Volume-Shape Dose Dependence for Gamma Radiation Brachytherapy: A Monte Carlo Study

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Abstract

The use of internal radiation from a gamma source in brachytherapy has been developing for several decades as a beneficial tool in the field of radiation therapy in medical physics. Brachytherapy has proved to be efficient for the treatment of tumors in a variety of organs that have different volumes and shapes. The use of brachytherapy treatment is based mainly on the AAPM protocol (TG-43) published in 2004. The calculations or measurements of dosimetry are based on the definition of dose, which is the ratio of absorbed energy in a volume to the volume mass. The study aimed to present volume shape influence on dose, calculated by using Monte Carlo code systems.

The general purpose radiation Monte Carlo codes used in this study are the MCNP5, and the EGS5. Three different basic shapes with the same volume were defined for each case, each having a monochromatic point gamma source, or a line source inside. Along the full range of energies of relevance for brachytherapy the absorbed dose results showed a remarkable dependence on the volume-shape. The shape dependence was found in several volumes, for a point source and for 8 mm line source.

Since the volume shape can influence the absorbed dose values, we conclude that in brachytherapy treatment planning, the dose dependence on the treated volume shape is significant.

Keywords: Simulation; Point-source; MCNP, EGS5

Introduction

Photon irradiation is one of the most useful radiation types for tumor treatments using X-rays or gamma point sources. In brachytherapy, the commonly used internal sources are gamma rays emitters inside seeds or other tiny sized radioactive materials. The two main types of brachytherapy treatments in terms of the placement of the radioactive source are interstitial and contact. The Contact Brachytherapy involves placement of the radiation source in a space next to the targeted tissue. Interstitial brachytherapy is performed by placing the sources directly into the treated tissue of the affected site, such as in the treatment of prostate or breast tumors. There are two main types of interstitial brachytherapy, temporary or permanent.

• Temporary brachytherapy involves placement of radiation sources for a fixed duration (usually a number of minutes or hours) before withdrawing them.

• Permanent brachytherapy, also known as seed implantation, involves placing small radioactive seeds inside the tumor or treatment site and leaving them there permanently until they gradually decay. Brachytherapy is commonly used in treating cervical, prostate, breast and skin cancers and can also be used to treat tumors in many other body sites as listed in table 1.1 in the GEC ESTRO Handbook of brachytherapy (Gerbaulet et al. 2002)[1].

Radiation damage is directly connected to the absorbed dose rate which is expressed as

$$\frac{\Delta E}{\Delta m} = \frac{\Delta E}{\rho \Delta V}$$
It is crucially important to know the exact dose rate planned for a given case in order to achieve an effective treatment. In radiation dosimetry in nuclear medicine the Medical Internal Radiation Dose (MIRD) method is introduced for aspects of exposure due to radionuclide use in diagnostics applications. The absorbed dose is separately calculated for every organ using the MIRD method (Stabin et al 1999) [2], however the use of common Monte Carlo code system is recommended as well, therefore the shape of each organ is inserted to some precision. If there is shape dose dependence in the organs absorption, it is already resulting including the overall considerations.

In 1995, the American Association of Physicians in Medicine (AAPM) Task Group No. 43 published the TG-43 protocol introducing new brachytherapy dose calculation formalism (Rivard et al 2004) [3]. TG-43 protocol employs dose-rate constants and other dosimetric parameters that depend on the specific source design, and are directly measured or calculated for each source design. In the TG-43 protocol dosimetry formalism, a source is defined as any encapsulated radioactive material that may be used for brachytherapy. A point source is a radioactivity dimensionless point with a dose distribution assumed to be spherically symmetric at a given radial distance.

The AAPM provides a list of methodological details and recommendations that must be taken into consideration in the brachytherapy dosimetry, such as choosing the detector or the referenced medium. Specific details of measurement methodology are given in the protocol as well as in the Monte Carlo simulations code to be compared with TG-43 protocol recommending the use of the MCNP code and the EGS4 code for brachytherapy simulations and dose calculations.

We would like to clarify that despite all the minute details and recommendations in the AAPM TG-43 protocols concerning the source design, there is no mention of the target tissue geometry relevance for dosimetry. As published recently, a later AAPM Task Group report (TG-186) [4] was published in 2012 in order to deal with brachytherapy as a more defined procedure. Therefore, detailed voxel and media definitions are recommended to be used for accurate calculations. (Presented in the 3rd European Workshop on Monte Carlo Treatment Planning, Seville, Spain, 15-18 May 2012, by Frank Verhaegen). This study shows the necessity for more defined details in the dose calculations around a radiation source.

