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Polish Journal of Medical Physics and Engineering
The Journal of Polish Society of Medical Physics
ISSN 1898-0309, doi: 10.2478/pjmpe-2022-0006

March 2022
Vol 28, Issue 1

Scientific Paper

Neutron conversion coefficients of ambient dose equivalent and personal dose equivalent

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(received 24 June 2021; revised 28 October and 18 November 2021; accepted 24 January 2022)

Abstract

Introduction: This work aims to calculate the ambient and personal dose equivalent conversion coefficients.
Material and methods: The conversion coefficients have been calculated using MC simulation. Additionally, this paper proposes a new method that depends on an analytical approach.
Results: The obtained results in good agreement between MC and an analytical approach were observed. The obtained results were compared to those published in ICRU 57 report.
Conclusions: We deduced that the analytical approach is as effective and suitable as the MC simulation to calculate the operational quantity conversion coefficients.

Keywords: $H^*(10)$; $H_p(10)$; neutrons; Monte Carlo; analytical fit.

Introduction

In order to implement the fundamental principles of limitation and optimization in practical radiological protection for workers and the general public, dosimeter quantities are required. For this purpose, the ICRP "International Commission on Radiological Protection" and the ICRU "International Commission on Radiation Units and Measurements" developed a system of protection quantities (equivalent dose for organs and tissues and effective dose) and operational quantities (ambient dose equivalent, directional dose equivalent and personal dose equivalent). Compliance with dose limits is expressed in terms of protection quantities and, for external radiation, is demonstrated by the determination of the appropriate operational quantity.[1-3] The quantities are related to basic physical quantities. It is necessary to use these conversion coefficients. The main characteristic of the protection quantities is that they are only calculable. So, the operational quantities seek to provide a reasonable estimate of the protection quantities.[4-10] The equivalent dose in the tissue or an organ, *H*, have given by:

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

Where:
$D_{T,R}$ is the main absorbed dose in the specified tissue or organ T from the radiation of type R. w_R is the radiation weight factor for neutron given by **Equation 2**.[11]

$$w_R = \begin{pmatrix} 2.5 + 18.2e^{\frac{-(ln(E_n))^2}{6}}, & E_n < 1MeV \\ 5.0 + 17.0e^{\frac{-(ln(2E_n))^2}{6}}, & 1MeV \le E_n \le 50MeV \\ 2.5 + 3.25e^{\frac{-(ln(0.04E_n))^2}{6}}, & E_n > 50MeV \end{pmatrix} \qquad \text{Eq. 2}$$

The dose equivalent, *H*, is the product of quality factor (Q) and dose equivalent (D) at a point in tissue,[10,11] by thus:

$$H = QD \qquad \text{Eq. 3}$$

The unit of dose equivalent is sievert (Sv).[11] Quality factor dependence of Q on (LET) (L) was given by ICRP. The quality factor Q at a point in tissue is:

$$Q = \frac{1}{D}\int_{L=0}^{\infty} Q(L) D_L dL \qquad \text{Eq. 4}$$

where D is the absorbed dose at that point, D_L is the distribution of D in unrestricted linear energy transfer L at the point of interest, and Q(L) is the quality factor as a function of L.[12]

The study aims to obtain a set of conversion coefficients relating to fluence to ambient and personal dose equivalent for monoenergetic neutrons energies from 10^{-9} to 200 MeV and from 10^{-9} to 20 MeV, respectively. We have used the MC GAMOS code and analytical approach to calculate the ambient and personal dose equivalent conversion coefficients. We concluded that the analytical approach is as effective and suitable as MC simulation to calculate the dose conversion coefficients.

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Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

Materials and methods

Monte Carlo simulation

GAMOS code

GAMOS (Geant4-based Architecture for Medicine-Oriented Simulations) is a GEANT4-based framework that is at the same time easy-to-use and flexible. The objective of GAMOS is to provide a software framework that serves the unexperienced user to simulate his project without having to code in C++ and with minimal knowledge of Geant4, and at the same time, let an advanced user add new functionalities and easily integrate it with the rest of GAMOS functionality.[13,14]

In this work, we implemented the GAMOS code (version 6.0.0) on Ubuntu 19.04.0 to calculate the fluence to ambient and personal dose equivalent conversion coefficients for monoenergetic neutron energies from 10^{-9} to 200 MeV and from 10^{-9} to 20 MeV, respectively.

