Research Article

Investigation of Dosimetric Parameters of HDR Cobalt-60 after-loading Brachytherapy Source using Monte Carlo Fluka Code

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Abstract

The purpose of this article is to calculate TG-43 dosimetric parameters for high-dose-rate BEBIG™ model of the ^{60}Co after-loading brachytherapy source in several phantoms including, water, polystyrene, PMMA and RW1 using Monte Carlo Fluka code. Cobalt-60 can be used as an alternativeradio-isotopeto iridium-192 for high-dose-rate brachytherapy treatment of a vast majority of cancers such as Lung, Cervix, malignancies. In addition, TG-43 protocol is presented by American Association of Physicists in Medicine (AAPM) to calculate dosimetric parameters of brachytherapy sources. The estimated dose rate constant in water is $1.0936 \frac{cGy}{h.U}$, intensity of air-Kermais $2.9429 \times 10^{-7} \frac{cGy.cm^2}{h.Bq}$ and 2D anisotropy function is in the range of 0.5 to 10 cm and angels change between 0 to 90 degrees. Consequently, the obtained results by the Fluka code were compared with those that were calculated by using MCNP and GEANT code. The comparison in this article has demonstrated a relatively good and acceptable similarity between these three codes. Overall, the Fluka code can be used to obtain dosimetric parameters in high-dose-rate brachytherapy sources.

Keywords: Brachytherapy; Co-60 source; High-dose-rate; Fluka code; Monte Carlo Code

Introduction

Cobalt-60 is a synthetic radioactive isotope of cobalt with a half-life of 5.2714 years ($E_{\gamma 1}$=1.33 MeV, $I_{\gamma 1}$=99.99%; $E_{\gamma 2}$=1.17 MeV, $I_{\gamma 2}$=99.97%). It is produced artificially by neutron activation of the isotope ^{59}Co. Corresponding to its half-life the radioactivity of one gram of ^{60}Co is about 50 curies. As cobalt-60 decays, 3 negative Beta, 6 Gamma and 15 X radiation will be produced [1].

High-dose-rate after loading brachytherapy has been demonstrated as a successful method in treatment of cancers such as prostate, cervix, internal uterus, breast, skin, lung, esophagus, head and neck malignances [1]. The optimal goal of radiotherapy is to expose radiation to the malignant cells with as little risk as possible to the normal cells, thus preserving normal organs function [2].

In addition, dosimetric calculations by modeling brachytherapy sources in the water phantom should be performed to fulfill the requirements according to American Association of Physicists in Medicine (AAPM) recommendations before the clinical use of new brachytherapy sources [3,4] Previously, American Association of Physicists in Medicine (AAPM) presented a protocol called TG-43 which offered formulation of dosage calculation and collection of data for dosimetric parameters of brachytherapy sources [5-13]. This protocol was revised in 2004 and its new edition was published as TG-43U1 [5]. Therefore, to meet the requirements of the protocol, dosimetric parameters of these sources need to be measured and calculated precisely. According to the updated TG-43 protocol, two methods need to be used in order to calculate the dosages around he radioactive sources. The first method is Monte Carlo simulation and the second one is completely experimental.

In this study, the simulation method for estimation of dosimetry parameters of the ^{60}Co sources was used BEBIG™ model of cobalt-60 source was simulated by using Fluka [6] as a Monte Carlo method and TG-43U1 dosimetric parameters such as radial-dose function, dose-rate constant, 2D anisotropy function and the air-Kerma strength were

computed. Lastly, the achieved results by the Fluka code were compared with the obtained results using a similar model source which was GEANT and MCNP codes.

Materials and Methods

^{60}Co seed description

Structure of brachytherapy source of new BEBIGTM ^{60}Co [7] differs slightly from the old type [8]. The usage of ^{60}Co in brachytherapy is in the form of cylindrical seeds with a length of 3.5 mm and a diameter of 0.5 mm. Details are shown in (Figure 1).

A seed of ^{60}Co with the mentioned dimensions in (Figure 1) is simulated by considering the center of active area coincide with the center of coordinate system. Also the energies that were considered for the definition of the source are two gamma rays of ^{60}Co with energies of 1.33 MeV and 1.17 MeV. However, the other sources of energy have been neglected due to their insignificant amount. In addition, cut off energy of the passing photon in all calculations is considered as 10 keV.

