Effective Doses and Organ Doses per Unit Fluence Calculated for Monoenegetic 0.1 to 100MeV Electrons by the MIRD-5 Phantom

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ABSTRACT

To determine quantities for radiation protection against high-energy electrons, such as those from LINAC, the organ dose equivalents and equivalent doses for the human body were calculated using EGS-4 Monte Carlo simulation code and an MIRD-5 mathematical human phantom. Conversion factors for the incident fluence to the organ dose equivalent, to the effective dose and to the effective dose equivalent for monoenergetic electrons were obtained for AP and PA geometrical irradiation conditions at incident energies from 0.1 to 100MeV.

The agreement between the results of the present study of effective doses and those of other studies was acceptable within the statistical uncertainties. At energies lower than 10MeV, the skin sensitive layer was taken into account in some computations.

It was found that the effective doses depend on the incident electron energy, beam size, and exposure position of the body.

1. Introduction

Due to recent increases in space exploration and the use of high-energy charged particles and secondary particles produced by linear accelerators, there is an increasing risk for humans to become exposed to high-energy radiation, and radiation protection of the human body against high-energy electrons (at more than 2MeV) has become a priority. Here it is necessary to consider dose equivalents to organs deeper than the skin [1]-[2].

There have been many studies to obtain conversion factors for effective doses of neutrons and photons with human phantoms and Monte Carlo code [3]-[7]. For electrons there are some data using the ICRU sphere and other simple phantoms, such as a slab phantom [8]-[11], but there have been few studies on electrons with the human phantom.

Schultz et al. calculated the organ and effective doses per unit fluence using the MCNP code version 4 for the mathematical adult male phantom (ADAM) [12], and for the female phantom (EVA) and the 7 year old girl phantom [13] in the AP direction with broad unidirectional electron beams from 0.1 to 10MeV. For monoenergetic electrons from 5MeV to 10GeV, Ferrari et al. [14] have calculated the effective dose equivalent and the effective dose per unit fluence using the FLUKA code for the anthropomorphic phantom (ADAMO) under various geometrical conditions (AP, PA, LAT, ISO).

To establish the conversion factors it is important to use different simulation code and different types of phantoms. The present study calculated the organ dose equivalents, the effective doses and the effective dose equivalents using the EGS-4 Monte Carlo simulation code and the MIRD-5 mathematical human phantom. Calculations were carried out for the AP and PA geometrical irradiation conditions at incident electron energies from 0.1 to 100MeV.

The results of the present study of effective doses agree well with other studies with other simulation codes and phantoms. At incident energies lower than 10MeV, the skin sensitive layer was taken into account in some computations.

2. Methods of Calculation

2.1. Mathematical Anthropomorphic Model

The mathematical anthropoid phantom used in this study is derived from MIRD pamphlet No.5 (revised) [15] to which a Lewis 's esophagus [16] is added. The MIRD-5 phantom is a hermaphrodite phantom that includes female-specific organs (breasts, ovaries, etc.) and was first developed for calculation of internal exposure doses. The dimensions of the phantom were chosen after considering the distribution of dimensions and weights of certain Western populations [17]-[18] and the ICRP Reference Man [19](height, 174 cm; weight, 70 kg). The phantom contains a total of 61 different kinds of tissue (2 kinds of lung tissue (0.296g cm-3), 38 kinds of soft tissue (0.987g cm-3) and 21 kinds of skeletal tissue (1.486g cm -3)), and the density and composition of each kind of tissue in relation to the interaction probability with irradiated particles are given [19]-[20]. All organs and tissue types except the skeleton and lungs are considered to be soft tissue of the same composition.

2.2. Monte Carlo Simulation and Irradiation Geometries

The simulations used the Electron Gamma Shower version 4 (EGS-4) Monte Carlo code [21], which was developed at the Stanford Linear Accelerator Center (SLAC) [22] and has been widely used in medical physics to study phenomena such as electron contamination by photon beams. This code enables a three-dimensional simulation of electromagnetic cascade transport and calculations of the energy deposited due to the transport of particles in a user-defined geometry. The EGS-4 code in this study used slightly modified EGS code which has a pre-processor to simplify the input and output data [23]. It was used on a Sun SPARC 10 workstation (36MHz Super SPARC processor, 64 Mb main memory, 1Gb hard disk) with a UNIX (SunOS 4.1.4).

