0.015	1.42	1.38	1.38	1.38	0.00%
0.4	1.89±0.015	1.94	1.89	1.89	1.89	0.00%
0.5	2.39±0.010	2.42	2.38	2.38	2.38	0.42%
0.6	2.82±0.019	2.83	2.84	2.84	2.84	0.70%
0.8	3.71±0.018	3.73	3.7	3.7	3.7	0.27%
1	4.48±0.017	4.42	4.47	4.47	4.48	0.22%
1.5	6.14±0.016	6.17	6.13	6.14	6.14	0.16%
2	7.54±0.015	7.48	7.54	7.55	7.55	0.00%
3	9.95±0.014	9.88	9.95	9.95	9.96	0.00%
4	12.26±0.013	12.08	12.1	12.11	12.12	1.32%
5	13.94±0.012	14.17	14.1	14.14	14.16	1.13%
6	16.29±0.012	16.20	16.1	16.13	16.16	1.18%
8	19.90±0.011	20.15	20.1	20.08	20.11	1.00%
10	24.10±0.011	24.03	24.1	24.05	24.1	0.00%

Table 8. Conversion coefficients from photon fluence to personal dose equivalent in (pSv·cm²) for angles of incidence from 0° to a 30°, in terms of absorbed dose.

Energy (MeV)	0°		15°		30°	
	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work
0.015	0.93±0.02	0.93	0.92±0.03	0.92	0.79±0.02	0.68
0.02	1.12±0.012	1.11	1.08±0.04	1.08	1.02±0.02	0.97
0.03	0.86±0.03	0.86	0.830±0.017	0.82	0.80±0.013	0.78
0.04	0.67±0.02	0.68	0.66±0.009	0.65	0.66±0.014	0.63
0.05	0.58±0.012	0.59	0.580±0.01	0.58	0.55±0.012	0.55
0.06	0.57±0.017	0.56	0.530±0.021	0.56	0.54±0.013	0.53
0.08	0.580±0.019	0.58	0.600±0.012	0.59	0.57±0.014	0.57
0.1	0.67±0.012	0.66	0.680±0.014	0.67	0.64±0.015	0.65
0.15	0.950±0.015	0.94	0.940±0.017	0.95	0.96±0.013	0.94
0.2	1.270±0.016	1.26	1.25±0.012	1.25	1.30±0.017	1.26
0.3	1.840±0.02	1.89	1.860±0.017	1.86	1.86±0.015	1.88
0.4	2.480±0.013	2.48	2.520±0.015	2.44	2.49±0.016	2.46
0.5	2.970±0.017	3.03	2.99±0.012	2.98	3.11±0.017	3.00
0.6	3.51±0.017	3.54	3.370±0.017	3.49	3.49±0.018	3.50
0.8	4.630±0.013	4.46	4.400±0.014	4.42	4.34±0.019	4.40
1	5.200±0.017	5.29	5.340±0.014	5.27	5.22±0.02	5.22
1.5	7.050±0.013	7.06	7.120±0.015	7.14	7.08±0.009	7.01
3	10.500±0.021	10.50	10.400±0.016	10.40	10.63±0.021	10.62
6	8.810±0.019	8.81	9.030±0.018	9.03	10.75±0.013	10.76
10	8.07±0.012	8.07	8.48±0.012	8.48	8.52±0.013	8.52

Table 9. Conversion coefficients from photon fluence to personal dose equivalent in (pSv·cm²) for angles of incidence from 45° to 75°, in terms of absorbed dose.