**Previous studies**

In a previous study made in the 1960's by G. L. Brownell some dose rate dependency on the phantom geometry, besides the mass dependence is mentioned. It appears from the publications that Brownell research dealt mainly with the influence of the phantom mass on the absorbed dose on any given phantom. In his article he summarized (Ellett et al 1964) [5] that the average absorbed dose rate, varies by a factor of 23 over the same range of phantom mass and is maximum for the smallest phantom, the A.F. being less energy dependent for smaller phantoms. In other words for a given amount of gamma activity, the average dose in a child will be much larger than that for the exponential nature of gamma-ray absorption.

Brownell's next objective is to examine the effect of different phantom geometries on the absorbed dose rate; for that purpose he uses three types of models, Ellipsoid, Sphere and Elliptical base cylinder. The absorbed dose which G. L. Brownell presents in his papers tables results of Absorbed Fraction (A.F.) that are calculated using Monte Carlo code. The A.F. is the fraction of the emitted gamma-rays energy absorbed by a phantom of specified mass and geometry.

$$A.F = \frac{Absorbed \gamma energy}{Total \ emitted \gamma energy}$$

The first point source comparison is made using ellipsoidal phantoms and elliptical base cylinder, while the ellipsoidal has the same maximum cross-section dimensions as an elliptical cylinder of the same mass. (Such ellipsoidal phantoms are necessarily much longer than an equal mass cylindrical phantom).

A comparison of Table II and the ellipsoidal data of Table III in Ellet paper (reference 4) shows that there is very little difference between these models at any energy or phantom mass. From these results the article concludes that for central point sources within the trunk, the use of an elliptical cylinder as a model for patient dose calculations is justifiable regardless of the patient's stature. The second point source comparison made between ellipsoidal and spherical in Table III shows that a 70 kg sphere has an A.F. which is 35 % much larger than an elongated phantom of the same mass. Spherical phantoms absorb a higher fraction of the initial gamma energy than elongated phantoms (such as the human body), due to a larger effective radius for a given mass. The article concludes that such spherical phantoms are an inappropriate geometric model for calculating gamma rays absorption in the human body.

Brownell's last objective is to examine the effect of the phantom source position on the dose rate, concluding that the source position in the array of elliptical cylinders has almost no effect on the A.F. Brownell's research group later publication (Ellet et al 1965) [6] reached the same conclusion. The absorbed fractions in equal mass spheres, elliptical cylinders, and ellipsoids containing a uniform distribution of a 0.662 MeV γ emitter are compared. As in the case of central point sources, the A.F. for spheres is considerably larger than for elongated phantoms. Unlike the central point source case, the A.F. for ellipsoids is significantly less than that of an elliptical cylinder of the same mass and maximum horizontal cross section. Because the body is tapered to the head and to the feet, the article concludes that the ellipsoidal model is probably the best choice for dosimetry calculations. Furthermore, a clear difference is demonstrated between A.F.s in ellipsoidal cylinders and spheres but negligible changes are found between spheres and thick ellipsoids – less than 3% at 0.662 MeV. Because gamma-rays escape is more probable in the case of flat ellipsoids, the A.F. values for these shapes are significantly lower. At low energy γ emitters, the absorbed fractions for a central point source either in ellipsoidal cylinders or in low mass ellipsoids in the mass ranges between 0.3 and 6 kg the A.Fs for spheres and for thick ellipsoids of the same mass did not significantly differ (Reddy et al 1967) [7].
Method

The Monte Carlo method provides approximate solutions to a variety of mathematical problems by performing statistical sampling that rely on repeated random sampling. A computer calculates the results of simulated experiments. The method is used to resolve problems with no probabilistic content as well as those with inherent probabilistic structure, such as the interaction of nuclear particles with materials. It is particularly useful for complex problems that cannot be modeled by computer codes that use deterministic methods. In this research the absorbed dose to the tissue by gamma source emitters has been calculated by means of the two most common Monte Carlo code systems used in medical physics, the MCNP5 (Briesmeister (ed.) 2000) [8] and the EGS5 (Hirayama et al 2007) [9].

