Radiation shielding parameters of some antioxidants using Monte Carlo method

Huseyin Ozan Tekin^{1,4} • Mesut Karahan² •
Turker Tekin Erguzel³ • Tugba Manici⁴ •
Muhsin Konuk⁵

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Abstract In this paper, radiation shielding parameters such as mass attenuation coefficients and half value layer (HVL) of some antioxidants are investigated using MCNPX (version 2.4.0). The validation of the generated MCNPX simulation geometry for antioxidant structures is provided by comparing the results with standard WinXcom data for radiation mass attenuation coefficients of antioxidants. Very good agreement between WINXCOM and MCNPX was obtained. The results from the validated geometry were used to calculate the shielding parameters of different antioxidants. The radiation attenuation properties of each antioxidant were compared with each other. The results showed that, on average, the highest and the lowest radiation mass attenuation coefficients were observed on hesperidin and delphinidin chloride, respectively. It can be concluded that Monte Carlo simulation is a strong tool and an alternate method where experimental investigations are not possible and a standard simulation setup can be used in further studies for different biological structures. It can also be concluded that the obtained results from this study are very useful for radiology and radiotherapy applications where antioxidants are frequently used.

✉ Huseyin Ozan Tekin
huseyinozan.tekin@uskudar.edu.tr

¹ Vocational School of Health Services, Radiotherapy Department, Uskudar University, 34672 Istanbul, Turkey

² Faculty of Engineering and Natural Sciences, Department of Bioengineering, Uskudar University, 34672 Istanbul, Turkey

³ Faculty of Engineering and Natural Sciences, Department of Computer Engineering, Uskudar University, 34672 Istanbul, Turkey

⁴ Medical Radiation Research Center (USMERA), Uskudar University Istanbul, 34672 Istanbul, Turkey

⁵ Faculty of Engineering and Natural Sciences, Department of Molecular Biology and Genetics, Uskudar University, 34672 Istanbul, Turkey

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1 Introduction

It is well known that high doses of ionizing radiation can cause damage to a biological system. Ionizing radiation exposure in living tissues can result in various organ dysfunctions. Depending on the total absorbed dose amount to the entire body, cerebrovascular, gastrointestinal, and hematopoietic systems can be damaged [1]. In addition, low doses of ionizing radiation can also increase the risk of genetic defects in present and future generations if no methods for radiation protection for biological systems against such damage are developed [2]. In theory, practically all materials can be employed for the attenuation of radiation if they are designed with a particular thickness. However, the attenuation features of those materials are dependent upon density and chemical composition. Radiation exposure is minimized by applying the ‘as low as reasonably achievable’ (ALARA) principle and three main rules – time, distance, and shielding. Time and distance are governable parameters to control radiation exposure. The third main rule, namely shielding, should be a pre-decided attenuation property for ionizing radiation. On the other hand, ionizing radiation is also used in the diagnosis and treatment of human diseases. Radiotherapy is for the treatment of human diseases. Radiation therapy has been used in cancer treatment for decades. Moreover, radiotherapy is also used to exterminate cancer and as a palliative method to alleviate the pain incorporated with metastases. The main aim of radiotherapy is to increase DNA damage in tumor cells. A supplementation term is quite important during radiotherapy. Moreover, antioxidants play an important role in all supplements [3]. Antioxidants can protect normal cells from reactive oxygen species. The importance of antioxidants for reducing the radiation effects from radiotherapy have been investigated by various researchers [1, 4–7]. However, simulation of antioxidants and investigation of their radiation attenuation properties by using the Monte Carlo method are not found in the literature.

This has encouraged us to generate a novel Monte Carlo simulation setup using MCNPX code for the investigation of radiation attenuation features of different types of antioxidant samples. Therefore, the present study aims to investigate the attenuation behaviors of antioxidant samples such as delphinidin chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol against 356 keV, 662 keV, 1173 keV, 1274 keV, 1333 keV photon energies of some radioisotopes.

