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Overview of Fluence to Dose Conversion Coefficients for High Energy Radiations
- Calculational Methods and Results of Two Kinds of Effective Dose per Unit Particle Fluence -

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In and around high energy accelerator facilities, high energy radiation dose estimation is important to the radiological protection of workers. The contribution of high energy protons and neutrons to the radiation exposure of astronauts can not also be disregarded inside a spacecraft. Effective doses are adequate radiological quantities to evaluate radiation risks of individuals, exposed to radiation not only of low and intermediate energy but also of high energy. The conversion coefficients of fluence to effective doses have not been specified for all kinds of radiation in any publications of ICRP or ICRU, except the data up to 180 MeV of neutron in the ICRP74.

This report provides an overview of calculational methodologies and estimated results of dose conversion coefficient of effective doses for high energy radiation such as photon, neutron, proton, alpha particle, electron, muon and pion in five groups: USA group (LAHET code), German group (LAHET), Japanese group (HERMES), Italian group (FLUKA) and Russian group (HADRON). This overview also summarized the calculational conditions and data such as computer codes, data libraries, mathematical phantoms and energy range of each particle for estimating dose conversion coefficient for each particle. Comparison of effective dose conversion coefficients of neutron, photon and proton in five groups were performed up to 10 GeV. These results will be helpful to establish an authoritative dose equivalent conversion coefficient for high energy radiation up to 10 GeV.

KEYWORDS : High energy radiation, accelerator facilities, spacecraft, conversion coefficients of fluence to effective doses up to 10GeV, calculational methodologies, mathematical phantom, computer code, date library, effective dose, effective dose equivalent, radiation weighting factor, quality factor

I. Introduction

Due to the increase of high energy accelerator facilities and space missions, high energy radiation has come to be an important issue on radiological protection.

Effective doses or effective dose equivalents are adequate radiological protection quantities to evaluate radiation risks of individuals, exposed to radiations not only of low and intermediate energy but also of high energy. In 1987, the ICRP51 (ICRP Publication 51) [(1)] showed the conversion coefficients of effective dose equivalents based on the ICRP26 [(2)] for photons from 10keV to 10MeV and for neutrons from 2.5×10^{-2}eV to 14MeV. In 1996, the ICRP74 [(3)] demonstrated the conversion coefficients of effective dose for photons from 10keV to 10MeV and for neutrons from 1×10^{-3}eV to 180MeV, but the conversion coefficient above 180MeV has not been specified for all kinds of particles in any publication of ICRP or ICRU.

This work summarized the comparisons of calculational methodologies and results of dose conversion coefficients of effective dose and effective dose equivalents for high energy neutrons, photons, protons, alpha particle, and electrons up to maximum 10GeV.

II. Maximum Energy Limit of Conversion Coefficients

The maximum energy investigated depends on the radiation environment of interest, and the energy of 10GeV is adopted to be the maximum energy limit of conversion coefficients calculated in this work. This value was derived from the radiation environment inside space vehicles in low earth orbits such as U.S. space shuttles, Russian space station "MIR" and the international space station "ISS".

Figure 1 shows one of the typical radiation environments inside the space vehicle of 70mm thickness of aluminum in the low earth orbit of 400km altitude and 51.6 inclination.

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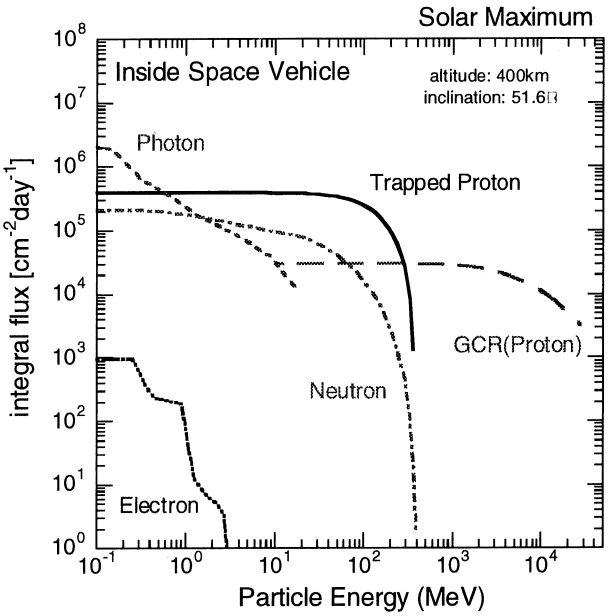