Fluka Monte Carlo code

In this study, in order to simulate the BEBIG™ ^{60}Co brachytherapy source, the Monte Carlo Fluka version 2013.5.10 ("Flair" version 1.1-3 [R2519]) was used. The Fluka method is one of the simulating programs for physical particles, which uses Monte Carlo method. The
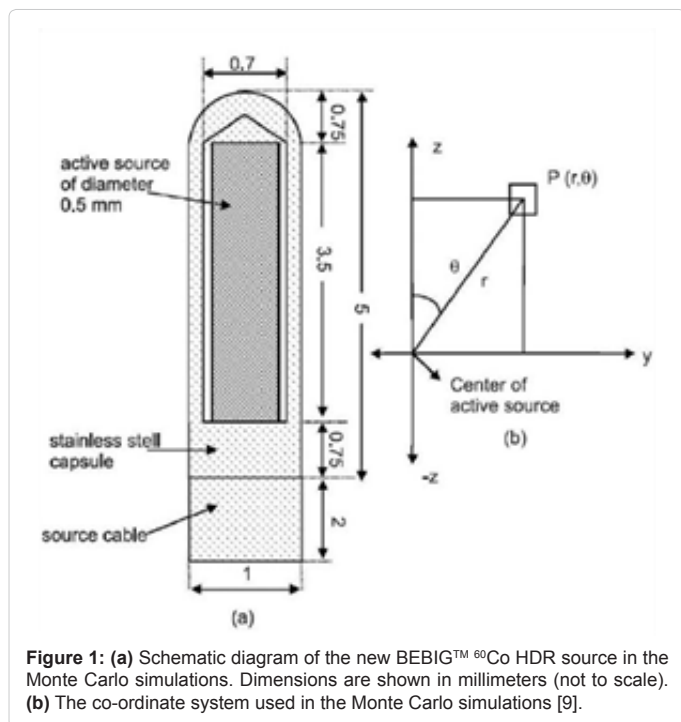
Figure 1: (a) Schematic diagram of the new BEBIG™ ^{60}Co HDR source in the Monte Carlo simulations. Dimensions are shown in millimeters (not to scale). **(b)** The co-ordinate system used in the Monte Carlo simulations [9].

Component	Source material	Atomic composition (%)	Density (g/cm³)
Active source	Cobalt	100	8.9
Encapsulation	Stainless steel (AISI 316L)	C (0.026), Mn (1.4), Si (0.42), P (0.019), S (0.003), Cr (16.8), Mo (2.11), Ni (11.01), Fe (68.21)	7.8

Table 1: Atomic composition by weight and density of the new BEBIG™ ^{60}Co HDR source [12].
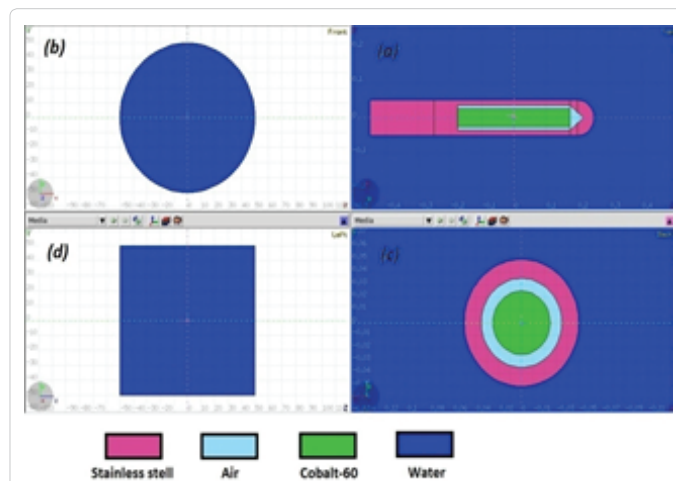

Figure 2: (a) Cutaway view in Z direction shows a seed of ^{60}Co brachytherapy in water phantom. **(b)** view of base of cylindrical water phantom. **(c)** cutaway view perpendicular to Z direction shows seed of ^{60}Co brachytherapy in water phantom. **(d)** cutaway view in Z direction (height) of cylindrical water phantom

main advantage of this method is high accuracy in a wide range of energy in simulation.For instance, this code can calculate interaction and diffusion processes of 60 different particles [6]. These particles include photons and electrons with 1 keV to thousands of TeV, neutron with any energy level, hadrons of energies up to 20 TeV. In addition, by linking the Fluka code with DPMJET code, calculation and simulation of energies up to 10 PeV and all antiparticles and massive particles could be possible [10]. A personal computer with specification: CPU: Intel Celeron 430 1.8 GHz was used for all calculation processes.

BEBIG™ Cobalt-60 was modeled with a dosimetric characterization including material, atomic composition and their density were taken from (Table 1) [11]. Consequently, the simulated source was placed in center of four different cylindrical phantoms with the same diameter and length as long as 100 cm.