The GAMOS code provides a physics list that includes all the electromagnetic processes. The use of different models (standard, low energy, or Penelope) can be selected for each particle type through a user command. The low energy model employs the evaluated data libraries from Lawrence Livermore National Laboratory, EPDL97 for photons, EEDL for electrons, and EADL for fluorescence and Auger effects.[13-16]

The neutron cross-section data for elastic, inelastic, capture, and fission processes are available with the G4NDL dataset derived from the recent ENDF database.[16,17] This data is used with all HP models. The physics list G4QGSP_BIC_HP was used for neutrons in this work.

Ambient and personal dose equivalent calculations

The $H^*(10)/\Phi$ and H_p $(10, \alpha)/\Phi$ conversion coefficients are the quantities recommended by the ICRU to be used as an approximation of the protection quantities.[1]

In this simulation, two phantoms were adopted, the ICRU sphere phantom diameter 30 cm for ambient dose equivalent and slab phantom $30 \times 30 \times 15$ cm^3 for personal dose equivalent. These phantoms consist of the ICRU tissue of density 1 g·cm^{-3} and are composed of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.[1,2,11,18,19] The number of particles about 1×10^8 were incident on the phantom, in order to have a statistical uncertainty lower than 1%.

An analytical fit

According to the **B**ritish **C**ommittee on **R**adiation **U**nits and Measurements (BCRU) memoranda,[20] the fluence to ambient dose equivalent for neutron were calculated by the following equation:

$$f(x) = \frac{a}{1+(b+cx)^2} + \frac{d}{1+exp(f-gx)} + \frac{h}{1+exp(j-kx)} \qquad \text{Eq. 5}$$

Where f(x) is the $\log_{10}(H^*(10)/\Phi)$, in pSv·cm^2, a = 1.02, b = 0.012, c = 0.208, d = 2.33, f = 9.56, g = 1.98, h = 0.187, j = 93.3, k = 13.1, and x = $\log_{10}$(Energy), with Energy in eV.

In previous works, the analytical fit for calculating the fluence to personal dose equivalent for neutron at different angles was not mentioned.

In this study, we propose a new equation to perform an analytical approach of our MC simulation calculated conversion coefficients for monoenergetic neutrons. The new analytical fit has been based on Levenberg Marquardt algorithm non-linear least squares to calculate the parameters of **Equation 6**.[21,22]

$$f(x) = \frac{\sum_{i=1}^{n+1} a_i \quad x^{n+1-i}}{x^m + \sum_{j=1}^{m} b_j \quad x^{m-j}} \qquad n, m = 5 \qquad \text{Eq. 6}$$

where:

f(x) is $H^*(10)/\Phi$ and $H_p(10, \alpha)/\Phi$ for neutrons.

x is the LOG_{10}(Energy), Energy in MeV for neutrons.

a_i, b_i $(i = 1,2,..6 \; and \; j = 1,2,..5)$, are the fit parameters of the conversion coefficients as summarized in **Tables 1** and **2**.

Results and discussion

Parameters of an analytical fit

Tables 1 and **2** show the analytical fit parameters of non-linear least squares for calculation of the conversion coefficients for neutrons by **Equation 6**. **Equation 6** and its fit parameters have been validated by comparison with the conversion coefficients calculated by MC simulation.

Ambient dose equivalent and personal dose equivalent for neutrons

Neutrons are not directly ionizing particles. By their interactions with matter, secondary charged particles such as recoil protons or electrons are produced. These secondary charged particles do not deposit their energy at the location of their creation. They deposit their energy continuously when slowing down via Coulomb interactions within the material. Those secondary charged particles are the contributors to the dose in the scoring volume.

The neutrons are divided into three groups, depending on their kinetic energy:[23]

· Thermal (E < 0.001×10^{-6} MeV) (0.025 eV)

· Intermediate (0.5×10^{-6} to 10^{-2} MeV)

· Fast (E >10^{-2} MeV)

Table 1. Analytical fit parameters of conversion coefficients for ambient dose equivalent and personal dose equivalent from 0° to 30° in step of 15° for neutrons.

