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Article

Different effective dose conversion coefficients for monoenergetic neutron fluence from 10^{-9} MeV to 20 MeV – A methodological comparative study

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ABSTRACT **Calculations are presented of the effective doses per unit neutron fluence according to the ICRP publications 60 and 103. Monte Carlo N-Particle (MCNPX) code was used for six geometrical conditions of irradiation (Anterior-Posterior, Posterior-Anterior, Left-Lateral, Right-Lateral, Rotation and Isotropic) on Oak Ridge National Laboratory (ORNL) modified mathematical adult phantoms for monoenergetic neutrons from 10^{-9} MeV to 20 MeV. The conversion coefficients were compared with the results of an analytical phantom (Medical Internal Radiation Dose (MIRD-5)) and some voxel model (ICRP/ICRU Reference Voxel Phantom (ICRP/ICRU RVP), HANAKO, TARO and Visible Human Project (VIPMAN)). From these comparisons, one can conclude that large discrepancies between data sets appear when w_R and different sizes of the phantoms have been used for calculations. Furthermore, the differences in applied Monte Carlo codes or simulated body models could make some discrepancies less than 15%.**

Keywords: Neutron effective dose / ORNL modified phantom / Monte Carlo codes / conversion coefficients

1. Introduction

The radiation dose distribution in the human body cannot be directly measured. This problem may be solved exactly by using conversion coefficients which convert a measurable quantity into organ absorbed or effective doses (Alghamdi *et al.,* 2005). Indeed, conversion coefficients are the most beneficial health physics quantities, which are necessary for assessing the risk of populations exposed to external radiation.

The International Commission on Radiological Protection (ICRP) introduced the effective dose as the basic quantity for determining the acceptable dose and radiation risk (ICRP, 1987). The effective dose, E, was defined by ICRP60 as the

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summation of the weighted equivalent doses in 12 critical organs of the body, and the 'remainder' composed of additional organs, given by the expression:

$$E = \sum_T w_T H_T \tag{1}$$

where H_T is the equivalent dose in the tissue or organ *T*, and w_T are the tissue weighting factors for the tissue *T*. The equivalent dose, H_T, is the mean absorbed dose in the organ or tissue *T* multiplied by the radiation weighting factor, and is obtained by:

$$H_T = \sum_R w_R D_{T,R} \tag{2}$$

where $D_{T,R}$ is the absorbed dose averaged over the tissue or organ *T* as a result of radiation *R*, and w_R is the radiation weighting factor for radiation *R*. The unit of both the equivalent dose and effective dose is sievert (Sv), where 1 Sv = 1 Jkg^{-1}.

In different neutron applications, quantities such as source strength, time exposure and irradiation geometries depend on the effective dose. On the other hand, the effective dose is a computational quantity. The question arises: how can a way be found to simplify the calculation so that the data is accurate enough? Three major factors can be mentioned that influence on the evaluation of the effective dose: the radiation and tissue weighting factors, the body model and the computational code. The aim of this study is to try to find out which one of these factors has the largest effect on the results of the calculations.

2. Materials and methods

In this paper the fluence to effective dose conversion coefficients, which are the effective dose values per unit fluence, were evaluated for the adult male and female Oak Ridge National Laboratory (ORNL) phantoms (Cristy and Eckermann, 1987, Hakimabad and Motavalli, 2007) with Monte Carlo N-Particle (MCNPX) code. These coefficients were calculated under six standard irradiation geometries: anterior-posterior (AP), posterior-anterior (PA), left-lateral (LLAT), right-lateral (RLAT), rotation (ROT) and isotropic (ISO) for neutrons in the energy range 10^{-9}-20 MeV on the basis of both ICRP60 (ICRP, 1991) and ICRP103 (ICRP, 2007) recommendations. The present results were compared with some published data (ICRP, 1995; Bozkurt *et al*., 2000) and estimated at 26 energy points which covered all energies considered in the selected reports.