2 Materials and methods

2.1 Antioxidants

Antioxidants protect the body from damage by free radicals [8, 9] such as O₂(superoxide anion), H₂O₂(hydrogen peroxide), OH(hydroxyl radical), ROOH(organic hydroperoxide), etc. It is well known that this damage causes the development of blood vessel disease (atherosclerosis), cancer, etc. Exogenic antioxidants comprise some vitamins (such as vitamins C and E), some minerals (such as selenium) and flavonoids, which are found abundantly in plants. The best sources of them are fruits and vegetables. The exogenic antioxidants such as delphinidin

chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol examined in this study are exogenous antioxidants and can be obtained commercially from a number of trading companies.

2.2 MCNPX Monte Carlo code

The Monte Carlo N-Particle Transport Code System-extended (MCNPX) version 2.4.0 (Los Alamos National Laboratory, NM, USA) general purpose Monte Carlo code was applied for the determination of mass attenuation coefficients of delphinidin chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol. MCNPX is a Monte Carlo code for the simulation of various physical interactions at a wide energy range. MCNPX is fully three-dimensional, utilizes extended nuclear cross-section libraries, and uses physics models for particle types [10]. MCNPX operates extended nuclear cross-section libraries and uses specific physics models for the different types of particles. This is a major and powerful code for photon attenuation and energy deposition studies. Similar to the methodology in this study, some MCNPX studies for different radiation applications were found in the literature [11–22]. In the present investigation, each simulation parameter, such as cell specifications, surface specifications, material specifications, and position determinations of each simulation tool have been defined in an input file according to their physical features. In the present investigation, gamma ray sources with various energies are defined as a point isotropic source. The source was defined in the mode card of the MCNPX input file as a point source at photon energies of 356 keV, 662 keV, 1173 keV, 1274 keV, 1333 keV, respectively. The total simulation geometry of the present investigation for mass attenuation coefficient calculations can be seen in Fig. 1. Moreover, a cross-sectional screenshot of the MCNPX Monte Carlo code can be seen in Fig. 2.

To explore the mass attenuation coefficients of the investigated antioxidants, the geometry and material composition of delphinidin chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol were defined in the input file. As can be seen from Fig. 1, an antioxidant sample was located as an attenuator material between the source and detection area. A point isotropic radiation source was also placed at a point before the antioxidant sample. To obtain the absorbed dose amount in the detection field, the average flux tally F4 was used. This type of tally in MCNPX scores the average flux in a point or cell. In addition, 10^8 particles were tracked as the number of the particle (NPS

Fig. 1 MCNPX simulation geometry

Fig. 2 Cross-sectional screenshot of MCNPX simulation setup

variable). MCNPX calculations were performed by using Intel® Core™ i7 CPU 2.80 GHz, computer hardware.

2.3 WinXcom program

In the present investigation, the WinXcom program [23] was also used to calculate the gamma ray mass attenuation coefficients of the investigated antioxidants. The WinXcom program is a user-friendly calculation program and the input parameter specifications are quite flexible and easy to access. In the WinXcom program, each antioxidant was defined by their elemental fractions (Table 1). Afterwards, the well-known gamma ray energies such as 356 keV, 662 keV, 1173 keV, 1274 keV and 1333 keV photon energies were defined. The attenuation coefficients of delphinidin

Table 1 Chemical formulas and elemental mass fractions of antioxidants

Sample	Sample name	Chemical formula	Mean atomic number (z) [21]	Mass fraction of C	Mass fraction of H	Mass fraction of Cl	Mass fraction of O
1	Delphinidin chloride	C ₁₅ H ₁₁ ClO ₇	5.11	%53.19	%3.28	%10.47	%33.06
2	Ferulic acid	C ₁₀ H ₁₀ O ₄	4.25	%61.84	%5.20	—	%32.96
3	Hesperidin	C ₂₈ H ₃₄ O ₁₅	4.18	%55.07	%5.63	—	%39.30
4	Kaempferol	C ₁₅ H ₁₀ O ₆	4.77	%62.93	%3.53	—	%33.54
5	Epicatechin gallate	C ₂₂ H ₁₈ O ₁₀	4.60	%59.72	%4.11	—	%36.17
6	<i>p</i> -Coumaric acid	C ₉ H ₈ O ₃	4.30	%65.84	%4.92	—	%29.24
7	Quercetin	C ₁₅ H ₁₀ O ₇	4.87	%59.60	%3.34	—	%37.06
8	Narirutin	C ₂₇ H ₃₂ O ₁₄	4.19	%55.85	%5.57	—	%38.58

chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol were calculated by the WinXcom program.