In this code, each electron and photon is followed until it either escapes from the system geometry or until its energy falls below a user-specified cut-off energy level. The cut-off energy for photons is 0.02MeV with incident energies of 0.1 to 20MeV and 0.05MeV for incident energies above 50MeV. For electrons, the cut-off energy is 0.531MeV (including rest mass energy) at 0.1 to 20MeV and 0.561MeV above 50MeV. To obtain sufficient statistical reliability in the simulation, 1,000,000 particle histories were simulated at every incident energy. This occupied between a few hours and 28days of CPU time depending on the initial incident electron energy.

Calculations were carried out for whole body exposure with parallel broad monoenergetic electrons of 0.1 to 100 MeV by 1,2,5 step, where the phantom was placed in a vacuum space. The direction of the incident beam was either anterior-posterior (AP) or posterior-anterior (PA).

2.3. Calculation of Effective Doses and Organ Equivalent Doses

The equivalent doses (H_T) in a tissue T has been given by ICRP [24], as

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

where $D_{T,R}$ is the absorbed dose averaged over the tissue T due to radiation R; w_R is a radiation weighting factor associated with the radiation particles with w_R=1 for electrons.

The effective dose (E) is the sum of the weighted equivalent doses in all kinds of tissue and organs of the body given by the expression

$$E = \sum_T w_T \cdot H_T$$

where H_T is the equivalent dose and w_T is the weighting factor for tissue T. The tissue weighting factor represents the relative contribution of that organ or tissue to the total detriment due to these effects resulting from uniform irradiation of the whole body.

The absorbed doses for a tissue consisting by more than two regions, such as lungs and breasts, were calculated as the average of the dose to each region weighted by the mass of that region. It is shown by the expression

$$D_T = \frac{m_1 \times D_1 + m_2 \times D_2 + \cdots}{m_1 + m_2 + \cdots} \qquad (1)$$

where m_1,m_2… are the masses of each region and D_1,D_2… are the absorbed doses of each region.

As mentioned above, the MIRD-5 phantom is a hermaphrodite which has both ovaries and testes. However a human being has either ovaries or testes and the absorbed dose for the gonads has determined as the average of the doses for the testes and ovaries, as

where $D_{ovaries}$ is the dose absorbed by the ovaries and D_{testes} is that for the testes.

$$D_{gonads} = \frac{(D_{ovaries} + D_{testes})}{2}$$

There are 21 regions of bone in the MIRD-5 phantom and the EGS-4 generates the energy deposited (Ed) in each bone region. The dose absorbed by all bone can be calculated by equation (1). There are two weighting factors for bone in ICRP, one is the weighting factor for bone surfaces and the other is for bone marrow and it is necessary to obtain the dose absorbed by both.

The skeletal tissue in the MIRD-5 phantom consists of a homogeneous mixture of bone surface and bone marrow. The energy deposited in the skeleton was separated by a weighted ratio of bone surface<bs>and bone marrow<bm>, as

$$Ed_{bone} = Ed_{bs} + Ed_{bm}$$

$$Ed_{bs} = Ed_{bone} \cdot \frac{M_{bs}}{M_{bone}}$$

$$Ed_{bm} = Ed_{bone} \cdot \frac{M_{bm}}{M_{bone}}$$

where Ed_{bone} is the energy deposited in all bone, M_{bs} and M_{bm} are the masses of bone surface and bone marrow. The masses of bone marrow in the phantom are described in the MIRD-5 pamphlet [15].

Muscle is not described as a specific locus in the phantom but is considered in the term "other tissue". This designation includes all tissue that remains after the specified organs are excluded.

In this study, the energy deposited in muscle is calculated as follows

$$Ed_{muscle} = Ed_{other} \times 0.58 + Ed_{heart}$$

The total mass of other tissue is 48.5kg, and muscle constitutes approximately 58%(28kg) of this mass [15]. In this study, the heart is regarded as muscle.

In the low energy region, it is important to take account of the complicated form of the skin because the top layer (70 μ m) of the skin consists of cells that are insensitive to radiation. The skin dose refers to only the sensitive layer, but the skin dose simulated by EGS-4 is related to the total 0.2mm skin thickness. The dose absorbed in the sensitive skin layer can be estimated as follows [12]:

1. A correction for the mass is made by the ratio of the thickness of the sensitive skin to the total thickness (0.2-0.007)/0.2 = 0.965; and
2. The energies absorbed in the sensitive layer and in the total skin are simulated in the same geometry as that used by Shultz [12]. All of this geometry is defined as soft tissue. The energies deposited in the three components (a 0.007cm thickness slice of insensitive skin, a 0.193cm thickness slice of sensitive skin and a 2.3cm thickness peace of soft tissue) are calculated by the original version of EGS-4. The ratio of the energy in the sensitive skin part to the sum of energies in the sensitive and insensitive part, C, can then be calculated.

