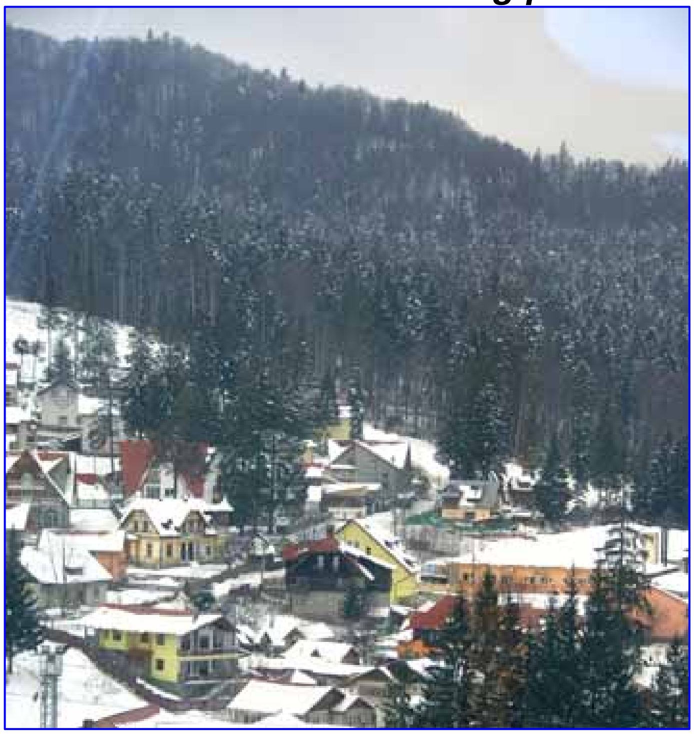
Calculation method for effective dose and ambient dose equivalent using particle fluence



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Abstract

This paper presents the effective dose and ambient dose equivalent determination method using particle fluences for photons and electrons up to 100 GeV and for neutrons, protons, pions, muons up to 10 TeV. The knowledge of dosimetric quantity values is necessary for radiation protection in high-energy accelerators, free electron lasers, high power lasers (>10^{15} W) and space missions.

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Abstract

This paper is a review about the effective dose and the ambient dose equivalent determination method using particle fluences for photons and electrons up to 100 GeV and for neutrons, protons, pions, muons up to 10 TeV. The knowledge of dosimetric quantity values is necessary for radiation protection in high-energy accelerators (TeV), free electron lasers, synchrotron radiation, space missions, high-gradient laser particle accelerators (TeV/m), yottawatt – zettawatt – exawatt - petawatt lasers (>10^{15-24} W; 10^{26-28} W/cm^2) and cosmic rays (3 x 10^{20} eV).

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Contents:

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1. Introduction

The effective dose is a radiological protection quantity used to evaluate radiation risks induced by radiation and related to all stochastic effects occurring in a human body. Because the effective dose can't be practically measured, fluence to dose conversion coefficients are calculated, in standard exposure condition. Thereby, conversion coefficients are needed in internal and external exposure. Such coefficients were determined using FLUKA, for a mathematic phantom containing 37 organ and tissues with different densities and composition. The same calculation program was employed for conversion coefficients determination in case of the ambient dose equivalent. Calculations were allowed for electromagnetic processes and photonuclear processes which occur due bremsstrahlung radiation generation in human body.

For effective dose calculation due photonuclear radiation, the next nuclear reaction: (γ, p), (γ, d), (γ, t), (γ,^{3}He), (γ, α) and (γ, n) has considered. The cross sections of six reactions including the giant dipole resonance peaks were given for the photon energy up to 140 MeV. Using the photon fluence averaged in each organ or tissue it was calculated the absorbed dose in each of these with the cross sections of photonuclear reactions.

2. Concept

2.1 Effective dose, E

$$E = \sum_T w_T H_T \,;\ [\text{Sv}]$$

-w_T is the weighting factor for tissue or organ *T*,

- H_T is the absorbed dose in tissue or organ *T*,

Organ or tissue	w_T
Bone surface, skin	0.01
Bladder, breast, liver, esophagus, thyroid	0.05
Bone marrow(red), colon, lung, stomach	0.12
Gonads	0.20
Remainder Tissues (10 in total: Adrenals, Brain, trachea small intestine, muscle, Pancreas, Kidneys, spleen, thymus & uterus)	0.05
Total Body	**1.00**

Values of tissue or organ weighting factor.