Fig.1 Radiation spectra inside a space vehicle of 70mm thickness aluminum (Solar activity is solar maximum)

In this figure, radiation integral spectra[1] (see footnote) were calculated by use of space radiation environment models and a high energy radiation code system; the formers are AP8 [4] (proton radiation belt model), AE8[6] (electron radiation belt model) and CREME [5] (galactic cosmic ray model) and the latter is the HERMES code system [7], which calculates high energy radiation transports and secondary particle productions.

The proton component above 10GeV is estimated to contribute less than 5% of proton effective doses of the crews inside space crafts in the low earth orbit, from the calculated result of the proton effective dose conversion coefficient [8] and the proton integral spectra show in Fig.1. This result leads to the findings that the energy of 10GeV is a adequate upper limit to evaluate the dose equivalents of space crews inside vehicles of low earth orbit, although conversion coefficient in excess of 10GeV are still useful for air crew dose calculations.

This energy limit is also suited to the radiation environments in and around high energy accelerator facilities of the maximum projectile energy of up to 10GeV.

III. Definitions of Effective Dose and Effective Dose Equivalent

The ICRP26 [2] introduced the averaged organ dose equivalent H_T expanded from the dose equivalent at a point in an organ or a tissue T. In 1978, by use of H_T this publication defined the effective dose equivalent H_E which is the weighted sum of the dose equivalents of six specified organs and a remainder consisting of five organs at most:

$$H_E = \sum_T W_{T,26} H_T \qquad (1)$$

where $W_{T,26}$ is the tissue weighting factor specified in the ICRP26.

In 1990, the ICRP60 [9] recommended new quantities used for radiological protection: equivalent dose H_T is defined as the average organ-absorbed-dose multiplied by a radiation weighting factor w_R; the ICRP recommended radiation weighting factors in place of effective quality factor Q because of the uncertainties in the radio-biological information for the high LET part of the Q-L relationship specified in the ICRP60. Although the radiation weighting factors are presented for the first time in the ICRP60, the theoretical background on the derivation of the factors is not explained in any documents.

The effective dose E is defined as the weighted sum of the equivalent dose of twelve specified organs[2] and of the remainder consisting of ten organs additionally specified in the ICRP60.

$$E = \sum_T W_{T,60} H_T \qquad (2)$$

where $W_{T,60}$ is the appropriate tissue weighting factor shown in the ICRP60.

In 1993, the ICRU51 [11] re-defined the effective dose equivalent H_E by use of the Equation (3) according to the consistency to the ICRP26, ICRP60, and ICRP67 [10].

$$H_E = \sum_T W_{T,60} D_T Q_T = \sum_T W_{T,60} H_T \qquad (3)$$

where D_T and Q_T are the mean absorbed dose and the mean quality factor in a specified tissue (or organ) T, respectively. In Equation (3) D_T and Q_T are defined as follows:

$$D_T = \frac{1}{m_T} \int_{m_T} D\,dm$$

$$Q_T = \frac{1}{m_T D_T} \int_{m_T} \int_L Q(L) \cdot D(L)\,dL\,dm \qquad (4)$$

where m_T is the mass of the tissue or organ T, D is the absorbed dose in the mass element dm, D(L) denotes an absorbed dose distribution in the tissue (or organ) T as a function of L (unrestricted linear energy transfer in water), and Q(L) denotes the Q-L relationship of ICRP60. H_T is the averaged dose equivalent in the tissue (or organ) T.

"Effective dose equivalent, H_E" of Equation(1) defined in the ICRP26 is defined again as "effective dose equivalent" in the ICRP74 [3] in 1995 and in the ICRU57 [43] in 1998. These definitions have led to the confusion of the term of "effective

[1] Integral flux $\psi(E)$ is expressed as shown below,

$$\psi(E) = \int_E^\infty \phi(e)de,$$

where $\phi(e)$ is a particle energy spectrum.

