Co-60 SPECIFIC GAMMA-RAY CONSTANT (Γ) DETERMINATIONS FOR VARIOUS BIOLOGICAL MATERIALS INVOLVED IN RADIOTHERAPY PROCEDURES, BY USING GEANT4 AND NIST XCOM

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Received July 4, 2017

Abstract. The specific gamma-ray constant (Γ) plays a very important role in dose calculations (absorbed dose, equivalent dose). Dose calculations are critical in nuclear medicine / radiotherapy applications, where precise doses must be delivered to patients. As it can be seen in literature, the value of the specific gamma-ray constant is reported only for few radionuclides and usually just for air. Often, it is given only for specific energy values and, therefore, when complex decay scheme radionuclides are used, the scheme factors must be carefully considered. The main issue related to specific gamma-ray constant found in literature is that of the inconsistencies between the values reported for the same radionuclide and for the same conditions. These previously presented aspects highlight the importance of the work presented in this paper. In this paper, the determination of the specific gamma-ray constant by using GEANT4 (Geometry And Tracking) and NIST XCOM (Photon Cross Section Database) is proposed. The determinations were made only for Co-60, which is a radionuclide highly used in radiotherapy practice (cobalt therapy, gamma knife), but the method can be extended to any other radionuclide. Co-60 specific gamma-ray constant values were determined for several materials of high interest in radiation therapy procedures (AIR; WATER; SKIN; SOFT TISSUE; ADIPOSE TISSUE; COMPACT BONE; CORTICAL BONE; SKELETAL MUSCLE; STRIATED MUSCLE; BRAIN; BLOOD; LUNG; EYE LENS; TESTES).

Key words: GEANT4, NIST XCOM, Co-60 gamma-ray source, specific gamma-ray constant (Γ), absorbed dose, biological materials.

1. INTRODUCTION

The important role that the radioactivity is playing in medicine was intuited by the bright minds from the end of 19th century even since its discovery. Initially, the X-rays started to be used in medical radiography procedures, in order to "view" inside patient's body, mainly to identify bones fractures.

Romanian Journal of Physics **63**, 701 (2018)

Beginning in the 1950s, the external use (tele-therapy) of Co-60 radionuclide in order to kill tumor tissue (cobalt radiotherapy) started to be used. Co-60 is an ideal radionuclide for these kinds of applications, since delivers stable, dichromatic beams (1173.24 keV (99.85%) and 1332.51 keV (99.9826%)), resulting in an average beam energy of about 1.25 MeV. Its relative long half-life, 5.2711(8) years, makes it economically efficient, since it can be used for long period of time before needing to be replaced. The main issue of this radiotherapy method is that of lack of precision, meaning that the healthy tissue surrounding the subjected tumor is also affected by the high energy deposition.

In the last years, the nuclear medicine/radiotherapy started to show tremendous development, due to the available state-of-the-art nuclear physics facilities, as ELI-NP (*Extreme Light Infrastructure – Nuclear Physics*) [1, 2]. Many research institutes started to study these subjects, mainly due to the increasing number of cases of cancer reported around the World. Now, new refined techniques as *Positron Emission Tomography – Computed Tomography* (PET-CT) combined with proton therapy started to replace the classical cobalt therapy, but Co-60 is still used in medicine in complex radiosurgery procedures (gamma-knife).

In all types of nuclear medicine/radiotherapy techniques, precise dose calculations are a very important task to be done. These kinds of calculations are made by well-trained medical physicists, using different data and constants from literature. In the case of gamma-ray involving applications, the specific gamma-ray constant (Γ) plays a very important role [3, 4]. Some inconsistences between its values for the same radionuclide and for the same conditions can be seen in literature, as it is shown in Table 1. These previously presented aspects highlight the importance of the work presented in this paper.