2.1. Dose calculation procedures

The values of the radiation weighing factors for a specified type and energy of radiation were represented by ICRP60 (ICRP, 1991). Thereafter, ICRP92

(ICPR, 2003) noted that the reported radiation weighting factors, w_R, are large, especially for below 1 MeV (ICRP, 2003). These values were not truly representative of the detrimental effects because the secondary photon contribution is ignored for these energies. ICRP92 suggested a different equation based on a fixed relationship between the radiation weighting factor and a mean quality factor (q_E) for all neutron energies (ICRP, 2003); but then the value of w_R was modified again in ICRP103 (2007). ICRP103 does not fully follow the procedure proposed in publication 92. However, for the energy range from thermal up to 1 MeV neutrons the energy dependence of mean $\mathrm{RBE_{ave}}$ (ICRP, 2003), which is the basis of the ICRP103 propositions, is similar to that of the mean quality factor which was calculated in ICRP92. The following equations were proposed by publication 103 for the neutron energies below 1 MeV, above 1 MeV and above 50 MeV, respectively (ICRP, 2007):

$$
\begin{aligned}
w_R &= 2.5 + 18.2 \exp\left(\frac{-(\ln(E_n))^2}{6}\right) && E_n < 1\ \mathrm{MeV} \\
w_R &= 5 + 17 \exp\left(\frac{-(\ln(2E_n))^2}{6}\right) && 1\ \mathrm{MeV} \le E_n \le 50\ \mathrm{MeV} \\
w_R &= 2.5 + 3.25 \exp\left(\frac{-(\ln(0.04E_n))^2}{6}\right) && E_n > 50\ \mathrm{MeV}
\end{aligned} \tag{3}
$$

Figure 1 represents radiation weighting factors using continuous functions from ICRP60 (ICPR, 1991), ICRP92 (ICPR, 2003) and ICRP103 (ICPR, 2007). *versus*

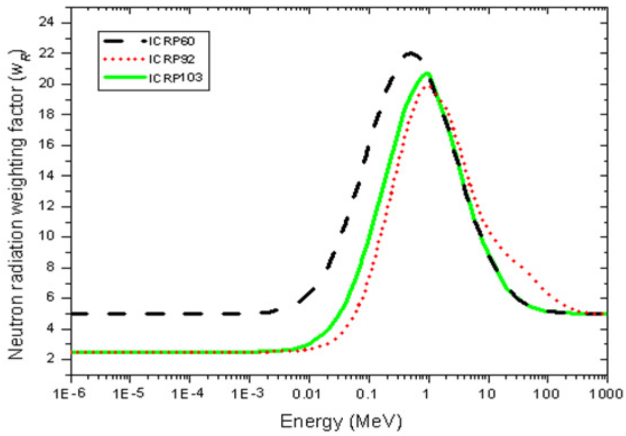


Figure 1 – ***Comparison of radiation weighting factors from ICRP60, ICRP92 and ICRP103.***

neutron energies. The values of publication 92 are only shown to complete the modification process of w_R historically and in this study; no data were calculated based on its values.

Tissue weighting factors, w_T, show the different relative radiosensitivities of various organs and tissues in the human body with respect to the radiation detriment from stochastic effects (ICPR, 1977). Tissue weighting factors have changed since they were introduced in 1977 in ICRP26. The process of these changes is shown in Table I.

The following formula was applied for average effective dose estimations:

$$E = w_{breast} H_{breast,\,female} + \sum_{T \neq breast} w_T \left[\frac{H_{T,\,male} + H_{T,\,female}}{2} \right]. \qquad (4)$$

TABLE I
ICRP recommendations for tissue weighting factors in publications 26, 60 and 103.

Tissue	Tissue weighting factor, w_T		
	Publication 26	Publication 60	Publication 103
Bone surface	0.03	0.01	0.01
Bladder	-	0.05	0.04
Breast	0.15	0.05	0.12
Colon	-	0.12	-
Gonads	0.25	0.20	0.08
Liver	-	0.05	0.04
Lungs	0.12	0.12	0.12
Esophagus	-	0.05	0.04
Bone marrow	0.12	0.12	0.12
Skin	-	0.01	0.01
Stomach	-	0.12	0.12
Thyroid	0.03	0.05	0.04
Remainder	0.30	0.05[1]	0.12[2]
Brain	0	0	0.01
Salivary glands	0	0	0.01
Total	1	1	1

1. Remainder: adrenals, brain, kidneys, muscle, pancreas, small intestine, spleen, thymus and uterus.
2. Remainder: adrenals, kidneys, muscle, pancreas, small intestine, spleen, thymus, heart, gall bladder and uterus.