Energy (MeV)	45°		60°		75°	
	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work
0.015	0.56±0.009	0.47	0.26±0.009	0.26	0.04±0.02	0.04
0.02	0.86±0.009	0.80	0.61±0.009	0.54	0.21±0.01	0.21
0.03	0.75±0.02	0.72	0.63±0.02	0.61	0.36±0.02	0.36
0.04	0.59±0.02	0.56	0.540±0.017	0.49	0.35±0.015	0.35
0.05	0.54±0.013	0.48	0.48±0.010	0.43	0.32±0.019	0.33
0.06	0.49±0.014	0.46	0.44±0.019	0.43	0.34±0.019	0.33
0.08	0.54±0.013	0.51	0.490±0.017	0.49	0.360±0.017	0.36
0.1	0.65±0.012	0.62	0.59±0.018	0.58	0.45±0.018	0.44
0.15	0.92±0.014	0.95	0.87±0.017	0.86	0.67±0.017	0.68
0.2	1.25±0.011	1.28	1.13±0.016	1.16	0.95±0.017	0.95
0.3	1.86±0.013	1.90	1.87±0.015	1.75	1.48±0.017	1.51
0.4	2.51±0.014	2.47	2.42±0.014	2.32	2.04±0.017	2.05
0.5	2.91±0.012	2.99	2.90±0.013	2.86	2.67±0.018	2.58
0.6	3.39±0.014	3.49	3.40±0.012	3.39	3.06±0.019	3.09
0.8	4.44±0.015	4.43	4.42±0.012	4.44	4.06±0.017	4.06
1	4.99±0.016	5.29	5.23±0.014	5.20	4.83±0.015	4.85
1.5	7.24±0.017	7.17	7.070±0.017	7.13	6.81±0.014	6.83
3	10.50±0.009	10.58	11.00±0.008	10.99	10.99±0.013	10.99
6	12.40±0.012	12.32	14.45±0.02	14.44	15.62±0.008	15.63
10	12.20±0.018	12.24	15.490±0.017	15.49	19.52±0.010	19.61

Table 10. Conversion coefficient from photon fluence to personal dose equivalent in (pSv·cm²) for angles of incidence from 0° to a 15°, in terms of Kerma approximation and relative differences.

Energy (MeV)	0°				15°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.93±0.010	0.82	0.82	11.52%	0.91±0.013	0.80	0.8	12.88%
0.02	1.12±0.011	1.06	1.06	5.66%	1.08±0.013	1.04	1.04	3.52%
0.03	0.86±0.011	0.82	0.82	3.85%	0.83±0.012	0.81	0.81	2.18%
0.04	0.66±0.012	0.65	0.65	1.32%	0.66±0.011	0.64	0.64	1.85%
0.05	0.57±0.013	0.57	0.58	0.54%	0.58±0.012	0.56	0.57	1.32%
0.06	0.56±0.014	0.55	0.55	1.96%	0.53±0.011	0.54	0.54	2.77%
0.08	0.58±0.015	0.59	0.58	0.00%	0.59±0.012	0.58	0.58	2.44%
0.1	0.66±0.016	0.67	0.67	0.31%	0.67±0.012	0.67	0.66	1.34%
0.15	0.94±0.017	0.96	0.95	1.26%	0.93±0.013	0.95	0.95	1.54%
0.2	1.26±0.017	1.27	1.27	0.70%	1.24±0.013	1.27	1.27	1.86%
0.3	1.83±0.018	1.88	1.89	3.16%	1.86±0.014	1.88	1.89	1.67%
0.4	2.45±0.019	2.46	2.46	0.23%	2.51±0.014	2.46	2.47	1.86%
0.5	3.00±0.010	2.99	3	0.13%	2.99±0.015	3.00	3.02	0.99%
0.6	3.49±0.011	3.49	3.46	0.88%	3.38±0.015	3.50	3.47	2.91%
0.8	4.54±0.012	4.40	4.41	2.75%	4.23±0.016	4.41	4.42	4.39%
1	5.33±0.012	5.22	5.23	1.82%	5.33±0.012	5.23	5.23	1.94%
1.5	7.05±0.013	6.99	6.99	0.80%	6.74±0.012	7.00	7.01	3.90%
3	11.10±0.013	11.09	11.11	0.13%	11.47±0.010	11.46	11.17	2.63%
6	17.74±0.013	18.08	18.08	1.93%	17.99±0.011	18.14	18.13	0.77%
10	26.60±0.014	26.66	26.66	0.24%	25.55±0.012	26.62	26.61	4.16%

Table 11. Conversion coefficient from photon fluence to personal dose equivalent in (pSv·cm²) for angles of incidence from 30° to a 45°, in terms of Kerma approximation and relative differences.