Parameter	$H^*(10)$		$H_p(10,0°)$		$H_p(10,15°)$		$H_p(10,30°)$	
	10^{-9} - 0.1 MeV	0.15 - 200 MeV	10^{-9} - 0.1 MeV	0.15 - 20 MeV	10^{-9} - 0.1 MeV	0.15 - 20 MeV	10^{-9} - 0.1 MeV	0.15 - 20 MeV
a_1	6.408E+00	1.343E+00	2.34E+00	4.00E+01	5.50E+00	-4.16E+01	-1.56E+00	-7.66E+01
a_2	1.091E+02	2.934E+02	1.85E+01	2.68E+02	9.40E+01	4.63E+02	-4.78E+01	3.99E+02
a_3	5.436E+02	-9.807E+02	4.04E+01	-2.58E+02	7.25E+02	-5.50E+02	-3.82E+02	1.16E+01
a_4	1.563E+02	8.520E+01	-3.79E+02	-5.36E+02	2.42E+03	-6.02E+02	-1.63E+03	-8.26E+02
a_5	-2.717E+03	2.111E+03	-1.36E+03	8.11E+02	3.96E+03	1.46E+03	-3.26E+03	4.89E+02
a_6	-4.216E+03	-1.796E+03	-1.35E+03	-9.80E+01	2.46E+03	-6.69E+02	-2.49E+03	3.74E+02
b_1	1.628E+01	-4.718E+00	1.48E+01	-2.37E+00	1.38E+01	-3.16E+00	1.53E+01	-2.18E+00
b_2	8.617E+01	7.718E+00	8.15E+01	2.41E+00	6.94E+01	4.50E+00	8.99E+01	1.82E+00
b_3	1.517E+02	-7.257E+00	1.81E+02	-2.35E+00	1.27E+02	-4.82E+00	2.22E+02	-1.44E+00
b_4	1.366E+02	6.980E+00	1.80E+02	2.01E+00	9.70E+01	4.22E+00	2.44E+02	6.73E-01
b_5	3.562E+01	-4.371E+00	6.24E+01	-2.32E-01	2.98E+01	-1.61E+00	9.16E+01	8.77E-01

Table 2. Analytical fit parameters of conversion coefficients for personal dose equivalent from 45° to 75° step 15° for neutrons.

Parameter	$H_p(10,45°)$		$H_p(10,60°)$		$H_p(10,75°)$	
	10^{-9} - 0.1 MeV	0.15 - 20 MeV	10^{-9} - 0.1 MeV	0.15 - 20 MeV	10^{-9} - 0.1 MeV	0.15 - 20 MeV
a_1	6.85E+00	1.20E+02	2.01E+00	-1.59E+02	-1.39E+00	-8.67E+01
a_2	1.44E+02	2.05E+02	3.80E+01	4.62E+02	-3.31E+01	2.74E+02
a_3	1.11E+03	-3.46E+02	2.90E+02	-3.03E+01	-2.39E+02	-1.92E+02
a_4	3.65E+03	-3.86E+02	9.13E+02	-6.83E+02	-8.03E+02	-1.79E+02
a_5	5.65E+03	6.64E+02	1.39E+03	5.28E+02	-1.25E+03	3.94E+02
a_6	3.29E+03	1.40E+01	8.23E+02	8.45E+01	-7.49E+02	-1.90E+02
b_1	1.59E+01	-2.16E+00	1.51E+01	-3.22E+00	1.20E+01	-4.44E+00
b_2	8.58E+01	2.04E+00	8.15E+01	4.28E+00	5.72E+01	7.87E+00
b_3	1.61E+02	-2.03E+00	1.67E+02	-3.22E+00	1.13E+02	-7.27E+00
b_4	1.27E+02	1.66E+00	1.45E+02	1.34E+00	9.53E+01	3.91E+00
b_5	4.15E+01	3.55E-02	4.75E+01	2.55E-01	1.91E+01	-1.03E+00

For thermal neutrons:

The interaction of thermal neutrons with tissues, there are two types important:[23]

***^{14}N(n, p)^{14}C, neutron capture by nitrogen.**

Thermal neutrons interact within a short distance of the tissue surface. The dose to the surface tissue in the body is primarily due to the protons produced in the reaction ^{14}N(n, p)^{14}C.

The number of atoms for ^{14}N per gram of tissue, $(N_t/m)_{N\text{-}14} = 0.026 \times N_A/A = 1.12 \times 10^{21}$ atom/g, (1 g of ICRU tissue contains 0.026 g of ^{14}N atoms, $N_A = 6.022\times10^{23}$ mol^{-1}, A = 14.01 g·mol^{-1}).