TABLE II
Information about phantoms compared with the ORNL phantom in this study.

Researcher	Phantom		Total height (cm)	Weight (kg)	results	Monte Carlo code	Neutron Energy Ranges (MeV)	Weighting factors reference
ICRP74	MIRD-5	ADAM	170	70.5	Sex-averaged	MCNP SAM-CE MORSE-CG HL-PL	10^{-9}-20	ICRP60
		EVE	160	59.2				
Sato *et al.*	ICRP/ ICRU RVP[1]	GSF and Rex	176	70	Sex-averaged	PHITS[2]	2.5×10^{-8}-10^5	ICRP103
		GSF and Regina	167	59				
Lee *et al.*	Japanese voxel	TARO	171.4	65	Male	MCNPX2.5.0	10^{-8}-20	ICRP60
		HANAKO	160	53	Female			
Bozkurt *et al.*	VIPMAN voxel		186	103	Male	MCNPX2.4.0	10^{-9}-20	ICRP60

1. ICRP/ICRU reference voxel phantoms (ICRP/ICRU RVP).
2. Particle and Heavy Ion Transport code System.

2.2. ORNL phantoms

In 1987, researchers of Oak Ridge National Laboratory (ORNL) developed a series of phantoms representing adults and children of different ages (Cristy and Eckerman, 1987). In this study, a modified ORNL adult phantom which concludes the revisions reported in 1996 (Eckerman *et al.*, 1996; Cristy, 1980) and the thyroid model provided by Ulanovsky (Ulanovsky and Eckerman, 1998) was used. Furthermore, it was assumed that the female phantom has the same size and weight as the male one (73 kg in weight and 168 cm in height). The elemental composition and density of body tissues and the mass of each body organ and tissue was chosen from Table A-I and Table B-III of ORNL/TM-8381, respectively (Cristy and Eckerman, 1987). These phantoms are the revised version of MIRD phantoms that are widely used (Manger and Eckerman, 2001).

Other phantoms have been used by other researchers to calculate the effective dose data sets. Detailed information about these studies is listed in Table II.

2.3. MCNP Code

The MCNPX.2.4.0 code (Briesmeister, 2000) was used to calculate the absorbed dose for each monoenergetic neutron source that was located out of the body. The code was installed on a personal computer (Pentium IV, 3.00GHZ processor and

512MB of RAM, and Windows XP). The cross-section data came from the ENDF/B-VI libraries, and the scattering treatment S(α,β) for light water at 300 K was applied for all materials involved in the model (data card: MTm LWTR.07). The energy deposited by neutrons and secondary photons in 23 major organs of the phantom was determined using the F6: n, p tally (energy deposition in $MeVg^{-1}$) in this code. The absorbed dose was calculated assuming that secondary charged particles are absorbed in the interaction region (kerma approximation), therefore only neutron and neutron-induced photon transport (mode n,p) is considered.

3. Results

All evaluations of the effective dose have a statistical uncertainty of less than 0.5% in this study. These uncertainties are based on 10^9 particles for low neutron energies and about 300 million particles for high neutron energies in all irradiation geometries. Computer runtime of up to a few days was sometimes necessary to obtain results with good precision, especially for deep or small organs (such as the adrenals and thymus). In addition, these times depend on the incident neutron energy.

The present effective doses were calculated for the ORNL male and female phantoms in AP, PA, LLAT, RLAT, ROT and ISO geometries. Also, the third data set, which contains sex-averaged effective doses (equation 4), was evaluated. The detailed results of this study, tables of calculated coefficients for the various irradiation conditions, are available at http://www.um.ac.ir/~mirihakim.