2.4 Mass attenuation coefficients

The linear attenuation coefficient depends on density. Due to this reason, data that are independent of the density (μ/ρ) of the substance are needed. This information, which is independent of density, is called the mass attenuation coefficient and its unit is m²/kg. The term of the mass attenuation coefficient (μ/ρ) is one of the important values to evaluate the shielding properties of shielding materials. The mass attenuation coefficient can be obtained by dividing the linear attenuation coefficient (μ) by density (ρ) of the investigated shielding material. On the other hand, the mass attenuation coefficient (μ/ρ) of a shielding material sample at a specific energy is the sum of the products of the weight fraction and the mass attenuation coefficient of the element *i* at that energy i.e.,

$$\mu/\rho = \sum_i w_i(\mu/\rho)_i$$

where w_i and $(\mu/\rho)_i$ are the fractional weight and the total mass attenuation coefficient of the *i*th constituent in the mixture shielding material sample.

2.5 Half-value layer (HVL)

The half-value layer (HVL) is the thickness of the material sample required to attenuate 50% of the incident gamma ray [10]. The HVL was calculated using the following equations [10]:

$$HVL = \frac{0.693}{\mu}$$

$$MFP = \frac{1}{\mu}$$

where μ is the linear attenuation coefficient (cm⁻¹) of the investigated material sample, calculated by multiplying the mass attenuation coefficient of the glass by its respective density.

3 Results and discussion

The mass attenuation coefficients of the different antioxidant samples such as delphinidin chloride, ferulic acid, hesperidin, epicatechin gallate, *p*-coumaric acid, quercetin, narirutin, and kaempferol against 356 keV, 662 keV, 1173 keV, 1274 keV, 1333 keV photon energies were investigated using MCNPX simulation and the results are shown in Table 2. These results are shown along with earlier reported data by using theory and simulation [24]. A comparison of the mass attenuation coefficients of the investigated antioxidant samples with WinXcom data is shown in Figs. 3 and 4. Moreover, the HVL of each antioxidant sample at different photon energies (356 keV, 662 keV, 1173 keV, 1274 keV, 1333 keV) is shown in Fig. 5. Table 2 shows the mass attenuation of antioxidant sample computation by using the MCNPX simulation code and a standardized simulation set-up. It is to be noted that the mass attenuation coefficients of each antioxidant decrease with the increase of photon energy, with the largest at 1333 keV. The behavior of the variation of mass attenuation coefficients with photon energy can be explained by the photon interaction process (photoelectric effect, Compton scattering and pair production) in low, intermedium and high-energy photon regions using an atomic number of elements and photon energy as cited in various literature elsewhere. Although hesperidin has shown the higher mass attenuation coefficient in all energies, it can be clearly seen that the mass attenuation coefficients of different antioxidants calculated from WinXcom and MCNPX code for five photon energies are almost the same for all investigated samples, regarding their similar composition. Similarly, the dependence of mass attenuation coefficients to incident photon energy has been observed strongly in low-energy values. This can be due to predominant photoelectric absorption in low-energy values. Figure 5 shows a variation of HVL thickness of antioxidant samples (1 to 8) with photon energy. It can be seen that the HVL thickness of antioxidant samples increases with increase in photon energy, i.e., a larger photo energy requires very thick material to obtain the desired level of radiation outside the material. In addition, slight differences between theoretical WinXcom and MCNPX mass attenuation coefficient values have been observed. This can be due to deviations from narrow-beam geometry in the source-detector geometry, statistical parameters such as counting quantity and gaps in the antioxidant material. On the other hand, statistical studies between the obtained results from the MCNPX Monte Carlo code and standard WinXcom results have been performed. According to Table 3a-b, different types of antioxidant samples are employed in order to compare mass attenuation coefficients of the MCNPX model with the standard WinXcom data. The performance evaluation process is presented considering both the absolute deviation of the MCNPX approach and the correlation coefficient (*R*). Here, the correlation coefficient of two variables (MCNPX output and the WinXcom data) is calculated by dividing their covariance to the product of each variable's standard deviations. This is a normalized measurement of how two variables are linearly correlated. If the parameter is close to 1, it indicates that the aforementioned variables are positively and linearly related. Besides, the scatter plot of the variables falls almost along a straight line with a positive slope. On the other hand, -1 for the parameter implies that the variables are negatively linearly related and the scatter plot almost falls along a straight line with a negative slope. Finally, if it is calculated as zero, it indicates a weak linear relation between those two variables. Here in our study, almost all the *R* values were calculated

