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OVERVIEW OF THE ICRP/ICRU ADULT REFERENCE COMPUTATIONAL PHANTOMS AND DOSE CONVERSION COEFFICIENTS FOR EXTERNAL IDEALISED EXPOSURES

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This paper reviews the ICRP Publications 110 and 116 describing the reference computational phantoms and dose conversion coefficients for external exposures. The International Commission on Radiological Protection (ICRP) in its 2007 Recommendations made several revisions to the methods of calculation of the protection quantities. In order to implement these recommendations, the DOCAL task group of the ICRP developed computational phantoms representing the reference adult male and female and then calculated a set of dose conversion coefficients for various types of idealised external exposures. This paper focuses on the dose conversion coefficients for neutrons and investigates their relationship with the conversion coefficients of the protection and operational quantities of ICRP Publication 74. Contributing factors to the differences between these sets of conversion coefficients are discussed in terms of the changes in phantoms employed and the radiation and tissue weighting factors.

INTRODUCTION

In order to implement the fundamental principles of limitation and optimisation in practical radiological protection for workers and the general public, dosimetric quantities are required. For this purpose, the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU) developed a system of protection quantities [1] (e.g. equivalent dose for organs and tissues and effective dose) and operational quantities [2] (e.g. ambient dose equivalent and personal dose equivalent). Compliance with dose limits is expressed in terms of protection quantities and, for external radiations, is demonstrated by determination of the appropriate operational quantity.

In 2007, the ICRP revised the basic recommendations of ICRP Publication 60 [3] (ICRP60) for a system of radiological protection. The 2007 Recommendations, issued in ICRP103 [4], updated the radiation and tissue weighting factors based on the latest information on radiobiological consequences of radiation exposure. Another important change is that doses from external and internal sources are calculated using the reference computational phantoms of the human body. The revisions in the methods for calculating protection quantities required re-calculation of the dose conversion coefficients to replace the existing ICRP and ICRU data sets.

This paper highlights some features of ICRP Publications 110 [5] and 116 [6], on computational phantoms and dose conversion coefficients for external exposures, which were published jointly with the ICRU. It focuses in particular on dose conversion coefficients for neutrons and investigates their relationship with the conversion coefficients of the protection and operational quantities of ICRP74 [7]/ICRU57 [8]. Contributing factors for differences between these sets of conversion coefficients are discussed in terms of the changes in the 2007 Recommendations.

MATERIALS AND METHODS

Procedures for determining protection quantities in the 2007 Recommendations

Figure 1 shows schematically the procedure for determining the effective dose as defined in the 2007 Recommendations. Absorbed doses in organs and tissues are assessed separately for males and females using the reference phantoms and then equivalent doses for the organs and tissues are calculated by applying the radiation weighting factors, w_{R}. The sex-averaged equivalent doses for a reference person are obtained by averaging

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male and female values, then weighted by the tissue weighting factors, w_{T}, and summed over all organs and tissues to obtain the effective dose, E. Tables 1 and 2 show the values of w_{R} and w_{T}, respectively. For neutrons, the values of w_{R} are defined by Eq. (1)–(3) in neutron energy, E_{n} (in MeV).

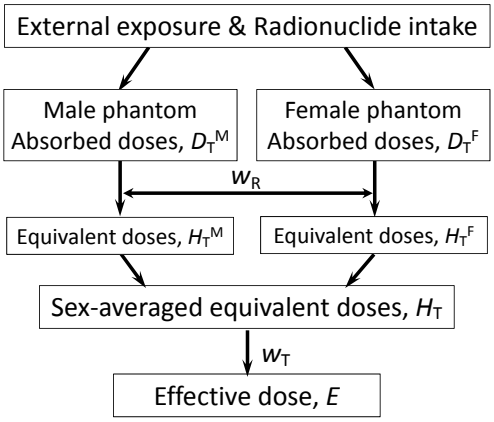

Figure 1. Schematic for calculation of effective dose as defined in the 2007 Recommendation of ICRP [4].