In the first step to investigate the effect of w_R and w_T, the results of the ORNL female phantom based on ICRP60 (ICRP, 1991) were compared with the data obtained from the new recommendation of ICRP103 (ICRP, 2007) (Fig. 2). Then to study other factors (body models and computational codes), ORNL data were compared with results of the other analytical phantom (MIRD-5) (ICRP, 1995) and also voxel models ICRP/ICRU RVP (Sato *et al.*, 2009), TARO and HANAKO (Lee *et al*., 2006) and VIPMAN (Bozkurt *et al.*, 2000) from the already published papers. For each comparison, according to the calculation method used, the gender of the human model and common energy points, corresponding data were selected from this study based on the ORNL phantom.

Comparison between our data and the results of ICRP/ICRU reference computational phantoms is necessary because these phantoms are widely used to estimate organ doses and other dosimetric quantities related to the human body. Tables III and IV show the results of these comparisons in more detail. The first cell of each row represents the ranges of ICRP/ICRU RVP data differences relative to the results of this study. The top cell in each column specifies the irradiation

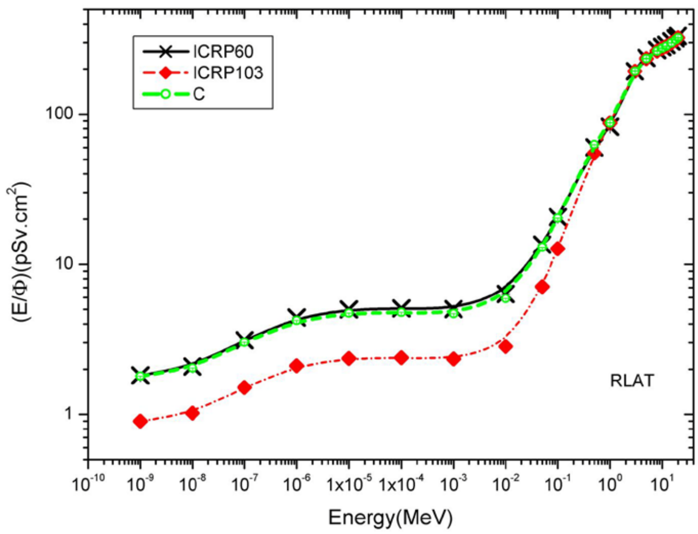


Figure 2 – ***Effective doses per unit fluence for the whole body in RLAT irradiation conditions are compared for the female ORNL phantom. The graphs of ICRP60 and 103 are drawn according to the parameters and calculation method in ICRP60 and ICRP103, respectively. Also, the graph C was obtained from the results calculated by w_R of ICRP60 and w_T and the calculation method in ICRP103.***

TABLE III
The comparison of the effective dose data between ORNL and ICRP/ICRU RVP (sex-averaged data) in various geometries. In spite of differences in the body model and computational code, good agreement between results is observed.

Relative Difference	PA	RLAT	LLAT	ROT	AP	ISO
0–5%	94.74	68.42	84.21	84.21	89.47	100
5–8%	5.26	15.79	15.79	15.79	10.53	-
8–15%	-	15.79	-	-	-	-

geometry. The values in each cell are the percent of cases that fall into the difference ranges specified for each row and the irradiation geometry specified for each column. For example, the first number in Table III means that 94.74% (18 out of 19) of the calculated energy points are 0 to 5% different for AP between the ORNL and the RVP ICRP/ICRU phantoms. Figures 3 and 4 are selected graphs from these comparisons on ICRP/ICRU RVP (Sato *et al.*, 2009) and MIRD-5 (ICRP, 1995), respectively.