The binding energies of a nitrogen nucleus (^{14}N) and a carbon nucleus (^{14}C) are 104.66 MeV and 105.29 MeV, respectively. Since the total binding energy of ^{14}C exceeds that of ^{14}N by 0.63 MeV. The cross-section for reaction ^{14}N(n, p)^{14}C is $\sigma_{N\text{-}14}$ = 1.84 barn/atom.[24]

The Kerma per unit thermal neutron fluence ϕ for the reaction ^{14}N(n, p)^{14}C is,

$K/\phi = \sigma_{N\text{-}14}\ (N_t/m)_{N\text{-}14}\ \overline{\Delta E_K} = 1.84 \times 10^{-24}$ (cm^2/atom) × 1.12×10^{21} (atom/g) × 0.63 MeV × 1.602×10^{-13} (J/MeV) = 2.079883×10^{-13} Gy·cm^{-2}/neutron = 0.2079883 pGy·cm^{-2}/neutron

***^{1}H(n, γ)^{2}H, neutron capture by hydrogen.**

The number of atoms for ^{1}H per gram of tissue, $(N_t/m)_{H\text{-}1} = 0.101 \times N_A/A = 6.08 \times 10^{22}$ atom/g, (1 g of ICRU tissue contains 0.101 g of H-1 atoms, $N_A = 6.022\times10^{23}$ mol^{-1}, A = 1 g·mol^{-1}).

The binding energies of a Hydrogen nucleus (^{1}H) and a Deuteron nucleus (^{2}H) are 0 and 2.22 MeV. The dose to the deeper tissues is due to the 2.22 MeV gamma rays from the reaction 1H(n, γ)2H. The cross-section for reaction 1H(n, γ)2H is $\sigma_{H\text{-}1}$ = 0.33 barn/atom.[24] The energy transfer to γ photons per thermal neutron fluence ϕ and per mass of tissue m for 1H(n, γ)2H:

$(E_\gamma/m)/\phi = \sigma_{H\text{-}1}\ (N_t/m)_{H\text{-}1}\ \Delta E_K = 0.33 \times 10^{-24}$ (cm^2/atom) × 6.08×10^{22} (atom/g) × 2.22 MeV × 1.602×10^{-13} (J/MeV) = 7.13564×10^{-12} Gy·cm^{-2}/neutron = 7.16457 pGy·cm^{-2}/neutron

The 7.16457 pGy·cm^{-2} value represents the energy transfer per thermal neutron fluence ϕ and per mass of tissue m that is transferred to γ photons.

The probability of capture by hydrogen by the interaction of thermal neutrons with tissues is larger than capture by nitrogen because the concentration (the number of atoms per gram of tissue) of H atoms over the N atoms is about 54 times more.[24]

For intermediate and fast neutrons:

The kinetic energy transfer ΔE_K from the neutron with mass m_n to tissue nucleus with mass *M*.

$$\Delta E_K = \frac{4m_n M}{(m_n+M)^2}(E_K)_n \cos^2\phi \qquad \text{Eq .7}$$

Where

$(E_K)_n$: is the kinetic energy of the incident neutron.

ϕ:is the recoil angle of the target M nucleus.

$(E_K)_{max}$, the maximum kinetic energy transfer, happens for $\phi = 0$ and is given as follows:

$$(\Delta E_K)\frac{4m_n M}{(m_n+M)^2}{}_{K n_{max}} \qquad \text{Eq .8}$$

The average energy transfer by elastic scattering from a neutron to tissue nucleus M is given by:

$$\overline{\Delta E_K} = \frac{4m_n M}{(m_n+M)^2}(E_K)_n \overline{\cos^2\phi} = \frac{2m_n M}{(m_n+M)^2}(E_K)_n = \frac{1}{2}(\Delta E_K)_{max} \qquad \text{Eq. 9}$$

$$\overline{\cos^2\phi} = \frac{\int_0^{\frac{\pi}{2}} \cos^2\phi \, d\phi}{\int_0^{\frac{\pi}{2}} d\phi} = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} \frac{1+\cos(2\phi)\, d(\phi)}{2} = \frac{1}{2} \qquad \text{Eq. 10}$$

In **Table 3**, the average energy $\overline{\Delta E_K}$ transferred to recoil nucleus *M* in tissue in elastic scattering depends on the nuclear mass *M* and ranges from 0.5 $(E_K)_n$ for H-1; 0.14 $(E_K)_n$ for C-12; 0.12 $(E_K)_n$ for N-14, and 0.11 $(E_K)_n$ for O-16. For monoenergetic neutrons up to approximately 10 keV, the absorbed dose in the depths of the body comes from the secondary photons. The absorbed dose comes from 2.22 MeV photons emitted during $^1H(n, \gamma)^2H$ reaction, represent approximately 90% at a depth of 10 mm in the body, as photons deposit their energy via electrons and positrons, as shown in **Figure 1**.[11]

In **Figure 1**, (~10%) of the absorbed dose comes during $^{14}N(n, p)^{14}C$ reaction, protons, and ^{14}C recoil nuclei deposit their energy. The absorbed dose contribution of the photons falls sharply at neutron energies above 10 keV (the relative contribution of the absorbed dose is less than 20% at 1 MeV).