Table 1. Energy deposited in sensitive skin and total (both sensitive and insensitive skin) and correction factors for the sensitive skin layer

Electron	Deposited energy (MeV per incident electron)				Corr. factor	
Energy	sensitive		total			
(MeV)	compartment	FSD(%)	skin	FSD(%)	C/0.965	FSD(%)
0.1	3.72E-02	8.38E-03	9.78E-02	3.42E-03	0.39384	8.87E-02
0.2	1.67E-01	1.20E-02	1.95E-01	6.73E-03	0.88634	4.73E-02
0.5	4.74E-01	1.59E-02	4.90E-01	1.45E-02	1.00256	1.01E-02
1	5.89E-01	4.86E-02	6.02E-01	4.85E-02	1.01388	5.54E-03
2	4.16E-01	5.02E-02	4.28E-01	5.05E-02	1.00745	5.58E-03
5	3.54E-01	3.59E-02	3.66E-01	3.63E-02	1.00373	5.95E-03
10	3.48E-01	2.91E-02	3.59E-01	2.91E-02	1.00319	6.18E-03

total = insensitive + sensitive , C = sensitive / total

The correction factor becomes C/0.965 and the total skin dose, already known, is multiplied by this factor to yield the dose in the sensitive part of the skin. In Table 1, the correction factor and the energy deposited in sensitive component and total skin are listed as a function of electron energy. The value of the correction factor is 0.39 at 0.1MeV, which shows that about 60% of the total energy deposited in the skin region are absorbed in the insensitive layer. At 0.2MeV, the correction factor is 0.89 and about 10% of the energy deposited in the skin region are in the insensitive layer. Though the skin is defined as soft tissue in this study and is defined as special skin tissue in Shultz's calculations, the value of the correction factor in this study is in good agreement with that of Shultz.

3. Results and Discussion

The effective dose equivalent and effective dose (with and without insensitive skin layer) for all electron energies and irradiation geometries are shown in Table 2. The organ equivalent and effective doses are

normalized to unit incident electron fluence. The organs contributing more than 10% to the effective dose are also presented in Table 2.

Table 2. Effective doses (total and skin correct) and effective dose equivalents per unit fluence as a function of electron energy and organs contributing more than 10% to the effective dose

(AP exposure)

Energy (MeV)	H_E (Sv cm2)	E (Sv cm2)	E(Skin correct) (Sv cm2)	Organ contributing to E(for skin total) (>10%)
1.00E-01	3.70E-14	2.78E-13	1.23E-13	skin(92.1)
2.00E-01	4.81E-15	5.15E-13	4.57E-13	skin(99.6)
5.00E-01	1.76E-14	1.29E-12	1.29E-12	skin(99.0)
1.00E+00	6.39E-12	4.19E-12	4.21E-12	breast(46.6),skin(43.0)
2.00E+00	3.16E-11	1.51E-11	1.51E-11	breast(55.9),gonads(21.7),skin(10.5)
5.00E+00	1.03E-10	6.21E-11	6.21E-11	gonads(40.4),breast(30.2),thyroid(15.5)
1.00E+01	1.67E-10	1.15E-10	1.15E-10	gonads(29.3),thyrsid(16.6),breast(13.9),stomach(11.9)
2.00E+01	2.71E-10	2.29E-10		gonads(20.4),lungs(16.0),stomach(13.8)
5.00E+01	3.40E-10	3.32E-10		gonads(19.9),lungs(13.7),colon(12.1),stomach(11.3),marrow(11.2)
1.00E+02	3.58E-10	3.43E-10		gonads(19.8),lungs(14.4),marrow(12.8),stomach(11.8),colon(10.7)

(PA exposure)

