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Spectrum-Averaged Neutron Fluence-to-Dose Conversion Coefficients of ^{252}Cf, $^{252}Cf/D_2O$, ^{241}AmB, $^{241}AmBe$ and $^{239}PuBe$ Neutron Sources, Using the New Dosimetric Quantities of ICRP/ICRU

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Abstract

The spectrum averaged neutron fluence-to-ambient dose conversion coefficient for ^{252}Cf, $^{252}Cf/D_2O$, ^{241}AmB, $^{241}AmBe$ and $^{239}PuBe$ neutron sources were calculated using the neutron fluence-to-dose conversion coefficients for the personal dose and the ambient dose which are the new dosimetric quantities, defined in the ICRP/ICRU joint report. One of the goals of defining these new dosimetric quantities is to harmonize the operational quantities with the protection quantities. By using Monte Carlo methods the spectra of the neutron sources and the total fluences were estimated, with the spectra and the neutron fluence-to- dose conversion coefficients the ambient and the personal dose were estimated. These values where normalized to the total neutron fluence to obtain the spectrum averaged neutron fluence-to-dose conversion coefficients that were compared with those obtained for the H*(10), $H_{p,s}(10,0°)$ and E_{AP} using the coefficients from the ICRP 74 and the ICRP 116. For 10^{-9} to 20 MeV neutrons, the new dosimetric quantities the operational and the protection quantities are harmonized.

Keywords

Neutron, Dose conversion coefficient, Personal dose, Ambient dose

Introduction

Living beings are exposed to ionizing radiation fields of natural and artificial origin. The uses and applications of ionizing radiation are very diverse and contribute to the well-being of the population. However, improper use of artificial radiation sources leads to unnecessary exposure, posing a risk to the exposed person.

The effects of exposure to ionizing radiation include reactions in the different tissues of the human body, known as Deterministic and Stochastic effects respectively. Stochastic effects include hereditary effects and the risk of inducing cancer. In the aim to reduce the risk of stochastic effects and to prevent the deterministic effects, the radiation protection defines limit annual doses evaluated by monitoring programs and supervised by radiation protection legislation [1].

The organ absorbed dose, equivalent dose and effective dose are protection quantities defined by the International Commission on Radiological Protection (ICRP) to act as optimization guidelines and to define dose limits for radiation workers and members of the public [2]. Protection dosimetric quantities are not-point quantities because are determined using anthropometric phantoms in order to determine the

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absorbed doses by organs and body tissues considering radiation weighting factors. On the other hand, protection quantities are not measurable, and the International Commission on Radiation Units and Measurements (ICRU) defined the ambient dose equivalent and the directional dose equivalent as operational quantities [3,4], which are measurable, whose values estimates the protection quantities [5]. Is worth to note that the operational dosimetric quantities are defined for external and internal exposure; for external exposure, operational quantities are used for the calibration of instruments and personal dosimeters [6].

External dose coefficients, traditionally known as fluence-to-dose conversion coefficients, are the link between the operational and protection quantities and the dosimetric and radiometric quantities, as is shown in equation (1) [7,8].

$$R = \int_0^\infty dE_s \int_{4\pi} d\hat{\Omega}_s \int_V R_s\left(\overline{r_s}, E_s, \hat{\Omega}_s\right)\Phi_s\left(\overline{r_s}, E_s, \hat{\Omega}_s\right) dV \qquad (1)$$

Here, R is the desired dosimetric quantity; the function $R_s\left(\overline{r_s}, E_s, \hat{\Omega}_s\right)$ represents the dosimetric quantity contribution, at point $\overline{r}$ in the target, due to a particle with energy E_s travelling in the $\hat{\Omega}_s$ direction per differential unit of path. The function $\Phi_s\left(\overline{r_s}, E_s, \hat{\Omega}_s\right)$ is the particle fluence (known as energy-and-angular fluence). In this equation, the target could be an area monitor, dosimeter, the human body, etc.

For external exposure, the desired dose at point $\overline{r}$ ($\Delta(\overline{r})$) is calculated using the fluence-to-dose conversion coefficients (δ (E)) and the equation (1) becomes equation (2).

$$\Delta\left(\overline{r}\right) = \int_{E_m}^{E_M} \Phi\left(\overline{r}, E\right)\, \delta\left(E\right) dE \qquad (2)$$

In this equation, $\Phi\left(\overline{r}, E\right)$ is the amount of particles at a point allocated in $\overline{r}$, with energy between E and E + dE, (from the lowest E_m energy to the largest E_M energy), also known as the particle spectrum.

Compared with another ways of producing neutrons, isotopic neutron sources, are inexpensive, small and easy to work with, their disadvantages includes the low neutron yield and that produce γ-rays. These sources includes those based on (α, n) and (γ, n) reactions and those that produce neutrons due to spontaneous fission [9].