Energy (MeV)	30°				45°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.79±0.013	0.68	0.68	13.96%	0.57±0.009	0.47	0.47	16.08%
0.02	1.01±0.013	0.97	0.97	4.87%	0.86±0.009	0.81	0.81	6.01%
0.03	0.80±0.013	0.78	0.78	1.86%	0.74±0.02	0.70	0.71	3.96%
0.04	0.66±0.013	0.63	0.63	4.64%	0.59±0.02	0.58	0.58	1.09%
0.05	0.54±0.013	0.56	0.56	2.51%	0.53±0.013	0.52	0.51	3.34%
0.06	0.54±0.014	0.53	0.53	0.80%	0.48±0.014	0.50	0.5	3.65%
0.08	0.57±0.014	0.56	0.56	1.31%	0.54±0.013	0.53	0.53	1.11%
0.1	0.63±0.013	0.65	0.65	2.62%	0.64±0.012	0.61	0.62	3.68%
0.15	0.95±0.013	0.94	0.94	1.78%	0.92±0.014	0.90	0.9	1.95%
0.2	1.28±0.012	1.26	1.26	1.92%	1.24±0.011	1.22	1.22	2.06%
0.3	1.84±0.011	1.88	1.88	2.34%	1.86±0.013	1.85	1.86	0.31%
0.4	2.47±0.011	2.46	2.46	0.23%	2.48±0.014	2.45	2.44	1.78%
0.5	3.08±0.011	3.00	3.01	2.20%	2.96±0.012	3.00	3	1.60%
0.6	3.55±0.012	3.49	3.47	2.15%	3.42±0.014	3.51	3.47	1.47%
0.8	4.37±0.013	4.41	4.43	1.31%	4.43±0.015	4.43	4.45	0.27%
1	5.35±0.014	5.23	5.21	2.65%	5.01±0.016	5.26	5.28	5.20%
1.5	7.24±0.015	7.00	7.01	3.17%	6.85±0.017	7.04	7.04	2.71%
3	10.62±0.016	11.23	11.23	5.72%	11.00±0.009	11.09	11.09	0.84%
6	17.15±0.019	18.13	18.13	5.75%	17.20±0.012	17.94	17.93	4.26%
10	25.44±0.010	26.53	26.53	4.30%	25.70±0.018	26.37	26.37	2.61%

Table 12. Conversion coefficient from photon fluence to personal dose equivalent in (pSv·cm²) for angles of incidence from 60° to a 75°, in terms of Kerma approximation and relative differences.

Energy (MeV)	60°				75°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.26±0.009	0.26	0.21	16.92%	0.04±0.02	0.02	0.02	29.57%
0.02	0.61±0.010	0.55	0.55	9.73%	0.21±0.010	0.19	0.18	16.63%
0.03	0.62±0.02	0.59	0.59	5.51%	0.36±0.02	0.33	0.34	4.90%
0.04	0.53±0.017	0.50	0.5	6.75%	0.35±0.015	0.33	0.32	6.98%
0.05	0.45±0.010	0.45	0.45	0.74%	0.32±0.019	0.31	0.3	5.20%
0.06	0.43±0.019	0.44	0.44	1.04%	0.33±0.019	0.30	0.31	7.40%
0.08	0.49±0.017	0.47	0.47	4.31%	0.35±0.017	0.34	0.34	2.94%
0.1	0.58±0.018	0.56	0.56	4.35%	0.42±0.018	0.41	0.41	3.62%
0.15	0.87±0.017	0.83	0.83	4.21%	0.68±0.017	0.65	0.64	4.66%
0.2	1.13±0.016	1.14	1.14	1.52%	0.95±0.017	0.92	0.92	3.30%
0.3	1.85±0.015	1.76	1.76	5.10%	1.48±0.017	1.47	1.46	1.65%
0.4	2.41±0.014	2.34	2.35	2.71%	2.05±0.017	2.00	2	2.29%
0.5	2.88±0.013	2.89	2.91	0.74%	2.64±0.018	2.52	2.54	3.66%
0.6	3.40±0.012	3.41	3.37	0.72%	3.05±0.019	3.02	3	1.47%
0.8	4.45±0.012	4.34	4.36	2.15%	4.10±0.017	3.93	3.94	3.97%
1	5.23±0.014	5.18	5.18	1.03%	4.87±0.015	4.76	4.76	2.39%
1.5	6.91±0.017	6.97	6.97	0.89%	6.90±0.014	6.53	6.53	5.38%
3	11.01±0.008	11.09	11.09	0.77%	10.46±0.013	10.65	10.65	1.78%
6	17.54±0.02	18.02	18.02	2.75%	17.33±0.008	17.99	17.99	3.77%
10	26.16±0.017	26.45	26.45	1.13%	24.89±0.010	25.77	25.76	3.48%

Table 13. Conversion coefficients from photon air Kerma to personal dose equivalent in (Sv/Gy) for angles of incidence from 0° to a 30°, in terms of absorbed dose.