The effective dose, *E*, incurred by an individual in the group of age, *g*, will be determined according to the following formula:

$$E = E_{externa} + \sum_j h(g)_{j,ing} J_{j,ing} + \sum_j h(g)_{j,inh} J_{j,inh}$$

- $E_{external}$ is the relevant effective dose from external exposure,

- $h(g)_{j,inh}$ and $h(g)_{j,ing}$ are the commited effective dose per unit-intake for ingested or inhaled radionuclide *j*, (Sv/Bq), by an individual in the group of age *g*,

- $J_{j,ing}$ and $J_{j,inh}$ respectively are the relevant intake via ingestion or inhalation of the radionuclide *j*, (Bq).

2. Concept

2.2 Equivalent dose in tissue, organ, H_T

$$H_T = w_R D_{T,R} \,;\ [\text{Sv}]$$

-w_R is the radiation weighting factor, due to *R* radiation,

- and $D_{T,R}$ is the absorbed dose averaged over on tissue or organ *T*, due to *R* radiation.

In the case when the radiation field is composed of more types of radiations heaving energies (different values of w_R), the total equivalent dose H_T, is given by the relation:

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

Type and energy range	w_R
Photon, all energies	1
Electron and muon, all energies	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil one, energies > 2 MeV	5
Alpha particle, fission fragments, heavy nucleus	20

Values of radiation weighting factor.

2. Concept

2.3 Ambient dose equivalent, H(d)*

The ambient dose equivalent *H*(10)* at the point of interest in the actual radiation field is the dose equivalent which would be generated in the associated oriented and expanded radiation field, at a depth of 10 mm on the radius of the ICRU sphere (30 cm diameter tissue equivalent) which is oriented opposite to the direction of the incident radiation. The measurement unit for ambient dose equivalent, in SI, is Sievert [Sv].

2.4 Absorbed dose in tissue, organ, D_T

$$D_T = \frac{1}{m_T}\int_{m_T} D\,dm \,;\ [\text{Gy}]$$

- m_T is the tissue or organ mass;
- *D* the absorbed dose in *dm* mass element;

In case of photonuclear reaction, using the average fluence in each tissue or organ, calculated by EGS4 programme, the absorbed dose for charged particles at internal irradiation was calculated using expression :

$$D_i = \frac{1}{\rho}\sum_j \int_{E_i} E_i \int_{E_\gamma} N_j \cdot \sigma_{ij}(E_\gamma)\cdot f_j(E_i, E_\gamma)\cdot \bar{\phi}(E_\gamma)\,dE_\gamma\,dE_i$$

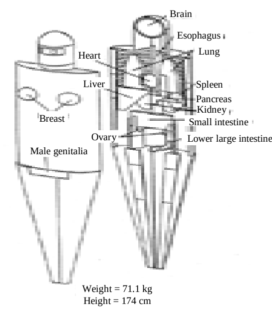
- D_i is the absorbed dose for charged particle *I*;
- ρ is density of tissue or organ;
- E_i is energy of charged particle, *i*;
- E_γ is the photons energy;
- N_j is the atom number density with *j* nucleus;
- $\sigma_{ij}(E_\gamma)$ is the cross section of *j* nucleus for *i* particle production when photons energy is E_γ;
- $f_j(E_i,E_\gamma)$ energy spectrum of secondary particle *i* by the reaction between photon and *j* nucleus;

3. Calculation materials and methods

3.1. The phantom used for dose calculation

The mathematical phantom used in the calculation was designed as hermaphroditic and included the 61 regions, or 37 organs and tissues with different densities and composition. Three tissues were considered: soft tissues, lung and skeletal tissue. The assumed density is 0.9869 g/cm³ for soft tissues, 0,2958g/cm³ for lungs and 1.4682 g/cm³ for skeletal tissue. The composition of the three tissues ware limited to the 17 elements: H, C, N, O, Na, Mg, P, S, Cl, K, Ca, Fe, Zn, Rb, Sr, Zr and Pb.

The phantom was irradiated by mono-energetic parallel electron beams. The selected irradiation geometries were: anterior-posterior (AP), posterior-anterior (PA), right lateral (RLAT), left lateral (LLAT), isotropic (ISO) and rotational (ROT).



