Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi https://dergipark.org.tr/sdufeffd
Süleyman Demirel University Faculty of Arts and Sciences Journal of Science e-ISSN: 1306-7575
Research Article, 2023, 18(1): 10-17, DOI: 10.29233/sdufeffd.1244542

Validation of a Proposed Equation for Determining the Half-Thickness Value of Gamma and X-Ray Radiation

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(Received: 30.01.2023, Accepted: 17.04.2023, Published: 25.05.2023)

Abstract: Half-value layer (HVL) is energy dependent on the photon, much as the attenuation coefficient. Increasing the penetrating energy of a photon stream causes an increase in a substance's HVL. Before calculating the HVL value, the linear attenuation coefficient (μ) must be established. A review of the literature indicated that there is presently no Monte Carlo-based sufficient tool for direct calculation of the HVL value and direct computation suitable for material design and all changes based on sophisticated simulation methods. This study aims to calculate HVL data with GAMOS simulation in the 0.1-20 MeV energy range for some anatomical structures defined in ICRU-44 (bone cortical, brain, gray/white matter, breast tissue, eye lens, and testis). The HVL values of the anatomical structures used in the GAMOS code were compared with the results in the literature. As a result, HVL values obtained from GAMOS simulation for different materials and biological structures were compatible with the literature.

Key words: GAMOS, Half-Value Layer, Radiation.

1. Introduction

X and gamma photons, commonly utilized for medical diagnosis and therapy, belong to the class of ionizing radiation. When photons transfer some of their energy to electrons in the medium, ionization and excitation occur, increasing the risk of future stochastic and deterministic effects in biological systems [1]. Deterministic or stochastic effects of radiation in biological environments are tried to be understood by using linear (μ) or mass (μ/ρ) energy absorption coefficients. Both quantities show how likely it is that one photon per unit mass of the absorbing medium will scatter or be absorbed or how likely it is that energy will be taken in [2]. Absorption coefficient calculations can be made with software such as FLUKA, GEANT, and MCNP based on the Monte Carlo technique [3-5]. Estimating the absorption coefficient can be approximated using weight ratios for biological tissues and chemical mixtures [6]. GAMOS is based on GEANT4 and is widely used for simulation studies in medical physics [7, 8]. It has not yet been possible to derive the radiation absorption parameters of materials (Half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), etc.) from a generic formula.

HVL is one of the key characteristics associated with ionizing radiation [9, 10]. HVL refers to the material thickness necessary to reduce the air kerma intensity of the photon to half of its starting value. It is related to the material's linear attenuation coefficient and photon energy. As opposed to linear and mass attenuation coefficients, which measure single energy rays, this coefficient is used to quantify polyenergetic rays [11]. The thickness of any substance in which fifty percent of incoming energy is absorbed is known as the HVL. Despite being a metric unit, HVL depends on energy and µ values. Increasing the penetrating energy of a photon beam causes the HVL of a substance to increase. The µ must be established before calculating the HVL value. HVL can be determined using µ, but there should be alternative, realistic ways independent of calculating the value of µ at any given energy level [12-14].

Bircan et al., in their article titled "A New Equation for Calculation of Gamma and X-ray Radiation Half Value Thickness", proposed an equation in which the half-value layer thickness can be directly calculated in the energy range of 0.001–20 MeV (Eq. 1) [15, 16].

$$Half\ Value\ Layer\ (HVL) = \frac{(a + bE + cE^2 + dE^3 + eE^4 + fE^5)}{(1 + gE + hE^2 + iE^3 + jE^4 + kE^5)} \quad (1)$$

They reported that the constants of the equation are specific for the radiation-absorbing substance, and the variation of half-value thickness values with energy can be shown [15].

This study aims to calculate HVL data with GAMOS simulation in the 0.1-20 MeV energy range for some anatomical structures defined in ICRU-44 (bone cortical, brain, gray/white matter, breast tissue, eye lens, and testis). The HVL values from the GAMOS simulation were compared with those from Equation 1 [15] and the NIST database [17].