Energy (MeV)	0°		15°		30°	
	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work
0.015	0.30±0.02	0.28	0.29±0.03	0.28	0.25±0.02	0.27
0.02	0.65±0.012	0.58	0.62±0.012	0.57	0.59±0.02	0.55
0.03	1.16±0.03	1.11	1.12±0.017	1.09	1.08±0.013	1.10
0.04	1.52±0.02	1.52	1.51±0.009	1.49	1.50±0.014	1.49
0.05	1.78±0.012	1.76	1.78±0.010	1.74	1.68±0.012	1.72
0.06	1.95±0.017	1.87	1.84±0.021	1.86	1.86±0.013	1.82
0.08	1.92±0.019	1.89	1.96±0.012	1.89	1.88±0.014	1.84
0.1	1.82±0.012	1.82	1.84±0.014	1.81	1.73±0.015	1.78
0.15	1.60±0.015	1.63	1.59±0.017	1.62	1.62±0.013	1.62
0.2	1.48±0.016	1.50	1.46±0.012	1.49	1.52±0.017	1.51
0.3	1.33±0.02	1.36	1.35±0.017	1.36	1.35±0.015	1.38
0.4	1.31±0.013	1.29	1.33±0.015	1.29	1.32±0.016	1.31
0.5	1.24±0.017	1.25	1.25±0.012	1.25	1.30±0.017	1.27
0.6	1.24±0.017	1.22	1.20±0.017	1.22	1.24±0.018	1.24
0.8	1.25±0.013	1.19	1.19±0.014	1.19	1.17±0.019	1.19
1	1.16±0.017	1.18	1.19±0.014	1.17	1.17±0.012	1.17
1.5	1.15±0.013	1.16	1.16±0.015	1.15	1.15±0.009	1.15
3	1.06±0.021	1.12	1.05±0.016	1.11	1.07±0.021	1.10
6	0.54±0.019	0.56	0.55±0.018	0.55	0.66±0.013	0.66
10	0.33±0.012	0.35	0.35±0.012	0.35	0.35±0.013	0.35

Table 14. Conversion coefficients from photon air Kerma to personal dose equivalent in (Sv/Gy) for angles of incidence from 45° to a 75°, in terms of absorbed dose.

Energy (MeV)	45°		60°		75°	
	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work	EGSnrc	Analytical fits in this work
0.015	0.18±0.01	0.20	0.08±0.01	0.07	0.01±0.01	0.00
0.02	0.50±0.01	0.48	0.35±0.01	0.36	0.12±0.01	0.14
0.03	1.01±0.01	1.01	0.85±0.01	0.85	0.48±0.01	0.46
0.04	1.35±0.01	1.38	1.22±0.01	1.20	0.79±0.01	0.79
0.05	1.65±0.01	1.61	1.40±0.01	1.41	0.99±0.01	1.02
0.06	1.68±0.01	1.72	1.50±0.01	1.53	1.16±0.01	1.13
0.08	1.78±0.01	1.77	1.62±0.01	1.60	1.18±0.01	1.18
0.1	1.76±0.01	1.73	1.59±0.01	1.58	1.13±0.01	1.16
0.15	1.56±0.01	1.59	1.46±0.01	1.46	1.14±0.01	1.12
0.2	1.47±0.01	1.49	1.32±0.01	1.38	1.12±0.01	1.10
0.3	1.35±0.01	1.36	1.35±0.01	1.30	1.07±0.01	1.09
0.4	1.33±0.01	1.29	1.28±0.01	1.26	1.08±0.01	1.09
0.5	1.22±0.01	1.24	1.21±0.01	1.23	1.12±0.01	1.09
0.6	1.20±0.01	1.21	1.21±0.01	1.21	1.08±0.01	1.09
0.8	1.20±0.01	1.16	1.19±0.01	1.19	1.09±0.01	1.09
1	1.11±0.01	1.12	1.17±0.01	1.18	1.08±0.01	1.09
1.5	1.18±0.01	1.18	1.15±0.01	1.14	1.11±0.01	1.10
3	1.06±0.01	1.07	1.11±0.01	1.10	1.10±0.01	1.10
6	0.76±0.01	0.76	0.89±0.01	0.89	0.96±0.01	0.96
10	0.51±0.01	0.51	0.64±0.01	0.64	0.81±0.01	0.81