Table 1. Radiation weighting factors, w_{R}

Radiation type	w_{R}
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	Eq. (1)–(3)

$$E_{\mathrm{n}} < 1\ \mathrm{MeV}$$

$$w_{\mathrm{R}} = 2.5 + 18.2\, e^{-[\ln(E_{\mathrm{n}})]^2/6} \quad (1)$$

$$1\ \mathrm{MeV} \leq E_{\mathrm{n}} \leq 50\ \mathrm{MeV}$$

$$w_{\mathrm{R}} = 5.0 + 17.0\, e^{-[\ln(2E_{\mathrm{n}})]^2/6} \quad (2)$$

$$E_{\mathrm{n}} > 50\ \mathrm{MeV}$$

$$w_{\mathrm{R}} = 2.5 + 3.25\, e^{-[\ln(0.04E_{\mathrm{n}})]^2/6} \quad (3)$$

ICRP/ICRU reference computational phantoms

For the computation of organ-absorbed doses, the DOCAL (Dose Calculations) task group of the ICRP has developed adult computational phantoms, representing a reference male and a reference female. These reference phantoms, published jointly by the ICRP and ICRU in publication ICRP110 [5], are used for computation of the ICRP/ICRU reference conversion coefficients.

Table 2. Tissue weighting factors, w_{T}

Organ and tissue	w_{T}
Red bone marrow, colon, lung, stomach, breast, remainder tissues[1]	0.12
Gonads	0.08
Bladder, oesophagus, liver, thyroid	0.04
Endosteum (bone surface), brain, salivary glands, skin	0.01

[1] Remainder tissues: adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (male), small intestine, spleen, thymus, and uterus/cervix (female).

Figure 2 shows images of the reference computational phantoms. The phantoms are three-dimensional digital representations of the human anatomy and are based on computed tomographic data of real people. They are consistent with the information given in ICRP89 [9] for the anatomical reference parameters for male and female adults.

Each phantom is represented by a three-dimensional array of cuboid volume elements (voxel). Each entry in the array identifies the organ or tissue to which the corresponding voxel belongs. The male reference phantom consists of approximately 1.95 million tissue voxels (excluding voxels representing the surrounding vacuum), each with a slice thickness of 8.0 mm and an in-plane resolution of 2.137 mm. The body height and mass are 1.76 m and 73 kg, respectively. The female reference phantom consists of approximately 3.89 million tissue voxels, each with a slice thickness of 4.84 mm and an in-plane resolution of 1.775 mm. The body height and mass are 1.63 m and 60 kg, respectively. There are 136 individually segmented structures in each phantom with 53 different tissue compositions assigned to them. The tissue compositions account for both the elemental composition of the tissue parenchyma and each organ's blood content.

Calculation of conversion coefficients for organ-absorbed doses and effective doses

By using the reference phantoms, dose conversion coefficients for various types of idealised external exposures have been calculated and published in ICRP116 [6].

Absorbed doses for organs and tissues in the reference phantoms were calculated using the radiation transport codes EGSnrc [10], FLUKA [11], PHITS [12], MCNPX [13], and GEANT4 [14]. These codes are

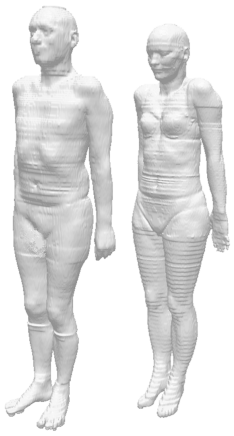

Figure 2. Images of the male (left) and female (right) reference computational phantoms of ICRP/ICRU.

three-dimensional Monte Carlo codes having the capability to describe repeated structure and lattice geometry for defining three-dimensional voxel phantoms. PHITS, FLUKA, MCNPX, and GEANT4 were used for the neutron calculation. These codes use evaluated neutron cross-section data to simulate the transport and interaction of neutrons and employ kerma approximation to evaluate energy deposition up to 20 MeV. At higher energies, various theoretical models are used to simulate nuclear reactions and energy deposition.

Calculations of organ-absorbed doses were performed specifically by members of the DOCAL task group. For quality assurance purposes, data sets for given radiations and irradiation geometries were generated by different groups using the same reference computational phantoms, but different Monte Carlo codes.

Calculations were carried out assuming whole-body irradiation of the phantoms in a vacuum. The irradiation geometries considered were unidirectional broad parallel beams along the antero-posterior (AP), postero-anterior (PA), left lateral (LLAT) and right lateral (RLAT) axes, and 360° rotational (ROT) directions around the phantoms' longitudinal axis. Fully isotropic (ISO) irradiation of the phantoms was also considered.