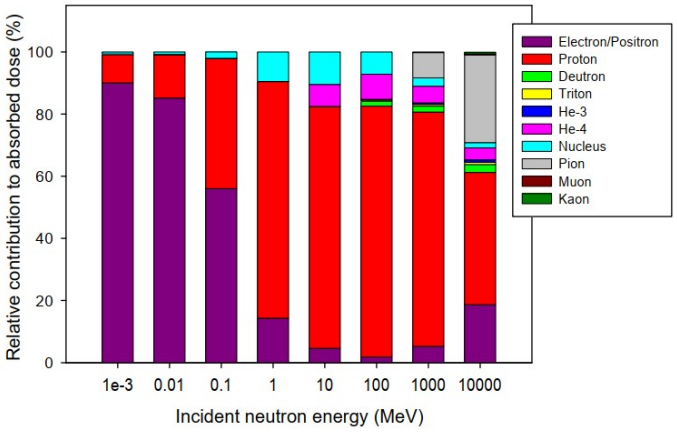


Figure 1. Relative energy deposition by neutrons in the human body.[11]

Above approximately 1 keV energies, the depose of energies become important by the recoil proton from elastic scattering. The largest dose from neutrons at these energies is due to elastic scattering with hydrogen in the reaction $^1H(n, n')^1H$. Whereas at the energies above a few MeV, the charged particle production by reaction of nuclear becomes an increasingly important mechanism for the deposition of incident neutron energy. At most, inelastic scattering contributes a few percent of the total dose. Above 20 MeV, nuclear reactions, especially with oxygen, become significant and can contribute 20% of the total dose. Spallation, the fragmentation of nuclei, becomes significant at 100 MeV where it might contribute 20% of the total dose. As the incident energy of the neutrons increases, various secondary particles emitted in inelastic nuclear reactions play an important part in the distribution of absorbed dose to internal organs.

For intermediate and fast energy neutrons (high energy), scattering interactions are more likely than capture interactions. Varying amounts of energy are transferred to the hydrogen nucleus (a proton). The fast neutron interactions with oxygen and carbon, so; elastic scattering involving oxygen and to a lesser extent, carbon and nitrogen might contribute 1% to 20% of the total dose. The interaction between neutrons and hydrogen nuclei is the dominant process of energy transfer in soft tissues.

Table 3. Parameters of tissue constituents relevant to neutron absorption and scattering.

ICRU Tissue compounds	Abundance (% by mass)	Abundance (atoms/g) of tissue	$\frac{(\Delta E_K)_{max}}{(E_K)_n}$	Abundance (relative to hydrogen)	$\overline{\Delta E_K}$ in % of $(E_K)_n$
Hydrogen-1	10.1	6.08E+22	1.000	1.000	0.50
Carbon-12	11.1	3.76E+22	0.286	0.092	0.14
Nitrogen-14	2.6	1.12E+21	0.251	0.018	0.13
Oxygen-16	76.2	2.87E+22	0.223	0.472	0.11

Figure 2 presents the curves of conversion coefficients from fluence to ambient dose equivalent for monoenergetic neutron. **Figure 3** presents the curves of Conversion coefficients from fluence to personal dose equivalent for incidents angles from 0° to 75° in the step of 15° for monoenergetic neutron. The $H^*(10)/\Phi$ and $H_p(10, \alpha)/\Phi$, (α: from 0° to 75° in the step of 15°) values are given in **Table 4**.