Table 15. Conversion coefficient from photon air Kerma to personal dose equivalent in (Sv/Gy), for angles of incidence from 0° to a 15°, in terms of Kerma-approximation and relative differences.

Energy (MeV)	0°				15°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.30±0.010	0.26	0.26	11.52%	0.29±0.013	0.26	0.26	12.88%
0.02	0.65±0.011	0.61	0.61	5.66%	0.62±0.013	0.60	0.6	3.52%
0.03	1.16±0.011	1.11	1.11	3.85%	1.12±0.012	1.09	1.09	2.18%
0.04	1.51±0.012	1.50	1.49	1.32%	1.50±0.011	1.47	1.47	1.85%
0.05	1.76±0.013	1.76	1.77	0.54%	1.77±0.012	1.74	1.74	1.32%
0.06	1.93±0.014	1.89	1.89	1.96%	1.82±0.011	1.88	1.87	2.77%
0.08	1.90±0.015	1.90	1.9	0.00%	1.94±0.012	1.90	1.9	2.44%
0.1	1.81±0.016	1.81	1.81	0.31%	1.82±0.012	1.80	1.8	1.34%
0.15	1.59±0.017	1.61	1.61	1.26%	1.58±0.013	1.60	1.6	1.54%
0.2	1.48±0.017	1.49	1.49	0.70%	1.46±0.013	1.49	1.49	1.86%
0.3	1.33±0.018	1.37	1.37	3.16%	1.35±0.014	1.37	1.37	1.67%
0.4	1.30±0.019	1.30	1.3	0.23%	1.33±0.014	1.31	1.31	1.86%
0.5	1.25±0.010	1.26	1.26	0.13%	1.25±0.015	1.26	1.26	0.99%
0.6	1.24±0.011	1.23	1.23	0.88%	1.20±0.015	1.23	1.23	2.91%
0.8	1.22±0.012	1.19	1.19	2.75%	1.14±0.016	1.19	1.19	4.39%
1	1.19±0.012	1.17	1.17	1.82%	1.19±0.012	1.17	1.17	1.94%
1.5	1.15±0.013	1.14	1.14	0.80%	1.10±0.012	1.14	1.14	3.90%
3	1.12±0.013	1.12	1.12	0.13%	1.15±0.010	1.12	1.12	2.63%
6	1.09±0.013	1.11	1.11	1.93%	1.10±0.011	1.11	1.11	0.77%
10	1.11±0.014	1.11	1.11	0.24%	1.06±0.012	1.11	1.11	4.16%

Table 16. Conversion coefficient from photon air Kerma to personal dose equivalent in (Sv/Gy), for angles of incidence from 30° to a 45°, in terms of Kerma-approximation and relative differences.