Due to their neutron spectra and dosimetric features Bare ^{252}Cf, D_2O-moderated ^{252}Cf (^{252}Cf/D_2O), ^{241}AmBe and ^{241}AmB are widely used for the calibration of neutron area monitors and neutron dosimeters [10-12], as well as ^{239}PuBe [13,14]. In this endeavor, the knowledge of fluence-to-dose conversion coefficients and the neutron spectra are important to determine the dose [15,16]. The spectrum-averaged neutron fluence-to-dose conversion coefficient (δ_ϕ) characterize any neutron source used for calibration. The δ_ϕ is the dose per unit of neutron flux, and it is calculated as is shown in equation 3.

$$\delta_\varnothing = \frac{\int_{E_m}^{E_M} \delta\left(E\right)\Phi\left(E\right) dE}{\int_{E_m}^{E_M} \Phi\left(E\right)\, dE} \qquad (3)$$

In 1971 was published the first set of neutron fluence-to dose conversion coefficients by the National Council on Radiation Protection and Measurements. In both cases, was estimated the maximum absorbed dose equivalent in two phantoms: A 30 cm-thick semi-infinite slab and 30 Ø × 60 cm cylinder. Since then, other reports have come to light including updated sets of fluence-to-dose conversion coefficients for different dosimetric quantities, different phantoms and other particles. Recently, in a ICRP/ICRU joint report are included changes in the concept of operational quantities, particularly for individual and area monitoring where the two new dosimetric quantities are defined and the neutron fluence-to-dose conversion coefficients are calculated using the same anthropomorphic phantoms used in the calculation of neutron fluence-to-dose conversion coefficient for protection quantities [17].

In the ICRU report 95, the neutron fluence-to-dose conversion coefficients for operational quantities were calculated using the same phantoms as the protection coefficients; thus, operational quantities are now closely related to dosimetric protection quantities. In addition, is defined a new operational quantity: The ambient dose (H*) and the personal dose (Hp). For H* the conversion coefficients (h*(E)) relates the neutron spectrum with the maximum value of the effective dose (E_{max}) among all irradiation conditions; for Hp, the conversion coefficients (hp (E)) relates the neutron spectrum to the effective dose (E) [17]. Therefore, is important to calculate the value of the new dosimetric quantities per unit neutron fluence for the neutron sources that are widely used to calibrate the neutron area monitors and the dosimeters used for individual dosimetry.

The objective of this work was to calculate the spectrum-averaged neutron fluence-to-dose conversion coefficient of bare ^{252}Cf, ^{252}Cf/D_2O, ^{241}AmB, ^{241}AmBe and ^{239}PuBe neutron sources for the new dosimetric quantities: Ambient dose and personal dose recommended in ICRP/ICRU joint report 95 [17]; and to compare with the spectrum-averaged neutron fluence-to-dose conversion coefficients using the neutron fluence-to-dose conversion coefficients for H*(10), $H_{p,s}$(10,0°) from the ICRP publication 74 [18] and the E_{AP} from the ICRP publication 116 [19]. In addition, to evaluate the use of different spectra as source-term for the ^{241}AmBe neutron source.

Materials and Methods

With the Monte Carlo code, MCNP5 [20] was built a model having a point-like neutron source and a point-like detector in vacuum. The source-to-detector distance was 100 cm. The source term were the neutron spectra, $\Phi(E)$ of bare ^{252}Cf, ^{252}Cf/D_2O, ^{241}AmB, ^{241}AmBe and ^{239}PuBe neutron sources [14,15]. For the ^{241}AmBe source calculations were also carried out using as source term the spectrum from ISO [12].

With tally *F5* the neutron spectrum ($\Phi(E)$) and the total neutron fluence (Ø) in the detector were estimated. The spectrum was multiplied by the neutron fluence-to-ambient dose and personal dose (*h*(E), hp (E)*) conversion coefficients from the ICRU report 95, and integrated in energy [17].

The spectrum-averaged neutron fluence-to-ambient dose conversion coefficient for each neutron source was calculated using equation 4, and the spectrum-averaged neutron fluence-to-personal dose conversion coefficient was calculated using equation 5.

$$h^*_\phi = \frac{1}{\phi}\int_{E_m}^{E_M} \Phi(E)\, h^*(E)\; dE \qquad (4)$$

$$h_p = \frac{1}{\phi}\int_{E_m}^{E_M} \Phi(E)\, h_p(E)\; dE \qquad (5)$$

For each source 10^8 histories were used obtaining uncertainties from 0 to 0.02%. For comparison with the new dosimetric quantities, the same calculations were carried out using the neutron fluence-to-dose conversion factors from the ICRP publication 74 [18] and the ICRP publication 116 [19].