Schematic representation of phantom used in calculation.

3. Calculation materials and methods

3.2 FLUKA routine

The effective dose and ambient dose equivalent conversion coefficients are implemented as FLUKA routine, a anthropomorphic phantom and an parallel and large radiation beam. The coefficients include the ICRP60 recommended, weighting factors. For each irradiation geometry two coefficients sets, are implemented: one set is based on weighting factors *wR* recommended by ICRP60 and the other uses the factors suggested by Pellicioni [5]. These coefficients are different at high energies, such as high energy protons of more than 2 MeV, for which ICRP60 recommend a value of 5 while Pellicioni suggested a value of 2.

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3.3 Calculation method presentation based on FLUKA routine

For dose and ambient dose equivalent one has started from knowing the fluence, Φ, defined like the incident particle number *dN*, entering into the sphere *dA* cross sectional area, given by formula:

$$\phi = \frac{dN}{dA}\frac{1}{[cm^2]}$$

The fluence Φ conversion coefficient *g*, in effective dose *E* is given by the relation:

$$g = \frac{E}{\phi}\frac{[pSv]}{\left[\frac{1}{cm^2}\right]}$$

$$E[pSv] = g \cdot \phi =$$

$$= g \cdot \phi \cdot \left[\frac{pSv}{\frac{1}{cm^2}}\frac{1}{cm^2}\right] = g \cdot \phi \cdot [pSv]$$

For example, at a energy of 1 000 MeV = 1 GeV, for a RLAT irradiation geometry, *g* = 518 pSv. Knowing the fluence it can be find the effective dose, so:

$$E = g \cdot \phi =$$

$$= 518\, pSv \cdot cm^2 \cdot 3.86 \cdot 10^7 \frac{1}{cm^2} =$$

$$= 518 \cdot 10^{-12} \cdot 3.86 \cdot 10^7\, Sv \cong$$

$$\cong 2 \cdot 10^3 \cdot 10^{-5}\, Sv \cong 2 \cdot 10^{-2}\, Sv \cong$$

$$\cong 0.02 Sv \cong 20 mSv$$

$$E \cong 20 mSv$$

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4. Results and discussions

4.1 Effective dose conversion coefficients calculation

Energy (MeV)	AP		PA		ISO		RLAT		LLAT		ROT	
1	3.65	0.6 %	1.94	1.6 %	2.08	0.3 %	2.25	1.3 %	1.17	0.7 %	7.15	0.6 %
5	77.3	0.8 %	13.6	1.4 %	32.9	0.8 %	8.91	1.6 %	9.33	0.5 %	28.7	1.0 %
10	131	0.7 %	40.1	1.3 %	57.1	0.4 %	21.3	1.3 %	21.7	0.9 %	60.6	0.6 %
20	243	0.9 %	114	1.1 %	101	0.7 %	69.5	1.3 %	63.6	0.9 %	133	0.7 %
30	312	1.0 %	230	1.6 %	161	0.8 %	115	1.4 %	126	0.9 %	209	0.7 %
50	339	1.2 %	340	0.7 %	243	0.9 %	210	1.4 %	236	0.9 %	295	1.1 %
100	353	0.8 %	367	0.8 %	329	0.8 %	324	1.0 %	339	0.9 %	353	1.0 %
200	360	0.9 %	382	0.8 %	384	0.6 %	395	0.9 %	395	0.9 %	385	1.0 %
500	368	1.1 %	400	1.2 %	454	1.4 %	460	1.0 %	463	1.2 %	419	1.1 %
1000	383	1.5 %	429	0.9 %	501	1.4 %	518	1.0 %	495	1.2 %	446	1.4 %
5000	407	1.1 %	473	1.0 %	650	1.0 %	652	1.3 %	602	1.3 %	507	1.1 %
10000	414	1.3 %	485	1.3 %	725	1.1 %	703	1.5 %	661	1.4 %	537	1.6 %
50000	438	1.4 %	535	1.3 %	913	1.1 %	862	1.2 %	795	1.2 %	630	1.6 %
100000	448	0.9 %	571	1.7 %	1039	1.0 %	933	1.0 %	846	1.1 %	653	1.2 %