Energy (MeV)	H_E (Sv cm2)	E (Sv cm2)	E(Skin correct) (Sv cm2)	Organ contributing to E(for skin total) (>10%)
1.00E-01	1.23E-14	2.68E-13	1.11E-13	skin(96.4)
2.00E-01	8.76E-15	5.24E-13	4.65E-13	skin(98.7)
5.00E-01	1.34E-14	1.30E-12	1.30E-12	skin(99.3)
1.00E+00	4.25E-13	2.16E-12	2.18E-12	skin(84.8)
2.00E+00	2.77E-12	3.90E-12	3.91E-12	skin(41.0),marrow(32.4),remainder(22.8)
5.00E+00	1.24E-11	1.15E-11	1.15E-11	marrow(50.7),skin(13.6),remainder(23.8)
1.00E+01	7.17E-11	3.93E-11	3.93E-11	marrow(39.3),lung(33.9),remainder(13.9)
2.00E+01	1.81E-10	1.12E-10		lung(38.8),marrow(27.7),
5.00E+01	3.36E-10	3.25E-10		gonads(19.0),lung(15.3),marrow(12.5),colon(12.2),stomach(11.4)
1.00E+02	3.85E-10	3.68E-10		gonads(21.2),lung(13.4),stomach(13.2),marrow(11.5)

At low energies, the proportion of the skin in the effective dose is more than 95%. However with increases in electron energy the skin proportion is lower and deeper organs such as breasts, gonads, and lungs become the main contributors. For AP irradiation, at electron energies below 0.5MeV, the organ equivalent dose of the skin comprises about 99% of the effective dose. At electron energies from 0.5MeV to 2MeV, the organ equivalent dose of the breasts, which is given a large tissue weighting factor, comprises more than half. At energies above 5MeV, the gonads, thyroids, and lungs become the main components, and above 50MeV, the proportion of the colon and stomach in the effective dose also become large. In PA irradiation at incident energies up to 1MeV, the organ equivalent dose of the skin comprises more than 80% because the posterior of the human body has no main specified organs such as the breasts. For electron energies above 2MeV, the deeper organs such as marrow, lungs, and gonads are the main components.

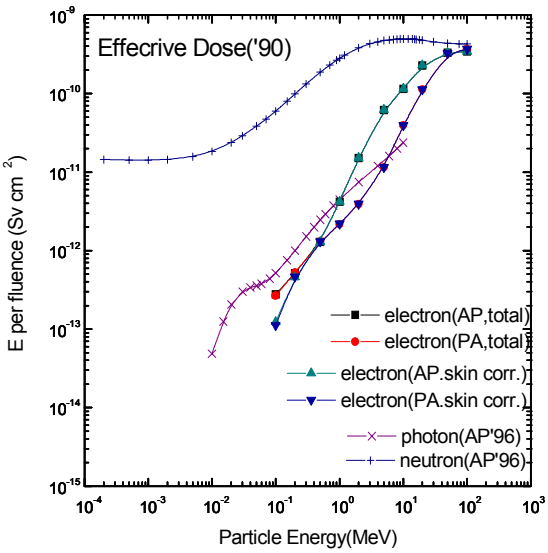

Figure 1. Effective dose per unit fluence as a function of electron energy for the AP and PA geometries (with and without correction for radiation sensitivity of the skin) and values for neutrons and photons from AP ('96)[25]

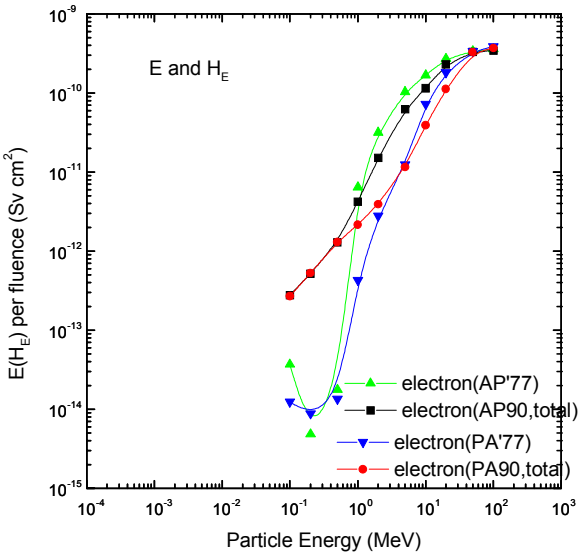

Figure 2. The effective dose and effective dose equivalent as a function of electron energy for AP and PA geometries

Figure 1 shows the effective dose per unit fluence calculated in this study for the AP and PA geometries as a function of electron energy. The results of photons and neutrons for AP geometry described in ICRP Publication 74 [25] are also shown in Figure 1. The effective dose per unit fluence increases with increases in incident energy and finally reaches an almost saturated level. The value of the conversion factor for electrons exceeded that for photons both above 1MeV (AP) and 5MeV(PA), and it is lower than the value for neutrons in the energy range studied here.