[2] The equivalent dose to the colon which is one of the twelve specified organs, Hcolon is given as:

$$Hcolon = 0.57H_{ULI} + 0.47H_{LLI}$$

where H_{ULI} and H_{LLI} are the equivalent doses to the ULI (upper large intestine) and the LLI(lower large intestine), according to the ICRP67 [10]

dose equivalent, H_E" again.

In the paper, the following terms and symbols are used;

E_{WR}, effective dose using radiation weighting factor w_R,

$$E_{WR}=E=\sum_T W_{T,60}H_T \quad (5)$$

$E_{Q\text{-}L}$, effective dose using Q(L) specified in the ICRP60,

$$E_{Q\text{-}L}=\sum_T W_{T,60}D_T\,Q_T=\sum_T W_{T,60}H_T \quad (6)$$

H_E, effective dose equivalent defined in the ICRPs26, 74 and the ICRU57.

$$H_E=\sum_T W_{T,26}H_T \quad (7)$$

IV. Calculational Methodologies and Conditions for Effective Dose and Effective Dose Equivalent

This section provides methodologies and conditions calculating conversion coefficients from unit particle fluence to effective doses, E_{WR}, $E_{Q\text{-}L}$, and effective dose equivalent, H_E. **Table 1** summarizes the protection quantities, emitted particles, energy ranges, Q(L)data, physical databases, application of kerma factors, anthropomorphic phantoms, and irradiation geometries used for the calculation of the dose conversion coefficients in each group of authors. The purpose of this study is an overview of conversion coefficients of particle fluence to effective doses and effective dose equivalent. Therefore in this table, data corresponding to effective doses, E_{WR}, $E_{Q\text{-}L}$, and effective dose equivalent, H_E are appeared, except the reference of the 10mm depth dose equivalent of Sanikov et al.[14] The conversion coefficients of ambient dose equivalent, H*(10) and the ICRU sphere depth dose calculated in each group are eliminated in principle, because these data are out of scope in this work.

V. Comparison of Conversion Coefficients of Effective Dose and Effective Dose Equivalent per Unit Particle Fluence Calculated in Each Group

1. Conversion coefficients for neutrons

Figure 2 shows the comparison of conversion coefficients of E_{WR} calculated by the four groups, for AP(Antero-poterior geometry), PA(Postero-anterior geometry), and ISO(Isotropic geometry) geometries with the reference of 10mm depth dose equivalent conversion coefficient for the ICRP60 Q(L) dependence, calculated by Sanikov et al[14] and the conversion coefficients specified in the ICRP74. Estimates E_{WR} values are fairly in good agreement below 500MeV in spite of several kinds of differences in computer codes, physical databases, and anthropomorphic phantom geometries. But the maximum difference of about 30% can be observed around 2GeV. The 10mm dose equivalent conversion dose not show conservative values above 50MeV.

Figure 3 provides the comparisons of estimates of $E_{Q\text{-}L}$ calculated by the three groups. The values of 10mm depth dose equivalent are also shown for reference. There is good agreement between the data of Nabelssi et al[15,16] and those of Yoshizawa et al[27]. The estimates of Mares et al[19] show 30% larger values than the former two kinds of data[15,16,27], especially at 100MeV. For a detailed analysis of the difference, comparison of organ doses will be required among the three groups. The 10mm depth dose equivalent of Sannikov et