The incident radiations and energy ranges considered were external beams of mono-energetic photons of 10 keV–10 GeV, electrons and positrons of 50 keV–10 GeV, neutrons of 0.001 eV–10 GeV, protons of 1 MeV–10 GeV, pions of 1 MeV–200 GeV, muons of 1 MeV–10 GeV, and helium ions of 1 MeV/u–100 GeV/u.

Reference values for organ-absorbed doses were then determined from the individual data through a procedure that included averaging, smoothing and data fitting where necessary. Equivalent doses for organs and tissues and the effective doses were derived using the procedures shown in Figure 1. The organ-absorbed doses and effective doses were normalised to incident particle fluence and are given in units of pSv cm^2. For photons of energies up to 10 MeV, the conversion coefficients were also tabulated as the organ-absorbed doses and effective doses per air kerma free-in-air in units of Sv Gy^{-1}.

RESULTS AND DISCUSSION

Differences between Monte Carlo codes for neutrons

Figure 3 shows a comparison of fluence to absorbed-dose conversion coefficients of the gonads for the female phantom calculated with the PHITS, FLUKA, MCNPX, and GEANT4 codes. Up to 20 MeV, all codes use evaluated cross-section data to simulate the transport and reaction of neutrons, therefore the agreement between the codes is good. Above 20 MeV, relative differences of the absorbed doses ranging from 10 % to 50 % are found. The difference of the absorbed doses is expected considering the use of different theoretical models and data for simulating the interactions of neutrons in the respective codes. Therefore, the reference dose conversion coefficients for neutrons were established from all calculations, by applying averaging, smoothing, and fitting techniques.

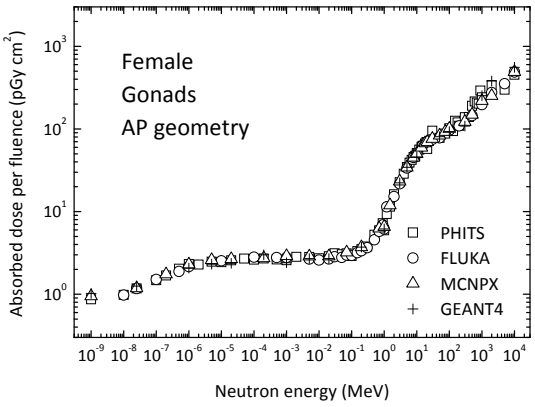

Figure 3. Absorbed-dose conversion coefficients of the gonads for the female phantom obtained using different Monte Carlo codes.

Difference between voxel and stylised phantoms

Figure 4 shows absorbed doses of the stomach calculated using the voxel phantoms and those of ICRP74 [7] evaluated from the calculations using stylised phantoms of sex-specific models and a hermaphrodite model. The female voxel phantom with its smaller stature leads to slightly higher values compared to those of the male voxel phantom. This is because the distance of the stomach to the body surface in the female voxel phantom is shorter compared to the male voxel phantoms.

As shown in Figure 1, equivalent doses of organs and tissues for the reference person are calculated by averaging the male and female values. The sex-averaged absorbed doses of the stomach obtained from the male and female voxel phantoms are close to the values calculated using the stylized phantoms. Then, the differences between absorbed doses obtained from the voxel phantoms and the stylised phantoms are not as large.

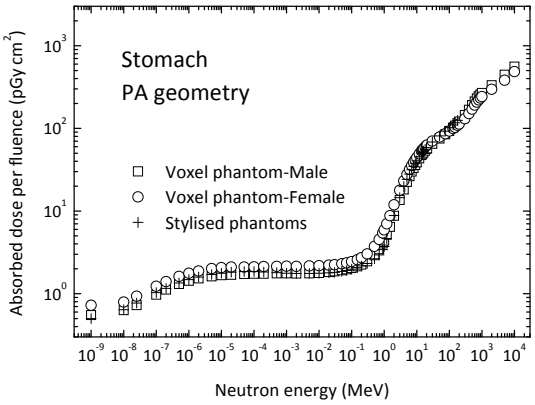

Figure 4. Comparison of absorbed dose conversion coefficients for the stomach calculated using the voxel and stylised phantoms.

Effective doses for neutrons and comparison with ICRP74

Figure 5 shows the effective dose conversion coefficients for neutrons for various irradiation geometries as a function of incident neutron energy. As the breast, colon, stomach and lungs, the organs with the highest values of w_{T}, are located near the front of the body, values of effective dose conversion coefficients for AP irradiation geometry are the highest among all irradiation geometries for neutrons up to 50 MeV.