With incident energies lower than about 0.5MeV, the calculated values of the effective doses for the AP condition show good agreement with those for PA. In this energy range almost all the energy of incident electrons (more than 95%) is absorbed in the skin layer, the absorbed doses of the skin for AP and PA are nearly the same as are the effective doses for AP and PA. For the effective dose, the influence of radiation insensitive skin layer is notable for electron energies below 0.5MeV. The effective dose with insensitive layer is lower than a half of that without it at 0.1MeV for AP irradiation. In this energy range, the dose absorbed in the insensitive layer is relatively large, in comparison to the dose in the sensitive part of skin and in other organs. Therefore, it is necessary to consider the insensitive skin layer at these energies.

Between 0.5MeV and 50MeV, the effective dose for AP is larger than that for PA, mainly due to the breasts that receive more energy in the AP geometry.

Above 50MeV the value for PA is closer to that for AP and becomes slightly larger than that for AP, as the increase in the dose absorbed by the breasts in PA becomes much larger, though the gonads contribute most to the conversion factor for both geometries at this energy level.

Effective dose and effective dose equivalent per unit fluence as a function of electron energy for AP and PA are shown in figure 2. For electron energies below 1.0MeV, the effective dose equivalent is much lower than the effective dose because the principal dose absorbing organ the skin, is excluded from calculations of the effective dose equivalent. Skin was not given a tissue weighting factor as an organ at risk in ICRP Publication 26 [26].

Above 5MeV, the values of the effective dose and the effective dose equivalent per unit fluence are similar for both geometries. In this energy range, Table 2 shows that the skin contribution is relatively small for both AP and PA.

In Figure 2, the effective dose equivalents per unit fluence for both geometries show a minimum value around 0.2MeV. That tendency is similar to the result of Shultz. However, the effective dose per unit fluence does not show a minimum value because the contribution of the skin is large in this energy range.

Figure 3 presents the effective doses per unit fluence calculated in this study and by others (Shultz – using MCNP code and the ADAM and EVA phantoms, Ferrari – using FLUKA code and the ADAMO phantom). The agreement between the results of the present and others studies is acceptable within the statistical uncertainties. However, the present results show some differences from those of Shultz above 0.5MeV. The reason for these differences is not clear, but the type of the phantom and the simulation code used in the calculations could be responsible.

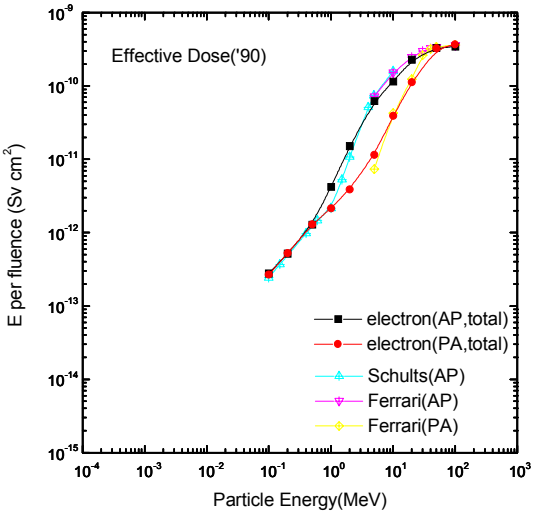

Figure 3. The effective dose as a function of electron energy, compared with results by Shultz (1996) and Ferrari (1997)

The geometrical irradiation condition in LINAC applications is mostly beam exposure. Dose equivalents in non-uniform beam exposure would depend on the beam intensity and also on beam size, beam position, and other beam parameters. This study calculated the conversion factors in non-uniform exposure with monoenergetic electrons of 0.1MeV to 100MeV by EGS-4 simulation code and the MIRD-5 phantom as well as whole body exposure, especially with regard to beam size and position. The incident beam size was 16.23cm x 20.0cm (default size), which corresponds to 1/10 of the region from the shoulders to the upper part of the legs. The phantom was irradiated from eight directions; three at the chest (right, left and center), three at the abdomen and one at each of the neck and lower abdomen. The irradiation geometry is AP for all beam exposures.