2. Materials and Methods

GAMOS v.6.2.0 software was used for the simulations in this study. The geometry of the simulation includes a point source, six different 10x10x1 cm^3 absorbing targets (anatomical structures) that are 50 cm away, and a 20x20x20 cm^3 detector that is 100 cm from the radiation source. To prevent photon interactions with materials outside the sample, all components of the to-be-collected geometry were enclosed in a vacuum cube (300x300x300 cm^3) (Figure 1).

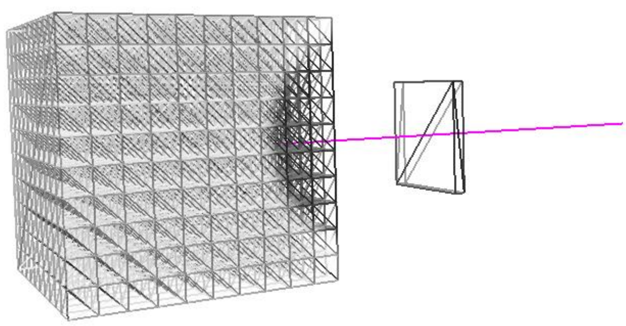

Figure 1. Simulation geometry.

The physics, generator, and dose collection parameters were defined in the input file. In the simulation, the electromagnetic physics package was utilized. The simulations were carried out at 9 different photon energies in the range of 0.1-20 MeV. The amount of dose that reached the detector via "dose deposit" was tallied for scoring criteria. Although all physics processes were included in the scoring, variance reduction techniques were not implemented. The I and I_0 values were acquired by repeatedly simulating the anatomical structures with and without shielding material. A history of 10^7 photons was utilized, yielding sufficient results to improve the precision of the Monte Carlo simulations and reduce statistical error.

$$I = I_0 . e^{(-\mu . x)} \tag{2}$$

μ values at different energies were calculated for anatomical structures using Beer Lambert's law (Eq. 2). As shown in Equation 2, μ/ρ is derived by dividing μ by the density (ρ) of the material (Eq. 3).

$$Mass\ Attenuation\ Coefficient\ = \mu/\rho \tag{3}$$

HVL is the shield material thickness corresponding to the half-values of the intensity of the incoming radiation, and they are given in Equation 4.

$$Half\ Value\ Layer\ (HVL) = \frac{ln2}{\mu} \tag{4}$$

HVL values of anatomical structures obtained from GAMOS simulation and Equation 1 were compared. The difference between the simulation and Equation 1 values of HVL was calculated using Equation 5.

$$Difference\ (\%) = \left|\frac{{}^{*}HVL - HVL}{HVL}\right| X\ 100\% \tag{5}$$

In Equation 5, *HVL values were obtained by Equation 1, and HVL values were obtained by GAMOS simulation.

3. Results and Discussion

In this study, the amount of X-ray absorption of different anatomical structures was investigated by GAMOS simulation. The μ and HVL parameters of some anatomical structures in the ICRU-44 were obtained from GAMOS simulation for 9 different photon energies ranging from 0.1-20 MeV. These parameters were compared with the HVL data from Equation 1 [15].

Figure 2 presents the energy-dependent graph of μ values obtained by the GAMOS simulation. It is seen that the value of μ decreases as the photon energy increases in all anatomical structures. The μ/energy curves for the brain, breast tissue, eye lens, and testis, which have similar densities, gave close results as expected. Bone with a density of 1.92 g/cm^3 had a decreasing curve as energy increased, but μ values were higher than those of other anatomical structures (Figure 2).

