Radiation Weighting Factors for High Energy Neutron, Proton, and Alpha Particles

N. Yoshizawa¹, O. Sato¹, S. Takagi¹, S. Furihata¹, J. Funabiki¹, S. Iwai², T. Uehara², S. Tanaka³, and Y. Sakamoto³

¹Mitsubishi Research Institute Inc., Otemachi, Chiyoda-ku, Tokyo, 100-8141, Japan
²Nuclear Development Corporation, Kitabukuro-cho, Omiya-shi, Saitama-ken, 330-0835, Japan
³Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan

INTRODUCTION

Estimation of radiation exposure against high-energy neutron above 20 MeV is very important to radiation protection around high energy and large intensity proton accelerators. For aircrew of high-altitude flight, radiation exposure from high-energy neutron and proton has come to be an important problem (1). High energy neutron, proton, and alpha exposure must be also estimated for radiation protection concerning the astronauts staying for a long time in a space station (2).

In ICRP 60 (3), the organ equivalent dose is defined as the averaged organ absorbed dose multiplied by a radiation weighting factor appropriate for the external radiation type and incident energy on the body rather than the radiation type and energy distributions in the body. The introduction of the radiation weighting factor for high energy radiation was discussed (4). For high energy neutron, proton, and alpha irradiation, several different types of radiations are produced from nuclear interaction in the body. National Council on Radiation Protection and Measurements (NCRP) defined the value of $R_w$ for proton as 2 (5). This value is less than the half of recommended value of 5 in ICRP 60.

We have reported dose conversion coefficients about two different types of effective doses, one was the effective dose using $R_w$ and the other one is the effective dose using $LQ$ relationship (6,7). In this paper, we propose modified radiation weighting factors for high energy neutron, proton, and alpha particles.

EFFECTIVE DOSE AND MEAN QUALITY FACTOR FOR THE WHOLE BODY

In ICRP60, the effective dose is defined as a summation of the equivalent doses for organs, with the term for each organ multiplied by an appropriate tissue weighting factor:

$$E_{w_s} = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

(1)

where $H_T$: equivalent dose in organ $T$

$w_T$: tissue weighting factor for $T$ (values recommended in ICRP 60)

$w_R$: radiation weighting factor for radiation $R$ (also recommended in ICRP 60)

$D_{T,R}$: absorbed dose of radiation $R$ averaged over $T$.

We call the above $E_{w_s}$ calculated using $w_R$ “the effective dose using radiation weighting factor” to distinguish from $E_{Q-L}$, defined later.

In the same ICRP60, it is recommended to replace the relationship given in ICRP 26 (8) with a new $Q-L$ relationship ($Q$: quality factor, $L$: unrestricted linear energy transfer in water). The effective dose calculated using the $Q-L$ relationship is given by

$$E_{Q-L} = \sum_T w_T \hat{H}_T$$

(2)

where $\hat{H}_T$: dose equivalent averaged over organ $T$ (diacritic mark ^ added to distinguish organ dose equivalent from equivalent dose). In order to obtain the organ dose equivalents, the energies deposited in the regions were weighted with the averaged quality factor in accordance with the methodology described in Ref.6. In this study, the mean quality factor for the whole body is given by
\[ \overline{Q}_{body} = \frac{E_{Q-L}}{\sum w_T D_T} \]  

(3)

The difference between \( \overline{Q}_{body} \) and \( w_R \) can be considered the factor that distinguishes \( E_{Q-L} \) from \( E_{Q} \).

**METHOD OF CALCULATION**

In this study, an adult hermaphroditic anthropomorphic phantom—modified MIRD5—was adopted for calculating the mean absorbed dose and the mean dose equivalent of an organ. Calculations were performed on whole-body irradiation with parallel broad monoenergetic beams incident on an anthropomorphic phantom placed in vacuum. Organ absorbed doses and organ dose equivalents were calculated by the HETC-3STEP(9) and the MORSE-CG/KFA(10) in the HERMES code system(10). In Ref.6, detailed method of calculation is described.

**RESULTS AND DISCUSSION**

Effective Dose Conversion Coefficients for high energy neutron, proton, and alpha particles have been already reported in Ref.6,7. Figure 1 plots the ratios \( E_{ns} / E_{Q-L} \) for neutron, proton, and alpha particles. It is found large differences between \( E_{ns} \) and \( E_{Q-L} \).