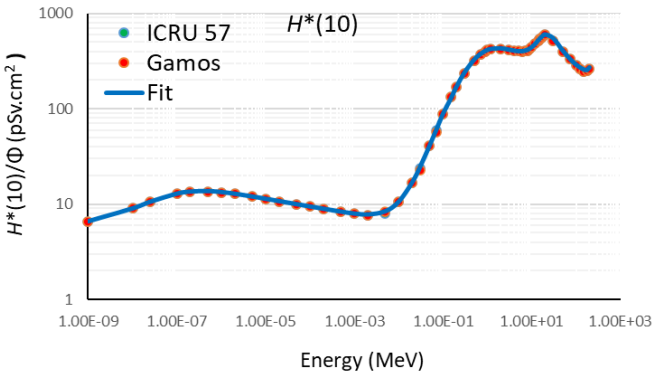


Figure 2. Neutron conversion coefficients *H(10) from fluence to ambient dose equivalent**

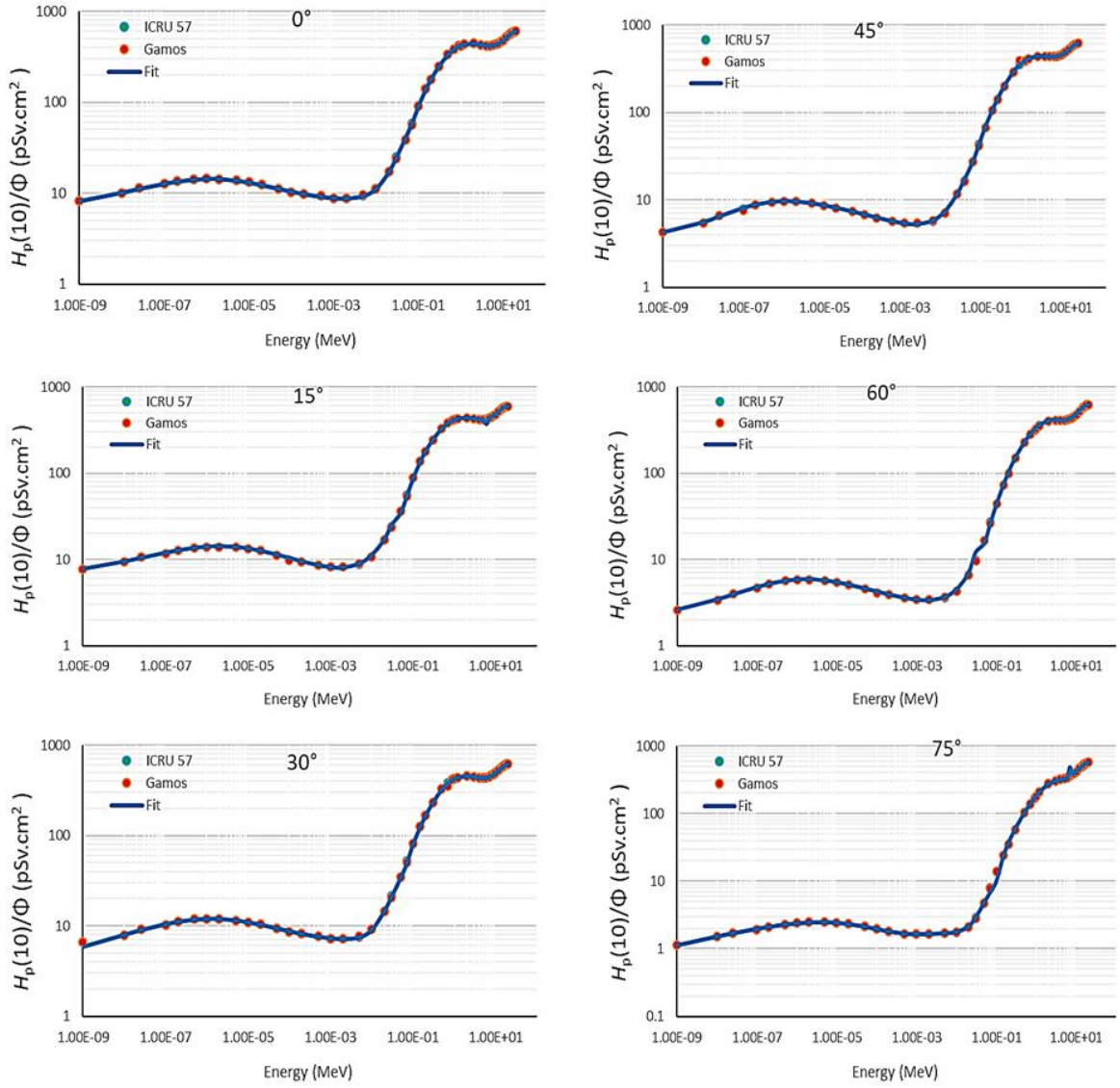


Figure 3. Neutron conversion coefficients from fluence to personal dose equivalent for the angle incidence from 0° to 75° in steps of 15°.