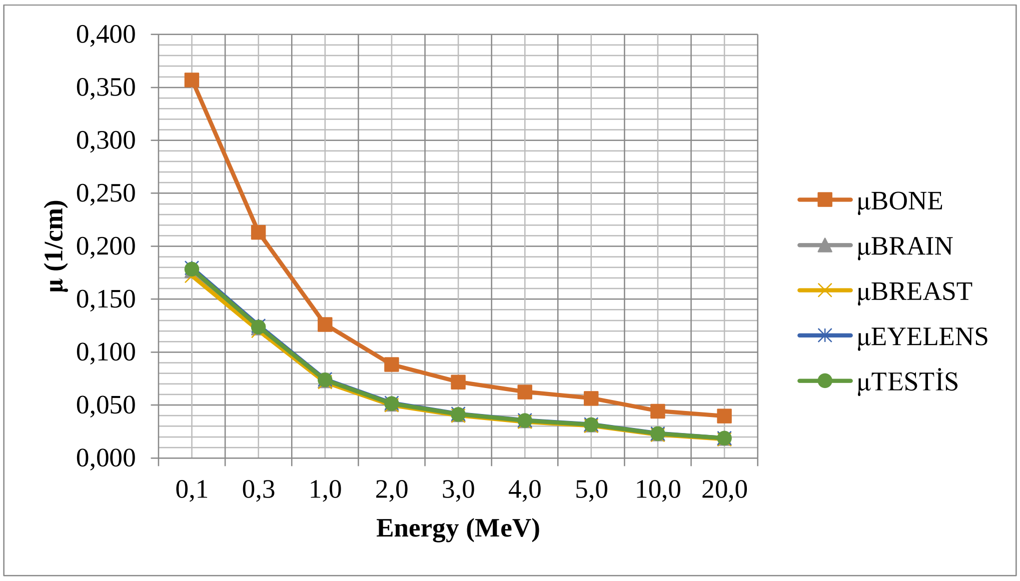

Figure 2. µ values of anatomical structures at different energies

The HVL values obtained with the GAMOS code of the anatomical structures and calculated with Equation 1 are shown in Table 1. HVL values obtained by both methods were compatible with each other. It has been verified by GAMOS simulation that Equation 1 can be used to quickly and reliably calculate the HVL value of a material.

Table 1. HVL values calculated using GAMOS, the NIST database and Equation 1.

Energy (MeV)	HVL_{BONE} (cm)			HVL_{BRAIN} (cm)			HVL_{BREAST} (cm)		
	**NIST	*Ref. Study	This Study	**NIST	*Ref. Study	This Study	**NIST	*Ref. Study	This Study
0.1	1.946	1.944	1.940	3.918	3.923	3.923	3.923	4.029	4.025
0.3	3.244	3.243	3.250	5.643	5.648	5.648	5.648	5.756	5.763
1.0	5.498	5.501	5.488	9.471	9.478	9.478	9.478	9.667	9.663
2.0	7.836	7.846	7.835	13.555	13.563	13.563	13.563	13.846	13.837
3.0	9.640	9.653	9.635	16.886	16.894	16.894	16.894	17.282	17.257
4.0	11.084	11.087	11.082	19.701	19.707	19.707	19.707	20.199	20.167
5.0	12.254	12.244	12.252	22.128	22.128	22.128	22.128	22.709	22.685
10.0	15.601	15.609	15.598	30.309	30.267	30.267	30.267	31.223	31.324
20.0	17.457	17.44	17.449	37.234	37.110	37.110	37.110	38.411	38.912

** Calculated with Equation 1 [15] **Calculated with NIST data [17].*

Table 1. HVL values calculated using GAMOS, NIST database and Equation 1. (continued)

Energy (MeV)	$HVL_{EYE\ LENS}$ (cm)			HVL_{TESTIS} (cm)		
	**NIST	*Ref. Study	This Study	**NIST	*Ref. Study	This Study
0.1	3.858	3.855	3.857	3.923	3.884	3.885
0.3	5.541	5.54	5.540	5.648	5.59	5.593
1.0	9.295	9.3	9.293	9.478	9.396	9.386
2.0	13.305	13.299	13.302	13.563	13.431	13.431
3.0	16.576	16.576	16.573	16.894	16.732	16.730
4.0	19.343	19.351	19.339	19.707	19.523	19.515
5.0	21.731	21.734	21.726	22.128	21.916	21.912
10.0	29.798	29.796	29.791	30.267	29.983	29.973
20.0	36.661	36.658	36.653	37.110	36.749	36.748