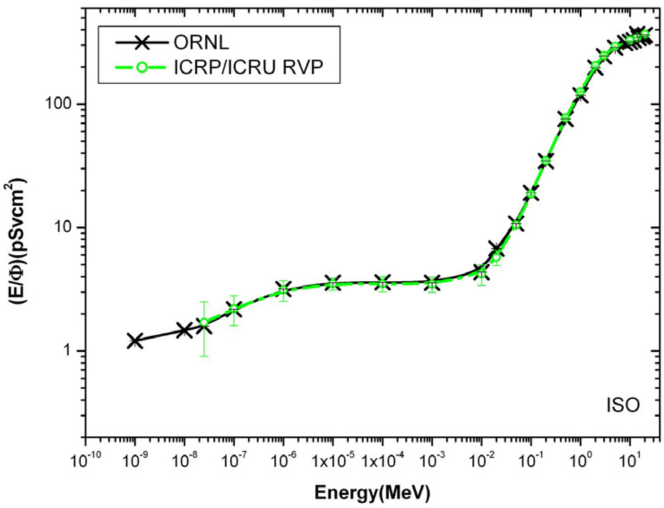


Figure 3 – ***Effective doses per unit fluence for the whole body in ISO irradiation geometry, according to ICRP103. The comparisons are made between mean data for the male and female ORNL and ICRP/ICRU RVP. The two sets are in good agreement with each other.***

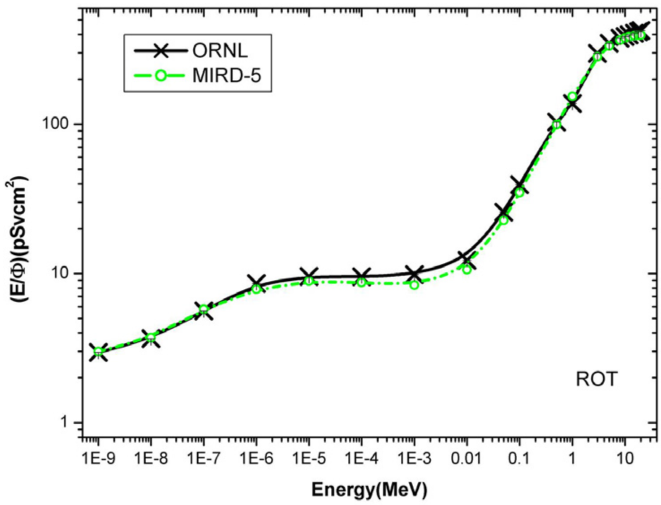
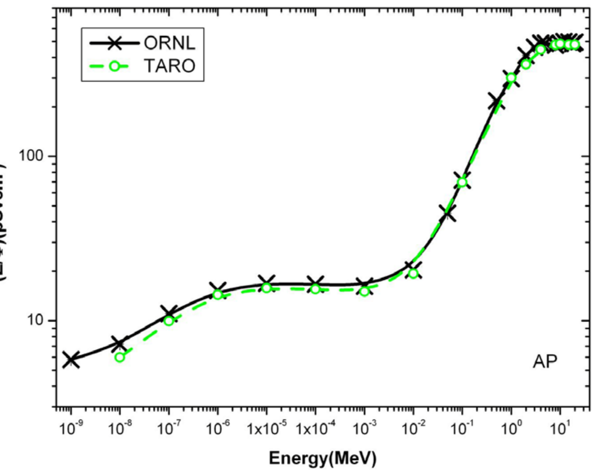
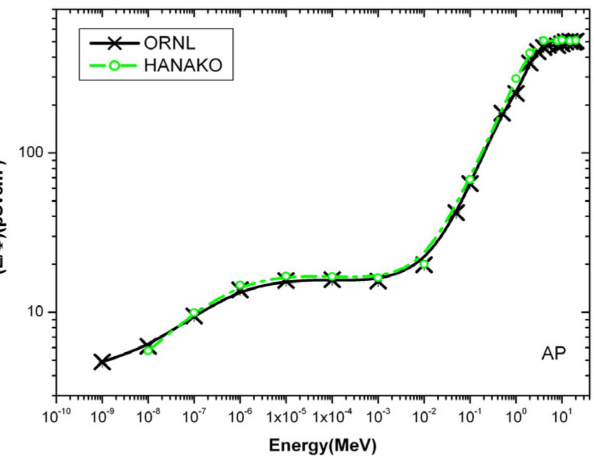


Figure 4 – ***Effective doses per unit fluence for the whole body in ROT irradiation conditions, according to ICRP60. Comparisons are between this study and ICRP data. Some differences between them can be seen in intermediate energies.***



(a)



(b)

Figure 5 – ***Effective doses per unit fluence for the whole body in AP irradiation conditions, according to ICRP60. Comparisons are made between the ORNL male and TARO in panel (a) and the ORNL female and HANAKO in panel (b). The data shows that the results of TARO have a slightly better agreement with ORNL rather than HANAKO.***

Also, ORNL adult male and female data are compared with TARO and HANAKO results in Figures 5a and 5b for AP irradiation geometry, respectively.