As shown in Figure 1, \( E_{ns} \) overestimates \( E_{Q-L} \) for neutron, proton, and alpha above 20 MeV. In ICRP60, \( w_R \) for neutron is defined as a continuous function of neutron energy as follows:

\[ w_R(E_n) = 5 + 17 \exp\left(-\frac{\ln(2E_n)^2}{6}\right) \]  

(4)\] (in ICRP 60)

Siebert et al.(11) described modification of \( w_R \) to reconcile a difference between \( w_R \) and \( Q-L \). Pelliccioni (4) also proposed radiation weighting factors for high energy neutron, proton, negative pions, positive pions, negative muons, and positive muons. For neutron above 20 MeV, the adjustment of \( w_R \) as a function of neutron energy \( E_n \) given by Eq. (5) will make an agreement between \( E_{ns} \) and \( E_{Q-L} \) within 40%.

\[ w_R(E_n) = 4 + 26 \exp\left(-\frac{\ln(2E_n)^2}{6}\right) \quad 20\text{MeV} \leq E_p \leq 10\text{GeV} \]  

(5)

In Eq. (5), only two coefficients in Eq. (4) are adjusted from 5 to 4 and from 17 to 26, respectively. Modified \( w_R \) given by Eq. (5) was shown in Fig. 2. comparing with \( \overline{Q}_{body} \).

Differences between \( E_{ns} \) and \( E_{Q-L} \) for proton and alpha are larger than those for neutron. The main reason is that \( w_R \) for proton is 5 and alpha is 20 in ICRP 60 independent on incident energy. For proton above 20 MeV, the adjustment of \( w_R \) as a step function of proton energy \( E_p \) given by the equation (6) will make an agreement between \( E_{ns} \) and \( E_{Q-L} \) within about 70%.

\[ w_R(E_p) = \begin{cases} 2.5 & 20\text{MeV} \leq E_p < 30\text{MeV} \\ 2 & 30\text{MeV} \leq E_p \leq 10\text{GeV} \end{cases} \]  

(6)

Modified \( w_R \) given by Eq. (6) was shown in Fig. 3 to compare with \( \overline{Q}_{body} \). NCRP 116 (5) recommends that \( w_R \) is 2 for proton independent on its energy. Above 30 MeV, adjusted \( w_R \) in this study is equal to the value in NCRP 116. However, \( E_{Q-L} \) will underestimate \( E_{ns} \) for proton with \( w_R = 2 \) below 30 MeV.

For alpha above 20 MeV, the adjusted \( w_R \) as a step function of alpha energy \( E_a \) is given by the equation (7).

\[ w_R(E_a) = \begin{cases} 5 & 20\text{MeV} \leq E_a < 30\text{MeV} \\ 3 & 30\text{MeV} \leq E_a \leq 10\text{GeV} \end{cases} \]  

(7)
Modified $w_R$ given by Eq. (7) was shown in Fig. 4 to compare with $Q_{body}$. Proposed radiation weighting factors are summarized in Table 1.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Radiation Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>$5+17\exp(-(\ln(2E_n))^2/6)$ $E_n$: neutron energy (MeV) $4+26\exp(-(\ln(2E_n))^2/6)$ $20\text{MeV} \leq E_n \leq 10\text{GeV}$ $E_n$: neutron energy (MeV)</td>
</tr>
<tr>
<td>Protons</td>
<td>$2.5$ $20\text{MeV} \leq E_p &lt; 30\text{MeV}$ $2$ $30\text{MeV} \leq E_p \leq 10\text{GeV}$ $E_p$: proton energy (MeV)</td>
</tr>
<tr>
<td>Alpha Particles</td>
<td>$20$ $20\text{MeV} \leq E_a &lt; 30\text{MeV}$ $3$ $30\text{MeV} \leq E_a \leq 10\text{GeV}$ $E_a$: alpha particle energy (MeV)</td>
</tr>
</tbody>
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**SUMMARY**

Effective doses using $w_R$ and effective doses using $Q-L$ relationship were compared. It was found that effective doses using $w_R$ overestimate effective doses using $Q-L$ relationship for neutron, proton, and alpha. Modifications of $w_R$ were proposed.

**REFERENCES**

Fig. 1 Ratio between $E_{wR}$ and $E_{Q-L}$ for neutron, proton, and alpha particle incident energy.

Fig. 2 Mean quality factor for whole body irradiated by neutron and proposed $w_R$. 

ICRP60
Fig. 3  Mean quality factor for whole body irradiated by proton and proposed $w_R$.

Fig. 4  Mean quality factor for whole body irradiated by alpha and proposed $w_R$. 