Table 2 Results of mass attenuation coefficients for antioxidant samples

ENERGY (KeV)	Delphinidin chloride		Ferulic acid		Hesperidin		Kaempferol		Epicatechin gallate		<i>p</i> -Coumaric acid		Quercetin		Narirutin	
	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM	MCNPX	XCOM
356	0.1034	0.103	0.1053	0.1051	0.1058	0.1056	0.1036	0.1035	0.1045	0.1041	0.1051	0.1048	0.1036	0.1033	0.1057	0.1055
662	0.0798	0.07941	0.0817	0.08114	0.0821	0.08147	0.0804	0.07987	0.0809	0.08031	0.0813	0.08092	0.0799	0.07973	0.0816	0.08143
1173	0.0619	0.06047	0.0624	0.06182	0.0628	0.06207	0.0612	0.06085	0.0619	0.06119	0.0621	0.06165	0.0612	0.06074	0.0623	0.06203
1274	0.0592	0.05797	0.0598	0.05926	0.0598	0.0595	0.0589	0.05833	0.0591	0.05865	0.0595	0.0591	0.0588	0.05823	0.0598	0.05946
1333	0.0571	0.05664	0.0586	0.05789	0.0584	0.05813	0.0573	0.05699	0.0577	0.0573	0.0579	0.05774	0.0571	0.05688	0.0584	0.05809

Fig. 3 Mass attenuation coefficients of delphinidin chloride, epicatechin gallate, ferulic acid, and hesperidin using MCNPX and XCOM data

Fig. 4 Mass attenuation coefficients of kaempferol, narirutin, *p*-coumaric acid, and quercetin using MCNPX and XCOM data

Fig. 5 Half value layer thickness of antioxidant samples

quite close to ‘1’ indicating that the performance of MCNPX is generating a remarkably rewarding execution in terms of converging to WinXcom reference data. In addition to the numerical comparison, a regression line is plotted for each antioxidant in order to underline that there is a strong correlation between MCNPX model output and the reference WinXcom data as shown in Figs. 3 and 5. In the figures, below the R2 parameter is a key output of regression analysis. It is interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable. The coefficient of determination is considered as a valuable tool in determining the degree of the linear-correlation of variables in regression analysis where the higher the value means the better the fit. For the plotted regressions lines, the R2 values of the MCNPX models are satisfactory for all types of antioxidants.

4 Conclusions

Apart from radiation accidents, radiation has been used increasingly in industry and different types of medical applications to help with treatment and diagnosis. However, radiation dangers present a significant challenge for biological and medical safety. The radioprotective effects of antioxidants against cellular damage caused by oxidative stress suggest antioxidants as a potential protective material in situations where the effects of ionizing radiation are to be controlled. In the present study, eight different kinds of antioxidant samples were used. The MCNPX Monte Carlo code (version 2.4.0) was used to investigate the shielding parameters of different kinds of antioxidant samples. The obtained results showed that attenuation of photons in antioxidant samples increased with decreased energy. Furthermore, it can be concluded that results obtained from the MCNPX Monte Carlo code had similar results with standard WinXcom data. It can also be concluded that modeled standard MCNPX geometry can be useful for the scientific community for similar future studies of radiation shielding by using different types of biological materials and systems. Because of its frequent use of different