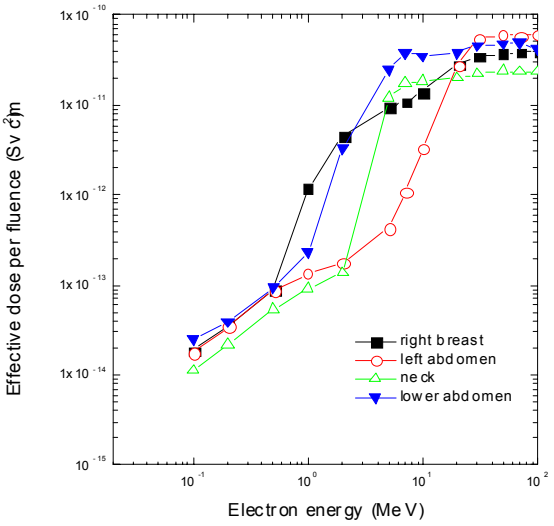

Figure 4. The effective doses as a function of electron energy for non-uniform beam exposure of several parts of the body (right breast, left abdomen, neck, and lower abdomen)

The figure 4 shows the effective doses per unit fluence in non-uniform exposure with irradiation of the chest, abdomen, neck, and lower abdomen. In uniform exposure the effective dose increases regularly with increases in incident electron energy, while in the non-uniform exposure it increases rapidly from an energy level depending on the exposure position, for example from 10 MeV for the abdomen. The effective dose depends on the organ location and on the radiation weighting factors that the organ has. To elucidate the phenomena, the organs that mainly contributed to the effective dose were investigated in each exposure geometry. In the exposure of the chest the percentage of the skin dose is high below 0.5MeV. From 1MeV to 7MeV, the breast dose percentage dominates, indicating that incident electrons of energies higher than 1MeV reach the breast and deposit energy here. Above 7MeV, the breast dose percentage decreases as the electrons reach the lungs and the percentage of the lung dose increases.

Further, to investigate the beam size effect, conversion factors were calculated as the phantom was irradiated by smaller incident beams (1/4 and 1/6 of the default size) on the chest and abdomen in the energy range of 0.1MeV to 20MeV. As the electrons reach the main organs in the abdomen at energies above 10MeV, it is necessary to simulate much higher energies than 20MeV to understand the dependence of the effective dose on the beam size.

Visual modeling of the phantom used in the EGS-4 simulation code was also considered in order to express the conversion factors and in order to construct a phantom with changeable physique and posture. Persistence of Vision Ray Tracer (POV-Ray), a software program for creating three-dimensional graphics by ray tracing, was used to three-dimensionally visualize the phantom. This is expressed by transparent material to visualize the distribution of deposited energy in internal organs. In the figure 5, the image of the phantom obtained by using POV-Ray was showed.

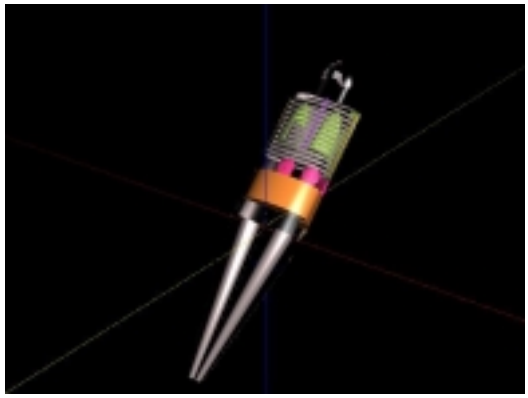

Figure 5. Image of the phantom obtained by POV-Ray

4. Conclusion

In the present study, the conversion factors for AP and PA geometrical irradiation conditions in the incident electron energy range of 0.1 to 100MeV are calculated. The results are in good agreement with the values of others within the statistical uncertainties, though the simulation code and the phantoms used are different.

At low energies, almost all the energy of an incident electron is absorbed in the skin layer. However the dose absorbed in the skin, with the MIRD-5 phantom, does not consider the insensitive skin layer, and the effective dose per unit fluence is overestimated.

Around 0.2MeV the effective dose for AP is similar to that of PA. With higher electron energies the skin contribution is reduced and deeper organs such as breasts, gonads, and lungs become the main contributors. From 0.5MeV to 50MeV the difference in the effective dose between AP and PA is because of the location of the main contribution. Above 50MeV, the values of the effective dose and the effective dose equivalent per unit fluence are very similar for the two geometries.

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