Above 10 MeV, the effective dose continues to increase with neutron energy for PA, RLAT, LLAT, ROT, and ISO irradiation geometries. For the AP geometry above 10 MeV, the effective dose decreases slightly with increasing neutron energy until around 300 MeV at which point the AP effective dose continues to increase with increasing neutron energy. The highest ISO values are found above 2 GeV, since high-energy neutrons can deposit more energy at deeper locations in the body by inducing a cascade of secondary particles, depending on incident angle and position.

Figure 6(a) shows the effective dose conversion coefficients for AP irradiation geometry, from ICRP116 and ICRP74. In ICRP74, the conversion coefficients are evaluated up to 180 MeV. The values in ICRP116 are lower than those given in ICRP74 for neutron energies below

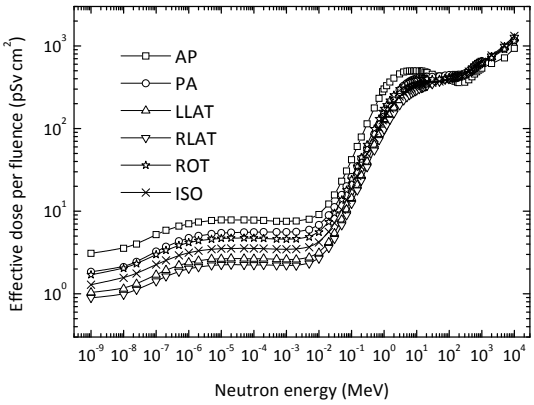

Figure 5. Effective dose per neutron fluence.

400 keV and above 50 MeV, while they show good agreement at intermediate energies.

Figure 6(b) shows the ratios of effective dose conversion coefficients presented in Figure 6(a) as well as the ratios of the w_{R} values used for the respective calculations recommended in ICRP103 and ICRP60. It can be seen that the differences in effective doses from ICRP116 compared to those from ICRP74 are mainly due to the use of the values of w_{R} as recommended in ICRP103. The differences between the ratios of the effective dose and w_{R} also indicate that the use of reference phantoms and the updated w_{T} values contributes to the change of the effective dose in ICRP116. However, these effects are smaller compared to the effect introduced by the updated values of w_{R}, as shown in Figure 6(b).

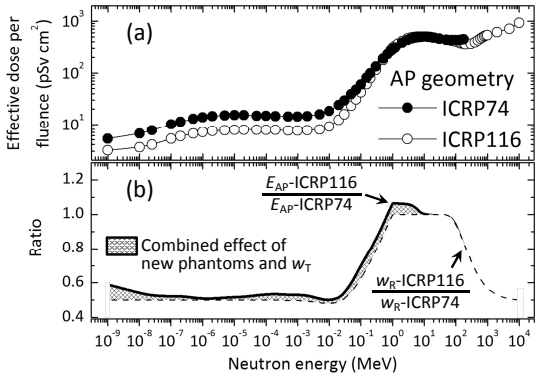

Figure 6. Comparison of effective dose conversion coefficients and w_{R} between ICRP Publications 116 and 74.

Comparison of effective doses with operational quantities

Figure 7 compares the ratios of effective dose conversion coefficients for AP and ISO irradiation geometries from ICRP116 and ICRP74 to those of $H^*(10)$, for energies up to 200 MeV. The ratios using the effective dose conversion coefficients from ICRP116 are smaller, compared to those from ICRP74 below hundreds of keV, the energy range where the values of w_{R} are reduced, according to the 2007 Recommendations. For AP irradiation geometry and energies up to 3 MeV, $H^*(10)$ conservatively estimates the effective dose, as defined in ICRP116. Above 3 MeV, $H^*(10)$ underestimates the effective dose, except for energies between 10 and 50 MeV. For ISO irradiation geometry, $H^*(10)$ is conservative in its estimate of the effective dose in ICRP116 up to 75 MeV, but underestimates the effective dose above this energy.

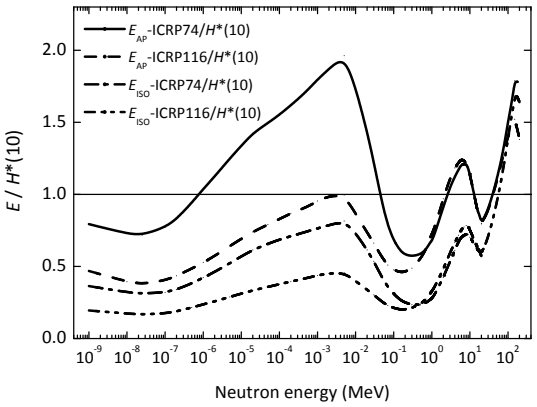

Figure 7. Ratios of effective dose to $H^*(10)$ for monoenergetic neutrons. E_{AP}, effective dose for AP irradiation geometry; E_{ISO}, effective dose for ISO irradiation geometry.