In this paper, a computational method for the determination of the specific gamma-ray constant (Γ) by using GEANT4 and NIST XCOM codes is proposed. The method is based on the fact that starting from an experimental determination of the absorbed dose rate value (well-knowing of all the exposure conditions) and knowing the activity of the involved gamma-rays source, the value for the specific gamma-ray constant can be determined. The experimental absorbed dose rate determination can be performed by using a calibrated high performance dosimeter [5], in order to assure the traceability of the result, or by any other validated dosimetry systems [6]. The determinations presented in this paper were made only for Co-60, which is a radionuclide highly used in radiotherapy, but the method used can be extended to any other radionuclide of interest.

Table 1

Different values of the Co-60 specific gamma-ray constant (in air) found in literature

Reference	Co-60 specific gamma-ray constant (air) (Gy m^2 s^{-1} Bq^{-1})	Average value of the Co-60 specific gamma-ray constant (Gy m^2 s^{-1} Bq^{-1})	Standard deviation of a single value (%)	Standard deviation of the average (%)
[7]	0.0856×10^{-15}	0.0856×10^{-15}	0.92	0.41
[8]	0.0868×10^{-15}			
[9]	0.0850×10^{-15}			
[10]	0.0848×10^{-15}			
[11, 12]	0.0858×10^{-15}			

In order to calculate an unknown absorbed dose rate/ absorbed dose value from a known activity value (radioactive point source, 4πsr geometry), a widely used equation (Equation (1)), can be found in literature [10, 11].

$$d = \frac{\Lambda \times \Gamma}{r^2}, \tag{1}$$

where: Γ – specific gamma-ray constant (Gy m^2 s^{-1} Bq^{-1});

Λ – activity (Bq);

r – linear distance from source to the center of the sensitive volume of the detector (m);

d – absorbed dose rate (Gy s^{-1}).

Using Equation (1), the specific gamma-rays constant (Γ) can be calculated as follows:

$$\Gamma = \frac{d \times r^2}{\Lambda}. \tag{2}$$

2. EXPERIMENTAL CONDITIONS AND GEANT4 SIMULATION

For this study a Co-60 gamma-rays source with the activity of 5.9234 TBq was used. A calibrated dosimeter was placed coaxially, at 1 meter from it, in order to measure the absorbed dose rate value in that point of space. An absorbed dose rate value of 5.0694×10^{-4} Gy s^{-1} was measured.

The source consisted of a 304 stainless steel capsule containing inside five Co-60 disks (20 mm diameter and 6 mm thickness each disk), as is shown in Fig. 1.

The capsule was a cylinder with a (23.4 ± 0.2) mm external diameter and a (36.4 ± 0.2) mm total length.

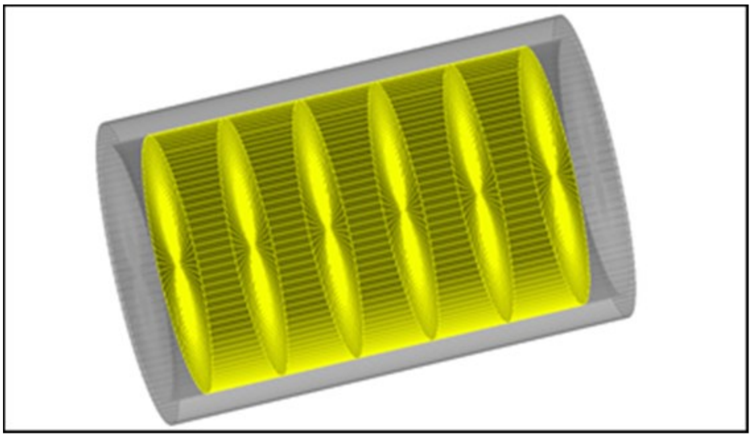

Fig. 1 – Co-60 source geometry (GEANT4 export).