Table 4. Conversion coefficients from fluence to ambient dose equivalent and personal dose equivalent for monoenergetic neutron $H^*(10)/\Phi$ and $H_p(10, \alpha)/\Phi$ in (pSv·cm^2).

Energy (MeV)	$H^*(10)$	H_p (10, 0°)	H_p(10, 15°)	H_p (10, 30°)	H_p (10, 45°)	H_p (10, 60°)	H_p (10, 75°)
1.00E-09	6.601065	8.19074883	7.640662	6.570626	4.230559	2.610354	1.130138
1.00E-08	9.001402	9.971060	9.350960	7.900981	5.380992	3.370559	1.500186
2.53E-08	10.600657	11.400573	10.600580	9.110504	6.610542	4.040311	1.730105
1.00E-07	12.899996	12.599996	11.699994	10.300001	7.539996	4.699999	1.940000
2.00E-07	13.500002	13.500002	12.599990	11.099992	8.730005	5.210003	2.119999
5.00E-07	13.600005	14.199976	13.499973	11.799973	9.399969	5.649987	2.309993
1.00E-06	13.299998	14.399990	13.899997	11.999991	9.559982	5.819987	2.399998
2.00E-06	12.904602	14.299247	13.996336	11.899351	9.488748	5.848423	2.458774
5.00E-06	11.999992	13.799991	13.900007	11.500009	9.110006	5.710002	2.480004
1.00E-05	11.300003	13.200018	13.400021	11.000018	8.650016	5.470007	2.440000
2.00E-05	10.600734	12.400172	12.599839	10.400058	8.099950	5.139929	2.349899
5.00E-05	9.913359	11.213283	11.211867	9.430625	7.329187	4.575358	2.161183
1.00E-04	9.40792	10.31247	9.86652	8.65046	6.74817	4.10613	1.99208
2.00E-04	8.89999	9.83999	9.41000	8.22000	6.21000	3.91000	1.83000
5.00E-04	8.30001	9.34000	8.66001	7.66001	5.67001	3.58001	1.68000
1.00E-03	7.9003	8.7804	8.2004	7.2903	5.4303	3.4602	1.6601
2.00E-03	7.7000	8.7200	8.2200	7.2700	5.4300	3.4600	1.6700
5.00E-03	8.2833	9.5552	8.9671	7.6314	5.8296	3.6598	1.7067
1.00E-02	10.5000	11.2000	10.79999	9.180005	7.089989	4.319996	1.7700
2.00E-02	16.6000	17.1000	17.0000	14.6000	11.6	6.640002	2.109996
3.00E-02	22.8239	24.0396	23.2855	20.5436	16.10728	9.48182	2.808191
5.00E-02	41.0996	38.9996	35.9997	34.3996	27.4997	16.69984	4.779959
7.00E-02	57.2109	56.3308	53.2930	50.1715	40.89465	26.00131	7.746642
1.00E-01	88.0000	90.6001	87.8001	81.3000	67.10006	44.60006	13.69997
1.50E-01	131.9981	138.9976	136.9981	125.9983	105.9985	73.29895	24.19967
2.00E-01	169.9996	179.9994	178.9992	165.9995	140.9995	100.0000	35.4999
3.00E-01	232.9903	245.9899	243.9901	231.9900	200.9918	148.993	58.49726
5.00E-01	321.9996	334.9996	329.9999	326.0001	290.9997	225.9993	101.9999
7.00E-01	375.0000	386.0005	379.0005	351.9996	395.0008	278.9996	139.0001
9.00E-01	400.0003	414.0001	407.0002	415.0005	382.9992	317.0002	170.9993
1.00E+00	416.0001	421.9998	416.0001	426.0001	394.9995	332.001	180.0009
1.20E+00	424.7196	432.7214	426.7159	439.6404	411.571	354.4271	209.3118
2.00E+00	419.9995	442.000	437.9221	456.8752	438.9899	401.8846	273.8848
3.00E+00	411.9993	431.0002	429.0003	448.9999	439.9994	411.9993	305.9994
4.00E+00	408.0004	422.000	421.0001	440.0007	435.0002	408.9995	319.9998
5.00E+00	405.000	420.000	418.0005	436.9997	435.0005	408.9996	331.0002
6.00E+00	400.0007	423.000	422.0006	440.0007	439.0007	413.9999	345.0005
7.00E+00	404.9999	432.000	432.000	449.0004	447.9997	425.0004	361.0006
8.00E+00	408.9998	444.999326	444.9993	462.0001	459.9997	439.9996	379.0001
9.00E+00	419.9999	461.000431	462.0006	478.0001	475.9997	457.9999	398.9996
1.00E+01	440.0006	479.999817	481.0001	497.0003	493.0002	479.9998	421.0007
1.20E+01	480.00	517.000418	518.9997	536.0001	528.9997	523.0006	463.9999
1.40E+01	519.9996	549.999545	551.9998	570.0003	560.9995	562.0002	502.9999
1.50E+01	539.9999	563.999478	564.9997	584.0003	575.0001	579.0001	520.0002
1.60E+01	554.9999	576.000163	576.9994	596.9993	588.0003	592.999	532.999
1.80E+01	570.0002	595.000412	593.0007	617.0005	609.0006	614.9997	560.9999
2.00E+01	600.000	600.0001	595.0023	618.998	615.0028	618.998	569.9993
3.00E+01	515.000	-	-	-	-	-	-
5.00E+01	400.000	-	-	-	-	-	-
7.50E+01	330.000	-	-	-	-	-	-
1.00E+02	285.000	-	-	-	-	-	-
1.25E+02	260.000	-	-	-	-	-	-
1.50E+02	245.000	-	-	-	-	-	-
1.75E+02	250.000	-	-	-	-	-	-
2.01E+02	260.000	-	-	-	-	-	-