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4. Results and discussions

4.1 Effective dose conversion coefficients calculation

The type of geometry with the *E* maximum is dependent on incident electron energy. In the energy range below 50 MeV, the *E* values are higher for AP that for any other geometry. This is because the range of electrons is short and most of electron energies are deposited in the area near the surface of the phantom, where organs or tissue with large w_T such as testes and breast are located. At 50 MeV, significant differences in the *E* values were not found among irradiation geometries. The reason is that the range of electrons with 50 MeV is estimated to be about 16 cm and nearly equal to the thickness of the phantom. For the energies above 50 MeV, *E* values are higher for AP irradiation geometry than PA irradiation geometry. For electron energy over 100 MeV, the *E* values for RLAT or ISO become the maximum. The range for electrons becomes larger and energy deposition increases in organs and tissues located inside and on the rear of the phantom against its incident direction. The variation of organ dose conversion coefficients decreases with incident electron energy in the energy range over 50 MeV.

For LAT irradiation, there are some differences in *E* between right lateral and left lateral geometries. This result can be explained by the position of specific organs, such as stomach and colon, with high tissue weighting factor. *E* is about 10 % higher for RLAT than for LLAT in the energy range over 5 GeV, mainly because stomach and colon were located at the left side of phantom. The w_T are: for stomach – 0.12 and or liver – 0.05, and the *E* was about 9 % higher for RLAT than for LLAT at 100 GeV. The *E* values for ROT resulted in nearly average values for AP, PA and LAT.

With other irradiation geometries there are not significant differences. As a result, the conversion coefficients calculated for the energy range over 10 MeV are valid data. On the other hand, some of the present results in the energy range below 10 MeV exceed by about 40 % those of the reference data. These discrepancies might be attributed to the difference in phantom.

4. Results and discussions

4.2 Dose evaluation by photonuclear reaction

It should be noted that charged particles produced by the interaction between high energy electrons and a human body contribute to doses in addition to the electromagnetic cascade shower calculated by EGS4. The contribution of photonuclear reactions was evaluated as a ratio of the absorbed doses by photonuclear reactions to the total absorbed doses. In case of AP irradiation geometry, the photonuclear reaction maximum contribution at absorbed dose is about 1%.

The predominant charged particles were recoiled ions for (γ, n) and (γ, p) reactions and proton for (γ, p) reaction, due to the larger cross sections than other reactions. The photonuclear reaction contribution gradually increases with incident electrons energy up to 500 MeV and then changes little up to 100 GeV. As for other irradiation geometries, each energy dependence of the ratio was similar to that in AP geometry and the maximum contributions to absorbed dose are within 0,2%. Usually, the doses for photons with energy up to 140 MeV were neglected because of the lack of the cross section in. In the case of the incident electron energy 100 GeV in AP geometry, the ratio of photon fluences above 140 MeV up to 100 GeV amounted to more than 50 % and the contribution of photon fluence above 140 MeV was estimated to be over 50 %. Then the contribution of photonuclear reactions to absorbed dose has been underestimated. The averaged quality factors of charged particles produced by the photonuclear reactions can be roughly estimated to be 10. However, the contribution of photonuclear reaction to absorbed dose was estimated to be 1 % and considerably small against the total adsorbed dose, even if the absorbed dose in the energies over 140 MeV was considered. The contribution of photonuclear reaction to effective dose will be about 6 % for AP, 9 % for ISO and 8 % for ROT geometry.

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5. Conclusions

This paper is a review of fluence conversion coefficients to effective dose and ambient dose equivalent calculation for electrons from 1 MeV to 100 GeV, using Monte Carlo simulation photons – electrons, combined with an anthropomorphic phantom given is also highlighted by several authors.

The photonuclear reaction, contribute to electrons with energy up to 140MeV. The absorbed dose ratio of photonuclear reactions to electromagnetic cascade reached about 0.6% for AP, 0.9% for ISO and 0.8% for ROT geometry.

By selecting the average quality factors of the charged particles produced by the photonuclear reactions to be 10, the contribution of photonuclear reactions to effective doses for all geometries was temporarily estimated to be 10%.

The results were generally concordant with the conversion coefficients for electrons up to 10 GeV calculated by FLUKA and suggest that the calculation methods such as a phantom and the simulation code may cause no significant difference in the effective doses and organ doses.

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Thank you

for your attention!