As a final step, the results for the ORNL male and VIPMAN (Bozkurt *et al.*, 2000) are compared in Table V (Figs. 6a and 6b).

TABLE IV
The comparison of effective dose data of this study and MIRD-5 (sex-averaged data) in six standard irradiation conditions. Large discrepancies between this study and MIRD-5 are observed in the intermediate energy range with the exception of RLAT irradiation geometry.

Relative Difference	AP	PA	RLAT	LLAT	ROT	ISO
0–5%	70	50	40	50	60	55
5–15%	30	45	30	50	40	45
15–25%	-	5	25	-	-	-
25–40%	-	-	5	-	-	-

TABLE V
The comparisons of ORNL male data with TARO and ORNL female data with HANAKO. The effective doses are calculated according to ICRP60 recommendations in the two sets. ORNL male data and TARO have better agreement than the results of the ORNL female and HANAKO.

Relative Difference	TARO	Relative Difference	HANAKO
0–1%	20	0-1%	20
1–7%	66.67	1-7%	66.67
7–17%	13.33	7-24%	13.33

4. Discussion

4.1. Old and new w_R and w_T

A large discrepancy (about 50%) was expected in low neutron energies (lower than 100 keV) due to the modification of w_R values from 5 to 2.5 in ICRP103 for these neutron energies. These discrepancies can be observed in Figure 2 in the range of 49%–56% for neutron energies below 0.1 MeV in all cases. Also, the differences in the effective dose values are the same as the differences between two sets of w_R values for energies greater than 0.1 MeV.

Comparison between graph C and the curve obtained from the ICRP60 recommendations shows the dependence of the effective dose on the w_T values. In this case, the observed differences are less than 6% for 1 to 20 MeV in irradiation geometries, with the exception of ISO geometry, where there are differences of between 10%–21% for 1 to 8 MeV.

4.2. Other phantoms

It is evident from Table III that there is good agreement between this study and ICRP/ICRU RVP results (Sato *et al.*, 2009), in spite of differences in the phantoms