The calibrated dosimeter used to measure the absorbed dose rate value, was a 30006 type "Farmer" ionization chamber (0.6 cm^3 active volume, 6.95 mm exterior diameter and 23.6 mm total length), as can be seen in Fig. 2. It is a waterproof standard chamber for absolute dosimetry (0.65 % combined standard uncertainty for a coverage factor k = 2, [5]). Chamber walls consist of 0.335 mm PMMA ($(C_5H_8O_2)_n$) supplemented with 0.09 mm Graphite layer. The dosimeter useful nominal energies range is between 30 keV and 50 MeV. The central (collecting) electrode is made of aluminum (1.1 mm diameter and 21.2 mm length).

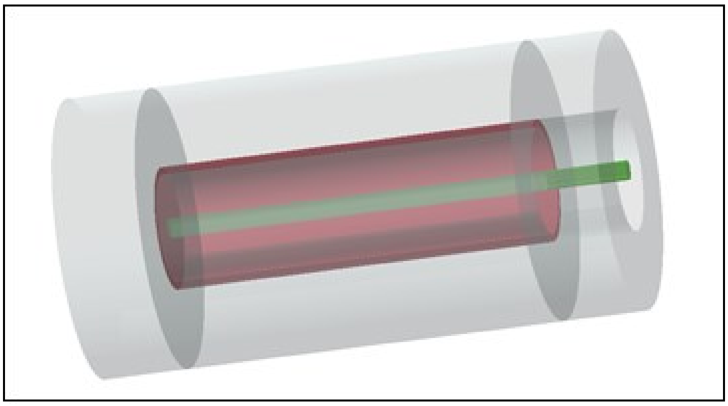

Fig. 2 – Dosimeter geometry (GEANT4 export).

GEANT4 is a toolkit for the simulation of the passage of particles through matter, using Monte Carlo methods. It is the successor of the GEANT series of software toolkits developed by CERN, and the first to use C++ object oriented programming [13–16]. In this paper its 10.03 release was used.

The geometry of the experimental set-up was built in the *Detector Construction class* using CSG (*Constructive Solid Geometry*) by assembling some solid 3D geometrical shapes, Boolean subtraction being used.

In order to define the composition of each material involved, the G4 material database was used.

The *Physics processes* taken into account were low-energy electromagnetic processes meaning photon interactions (photoelectric effect, Compton scattering, pair production, Rayleigh scattering) and electrons interactions (bremsstrahlung, multiple scattering and ionization). Atomic effects as X-rays emission and Auger emission, following the photoelectric effect, were also included [17].

Since the distance between the Co-60 source and the dosimeter was long enough (1m) related to their dimensions, a point approximation of them as well as a quasi-isotropical distribution of the source can be considered. The Co-60 volume source was modelled using GPS (*General Particle Source class*).

3. RESULTS AND DISCUSSIONS

Using the previously described GEANT4 model, a number of 10^7 events were processed (10^7 decays in one second). The energy deposited in the dosimeter active volume (scoring volume) was determined as being $E_{dep} = 3862.76$ eV (both Co-60 gamma quanta were considered). The total mass of the gas inside the active region (sensitive region) of the dosimeter was m = 0.7225 mg. By dividing the E_{dep} (J) with the mass of the active volume of the dosimeter (kg), following Equation (3), an absorbed dose debit of 8.5658×10^{-10} Gy s^{-1} was determined (d_{sim}).

$$d_{sim} = \frac{E_{dep}}{m \times t} \tag{3}$$

where: E_{dep} – energy deposited in the active volume of the dosimeter (J);

m – mass of the gas inside the sensitive volume of the dosimeter (kg);

t – time in which the energy was deposited (1 s).

Knowing that the 8.5658×10^{-10} Gy s^{-1} absorbed dose rate (d_{sim}) was obtained for 10^7 events, meaning actually a 10^7 Bq activity (Λ_{sim}), the absorbed dose rate value corresponding to our Co-60 source (d_{source}) can be calculated, using Equation (4):

$$d_{source} = \frac{\Lambda_{source} \times d_{sim}}{\Lambda_{sim}}\,, \tag{4}$$

where: Λ_{sim} – simulated activity (decays s^{-1});

Λ_{source} – known activity of the Co-60 source (decays s^{-1});

d_{sim} – absorbed dose rate value obtained for Λsim (Gy s^{-1});

d_{source} – obtained absorbed dose rate for the activity of our Co-60 source (Gy s^{-1}).

