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Application of FLUKA code to gamma-ray attenuation, energy deposition and dose calculations

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► ***Technical Note***

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ABSTRACT

Background: In radiation therapy, water is the phantom material of choice, both for reference and for relative dosimetry measurements. Solid phantoms, however, are more useful for routine measurements because they tend to be more robust and easier to set up than water phantoms. ***Materials and Methods***: FLUKA input data cards have been arranged in sequential order. A simple cylindrical geometry with the axis along the z-direction was described in the input file. A beam of $1x10^5$ gamma-rays was directed towards the materials in the z-direction. The results of photon transmission, I/I_0, were obtained from output files for each of the material thicknesses using the USRBDX score card. The USRBIN score card was also included in the input file, and the energy deposited by 661.6 keV photons into water and solid phantom materials has been obtained. ***Results:*** The values of linear attenuation coefficients calculated by FLUKA are closer to experimentally obtained ones. The values of the linear attenuation coefficients derived from XCOM are greater than those derived from the FLUKA transmission data. The values of dose absorbed in Perspex are smaller than those of other materials, which are closer to each other. ***Conclusion:*** RMI-457, plastic water and RW solid phantoms can be used for radiation dosimetry of photons in the energy range from 59.5 to 1332.5 keV. From the investigation of absorbed dose values versus thickness of absorber, Perspex is not a suitable equivalent to water for the tested energies.

Keywords: *Gamma-ray, Monte Carlo, radiation dose, radiation shielding, solid phantom.*

INTRODUCTION

In radiation therapy, water is the phantom material of choice both for reference and for relative dosimetry measurements. Solid water-equivalent phantoms are used extensively for the dosimetry of photon and electron beams as used in radiation therapy, radiology, nuclear medicine and radiation safety. Solid phantoms are also more useful for routine measurements because they tend to be more robust and easier to set up than water phantoms [1].

Plastic-water phantom materials are not exactly water equivalent because they have a different elemental composition and different interaction cross sections for photons than water [2]. For a solid phantom to be considered water-equivalent, it must have radiological properties similar to those of water. These properties include physical density, relative electron density and effective atomic number as well as similar absorption and scattering of radiation [1,3,4].

Numerous experiments and Monte Carlo studies of the water equivalence of plastic-water phantoms have been reported for photon and electron beams [5-14]. FLUKA is a Monte Carlo simulation package for a variety of models of particle transport and interaction with matter [15]. It can simulate with high accuracy the interaction and propagation in matter of approximately 60 different particles, including

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photons, electrons, neutrinos, muons, hadrons, all the corresponding antiparticles, neutrons and heavy ions. For most applications, no programming is required from the user. FLUKA input files consist of a variable number of cards (commands), each consisting of one or more lines. The typical structure of a FLUKA input file is: titles and comments for documentation purposes, description of the problem geometry, definition of the materials, material assignments, definition of the particle source, definition of the requested detectors, initialization of the random number sequence, starting signal and number of requested histories [15].

The goal of the present work has been to build FLUKA input to calculate linear attenuation coefficients of water and four solid phantom materials that were previously studied by Hill *et al.* [1]. This input has also been employed to calculate the dose (Gy) absorbed by phantoms and the energies deposited in these materials.

MATERIALS AND METHODS

Materials studied

Water and four phantom materials investigated in the present study are shown in table 1 with their elemental compositions and mass densities. In the simulations, photon beams at seven different energies, 59.5, 80.9, 140.5, 356.5, 661.6, 1173.2 and 1332.5 keV, impinged on the targets in vacuum.

Table 1. Composition by relative weight and physical density of water and the four phantom materials [1] investigated.

Element	Investigated materials				
	Water	RMI-457	Plastic water	RW3	Perspex
	ρ=1.000 g cm^{-3}	ρ=1.030 g cm^{-3}	ρ=1.013 g cm^{-3}	ρ=1.045 g cm^{-3}	ρ=1.190 g cm^{-3}
H	0.1119	0.0809	0.0925	0.0759	0.0805
C	-	0.6722	0.6282	0.9041	0.5998
N	-	0.0240	0.0100	-	-
O	0.8881	0.1984	0.1794	0.0080	0.3996
F	-	-	-	-	-
Cl	-	0.0013	0.0096	-	-
Ca	-	0.0232	0.0795	-	-
Br	-	-	0.0003	-	-
Ti	-	-	-	0.0120	-