MCNP (Monte Carlo N–Particle) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled neutron/photon/electron Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, the photon and electron energies in the simulations are from 1 keV to 1000 MeV. MCNP is an input/output program; the user creates an input file that is subsequently read by the MCNP. This file contains information about the program such as geometry specification, description of materials and selection of cross-section evaluations, location and characteristics of the source and the type of answers or tallies desired. The program creates an output file which provides information about the simulation, including source information, cross section tables, and neutron/photon nuclide activity.

The EGS (Electron-Gamma Shower) code system is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies ranging from above a few keV up to several hundred GeV. The EGS5 is a FORTRAN open source program. Since the 1990s when the previous EGS4 code was released, it has been used in a wide variety of applications, particularly in medical physics, radiation measurement studies, and industrial development. The EGS5 code system contains, among many other subprograms, four user-callable subroutines: BLOCK SET, PEGS5, HATCH, and SHOWER. These routines call other subroutines in the EGS5 code, some of which call two user-written subroutines, HOWFAR and AUSGAB, which respectively define the geometry and scoring output. The user communicates with EGS5 by means of the subroutines mentioned above which enable him to access variables contained in various COMMON blocks. To use EGS5, the user must write a MAIN program and the subroutines HOWFAR and AUSGAB.

Medical physicists are familiar to the MCNP and EGS codes, and their simulation results are well-known as reliable for the radiotherapy calculations.

The sphere volumes are calculated using the formula

\[ V = \frac{4}{3} \pi r^3 \]

and the radius \( r \) extract while choosing the desire volume. The cylinder volumes calculated using the volume formula

\[ V = \pi r^2 h \]

while choosing the desire volume and height to extract the radius \( r \). The parameters needed for the MCNP simulations are \( r \) for a sphere, and \( r \) and \( h \) for a cylinder. The volume formulas for ellipsoid given by

\[ V = \frac{4}{3} \pi abc \]

when using the same volume as before and choosing the ‘b’ and ‘c’ dimensions to extract the dimension ‘a’, it is important to select \( a>b>c \) to receive proper outcomes. The MCNP parameters were received from the ellipsoids formula:

\[ \left( \frac{x}{a} \right)^2 + \left( \frac{y}{b} \right)^2 + \left( \frac{z}{c} \right)^2 = 1 \]

the parameters

\[ A = b^2 c^2, \quad B = a^2 c^2, \quad C = b^2 a^2, \quad G = -b^2 c^2 a^2, \]

D=E=F=0 were received while using a common denominator at the above equation. An example for the 19.5 cm³ volume that was used is shown in Table 1. The sphere, cylinder and ellipsoid of the same volume were input into the EGS5 CGView program and plotted as shown in Figure 1.

Results

The first simulations set was carried out for three different shapes, each with a volume of 19.509 cm³, using the MCNP and the EGS5 Monte Carlo codes. In these simulations, a varying mono-energetic photon source in the range of 9-400 keV was defined for the center of the shape. This stage was planned in order to compare the results of the two codes, EGS5 and MCNP, along the brachytherapy typical energy range. The results of this comparison are presented in Figure 2, and the average values, from the two codes, of absolute dose per fluence are listed in Table 2. The nominal statistical uncertainty, as calculated by the MCNP simulations, was around 0.02% for each one of the simulations. (Same should be for EGS5 due to similar conditions). The differences between the MCNP and EGS5 results listed in Table 2 were found to be vary up to 2.9%, having non significance for the desired medical treatments precision. Figure 2 shows the agreement, for each one of the shapes versus the photon energy, between the MCNP and EGS5 results. In addition, Table 2 shows that at the lowest energy of 9 keV all the shapes absorbed the same dose value with no remarkable difference, due to full absorption because of such a low energy.
Figure 1. The three basic shapes with the same volume for the Brachytherapy Monte Carlo simulations. The parameters are listed in Table 1.

Table 1: Parameters used for the 19.5 cm$^3$ volume for three geometries.

| Geometry  | Ellipsoid | Cylinder | Sphere  |
|-----------|-----------|----------|---------|
| Volume equation | $\frac{4}{3} \pi abc$ | $\pi r^2 h$ | $\frac{4}{3} \pi r^3$ |
| Geometry Parameters | $a=3$, $b=1.5$, $c=1.03492$ | $R=0.909941$, $h=7.5$ | $R=1.67$ |
| MCNP card entries | $A=2.41; B=9.64; C=20.25; G=-21.6919; D=E=F=0$ | $R=0.9099414; h=7.5$ | $R=1.67$ |
| Volume    | 19.509 cm$^3$ | 19.509 cm$^3$ | 19.509 cm$^3$ |

Figure 2: The EGS5 and MCNP calculated absorbed dose results for a point source inside a volume of 19.5 cm$^3$ in sphere, cylinder and ellipsoid.