Results and Discussion

In Figure 1 are the neutron fluence-to-dose conversion coefficients for the new ICRU dosimetric quantities, $h_p(E)$ and h*(E). In addition, are included the dose coefficients for the ambient dose equivalent (*h*(10) (E)*), and the effective dose equivalent for anterior-posterior exposure ($e_{AP}(E)$).

From 10^{-9} to 50 MeV dose coefficients of operational quantities $h_p(E, 0°)$ and *h*(E)* are equal than the protection quantity $e_{AP}(E)$, for larger energies the *h*(E)* is larger, while $h_p(E,0°)$ remains the same as $e_{AP}(E)$. The goal of the new operational quantities of matching the protection quantities is satisfied.

In Table 1, is the spectrum-averaged neutron fluence-

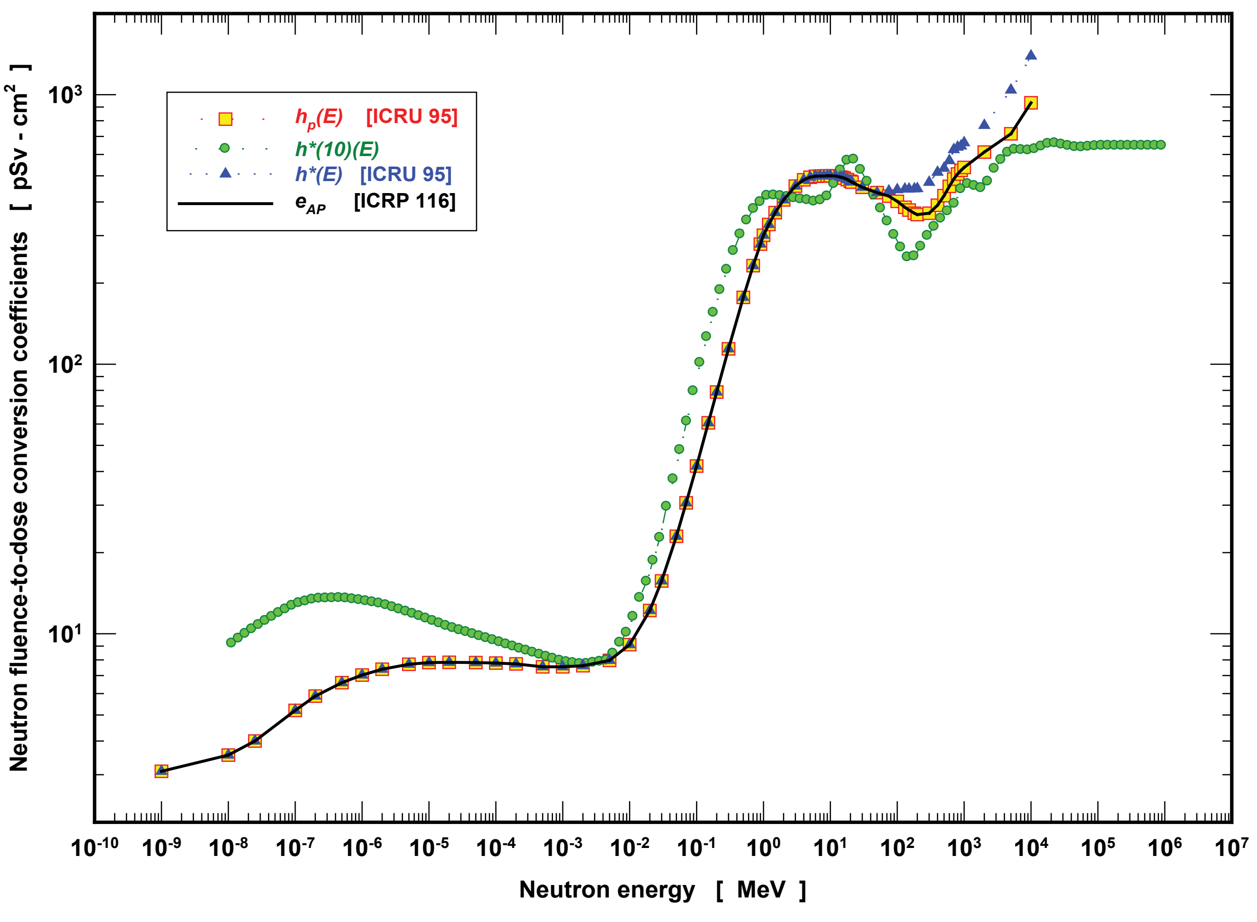

Figure 1: Dose coefficients.

Table 1: δ_ϕ for e_{AP}, h*(10), and $h_{p,s}$(10,0°) for ^{241}AmBe, ^{239}PuBe, ^{241}AmB, ^{252}Cf and ^{252}Cf/D$_2$O neutron sources using the ICRP publication 74 dose coefficients.