A value of the absorbed dose rate for the activity of our Co-60 source (d_{source}) of 5.0739×10^{-4} Gy s^{-1} was obtained. From this value and using Equation (2), a new value of 0.0857×10^{-15} Gy m^2 s^{-1} Bq^{-1} for the Co-60 specific gamma-ray constant (Γ) (in air) was determined. The value of the specific gamma-ray constant determined by using the developed GEANT4 model is in a very good agreement with the average value of the ones found in literature of 0.0856×10^{-15} Gy m^2 s^{-1} Bq^{-1} (Table 1). The relative difference between the two values is of only 0.12 %.

Having the previously validated value of the Co-60 specific gamma-ray constant for air (by using GEANT4) and the mass attenuation coefficient for several materials of high interest in radiotherapy (by using NIST XCOM), the Co-60 specific gamma-ray constant for each one can be determined following Equation (5), as it can be seen in Table 2.

$$\Gamma_{\gamma(material)} = \frac{\mu_{\gamma(material)}}{\mu_{\gamma(air)}} \times \Gamma_{\gamma(air)}\,, \tag{5}$$

where: $\Gamma_{\gamma(air)}$ – Co-60 specific gamma-ray constant in air (GEANT4);

$\mu_{\gamma(air)}$ – mass attenuation coefficient for Co-60 in air (NIST XCOM);

$\mu_{\gamma(material)}$ – mass attenuation coefficient for Co-60 in a specific material (NIST XCOM);

$\Gamma_{\gamma(material)}$ – unknown value of Co-60 specific gamma-ray constant in a specific material (GEANT4 + NIST XCOM).

XCOM is a program provided by NIST which determines photo-absorption cross sections and total attenuation coefficients for any element, compound or mixture, at energies between 1 keV and 100 GeV. The weighting factors are calculated by XCOM from the chemical formula entered by the user. For mixtures, the fractions by weight are supplied by the user, as it was the case of this paper.

The following processes are considered by XCOM: incoherent scattering, coherent scattering, photoelectric absorption, and pair production in the field of the atomic nucleus and in the field of the atomic electrons. The total attenuation coefficient is equal to the sum of the interaction coefficients for the individual processes [18–20].

Using the validated GEANT4 model, G4 NIST materials library and NIST XCOM program, several materials of high interest in radiotherapy practice were simulated in order to determine the Co-60 specific gamma-ray constant (Γ) for each of them, as follows:

- **G4_AIR** (C = 0.0001240; N = 0.7552680; O = 0.2317810; Ar = 0.0128270);

- **G4_WATER** (H = 0.1118940; O = 0.8881060);

- **G4_SKIN_ICRP** (H = 0.1005880; C = 0.2282500; N = 0.0464200; O = 0.6190020; Na = 0.0000700; Mg = 0.0000600; P = 0.0003300; S = 0.0015900; Cl = 0.0026700; K = 0.0008500; Ca = 0.0001500; Fe = 0.0000100; Zn = 0.0000100);

- **G4_TISSUE_SOFT_ICRP** (H = 0.1044720; C = 0.2321900; N = 0.0248800; O = 0.6302380; Na = 0.0011300; Mg = 0.0001300; P = 0.0013300; S = 0.0019900; Cl = 0.0013400; K = 0.0019900; Ca = 0.0002300; Fe = 0.0000500; Zn = 0.0000300);

- **G4_TISSUE_SOFT_ICRU-4** (H = 0.1011720; C = 0.1110000; N = 0.0260000; O = 0.7618280);

- **G4_ADIPOSE_TISSUE_ICRP** (H = 0.1194770; C = 0.6372400; N = 0.0079700; O = 0.2323330; Na = 0.0005000; Mg = 0.0000200; P = 0.0001600; S = 0.0007300; Cl = 0.0011900; K = 0.0003200; Ca = 0.0000200; Fe = 0.0000200; Zn = 0.0000200);