![Dose vs Energy](image)

**Legend:**
- **MCNP Cylinder**
- **MCNP Sphere**
- **MCNP Ellipsoid**
- **EGS Cylinder**
- **EGS Sphere**
- **EGS Ellipsoid**
Table 2: Monte Carlo results of the absorbed dose and the percentage difference between the two codes results for volume of 19.509 cm³.

| Energy [keV] | Ellipsoid Dose | Sphere Dose | Cylinder Dose |
|--------------|---------------|-------------|---------------|
|              | Average [MeV/g] | MC difference [%] | Average [MeV/g] | MC difference [%] | Average [MeV/g] | MC difference [%] |
| 9            | 4.61E-04       | 0.1         | 4.609E-04     | 0.1         | 4.605E-04     | 0.1         |
| 11           | 5.57E-04       | 0.5         | 5.598E-04     | 0.4         | 5.490E-04     | 0.4         |
| 12           | 5.96E-04       | 0.7         | 6.045E-04     | 0.6         | 5.798E-04     | 0.6         |
| 13           | 6.27E-04       | 0.7         | 6.430E-04     | 0.6         | 5.994E-04     | 0.5         |
| 14           | 6.49E-04       | 0.5         | 6.722E-04     | 0.4         | 6.082E-04     | 0.3         |
| 15           | 6.60E-04       | 0.7         | 6.909E-04     | 0.4         | 6.077E-04     | 0.1         |
| 16           | 6.55E-04       | 0.7         | 6.915E-04     | 0.4         | 5.929E-04     | 0.4         |
| 17           | 6.42E-04       | 1.0         | 6.830E-04     | 0.7         | 5.730E-04     | 0.7         |
| 20           | 5.80E-04       | 0.8         | 6.262E-04     | 0.3         | 5.021E-04     | 0.3         |
| 25*          | 4.36E-04       | 2.9         | 4.769E-04     | 2.4         | 3.686E-04     | 2.4         |
| 30*          | 3.39E-04       | 2.2         | 3.708E-04     | 1.1         | 2.821E-04     | 1.0         |
| 35           | 2.66E-04       | 2.1         | 2.922E-04     | 1.2         | 2.208E-04     | 1.2         |
| 40           | 2.21E-04       | 1.8         | 2.422E-04     | 0.8         | 1.824E-04     | 0.7         |
| 45           | 1.91E-04       | 0.9         | 2.106E-04     | 0.4         | 1.583E-04     | 0.1         |
| 50           | 1.73E-04       | 1.3         | 1.904E-04     | 0.5         | 1.432E-04     | 0.2         |
| 55           | 1.63E-04       | 0.4         | 1.797E-04     | 0.2         | 1.354E-04     | 0.4         |
| 59           | 1.59E-04       | 0.8         | 1.746E-04     | 0.2         | 1.319E-04     | 0.3         |
| 60           | 1.57E-04       | 0.1         | 1.741E-04     | 0.1         | 1.314E-04     | 0.2         |
| 61           | 1.58E-04       | 0.5         | 1.739E-04     | 0.2         | 1.313E-04     | 0.5         |
| 62           | 1.59E-04       | 0.5         | 1.738E-04     | 0.5         | 1.314E-04     | 0.7         |
| 63           | 1.60E-04       | 0.9         | 1.740E-04     | 0.7         | 1.315E-04     | 0.9         |
| 64           | 1.58E-04       | 0.8         | 1.742E-04     | 0.8         | 1.318E-04     | 1.1         |
| 65           | 1.58E-04       | 0.8         | 1.744E-04     | 1.0         | 1.321E-04     | 1.2         |
| 66           | 1.58E-04       | 1.3         | 1.748E-04     | 1.1         | 1.323E-04     | 1.4         |
| 67           | 1.60E-04       | 0.3         | 1.754E-04     | 1.2         | 1.329E-04     | 1.4         |
| 75           | 1.66E-04       | 0.5         | 1.816E-04     | 1.2         | 1.381E-04     | 1.4         |
| 100          | 2.07E-04       | 0.1         | 2.267E-04     | 0.7         | 1.738E-04     | 0.9         |
| 150          | 3.31E-04       | 0.2         | 3.603E-04     | 0.7         | 2.787E-04     | 0.9         |
| 310*         | 7.71E-04       | 0.6         | 8.407E-04     | 0.7         | 6.553E-04     | 1.1         |
| 350          | 8.79E-04       | 0.5         | 9.564E-04     | 0.8         | 7.478E-04     | 1.0         |
| 400          | 1.03E-03       | 0.5         | 1.103E-03     | 1.0         | 8.624E-04     | 1.3         |