Figure 4 shows the conversion coefficient of ambient and personal dose equivalent from fluence for monoenergetic neutrons at incident angles from 0° to 75° in steps of 15°. According to **Figure 4**, the conversion coefficients for personal dose equivalent to fluence generally decrease with increasing the angle of incidence. For the effect of irradiation geometry, for example, the conversion coefficients for 1 MeV neutrons range from 416 to 180 pSv·cm^2, for phantoms simulating from 0° to 75°. The principal reason for this decrease is the long distance between the source and the volume of interest. As a result, the protection quantities for all irradiation geometries at energies ≤ 0.1 MeV must be significantly underestimated, especially at 60° and 75°. Also, we have to overestimate the protection quantities for all irradiation geometries at high energies (> 0.1 MeV).

These effects can be explained by the fact that the primary particles play a dominant role in the energy-deposition processes for low-energy neutron irradiations, while the secondary particles play a dominant role for high-energy neutron irradiations.[11]

The fluence of the primary particles decreases with increasing distance from the irradiation surface, while the fluence of the secondary particles increases. High neutron energy can trigger a cascade of secondary particles by inducing complex reactions successively in the human body.[11]

The obtained results in good agreement between MC and an analytical approach were observed. The obtained results were compared to those published in ICRU 57 report.

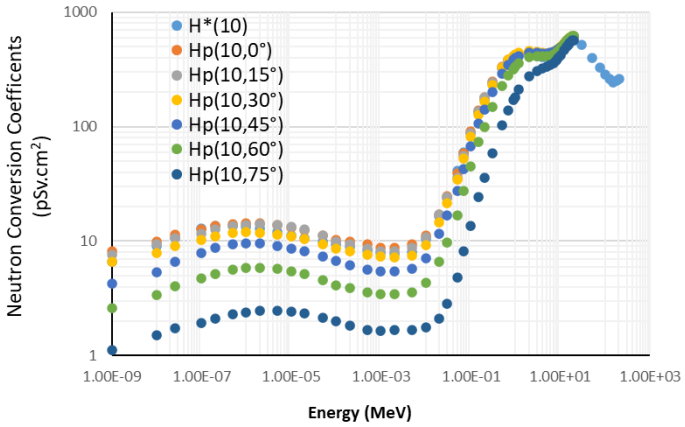


Figure 4. Neutron conversion coefficients for ambient and personal dose equivalent.

Conclusions

The neutron conversion coefficients have been calculated using MC, and a new analytical fit is applied to the data. The GAMOS code and an analytical fit have been validated for calculating the conversion coefficients for monoenergetic neutrons. At high energies, the maximum dose of conversion coefficients for monoenergetic neutron. As a result, we must overestimate the protection quantities for all irradiation geometries at high energies (≥ 0.1 MeV), including the whole body. Also, we must underestimate the protection quantities for all irradiation geometries at energies < 0.1 MeV, especially at incident angles of 60° and 75°. Our results in good agreement between MC and an analytical approach were observed. The new analytical fits provide a suitable process for determining discrete incidents for conversion coefficients.

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