- **G4_BONE_COMPACT_ICRU** (H = 0.0639840; C = 0.2780000; N = 0.0270000; O = 0.4100160; Mg = 0.0020000; P = 0.0700000; S = 0.0020000; Ca = 0.1470000);

- **G4_BONE_CORTICAL_ICRP** (H = 0.0472340; C = 0.1443300; N = 0.0419900; O = 0.4460960; Mg = 0.0022000; P = 0.1049700; S = 0.0031500; Ca = 0.2099300; Zn = 0.0001000);

- **G4_MUSCLE_SKELETAL_ICRP** (H = 0.1006370; C = 0.1078300; N = 0.0276800; O = 0.7547730; Na = 0.0007500; Mg = 0.0001900; P = 0.0018000; S =

0.0024100; Cl = 0.0007900; K = 0.0030200; Ca = 0.0000300; Fe = 0.0000400; Zn = 0.0000500);

- **G4_MUSCLE_STRIATED_ICRU** (H = 0.1019970; C = 0.1230000; N = 0.0350000; O = 0.7290030; Na = 0.0008000; Mg = 0.0002000; P = 0.0020000; S = 0.0050000; K = 0.0030000);

- **G4_BRAIN_ICRP** (H = 0.1106670; C = 0.1254200; N = 0.0132800; O = 0.7377230; Na = 0.0018400; Mg = 0.0001500; P = 0.0035400; S = 0.0017700; Cl = 0.0023600; K = 0.0031000; Ca = 0.0000900; Fe = 0.0000500; Zn = 0.0000100);

- **G4_BLOOD_ICRP** (H = 0.1018660; C = 0.1000200; N = 0.0296400; O = 0.7594140; Na = 0.0018500; Mg = 0.0000400; Si = 0.0000300; P = 0.0003500; S = 0.0018500; Cl = 0.0027800; K = 0.0016300; Ca = 0.0000600; Fe = 0.0004600; Zn = 0.0000100);

- **G4_LUNG_ICRP** (H = 0.1012780; C = 0.1023100; N = 0.0286500; O = 0.7570720; Na = 0.0018400; Mg = 0.0007300; P = 0.0008000; S = 0.0022500; Cl = 0.0026600; K = 0.0019400; Ca = 0.0000900; Fe = 0.0003700; Zn = 0.0000100);

- **G4_EYE_LENS_ICRP** (H = 0.0992690; C = 0.1937100; N = 0.0532700; O = 0.6537510);

- **G4_TESTES_ICRP** (H = 0.1041660; C = 0.0922700; N = 0.0199400; O = 0.7738840; Na = 0.0022600; Mg = 0.0001100; P = 0.0012500; S = 0.0014600; Cl = 0.0024400; K = 0.0020800; Ca = 0.0001000; Fe = 0.0000200; Zn = 0.0000200).

The obtained results were verified by using the Equation (6) and are presented in Table 2.

$$\Gamma = \frac{E_\gamma}{4 \times \pi}\left(\frac{\mu_{en}}{\rho}\right) \tag{6}$$

where: Γ – unknown value of specific gamma-ray constant in a material (Gy m^2 s^{-1} Bq^{-1});

E_γ – gamma quanta energy (J);

$\frac{\mu_{en}}{\rho}$ – mass attenuation coefficient (m^2 kg^{-1}).