*** *Calculated with Equation 1 [15] **Calculated with NIST data [17].*

The HVL values calculated by both methods increased as the photon energy increased for all anatomical structures. The HVL value for bone tissue of an x-ray photon with an energy of 0.1 MeV has been reported to be 1.94 cm [18]. Jarrah et al., in the study in which they compared the results obtained with the Monte Carlo simulation and the Geometric Progression fitting method, the HVL value for the breast tissue is approximately 30 cm [19]. Breast tissue was the anatomical structure with the highest HVL value in all photon energies. It was observed that the large photon attenuation effect of bone tissue made the HVL value lower than all other tissues examined.

The difference between the HVL values obtained by the two methods was below 2% for all anatomical structures (Table 2). For the breast, the difference between GAMOS at 20 MeV energy and the HVL value calculated with the formula suggested in the reference article is 1.3055% (Figure 3).

Table 2. Difference between HVL values obtained from GAMOS and reference article for each anatomical structure.

Energy (MeV)	Bone	Brain	Breast	Eye Lens	Testis
0.1	0.1900	0.1631	0.1005	0.0632	0.0164
0.3	0.2303	0.0493	0.1148	0.0058	0.0576
1.0	0.2298	0.0720	0.0405	0.0700	0.1100
2.0	0.1460	0.0213	0.0628	0.0209	0.0001
3.0	0.1847	0.0216	0.1441	0.0195	0.0117
4.0	0.0460	0.0665	0.1605	0.0619	0.0406
5.0	0.0636	0.0405	0.1063	0.0350	0.0167
10.0	0.0705	0.0124	0.3226	0.0157	0.0342
20.0	0.0520	0.0026	1.3055	0.0129	0.0018

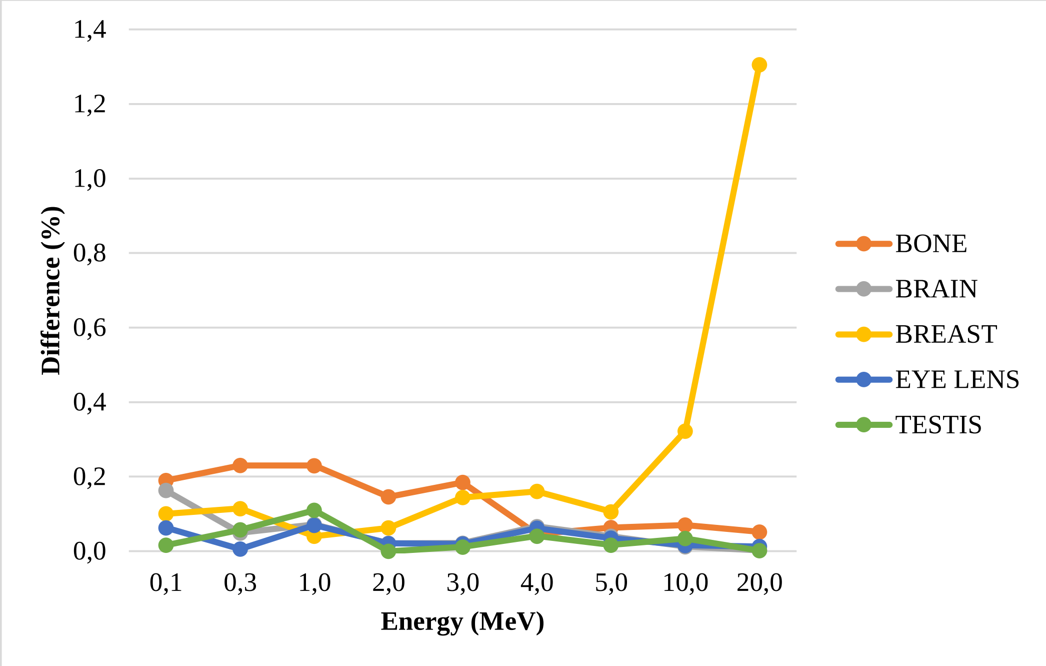

Figure 3. Difference between HVL values for each anatomical structure.