FLUKA code

For this study, input data cards have been represented in a sequential order. A simple cylindrical geometry, with a diameter of 10 cm and several cm in thickness with the axis along the z-direction, was described in the input file. A beam of 1x10^5 gamma-rays was directed towards the materials in the z-direction and attenuated in cylindrical samples. The code was run for 5 cycles. The results of photon transmission, I_0/I, for each material thickness obtained using the USRBDX score card were read from output files. By plotting ln(I_0/I) versus t as shown in figure 1, the slope is calculated and this value, called the transmission value, is used in following equation. The linear attenuation coefficients (μ) were calculated by equation (1), based on the Lambert-Beer law:

$$\mu = \frac{1}{t}\ln\left(\frac{I_0}{I}\right) \qquad (1)$$

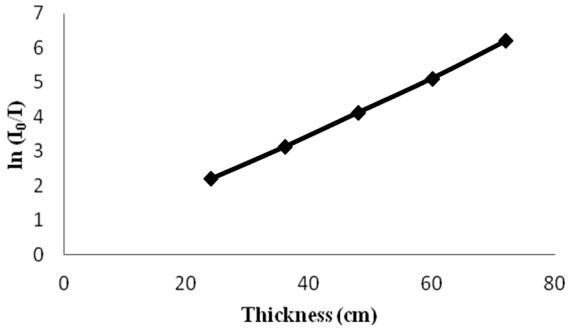

Figure 1. Plot of ln(I_0/I) values versus thickness of attenuator medium (661.6 keV in water).

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The USRBIN score card has also been included in the input file, and the energy deposited by the 661.6 keV photons in water and solid phantom materials was obtained as a contour with FLAIR, a data analysis interface compatible with FLUKA. The values of absorbed dose at several depths of each material were calculated by this score card.

RESULTS

The values of the linear attenuation coefficients derived from XCOM [16] were greater than those derived from the FLUKA transmission data. Values calculated by FLUKA compare more closely to experimental ones. Based on the observed agreement of the results of the discussed three methods (table 2), we calculated the values of absorbed dose at several depths of RMI-457, Plastic water, RW3 and Perspex, and deposited energies at several depths of water. Additionally, the effect of primary photon energy on deposited energy has been surveyed.

Values of absorbed dose of all investigated materials have been plotted versus thickness of the absorber in figure 2. It is clear from figure 2 that the values of absorbed dose in Perspex are smaller than those of other materials, which are closer to each other.

Energy deposition by 661. 6 keV photons versus depth has been presented for two thicknesses of water, 2 cm and 14 cm (figure 3). It is clear from figure 3 that deposited energy per unit volume increases with the increase in material depth.

Figure 4 shows the energies deposited in several thicknesses of a water medium versus a range of primary photon energies from 59.5 to 1332.5 keV. As a result expected, deposited energy at a certain region increases with the increase in primary photon energy.

Table 2. Linear attenuation coefficients of water and four solid phantom materials: calculated by FLUKA code (this study), EGSnrc [1] and XCOM database [15] and measured [1].

Energy (keV)	Linear attenuation coefficients (cm^{-1})																			
	Water				RMI-457				Plastic water				RW3				Perspex			
	FLUKA	EGSnrc	XCOM	Meas-ured	FLUKA	EGSnrc	XCOM	Meas ured	FLUKA	EGSnrc	XCOM	Meas ured	FLUKA	EGSnrc	XCOM	Meas-ured	FLUKA	EGSnrc	XCOM	Meas-ured
59.5	0.193	----	0.207	----	0.196	----	0.209	----	0.229	----	0.239	----	0.192	----	0.204	----	0.218	----	0.230	----
80.9	0.174	----	0.183	----	0.176	----	0.184	----	0.186	----	0.195	----	0.172	----	0.182	----	0.195	----	0.207	----
140.5	0.145	0.151	0.154	0.148	0.146	0.151	0.154	0.151	0.150	0.152	0.156	0.151	0.146	0.153	0.155	0.149	0.168	0.170	0.177	0.166
356.5	0.108	----	0.111	----	0.109	----	0.112	----	0.108	----	0.111	----	0.110	----	0.113	----	0.125	----	0.128	----
661.6	0.083	----	0.086	----	0.083	----	0.086	----	0.083	----	0.086	----	0.084	----	0.087	----	0.096	----	0.099	----
1173.2	0.065	----	0.065	----	0.065	----	0.066	----	0.064	----	0.065	----	0.065	----	0.066	----	0.074	----	0.075	----
1332.5	0.059	----	0.061	----	0.060	----	0.061	----	0.060	----	0.061	----	0.061	----	0.062	----	0.068	----	0.070	----