Table 3 Deviation values between MCNPX simulation results and standard XCOM data

ENERGY (KeV)	MCNPX	XCOM	% Abs. Dev.	MCNPX	XCOM	% Abs. Dev.	MCNPX	XCOM	% Abs. Dev.
		Delphinidin chloride			Ferulic acid			Hesperidin	
356	0,10,340	0,10,300	0,3883%	0,10,530	0,10,510	0,1903%	0,10,580	0,10,560	0,1894%
662	0,07980	0,07941	0,4911%	0,08170	0,08114	0,6902%	0,08210	0,08147	0,7733%
1173	0,06190	0,06047	2,3648%	0,06240	0,06182	0,9382%	0,06280	0,06207	1,1761%
1274	0,05920	0,05797	2,1218%	0,05980	0,05926	0,9112%	0,05980	0,05950	0,5042%
1333	0,05710	0,05664	0,8121%	0,05860	0,05789	1,2265%	0,05840	0,05813	0,4645%
Corr. coeff.	0,999,877,485			0,999,991,156			0,999,936,072		
		Epicatechin gallate			<i>p</i> -Coumaric acid			Quercetin	
356	0,10,450	0,10,410	0,3842%	0,10,510	0,10,480	0,2863%	0,10,360	0,10,330	0,2904%
662	0,08090	0,08031	0,7347%	0,08130	0,08092	0,4696%	0,07990	0,07973	0,2132%
1173	0,06190	0,06119	1,1603%	0,06210	0,06165	0,7299%	0,06120	0,06074	0,7573%
1274	0,05910	0,05865	0,7673%	0,05950	0,05910	0,6768%	0,05880	0,05823	0,9789%
1333	0,05770	0,05730	0,6981%	0,05790	0,05774	0,2771%	0,05710	0,05688	0,3868%
Corr. coeff.	0,999,978,203			0,999,984,269			0,999,969,939		
								Kaempferol	
								0,10,360	0,10,350
								0,08040	0,07987
								0,06120	0,06085
								0,05890	0,05833
								0,05730	0,05699
								0,999,970,382	
								Narirutin	
								0,10,570	0,10,550
								0,08160	0,08143
								0,06230	0,06203
								0,05980	0,05946
								0,05840	0,05809
								0,999,997,678	

biological and pharmacological systems, especially for therapeutic applications due to its radiation-reducing properties, this study can be very beneficial to the scientific community for future studies on related subjects. In summary, the investigated physical principles of radiation protection and the guidelines of ALARA, combined with the biological protection provided by multiple antioxidants, may further decrease the health risks of low doses of radiation no matter how small that risk might be.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

References

1. Ramachandran, L., Nair, C.K.: Radioprotection by tempol: studies on tissue antioxidant levels, hematopoietic and gastrointestinal systems, in mice whole body exposed to sub-lethal doses of gamma radiation. *Iran. J. Radiat. Res.* **10**(1), 1–10 (2012)
2. Little, J.B.: Genomic instability and bystander effects: a historical perspective. *Oncogene* **45**, 6978–6987 (2003)
3. Eric, J.H., Amato J.G.: Radiobiology for the Radiologist. Lippincott Williams & Wilkins (2006)
4. El-Missiry, M.A., Othman, A.I., Alabdan, M.A.: Melatonin for protection against ionizing radiation. *Current Topics in Ionizing Radiation Research*, Dr. Mitsuru Neno (ed.) (2012)
5. Greenberger, J., Kagan, V., Bayir, H., Wipf, P., Epperly, M.: Antioxidant approaches to management of ionizing irradiation injury. *Antioxidants* (2015). <https://doi.org/10.3390/antiox4010082>
6. Prasad, K.N.: Rationale for using multiple antioxidants in protecting humans against low doses of ionizing radiation. *Br. J. Radiol.* **78**, 485–492 (2005). <https://doi.org/10.1259/bjr/87552880>
7. Einor, D., Bonisoli, A., Constantini, D., Mousseau, T.A., Moller, A.P.: Ionizing radiation, antioxidant response and oxidative damage: a meta-analysis. *Sci. Total Environ.* **548**, 463–471 (2016). <https://doi.org/10.1016/j.scitotenv.2016.01.027>
8. Borek, C.: Antioxidants and radiation therapy. *J. Nutr.* **134**, 3207–3209 (2004)
9. Barry, H.B., Gutteridge, J.M.C.: Free Radicals in Biology and Medicine, Oxford University Press (2015)
10. RSICC Computer Code Collection. MCNPX User's Manual Version 2.4.0. Monte Carlo N-Particle Transport Code System for Multiple and High Energy Applications, (2002).
11. Tekin, H.O.: MCNP-X Monte Carlo code application for mass attenuation coefficients of concrete at different energies by modeling 3×3 inch nai(tl) detector and comparison with xcom and Monte Carlo data. *Sci. Technol. Nucl. Inst.* (2016). <https://doi.org/10.1155/2016/6547318>
12. Tekin, H.O., Sayyed, M.I., Manici, T., Altunsoy, E.E.: Photon shielding characterizations of bismuth modified borate - silicate-tellurite glasses using MCNPX Monte Carlo code. *Mater. Chem. Phys.* (2018). <https://doi.org/10.1016/j.matchemphys.2018.02.009>
13. Shams, A.M., Yasser, B., Tekin, H.O., Sayyed, M.I., Khamies, S.S.: Investigations of radiation shielding and elastic properties of $\text{PbO-SiO}_2\text{-B}_2\text{O}_3\text{-Na}_2\text{O}$ glasses using Monte Carlo method. *Curr. Appl. Phys.* (2018). <https://doi.org/10.1016/j.cap.2018.02.018>
14. Tekin, H.O., Singh, V.P., Kara, U., Manici, T., Altunsoy, E.E.: Investigation of nanoparticle effect on radiation shielding property using Monte Carlo method. *CBU J. Sci.* **12**, 2 (2016). <https://doi.org/10.18466/cbujos.15586>
15. Tekin, H.O., Sayyed, M.I., Shams, A.M.: Gamma radiation shielding properties of the hematite-serpentine concrete blended with WO_3 and Bi_2O_3 micro and nano particles using MCNPX code. *Radiat. Phys. Chem.* (2018). <https://doi.org/10.1016/j.radphyschem.2018.05.002>
16. Tekin, H.O., Singh, V.P., Manici, T.: Effects of micro-sized and nano-sized WO_3 on mass attenuation coefficients of concrete by using MCNPX code. *Appl. Radiat. Isot.* (2016). <https://doi.org/10.1016/j.apradiso.2016.12.040>