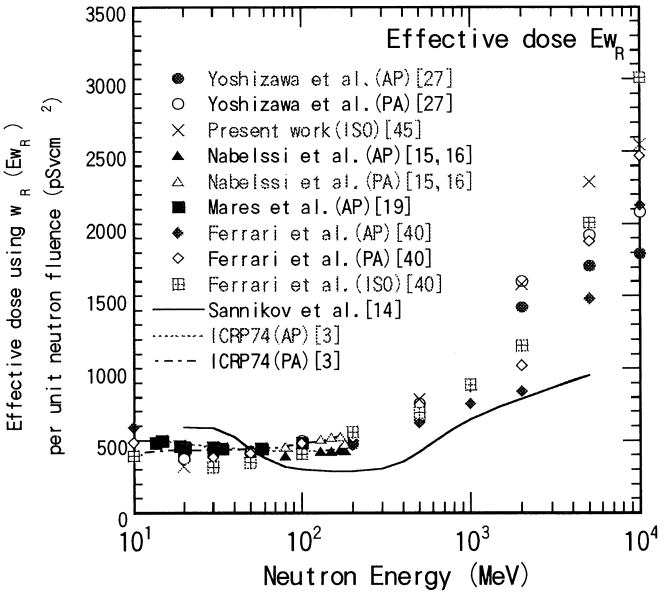

Fig.2 Comparison of effective dose using $W_R(Ew_R)$ for AP, PA and ISO irradiation neutron beams (The error bar are within symbols)

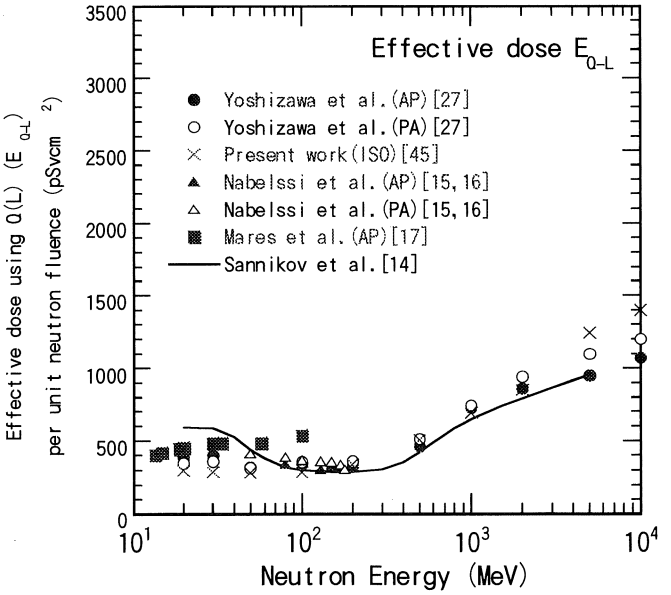

Fig.3 Comparison of effective dose using Q(L) ($E_{Q\text{-}L}$) for AP, PA and ISO irradiation neutron beams (The error bar are within symbols)

Table 1(1) Summary of calculational methodologies and conditions of conversion coefficients

Group	Contributors	Particles (energy range)	Calculated Dose Equivalent
The Univ. of Texas at Austin	B.K.Nabelssi N.E.Hertel	Neutron [15,16] (10MeV−180MeV)	(1)Effective Dose using W_R (E_{WR}) (2)Effective Dose using Q(L) ($E_{Q\text{-}L}$) (3)Effective Dose Equivalent (H_E)
GSF	V.Mares G.Leuthold H.Schraube	Neutron [19] (20MeV−100MeV)	(1)Effective Dose using W_R (E_{WR}) (2)Effective Dose using Q(L) ($E_{Q\text{-}L}$) (Q(L),W_T:ICRP60)
Mitsubishi & JAERI	S.Iwai, T.Uehara O.Sato, N.Yoshizawa S.Furihata, S.Takagi S.Tanaka, Y.Sakamoto	Neutron [26,27,45,48], Proton [27,45,48], alpha [49] (20MeV−10GeV) Photon [28,44] (1MeV−10GeV)	(1)Effective Dose using W_R (E_{WR}) (2)Effective Dose using Q(L) ($E_{Q\text{-}L}$) (Q(L),W_T:ICRP60)
	S.Tsuda	Electron(1MeV-100GeV) [30]	Effective Dose
INFN & EURATOM-ENEA	A.Ferrari M.Pelliccioni M.Pillon	Proton [8] (5MeV−10TeV) Neutron [40] (0.025eV−10TeV) Photon [12](50keV−10GeV) Electron [13](5MeV−10GeV) Muon*[46] Pion*[47] (1MeV−10TeV) Kaon*[50] (1MeV−10TeV)	(1)Effective Dose using W_R (E_{WR}) (2)Effective Dose Equivalent (H_E) (H_E,Q(L)=1, W_T:ICRP26 for photon and electron)
IHEP	A.V.Sanikov E.N.Savitskaya V.T.Golovachik	Neutron [14] (20MeV−5GeV)	Ambient Dose Equivalent (h*(10))† (Q(L):ICRP60)