* E = 25-27 keV $^{125}$I energies.

# E = 310 keV represents $^{192}$Ir main energy.

The highlighted 20, 25 keV lines in Table 2 represent the $^{125}$I photon source results. The dose ratio differences by shape were: 77-80 % cylinder/sphere, and 91-92 % ellipsoid/sphere. The 310 keV (also highlighted) represents the most probable $^{192}$Ir source energy lines. At 310 keV the dose ratio differences by shape were: 78% cylinder/sphere, and 92 % ellipsoid/sphere.

The simulations set with a volume of 156.07 cm³ was carried out for three different shapes, using the MCNP and the EGS5 Monte Carlo codes. The results of this comparison are the average values, from the two codes, of absolute dose per fluence are listed in Table 3. Two larger volumes, 39 cm³ and 156 cm³, were examined in the same way as shown in Figure 3.

In order to contrast the revealed dose function behavior, we also examined two extreme volumes, the largest was 526 cm³ and the smallest was 1 cm³. Both cases showed similar shape dependence.

It is very common to use line sources in the brachytherapy practice. Therefore we simulated 8 mm line-sources at the center of the spherical shapes, and in axial position for cylinders and ellipsoids. In Figure 4 (a, b) the line source simulation results are shown for 39 cm³ and for 156 cm³, respectively. The line-source results present a similar picture to that of the point source shape dependence.
Figure 3: The calculated absorbed dose results for a point source inside a volume of 39 cm³ and 156 cm³ in sphere, cylinder and ellipsoid.

Figure 4: The calculated absorbed dose results for an 8-mm line source inside a volume of 39 cm³ and 156 cm³ in sphere, cylinder and ellipsoid.
Discussion

We can see a similar result along the energy range in all the figures. There is a clear peak at around 15 keV, where the radiation energy is fully absorbed, and at a higher energy, around 50 keV, a valley appears. The appearance of a valley is due to the water total absorption cross-section dependence on energy (can be obtained using XCOM (Berger et al 1998) [10]). This valley can be explained by considering the photoelectric decrease vs. energy, and the Compton Effect cross-section increase vs. energy. Beyond that valley the absorption increased due to the radiation energy availability.

All three shapes up to 100 keV have similar radiation absorption in small and large volumes. The shape difference take place mostly with the photon energy increase, due to transparency development in water, so the mean free path becomes larger than the shape dimensions and therefore the escape rays is affected by the shape boundaries. In small volumes the sphere receives the highest dose and the cylinder received the lowest dose.

Figure 5 presents the sphere results and shows the volume dependence absorption peak-shift, revealed in this study. The peak-shift response can be explained due to the mean free path alteration.

Conclusions

The research objective of this study aims to inspect the dose absorption from internal photon sources which are commonly used in brachytherapy methods. We used the Monte Carlo code systems, the EGS and the MCNP to calculate the doses in various body shapes and energies.

A good agreement between the MCNP and EGS5 dose absorption results, for photon sources, was found, as listed in Tables 2, 3. The differences between the two codes is mostly due to different photon cross-section database of each code. The difference between MCNP and EGS5 is consistent for the two volumes.

The dose absorption results for different body shapes of the same volume and irradiation conditions demonstrates a remarkable dependence on the volume shape, especially on small volumes that are necessary for brachytherapy. Our findings on shape dependence have a great importance for dosimetry measurements procedures, since the dosimeter active volume shape can influence its dose response, and therefore must be taken into consideration. The brachytherapy dosimetry routines take into consideration very delicate source encapsulation details in order to achieve the best possible precision. This study shows that the volume shape accuracy must be carefully considered in these dosimetry routines. Dosimeters shape and dimensions must be fitted to the inspected organs or routines.