Neutron fields to which workers are exposed have a wide energy distribution. In the following, the impact of adopting dose conversion coefficients from ICRP116 for radiation monitoring and dose assessment is analysed for some operational neutron fields. The analysis is performed for accelerator facilities, an irradiation facility and nuclear power plants. The neutron energy spectra are taken from the IAEA Technical Report 403 [15]. The effective doses in the neutron fields are calculated by assuming AP irradiation geometry using the conversion coefficients from ICRP116 and ICRP74 and then compared to $H^*(10)$ from ICRP74.

Figure 8 shows the ratios of the calculated effective doses from ICRP116 and ICRP74 respectively to the corresponding $H^*(10)$. As expected from Figure 6, the values of the effective doses based on ICRP116 are generally lower than those based on ICRP74, the ratios depending strongly on the neutron fields. This tendency is attributed to the differences in the effective dose conversion coefficients between ICRP116 and ICRP74 and the neutron energy spectra of the respective fields. In the neutron fields of 'CERN, concrete' and 'Am-Be, in glovebox', neutrons of several MeV to several tens of MeV are present and differences in the ratios are small, since the values of w_{R} are unchanged in this energy range. However, in the neutron fields of 'Tohoku U. 35 MeV Cyclotron' and 'BWR, maze entrance', neutrons below 1 MeV are dominant and the ratios of effective dose to $H^*(10)$ decrease due to the decrease of w_{R} in this energy range.

Figure 8 also shows that the ratios of the effective doses based on ICRP116 to $H^*(10)$ are less than unity except for the 'CERN, concrete' situation. The results indicate that the operational quantity $H^*(10)$, as currently defined, adequately represents the protection quantities and provides a satisfactory basis for most measurements in radiological protection against external radiation. However, the result for 'CERN, concrete' where the ratios exceed unity, demonstrates a need to further examine the relationship between the operational and protection quantities.

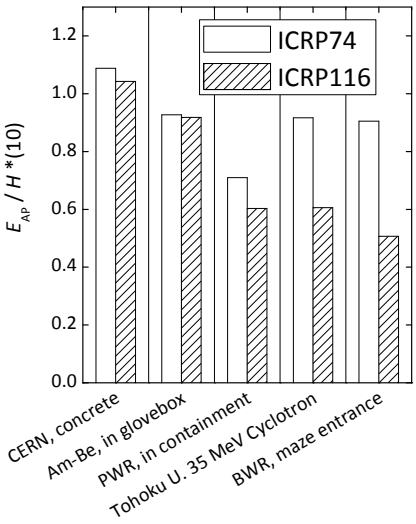

Figure 8. Ratios of calculated effective doses based on ICRP116 and ICRP74 to the corresponding $H^*(10)$ for various operational neutron fields.

CONCLUSIONS

This paper briefly reviews the reference computational phantoms and dose conversion coefficients for external exposures which were published jointly by ICRP and ICRU [5, 6]. Both these publications appeared

as a consequence of the ICRP 2007 Recommendations [4] to implement these recommendations, the ICRP has developed reference computational phantoms representing the adult male and female. These phantoms are used to calculate reference dose conversion coefficients for external and internal sources. Using the reference phantoms and methodology consistent with the 2007 Recommendations, dose conversion coefficients for both effective doses and organ-absorbed doses for various types of idealised external exposures have been calculated. These data sets supersede the existing ICRP/ICRU data sets [7, 8], and expand the particle types and energy ranges. For neutrons, the new effective dose conversion coefficients become smaller compared to those in ICRP74, for energies below hundreds of keV. This is mainly due to the decrease of the radiation weighting factors for neutrons, and the effects of anatomical differences between the reference voxel phantoms and the stylised phantoms and the update of the tissue weighting factors are relatively small. Comparisons of effective doses and ambient dose equivalents in several operational neutron fields indicate that the ambient dose equivalent still adequately represents the effective doses and provides a satisfactory basis for most measurements for radiological protection against external radiation.

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