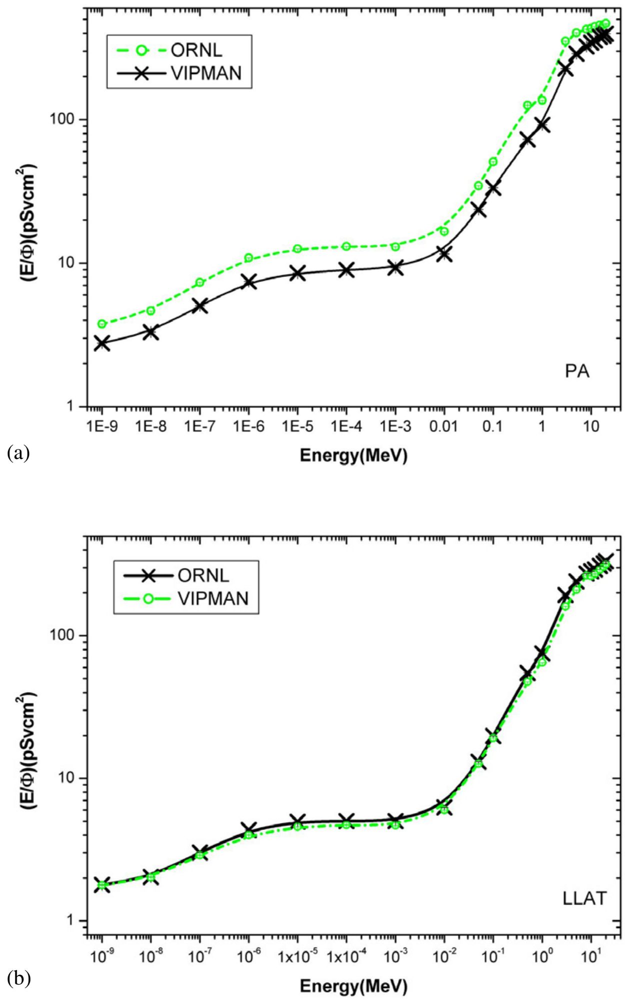


Figure 6 – ***Effective doses per unit fluence for the whole body in PA and LLAT irradiation conditions, according to ICRP60. Comparisons between this study and VIPMAN data for PA geometry are made in panel (a). The results show that the two sets have large discrepancies. In panel (b) this study is compared with VIPMAN in LLAT geometry. These two sets have good agreement with each other.***

and computational codes. This good agreement can at least partly be explained by the similarity between the mean sizes of ORNL and ICRP/ICRU RVP models (Sato *et al.*, 2009). The same cross-section data are used in MCNPX and PHITS codes.

TABLE VI
The comparison of VIPMAN effective dose data with ORNL male data. A large discrepancy is observed in PA irradiation conditions. The reason for the differences may be related to phantom size.

Relative Difference	AP	PA	RLAT	LLAT	ROT	ISO
0–5%	45	-	20	40	55	20
5–15%	55	25	65	60	40	80
15–25%	-	65	15	-	5	-
25–40%	-	10	-	-	-	-

MIRD-5 models are analytical phantoms similar to the ORNL ones, but different Monte Carlo codes with different cross-section data were used to calculate absorbed and effective doses in this phantom (ICRP, 1995). As the body size of MIRD-5 is close to ORNL phantoms, it was expected that the present study should be in better agreement with MIRD-5 data (ICRP, 1995) rather than ICRP/ICRU RVP (Sato *et al.*, 2009) results.

On the contrary, our results indicate that the resemblance of the present data to ICRP/ICRU RVP (Sato *et al.*, 2009) is greater than to MIRD-5 (ICRP, 1995). As is clear from Figure 4, the results of MIRD-5 are lower than ORNL data for almost all of the energies. Large discrepancies between ORNL and MIRD-5 (ICRP, 1995) are observed in the intermediate energy range (10^{-5} to 1 MeV).

It is shown that there are differences between the absorbed doses in ORNL and MIRD-5 phantoms (Miri Hakimabad, 2009). The observed discrepancies related to the library data used for Monte Carlo calculations (Miri Hakimabad, 2009). These discrepancies are also observed in effective dose data.

TARO and HANAKO calculations (Lee *et al.*, 2006) were performed using the Monte Carlo code MCNPX2.5.0. So, the body model is the only different factor between TARO and HANAKO with ORNL phantoms for estimation of effective dose values. Figure 5 illustrates that the agreement between effective dose data of male phantoms is a little better than female models. This can be related to the fact that the body size of the TARO model is closer than the HANAKO phantom (Lee *et al.*, 2006) to ORNL models. Very good agreement between the two data series can be concluded from Table V.

The greatest differences in effective dose values are observed between the ORNL and VIPMAN phantoms (Bozkurt *et al.*, 2000), especially in PA irradiation conditions. These differences could be related to the size of the phantoms. The organs such as the adrenals and stomach are much more shielded with a thicker layer of muscle and more fat in the VIPMAN voxel phantom (Bozkurt *et al*., 2000) than in the ORNL mathematical model. Therefore, the absorbed dose and the effective dose data are smaller than ORNL data in all irradiation geometries.

5. Conclusion

The results of this study indicate that the influence of the small changes in factors such as correction of w_T or a change in computational codes and body model type (mathematical or voxel models) is not significant on the whole-body effective dose values. However, big changes in w_R and also the size of the phantom (VIPMAN versus ORNL) noticeably influence the effective dose in all irradiation geometries.

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