Figure 5: The energy deposition peak-shift due to sphere volume change.
Table 3: Monte Carlo results of the absorbed dose and the percentage difference between the two codes results for volume of 156.07 cm³.

| Energy [keV] | Ellipsoid Dose | Sphere Dose | Cylinder Dose |
|--------------|----------------|-------------|---------------|
|              | Average [MeV/g] | MC difference [%] | Average [MeV/g] | MC difference [%] | Average [MeV/g] | MC difference [%] |
| 9            | 5.76E-05        | 0.1         | 5.761E-05     | 0.1              | 5.761E-05     | 0.1              |
| 11           | 7.01E-05        | 0.5         | 7.016E-05     | 0.5              | 7.016E-05     | 0.5              |
| 12           | 7.63E-05        | 0.7         | 7.636E-05     | 0.7              | 7.634E-05     | 0.7              |
| 13           | 8.25E-05        | 0.7         | 8.267E-05     | 0.7              | 8.258E-05     | 0.7              |
| 14           | 8.85E-05        | 0.4         | 8.902E-05     | 0.4              | 8.876E-05     | 0.4              |
| 15           | 9.40E-05        | 0.03        | 9.521E-05     | 0.01             | 9.464E-05     | 0.01             |
| 16           | 9.80E-05        | 0.4         | 9.996E-05     | 0.4              | 9.893E-05     | 0.4              |
| 17           | 1.01E-04        | 0.6         | 1.039E-04     | 0.7              | 1.024E-04     | 0.6              |
| 20           | 1.05E-04        | 0.2         | 1.107E-04     | 0.2              | 1.076E-04     | 0.01             |
| 25*          | 9.42E-05        | 2.4         | 1.016E-04     | 2.2              | 9.724E-05     | 1.8              |
| 30*          | 8.05E-05        | 1.1         | 8.819E-05     | 1.1              | 8.370E-05     | 0.5              |
| 35           | 6.73E-05        | 0.9         | 7.443E-05     | 1.1              | 7.026E-05     | 0.4              |
| 40           | 5.77E-05        | 0.6         | 6.415E-05     | 0.8              | 6.038E-05     | 0.1              |
| 45           | 5.13E-05        | 0.3         | 5.700E-05     | 0.4              | 5.359E-05     | 0.4              |
| 47           | 4.96E-05        | 0.8         | 5.482E-05     | 0.4              | 5.151E-05     | 0.4              |
| 48           | 4.83E-05        | 0.1         | 5.384E-05     | 0.3              | 5.057E-05     | 0.5              |
| 49           | 4.74E-05        | 0.1         | 5.293E-05     | 0.3              | 4.973E-05     | 0.5              |
| 50           | 4.71E-05        | 1.0         | 5.213E-05     | 0.4              | 4.898E-05     | 0.4              |
| 51           | 4.62E-05        | 0.1         | 5.145E-05     | 0.3              | 4.833E-05     | 0.6              |
| 52           | 4.55E-05        | 0.4         | 5.085E-05     | 0.1              | 4.777E-05     | 0.7              |
| 53           | 4.54E-05        | 0.3         | 5.031E-05     | 0.0              | 4.725E-05     | 0.8              |
| 55           | 4.47E-05        | 0.5         | 4.934E-05     | 0.1              | 4.635E-05     | 1.0              |
| 64           | 4.26E-05        | 1.4         | 4.757E-05     | 0.7              | 4.476E-05     | 1.5              |
| 75           | 4.41E-05        | 1.5         | 4.901E-05     | 1.1              | 4.617E-05     | 1.9              |
| 100          | 5.60E-05        | 2.6         | 5.953E-05     | 0.7              | 5.628E-05     | 1.6              |
| 150          | 8.48E-05        | 0.03        | 9.195E-05     | 0.7              | 8.728E-05     | 1.5              |
| 310*         | 1.92E-04        | 1.0         | 2.094E-04     | 0.6              | 1.995E-04     | 1.4              |
| 350          | 2.19E-04        | 0.8         | 2.379E-04     | 0.6              | 2.268E-04     | 1.3              |
| 400          | 2.53E-04        | 0.5         | 2.736E-04     | 0.7              | 2.608E-04     | 1.5              |

* E = 25-27 keV $^{125}$I energies.
# E = 310 keV represents $^{192}$Ir main energy.
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