HVL is energy dependent on the photon, much as the attenuation coefficient. Increasing the penetrating energy of a photon stream causes an increase in a substance's HVL. The linear attenuation coefficient (μ) must be known before calculating the HVL value. While HVL can be computed using μ, alternative and practical techniques independent of the calculation of μ, the value at any energy level should be available [12-14]. The linear attenuation coefficient should be mainly obtained by experimental or theoretical approaches to compute the HVL. Since the linear attenuation coefficient is calculated for each energy value, the estimated HVL value will also include the half-value thickness at the relevant energy [20].

When reviewing the literature, it is discovered that innovative methodologies for computing HVL values are presented, which may give answers for medical and industrial radiation applications [9, 10, 18, 19]. A review of the literature indicated that there is presently no Monte Carlo-based sufficient tool for direct calculation of the HVL value and direct computation suitable for material design and all changes based on sophisticated simulation methods [9, 20]. The GAMOS code for all anatomical structures and the HVL data obtained with the formula suggested in the reference article were compatible.

4. Conclusion

In conclusion, the formula (Eq. 1) presented in the article "A New Equation for Calculation of Gamma and X-ray Radiation Half Value Thickness" agreed with the data from the GAMOS simulation. It was observed that the data obtained from the GAMOS simulation agreed with the findings obtained from both equation 1 presented in the reference article and the NIST database. Different radiation parameters can be formulated and brought to a level where they can be used, especially in medical physics.

Authorship Contribution Statement

M.C. Şahin: Conceptualization, Methodology, Data Curation, Original Draft Writing; **K. Manisa**: Visualization, Supervision/Advice; **H. Bircan:** Conceptualization, Methodology, Data Curation, Original Draft Writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Committee Approval and/or Informed Consent Information

As the authors of this study, we declare that we do not have any ethics committee approval and/or informed consent statement.

References

[1] E. A. Domina and O. L. Kopylenko, "Role of radioprotectors in minimization of stochastic effects of radiation incidents", *Experimental Oncology*, 44(3), 186-189, 2022.

[2] J. K. Shultis and R. E. Faw, Fundamentals of Nuclear Science and Engineering, New York, Marcel Dekker Inc., 506 pages, 2002.

[3] T. Korkut, A. Karabulut, G. Budak and F. Demir, “Monte Carlo Simülasyonu ile Kolemanit Cevherinin Çeşitli Foton Enerjileri için Radyasyon Soğurganlığının Belirlenmesi,” *X. Ulusal Nükleer Bilimler ve Teknolojileri Kongresi*, 6-9 Ekim, 2009, Muğla, s. 428–431.

[4] M. E. Medhat and V. P. Singh, “Mass attenuation coefficients of composite materials by Geant4, XCOM and experimental data: comparative study”, *Radiation Effects & Defects in Solids*, 169(9), 800–807, 2014.

[5] P. Singh, A. M. Ali, N. M. Badiger and A. M. El-Khayatt, “Monte Carlo simulation of gamma ray shielding parameters of concretes”, *Nuclear Engineering and Design*, 265, 1071–1077, 2013.

[6] National Institute of Standards and Technology Database, NIST. [Online]. Available: http://physics.nist.gov/xaamdi, Accessed: 21.02.2023.

[7] P. Arce, S. Banerjee, T. Boccali, M. Case, A. Roeck, V. Lara, M. Liendl, A. Nikitenko, M. Schroder, A. Straessner, H. P. Wellisch and H. Wenzel, "Simulation framework and XML detector description for the CMS experiment", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 502(2), 687-688, 2003.

[8] P. Arce, I. J. Lagares, L. Harkness, D. P. Astudillo, M. Cañadas, P. Rato, M. Prado, Y. Abreu, G. Lorenzo, M. Kolstein and A. Díaz, "Gamos: A framework to do Geant4 simulations in different physics fields with an user-friendly interface", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*,735,304-313, 2014.

