**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 (>10¹⁵ W) and space missions.
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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 conditions. Thereby, conversion coefficients are needed in internal and external exposure. Such coefficients were determined using FLUKA, for a mathematical phantom containing 37 organs and tissues with different densities and compositions. 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: \( \gamma, p \), \( \gamma, d \), \( \gamma, t \), \( \gamma, \alpha \) and \( \gamma, n \) 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, \(E\)

\[ E = \sum w_i H_i \text{ [Sv]} \]

- \(w_i\) is the weighting factor for tissue or organ \(T\);
- \(H_i\) is the absorbed dose in tissue or organ \(T\).

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

\[ E = \sum w_T H_{\text{ex}} \left( \sum w_J J_{\text{inh}} + \sum w_J J_{\text{ing}} \right) \]

- \(w_T\) is the weighting factor for tissue or organ \(T\);
- \(H_{\text{ex}}\) is the relevant effective dose from external exposure;
- \(J_{\text{inh}}\) and \(J_{\text{ing}}\) are the committed effective dose per unit-intake for ingested or inhaled radionuclide \(i\), \([\text{Sv}]/[\text{Bq}]\), by an individual in the group of age \(g\);
- \(J_{\text{inh}}\) and \(J_{\text{ing}}\) respectively are the relevant intake via ingestion or inhalation of the radionuclide \(i\), \([\text{Sv}]/[\text{Bq}]\).

<table>
<thead>
<tr>
<th>Organ or tissue</th>
<th>(w_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone, surface, skin</td>
<td>0.91</td>
</tr>
<tr>
<td>Brain, Brain stem, cerebellum, brain stem</td>
<td>0.90</td>
</tr>
<tr>
<td>Brain, meningesoral, caj, meninges</td>
<td>0.82</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>0.10</td>
</tr>
<tr>
<td>Miscellaneous Tissues</td>
<td>0.10</td>
</tr>
<tr>
<td>(in total: Adrenals, Bladder, breast, liver, esophagus, thyroid)</td>
<td>0.10</td>
</tr>
<tr>
<td>Total Body</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Values of tissue or organ weighting factor.

2.4 Absorbed dose in tissue, organ, \(D_T\)

\[ D_T = \sum_D \left( \frac{D_{\text{abs}}}{m_T} \right) \]

- \(D_{\text{abs}}\) is the tissue or organ mass;
- \(D\) is the absorbed dose in ab 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:

\[ D_T = \frac{1}{D_{\text{abs}}} \sum_{E_i} \sum_{N_j} \sigma_{ij} \left( \frac{E_i}{N_j} \right) f(E_i, E_j) \frac{[\text{Sv}]}{[\text{Bq}]} \]

- \(D_{\text{abs}}\) is the absorbed dose for charged particle \(i\);
- \(\rho\) is density of tissue or organ;
- \(E_i\) is energy of charged particle, \(i\);
- \(E_j\) is the photons energy;
- \(N_j\) is the atom number density with \(j\) nucleus;
- \(\sigma_{ij}\) is the cross section of \(j\) nucleus for \(i\) particle production when photons energy is \(E_j\);
- \(f(E_i, E_j)\) is energy spectrum of secondary particle \(j\) by the reaction between photon and \(j\) nucleus.

2.2 Equivalent dose in tissue, organ, \(H_T\)

\[ H_T = w_\gamma D_{\gamma,\text{av}} \text{ [Sv]} \]

- \(w_\gamma\) is the radiation weighting factor, due to \(\gamma\) radiation;
- \(D_{\gamma,\text{av}}\) is the absorbed dose averaged over on tissue or organ \(T\), due to \(\gamma\) radiation.

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

\[ H_T = \sum w_\gamma D_{\gamma,\text{av}} \]

2.3 Ambient dose equivalent, \(H^*(d)\)

The ambient dose equivalent \(H^*(d)\) 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 (50 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 \([\text{Sv}]\).

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 0.0890 g/cm³ for soft tissues, 0.2058 g/cm³ for lungs and 1.4682 g/cm³ for skeletal tissue. The phantom was irradiated by mono-energetic parallel electron beams. The selected irradiation geometries were: anterior-posterior (AP), posterior-anterior (PA), right lateral (LLAT), 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 self recommended by ICRP60 and the other uses the factors suggested by Pellicioni [3]. 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.

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 size, 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, the $E$ values are higher for AP irradiation geometry than PA irradiation geometry. For electron energy over 100 MeV, $E$ 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 factors. $E$ 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 $E$ 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 50 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 ($\gamma$, n) and ($\gamma$, p) reactions and protons for ($\pi$, 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 nuclear reaction to absorbed dose 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 absorbed 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.

References:


Thank you for your attention!