Quantity	^{241}AmBe [pSv-cm^2]	^{239}PuBe [pSv-cm^2]	^{241}AmB [pSv-cm^2]	^{252}Cf [pSv-cm^2]	^{252}Cf/D$_2$O [pSv-cm^2]	^{241}AmBe$^{(*)}$ [pSv-cm^2]
e_{AP}	392	441	392	309	90	412
h*(10)	391	412	417	373	102	392
$h_{p,s}$(10,0°)	408	433	435	387	106	412

(*) Using the ISO [12] spectrum as source term.

Table 2: δ_ϕ for e_{AP}, $h_p(0°)$, and h^* for ^{241}AmBe, ^{239}PuBe, ^{241}AmB, ^{252}Cf and ^{252}Cf/D_2O neutron sources using the ICRU report 95 dose coefficients.

Quantity	^{241}AmBe [pSv-cm^2]	^{239}PuBe [pSv-cm^2]	^{241}AmB [pSv-cm^2]	^{252}Cf [pSv-cm^2]	^{252}Cf/D_2O [pSv-cm^2]	^{241}AmBe$^{(*)}$ [pSv-cm^2]
e_{AP}	409	458	417	321	85	427
$h_p(0°)$	409	458	417	321	85	427
h*	409	458	417	321	85	427

(*) Using the ISO [12] spectrum as source term.

to-dose conversion coefficient for the effective dose for antero-posterior exposure (e_{AP}), the ambient dose equivalent ($h^*(10)$), and the personal dose equivalent ($h_{p,s}(10, 0°)$) using the ICRP 74 [18] neutron fluence-to-dose conversion coefficients, for the neutron sources.

Both operational values (h*(10) and $h_{p,s}(10,0°)$) are different from the protection values, and corrections are required during the calibration of personal dosimeters and neutron area monitors. The spectrum-averaged neutron fluence-to-ambient dose conversion coefficient varies as the neutron mean energy changes.

As source term were used the neutron spectra from the International Atomic Energy Agency [14,13]. Also, the ISO [12] ^{241}AmBe spectrum was used as source term. The neutron spectrum used as source term impact in the spectrum-averaged neutron fluence-to dose conversion coefficients. Using the ISO spectrum the coefficients are 5.10, 0.26, and 0.98% larger in comparison with coefficients calculated with the neutron spectra published by the IAEA.

In Table 2 is the spectrum-averaged neutron fluence-to-dose conversion coefficient for the effective dose for antero-posterior exposure (e_{AP}), the personal dose ($h_p(0°)$), and the ambient dose (h^*) using the ICRU Report 95 [17] neutron fluence-to-dose conversion coefficients, for the neutron sources.

For both new operational quantities, the spectrum-averaged neutron fluence-to-dose conversion coefficient, for the personal dose (hp (0°) and the ambient dose (h*) are equal to the effective dose for antero-posterior exposure (e_{AP}), which is a protection quantity: Fulfilling, the objective of the ICRP/ICRU joint report [17]. Due to this, the neutron fluence-to-dose conversion coefficients of the three dosimetric quantities are the same for 10^{-9} to 50 MeV neutrons (Figure 1).

For the three quantities, the δ_ϕ, using as source-term, the ^{241}AmBe spectrum from the ISO [12] is 4.4% larger in comparison of using the spectra from the IAEA [13,14]. For h* obtained with the ISO spectrum is the same reported by [21] using the ICRP/ICRU joint report draft.

Conclusions

In this work was calculated the spectrum-averaged neutron fluence-to-dose conversion coefficient of bare ^{252}Cf, ^{252}Cf/D_2O, ^{241}AmB, ^{241}AmBe and ^{239}PuBe neutron sources for Ambient dose and personal dose, which are new dosimetric quantities recommended by ICRP/ICRU joint report 95. These values, were compared with the spectrum-averaged neutron fluence-to-dose conversion coefficients using the neutron dose coefficients for H*(10), $H_{p,s}(10,0°)$ from the ICRP publication 74 and the E_{AP} from the ICRP publication 116. For the ^{241}AmBe source was evaluated the effect of using different spectra as source-term.

The use of the new dosimetric quantities for 10^{-9} to 20 MeV improves the coherence between operational and protection quantities.

The spectrum-averaged neutron fluence-to-dose conversion coefficients (δ_ϕ) of bare ^{252}Cf, ^{252}Cf/D_2O, ^{241}AmB, ^{241}AmBe, and ^{239}PuBe neutron sources are larger than the δ_ϕ obtained with the dose coefficients from the ICRP 74 and ICRP 116, because the new dosimetric quantities are based in different paradigm.

Regardless the dose coefficients, the use of different neutron spectrum, as source-term, for ^{241}AmBe, produces different δ_ϕ, being larger when the ISO spectrum is used in comparison of using the IAEA neutron spectra.

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