[9] K. Matsubara, H. Nagata, R. Okubo, T. Takata and M. Kobayashi, ‘’Method for determining the half-value layer in computed tomography scans using a real-time dosimeter: application to dual-source dual-energy acquisition’’, *Physica Medica*, 44(2017), 227-231, 2017.

[10] T. Gotanda, T. Katsuda, R. Gotanda, A. Tabuchi, K. Yamamoto, T. Kuwano, H. Yatake, K. Kashiyama and Y. Takeda, ‘’Half-value layer measurement: simple process method using radiochromic film’’, *Australasian Physics & Engineering Sciences in Medicine*, 32(2009), 150-158, 2009.

[11] A. Fukuda, I. Nao, T. Masami, Y. Tensho, M. Katsuhiko and K. Hitoshi, ‘’Measurement of the half-value layer for CT systems in a single-rotation technique: Reduction of stray radiation with lead apertures’’, *Physica Medica: European Journal of Medical Physics*, 76, 221 – 226, 2020.

[12] H.O. Tekin, F.T. Ali, G. Almisned, G. Susoy, S.A.M. Issa, A. Ene, W. Elshami and H.M.H. Zakaly, ‘’Multiple assessments on the gamma-ray protection properties of niobium-doped borotellurite glasses: a wide range investigation using Monte Carlo simulations’’, *Science And Technology Of Nuclear Installation*, 2022, 1-17, 2022.

[13] H. M. H. Zakaly, Y. S. Rammah, H. O. Tekin, A. Ene, A. Badawi and S. A. M. Issa, ‘’Nuclear shielding performances of borate/sodium/potassium glasses doped with Sm3þ ions’’, *Journal of Materials Research and Technology*, 47(4), 5587-5596, 2022.

[14] H. M. H. Zakaly, H. A. Saudi, S. A. M. Issa, M. Rashad, A. I. Elazaka, H. O. Tekin and Y. B. Saddeek, ‘’Alteration of optical, structural, mechanical durability and nuclear radiation attenuation

properties of barium borosilicate glasses through BaO reinforcement: experimental and numerical analyses'', *Ceramics International*, 47(2021), 5587-5596, 2021.

[15] H. Bircan , K. Manisa , A. S. Atan and M. Erdoğan , "Gama ve X-Işını Radyasyonu Yarı Değer Kalınlık Değerinin Hesaplanması için Yeni Bir Denklem", *Süleyman Demirel University Faculty of Arts and Science Journal of Science*, 12(1), 23-29, 2017.

[16] A. S. Ceyhan, ''Bazı metal elementlerinin ve biyolojik maddelerin 0,001-20 MeV enerji aralığında X-ışını radyasyonu kütle soğurma katsayılarının incelenmesi'', MS thesis, Department of Physics, Kutahya Dumlupınar University, Kutahya, Turkey 2018.

[17] J.H. Hubbell and S.M. Seltzer, 2004., Tables of X-Ray Mass Attenuation Coefficients and Mass EnergyAbsorption Coefficients (version 1.4). [Online]. National Institute of Standards and Technology, Gaithersburg, MD. Available: http://physics.nist.gov/xaamdi. Accessed: 17.04.2023.

[18] H. C. Manjunatha, L. Seenappa, K. N. Sridhar and C. Hanumantharayappa, ''Photon interaction parameters of different tissues of human organs'', *Defence Life Science Journal*, 2(3), 358-362, 2017.

[19] I. Jarrah, M. I. Radaideh, T. Kozlowski and Rizwan-Uddin, ''Determination and validation of photon energy absorption buildup factor in human tissues using Monte Carlo simulation'', *Radiation Physics and Chemistry*, 2019(160), 15-25, 2019.

[20] H. O. Tekin, G. Misned, S. A. M. Issa and H. M. H. Zakaly, ''A rapid and direct method for half value layer calculations for nuclear safety studies using MCNPX Monte Carlo code'', *Nuclear Engineering and Technology*, 54(9), 3317-3323, 2022.