* charged (positive and negative)
† reference data

Table 1(2) Summary of calculational methodologies and conditions of conversion coefficients

Group	Application of Q(L) for calculating	Application of Kerma factor
The Univ. of Texas at Austin	p, d, t, ^{3}He, α −Q(L) of ICRP60 recoil nuclei (A>4)−Q(L)=20	Below 20MeV (neutron)
GSF	q*(10) is used as neutron quality factor (q*(10)=H*(10)／D*(10) at 10mm depth in ICRU sphere)	Below 100MeV (neutron) (all energy range)
Mitsubishi & JAERI	Q(L) of ICRP60 for all charged particles	Below 15MeV (neutron)
INFN & EURATOM-ENEA	Q(L)=1 : for photon, electron, and positron W_R=H*(10)/D*(10)at 10mm depth in ICRU sphere for charged pions	
IHEP	Q(L) of ICRP60 for all charged particles	

Table 1(3) Summary of calculational methodologies and conditions of conversion coefficients

Group	Computer Code and Data Library			Phantom	Irradiation geometries
The Univ. of Texas at Austin	Above 20MeV neutron LAHET [17]		HMCNP [17] { ENDF/B-V−n DLC-7E−γ } [42]	Modified PNL phantom [18] (male, female)	AP, PA,R-LAT (L-LAT)† ROT
GSF	MCNP [20]	{ LA100 [21] ENDF/B-VI [22] extraporation } n Hubbell's data [23] ——— γ		ADAM phantom[24,25] (male)	AP, Different angle of incidence (15°,30°,45°,60°,75°)
Mitsubishi & JAERI	Above15MeV neutron Modified HERMES (HETC-3STEP [29])	Blow 15MeV neutron MORSE-CG/KFA[30] (JENDL-3.1[31]) (PHOTX [33])	photon, electron EGS4[32] (PHOTX, ICRU37[34])	Modified Christy adult phantom[26] (hemaphrodite)	(neutron, proton, alpha) AP, PA, ISO (photon) AP, PA, ISO, L-LAT, R-LAT, ROT (electron) AP
INFN & EURATOM-ENEA	FLUKA [41]			Modified ADAMO.phantom[51,12] (hemaphrodite)	AP, PA R-LAT ISO
IHEP	HADRON [38,39]			ICRU sphere	Parallel incidence

† The conversion coefficient of the L-LAT geometry was calculated from 10-20MeV.

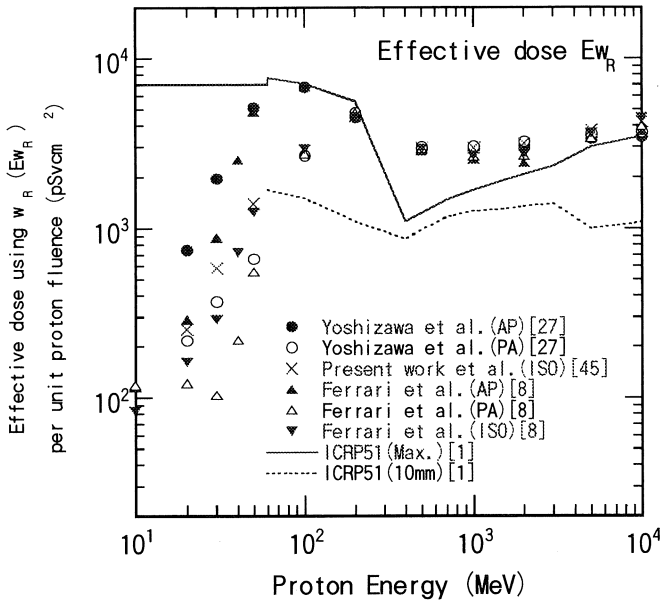

Fig.4 Comparison of effective dose using Wr (Ew_R) for AP, PA and ISO irradiation proton beams (The error bar are within symbols)

al. shows a fairly good agreement with the $E_{Q\text{-}L}$ for AP geometry of Ref. [27] above 50MeV. But the h*(10) is also a little lower than the estimates of $E_{Q\text{-}L}$ for PA within the difference of 5%, although the 10mm depth dose equivalent shows about 50% smaller values than E_{WR} above 50MeV at maximum difference.