17. Tekin, H.O., Manici, T.: Simulations of mass attenuation coefficients for shielding materials using the MCNP-X code. *Nucl. Sci. Tech.* **28**, 95 (2017). <https://doi.org/10.1007/s41365-017-0253-4>
18. Tekin, H.O., Singh, V.P., Altunsoy, E.E., Manici, T., Sayyed, M.I.: Mass attenuation coefficients of human body organs using MCNPX Monte Carlo code. *Iran. J. Med. Phys.* <https://doi.org/10.22038/ijmp.2017.23478.1230>
19. Sayyed, M.I., Al-Zaatreh, M.Y., Dong, M.G., Zaid, M.H.M., Matori, K.A., Tekin, H.O.: A comprehensive study of the energy absorption and exposure buildup factors of different bricks for gamma-rays shielding. *Results Phys.* **7**, 2528–2533 (2017). <https://doi.org/10.1016/j.rinp.2017.07.028>
20. Dong, M.G., El-Mallawany, R., Sayyed, M.I., Tekin, H.O.: Shielding properties of $80\text{TeO}_2\text{--}5\text{TiO}_2\text{--}(15\text{--}x)\text{WO}_3\text{--}x\text{AnOm}$ glasses using WinXcom and MCNP5 code. *Radiat. Phys. Chem.* **141**, 172–178 (2017). <https://doi.org/10.1016/j.radphyschem.2017.07.006>
21. Lakshminarayana, G., Baki, S.O., Kaky, K.M., Sayyed, M.I., Tekin, H.O., Lira, A., Kityk, I.V., Mahdi, M.A.: Investigation of structural, thermal properties and shielding parameters for multicomponent borate glasses for gamma and neutron radiation shielding applications. *J. Non-Crystal. Solids* **471**: 222–237 (2017). <https://doi.org/10.1016/j.jnoncrysol.2017.06.001>
22. Tekin, H.O., Sayyed, M.I., Altunsoy, E.E., Manici, T.: Shielding properties and effects of WO_3 and PbO on mass attenuation coefficients by using MCNPX code. *Digest J. Nanomater. Biostruct.* **12**, 861–867 (2017)
23. Gerward, L., Guilbert, N., Jensen, K.B.: WinXCom-a program for calculating X-ray attenuation coefficients. *Radiat. Phys. Chem.* **71**, 653–654 (2004). <https://doi.org/10.1016/j.radphyschem.2004.04.040>
24. Isikli, Z., Oto, B.: Gamma or X-ray attenuation properties of some biochemical compounds. *Radiat. Eff. Defects. Solids* **172**, 3–4 (2017). <https://doi.org/10.1080/10420150.2017.1307194>