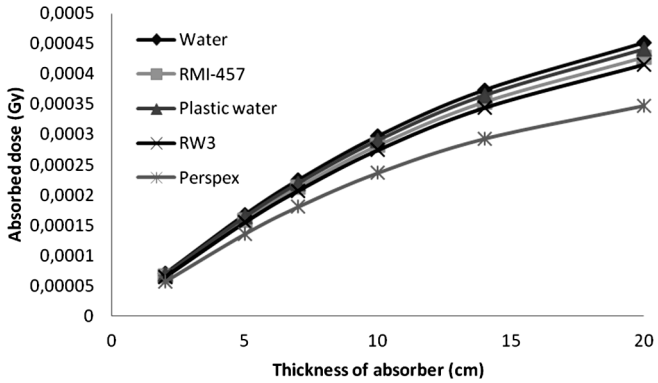

Figure 2. The values of absorbed dose (Gy) at several depths of water and solid phantom materials: RMI-457, Plastic water, RW3 and Perspex.

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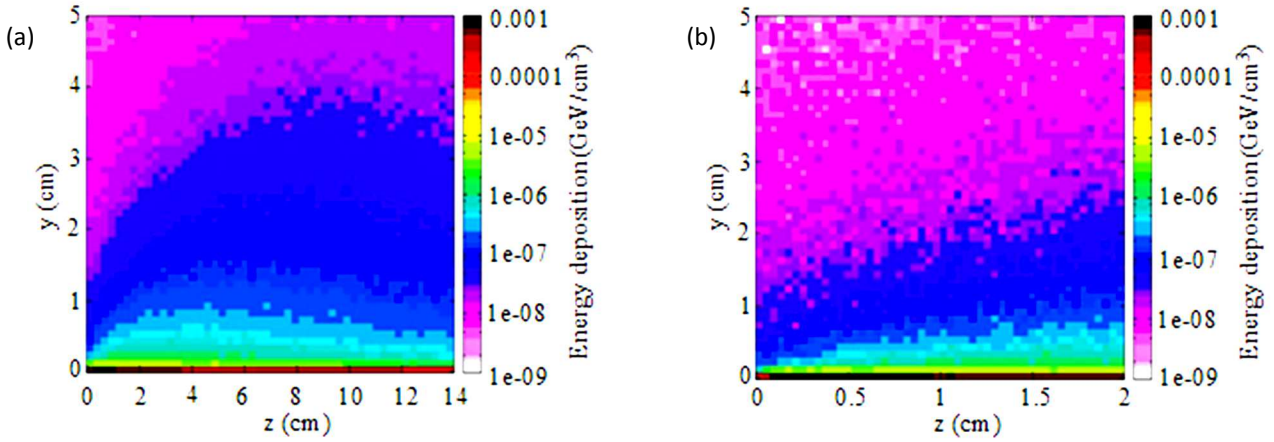

Figure 3. Energy deposition by 661.6 keV photons versus depth (a) 2 cm (b) 14 cm.