2. Conversion Coefficients for photons

The comparison of estimates of E calculated by two groups are performed for AP geometry, for PA geometry, for LAT geometry, and for ISO geometry. These data are in good agreement except some data within maximum 20% difference, in spite of difference of computer codes, databases, and phantom geometries. The analysis of these differences are discussed in Ref. [12] in detail.

3. Conversion coefficients for protons

High energy protons inside space shuttles are estimated to be the major component of astronauts' whole body dose equivalents. Nevertheless proton dose conversion coefficients of fluence to E_{WR} and $E_{Q\text{-}L}$ are not shown in any document except Refs.8,27,45 and 48. The ICRP 51 [1] provides the maximum dose equivalent and 10mm depth dose equivalent in 30cm thick semi-infinite slab phantom for proton incidence up to 10GeV.

Figure 4 represents the comparisons of E_{WR} for AP, PA, and ISO irradiation geometries calculated in the two groups, with the reference data of the maximum dose equivalent and the 10mm depth dose equivalent in the 30cm thickness semi-infinite slab phantom in the ICRP 51. The E_{WR} shown in Ref.8 are also exhibited for R-LAT geometries in Fig.4. Above 50MeV, there is good agreement between the data of Yoshizawa et al. [27,48] and those of Ferrari et al. [8] for AP, PA, and ISO geometries. Above 200MeV, good agreement can be observed among the effective doses E_{WR} for the three irradiation geometries. The estimates E_{WR} represent a little larger values than the maximum dose equivalents shown in the ICRP51 from the energy of 200MeV to 10GeV.

The comparisons of $E_{Q\text{-}L}$ were performed for AP, PA, and ISO irradiations and the maximum dose equivalent and the 10mm depth dose equivalent in the ICRP51. The estimates of $E_{Q\text{-}L}$ of Yoshizawa et al [27,45,48] show fairly good agreement with the 10mm depth dose in the ICRP51 above 200MeV.

VI. Summary

(1) Dose equivalent conversion coefficients from particle fluence to effective dose were overviewed for high energy neutron, proton, photon, electron, and charge muon and pions. Comprehensive comparisons were performed for the methodologies and conditions adopted in the four different groups calculating dose conversion coefficients from fluence to two kinds of effective dose , E_{WR}, and $E_{Q\text{-}L}$ of high energy neutrons, photons, protons.

(2) Comparisons of high energy neutron conversion coefficients of E_{WR}, and $E_{Q\text{-}L}$ were performed in the four groups. The estimates of E_{WR} in the four group show fairly good agreement below 500MeV. The estimates of $E_{Q\text{-}L}$ agree well without one exception of 30% difference.

(3) The 10mm depth dose equivalent of high energy neutron shows less than 50% lower values than E_{WR} above 50MeV. The quantity of 10mm depth dose equivalent agrees well with $E_{Q\text{-}L}$ especially for AP irradiation geometry above 50MeV, but for PA, and ISO irradiation geometries, it shows a little smaller values than $E_{Q\text{-}L}$ within the maximum difference of 30%.

(4) Comparisons were performed for the dose conversion coefficients of high energy photons calculated in the two groups. These data agree well within the maximum difference of 20% for the irradiation geometries of AP, PA, R-LAT, and ISO conditions.

(5) Comparisons of high energy proton conversion coefficients of E_{WR} were performed between the two groups from 20MeV to 10GeV. Good agreement can be observed for AP, PA and ISO geometries above 50MeV. The estimates E_{WR} represent a little larger values than the maximum dose equivalents in the slab phantom of the ICRP51 from 200MeV to 10GeV.

(6) The estimates $E_{Q\text{-}L}$ of high energy proton show fairly good agreement with the 10mm depth dose in the slab phantom in the ICRP51 above 200MeV.

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