Table 2

Co-60 specific gamma-ray constant (Γ) for several materials of high interest in radiotherapy practice

Material	Density (g cm^{-3})	Mass Attenuation – NIST XCOM (m^2 kg^{-1})	Co-60 specific gamma-ray constant (Gy m^2 s^{-1} Bq^{-1}) (Equation (5))	Co-60 specific gamma-ray constant (Gy m^2 s^{-1} Bq^{-1}) (Equation (6))
G4_AIR	1.20479×10^{-3}	5.680×10^{-3}	8.5700×10^{-17} (GEANT4)	9.0617×10^{-17}
G4_WATER	1.00	6.316×10^{-3}	9.5296×10^{-17}	1.0076×10^{-16}
G4_SKIN_ICRP	1.10	6.250×10^{-3}	9.4300×10^{-17}	9.9711×10^{-17}
G4_TISSUE_SOFT_ICRP	1.00	6.271×10^{-3}	9.4617×10^{-17}	1.0003×10^{-16}
G4_TISSUE_SOFT_ICRU-4	1.00	6.255×10^{-3}	9.4376×10^{-17}	1.0005×10^{-16}
G4_ADIPOSE_TISSUE_ICRP	0.92	6.353×10^{-3}	9.5854×10^{-17}	1.0135×10^{-16}
G4_BONE_COMPACT_ICRU	1.85	6.035×10^{-3}	9.1056×10^{-17}	9.6281×10^{-17}
G4_BONE_CORTICAL_ICRP	1.85	6.937×10^{-3}	8.9578×10^{-17}	9.4717×10^{-17}
G4_MUSCLE_SKELETAL_ICRP	1.04	6.251×10^{-3}	9.4315×10^{-17}	9.9727×10^{-17}
G4_MUSCLE_STRIATED_ICRU	1.04	6.258×10^{-3}	9.4421×10^{-17}	9.9838×10^{-17}
G4_BRAIN_ICRP	1.03	6.306×10^{-3}	9.5145×10^{-17}	1.0060×10^{-16}
G4_BLOOD_ICRP	1.06	6.257×10^{-3}	9.4406×10^{-17}	9.9822×10^{-17}
G4_LUNG_ICRP	1.05	6.254×10^{-3}	9.4361×10^{-17}	9.9774×10^{-17}
G4_EYE_LENS_ICRP	1.10	6.243×10^{-3}	9.4195×10^{-17}	9.9599×10^{-17}
G4_TESTES_ICRP	1.04	6.270×10^{-3}	9.4602×10^{-17}	1.0003×10^{-16}

As it can be seen from Table 2, the relative difference between the results obtained using Equation (5) (GEANT4 + NIST XCOM) and the ones obtained using Equation (6) (NIST XCOM) is of about 5.4 %. The good agreement between the results validates both approaches. However, as it can be seen in the case of air, since the value obtained using GEANT 4 (8.5700×10^{-17} Gy m^2 s^{-1} Bq^{-1}) is closer to the average value of the ones found in literature (8.5600×10^{-17} Gy m^2 s^{-1} Bq^{-1}), GEANT4 values are recommended by the authors to be considered by end users.

4. CONCLUSIONS

A new method for determinations of the specific gamma-ray constant (Γ) by using GEANT4 (Geometry And Tracking) and NIST XCOM was proposed. The obtained results are more appropriate to be used in practice since they simulate real-life conditions and not pure theoretical ideal ones.

A value of 0.0857×10^{-15} Gy m^2 s^{-1} Bq^{-1} for the Co-60 gamma-ray specific constant (Γ) in air was determined using the developed GEANT4 model, which is in a very good agreement with the average value of the ones found in literature of 0.0856×10^{-15} Gy m^2 s^{-1} Bq^{-1}. The relative difference between the two values is of only 0.12 %, which validates the proposed method and the developed GEANT4 model.

As it can be seen from Table 2, the relative difference between the results obtained using Equation (5) and the ones obtained using Equation (6) is of about 5.4 %. The good agreement between the results validates both approaches. However, since the values obtained using GEANT 4 are closer to the ones found in literature, these values are recommended to be considered by the medical physicist involved in radiotherapy activities in order to calculate equivalent doses delivered to patients.

A list with Co-60 specific gamma-ray constant (Γ) values for several materials of high interest in radiotherapy practice was obtained.

Acknowledgements. This work was supported by the Project ELI-RO 13/2016 from Ministry of Research and Innovation of Romania.

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