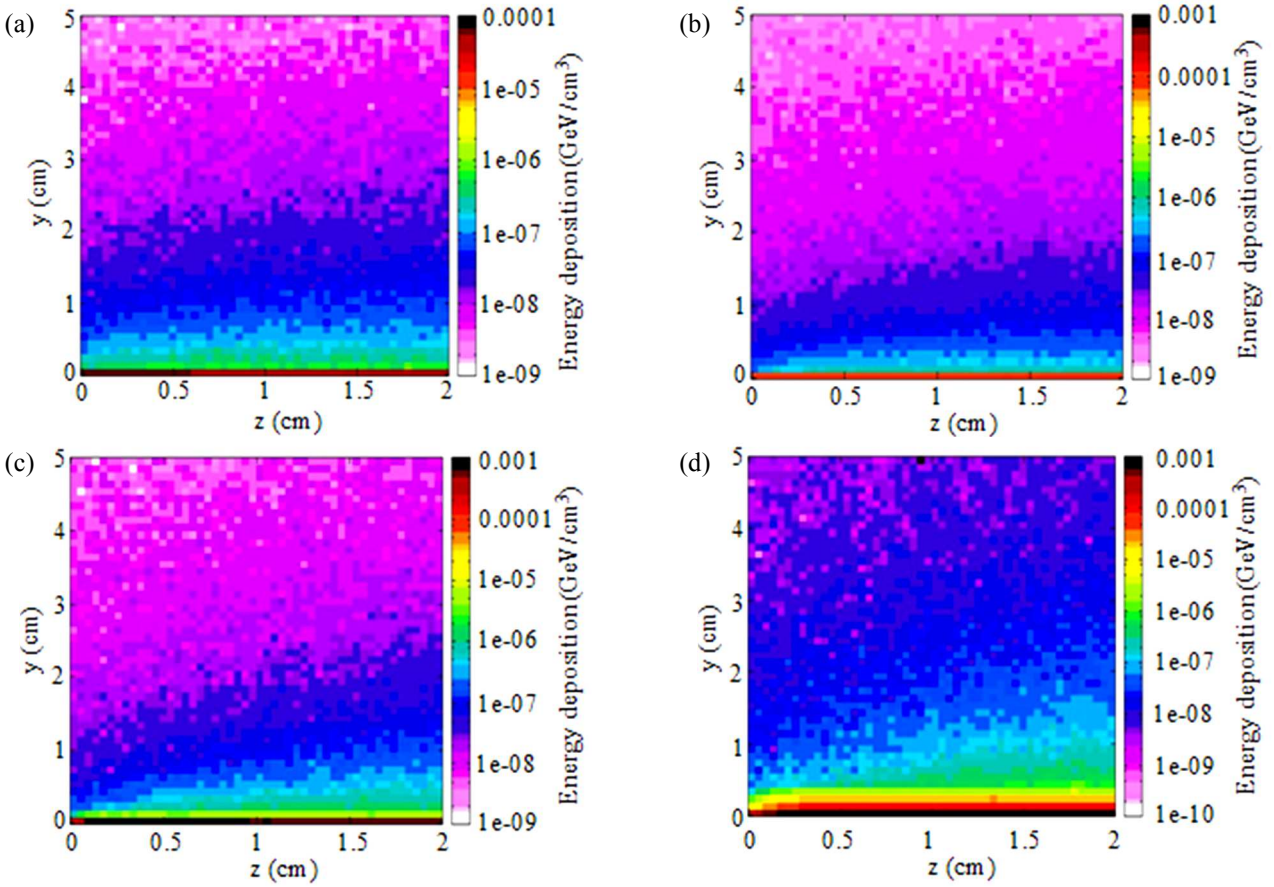

Figure 4. Energy deposition versus primary photon energy (a) 59.5 (b) 140.5 (c) 661.6 and (d) 1332.5 keV.

DISCUSSION

The conclusion on comparison of the results for attenuation coefficients resembles the results derived from the measurements and EGSnrc calculations by Hill *et al.* [1]. Based on the observed agreement of the results of these three methods and the similarity with findings by Hill *et al.*[1], the values of absorbed dose have been calculated at several depths of RMI-457, Plastic water, RW3 and Perspex, and deposited energies have been calculated at several depths

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of water. Additionally, the effect of primary photon energy on deposited energy has been surveyed.

Also the test for water equivalence of Perspex for the same photon energy range yielded results consistent with the those of Hill *et al.* [1]; from the investigation of absorbed dose values versus thickness of absorber, it is not suitable to consider Perspex to be water-equivalent for the tested energies. Moreover, simulation results for dose distribution presented by Faez and Sarkar [17] demonstrate our findings in figure 2.

Monte Carlo method is very accurate in all field dimensions and in all cases as previously reported by Mostaar *et al.* [18]. Our results and discussion confirmed that designed FLUKA input has the ability to be used evaluating the absorbed doses at several media and energy deposited by gamma-rays as well as the transmission of them.

Finally at last, considering also our earlier studies [19, 20], proposed method would have such potency to be used for reliable calculations of absorbed dose and energy deposited by gamma-rays at any material, not only watery substances.

CONCLUSIONS

In this study, the FLUKA code has been utilized for the transport and energy depositions of gamma-rays, and for doses of them absorbed in several depths of water and surveyed phantom materials. It is clear from our findings on gamma-ray attenuation that RMI-457, plastic water and RW solid phantoms can be used for radiation dosimetry of photons in the energy range from 59.5 to 1332.5 keV, as reported previously by Hill *et al.* [1].

***Conflict of interest*:** *Declared none.*

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