Energy (MeV)	30°				45°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.25±0.013	0.22	0.22	13.96%	0.18±0.00	0.15	0.15	16.08%
0.02	0.59±0.013	0.56	0.56	4.87%	0.50±0.009	0.47	0.47	6.01%
0.03	1.08±0.013	1.06	1.06	1.86%	1.01±0.02	0.97	0.97	3.96%
0.04	1.50±0.013	1.43	1.43	4.64%	1.35±0.02	1.33	1.33	1.09%
0.05	1.66±0.013	1.69	1.7	2.51%	1.63±0.013	1.58	1.57	3.34%
0.06	1.85±0.014	1.83	1.83	0.80%	1.66±0.014	1.71	1.72	3.65%
0.08	1.87±0.014	1.85	1.85	1.31%	1.77±0.013	1.75	1.75	1.11%
0.1	1.72±0.013	1.76	1.76	2.62%	1.74±0.012	1.68	1.68	3.68%
0.15	1.61±0.013	1.58	1.58	1.78%	1.55±0.014	1.52	1.52	1.95%
0.2	1.51±0.012	1.48	1.48	1.92%	1.46±0.011	1.43	1.43	2.06%
0.3	1.33±0.011	1.36	1.36	2.34%	1.35±0.013	1.34	1.35	0.31%
0.4	1.30±0.011	1.30	1.3	0.23%	1.31±0.014	1.29	1.29	1.78%
0.5	1.29±0.011	1.26	1.26	2.20%	1.24±0.014	1.26	1.26	1.60%
0.6	1.26±0.012	1.23	1.23	2.15%	1.21±0.012	1.23	1.23	1.47%
0.8	1.18±0.013	1.19	1.19	1.31%	1.20±0.015	1.20	1.2	0.27%
1	1.19±0.014	1.17	1.16	2.65%	1.12±0.016	1.18	1.18	5.20%
1.5	1.18±0.015	1.14	1.14	3.17%	1.12±0.017	1.15	1.15	2.71%
3	1.07±0.016	1.12	1.13	5.72%	1.11±0.009	1.11	1.11	0.84%
6	1.05±0.019	1.11	1.11	5.75%	1.06±0.012	1.10	1.1	4.26%
10	1.06±0.010	1.11	1.11	4.30%	1.07±0.018	1.10	1.1	2.61%

Table 17. Conversion coefficient from photon air Kerma to personal dose equivalent in (Sv/Gy), for angles of incidence from 60° to a 75°, in terms of Kerma-approximation and relative differences.

Energy (MeV)	60°				75°			
	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %	EGSnrc	Analytical fits in this work	ICRU 57	Relative differences %
0.015	0.08±0.009	0.07	0.07	16.92%	0.01±0.02	0.01	0.008	29.57%
0.02	0.35±0.010	0.33	0.32	9.73%	0.12±0.010	0.10	0.102	16.63%
0.03	0.84±0.02	0.79	0.8	5.51%	0.48±0.02	0.46	0.457	4.90%
0.04	1.21±0.017	1.14	1.13	6.75%	0.79±0.015	0.74	0.736	6.98%
0.05	1.39±0.010	1.38	1.38	0.74%	0.98±0.019	0.92	0.929	5.20%
0.06	1.48±0.019	1.50	1.5	1.04%	1.11±0.019	1.05	1.061	4.53%
0.08	1.61±0.017	1.55	1.54	4.31%	1.16±0.017	1.12	1.130	2.94%
0.1	1.58±0.018	1.51	1.51	4.35%	1.15±0.018	1.11	1.108	3.62%
0.15	1.46±0.017	1.40	1.4	4.21%	1.14±0.017	1.09	1.088	4.66%
0.2	1.32±0.016	1.34	1.34	1.52%	1.12±0.017	1.07	1.080	3.30%
0.3	1.34±0.015	1.27	1.27	5.10%	1.07±0.017	1.06	1.055	1.65%
0.4	1.28±0.014	1.24	1.24	2.71%	1.08±0.017	1.06	1.058	2.29%
0.5	1.21±0.013	1.22	1.22	0.74%	1.10±0.018	1.06	1.063	3.66%
0.6	1.20±0.012	1.20	1.2	0.72%	1.08±0.019	1.06	1.064	1.47%
0.8	1.20±0.012	1.17	1.17	2.15%	1.11±0.017	1.06	1.061	3.97%
1	1.17±0.014	1.16	1.16	1.03%	1.09±0.015	1.06	1.062	2.39%
1.5	1.13±0.017	1.14	1.14	0.89%	1.12±0.014	1.06	1.064	5.38%
3	1.11±0.018	1.11	1.11	0.77%	1.05±0.013	1.07	1.070	1.78%
6	1.08±0.02	1.10	1.11	2.75%	1.06±0.008	1.07	1.103	3.77%
10	1.09±0.01	1.10	1.1	1.13%	1.04±0.010	1.08	1.073	3.48%