Different phantoms based on their major materials including water, PMMA, Polystyrene and RW1 were designed. Figure 2 shows the seed of ^{60}Co brachytherapy in water phantom that is simulated by Fluka code. The amounts of the absorbed radiation from different distance to each phantom were calculated (GeV/g). The data related to the constituent elements of each phantom are presented on (Table 2).

To obtain suitable dose from the source, a detector simulator in different parts is needed. In this research, for a definition of the detector applying Fluka code, the presented method by Anjomrouz et al. [10] and Hadadi et al. has been employed [13]. This method utilizes virtual cylinders that classified in USRBIN card and lattice structure of R-ϕ-Z. The network detectors are designed at a distance of 10 cm from the center of coordinate system in the form of cylindrical shells with different dimensions (Figure 3). The lattice system for detectors was used due to the ease of finding dosage in any desired point in 3 dimensions with distance up to 10 cm from the center, the reduced process time, and the increased accuracy.

AAPM and working group of High Energy Brachytherapy Dosimetry (HEBD) presented a comprehensive report, which had

concentrated on dosage calculation of brachytherapy sources with average photon energy level higher than 50 KeV [13]. According to both standard ways of cylindrical source classifications, 2D dosage rate formula is demonstrated in formula-1 [13].

$$\dot{D}(r,\theta) = S_k \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r)F(r,\theta) \qquad (1)$$

For calculation of Kerma, seed of ^{60}Co brachytherapy was located in center of a vacuumed phantom and by using an air-assisted detector which inserted among the internal space between two spherical skins with radiuses of 97.5 and 102.5 cm and a cone with angular aperture of 4, absorbed energy is calculated (Figure 4) [12].

By running the Fluka program the absorbed energy that is acquired per GeV is E=1.0434 GeV and by applying Kerma calculation formula and necessary unit conversion the value of 8.1747×10^{-7} Gy is obtained. Air-Kerma Strength in distance of "d" from center of a source is calculated from below formula

$$S_K = \dot{K}(d).d^2 \qquad (2)$$

Using output of the program and parameters in formula no. 2 value for S_k/A is calculated as 2.9429×10^{-7} (cGy·cm²/h·Bq). Dose-rate constant is defined in lateral direction with distance of 1 cm from geometrical center of a source with strength of 1 air-Kerma and is calculated from following formula.

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_k} \qquad (3)$$

Using (formula 3) and make necessary unit conversion, value of

Element	Z	A	water	RW1	PMMA	Polystyrene
Composition and mass fraction in %	H	1	1.008	0.112	0.132	0.081	0.077
	C	6	12.011	-	0.794	0.6	0.923
	N	7	14.007	-	-	-	-
	O	8	15.999	0.888	0.038	0.32	-
	Mg	12	24.305	-	0.009	-	-
	Cl	17	35.457	-	0.027	-	-
	Ca	20	40.078	-	-	-	-
Mass density (g/cm³)	-	-	-	0.998	0.97	1.19	1.06
Zeff.(calculated)	-	-	-	7.416	7.21	6.096	5.584

Table 2: Elemental composition, mass fraction, density and Z_{eff}. of water and water-substitute solid phantom materials [12].

Figure 3: Configuration of region inning by FLUKA for geometry of detectors: **(a)** The view of virtual cylindrical rings; **(b)** cross-sectional view of sources along with ring detectors [13].

Figure 4: Cut away view in Z direction shows position of air-assisted detector relative to the seed of ^{60}Co brachytherapy inside of an internal sphere of the vacuum phantom.

dose-rate constant for different phantoms achieved as following values: Λ_{water} = 1.0936 (cGy/h U), Λ_{PMMA} = 1.0662 (cGy/h U), Λ_{poly} = 1.072 (cGy/h U), Λ_{RW1} = 1.0662 (cGy/h U).

Results

The value of radial dose function of four different phantoms has been presented on (Table 3). Also, the radial dose function based on different distances is shown in (Figure 5).

Eventually the estimated dosimetric parameters are demonstrated

r	g(r)-water	g(r)-PMMA	g(r)-polystyrene	g(r)-RW1
0.5	0.968	0.94	0.943	0.968
1	1	1	1	1
2	1.012	0.999	0.962	0.972
3	0.997	0.972	0.992	0.972
4	0.925	0.945	0.939	0.956
5	0.971	0.943	0.924	0.947
6	0.938	0.926	0.928	0.942
7	0.939	0.882	0.898	0.913
8	0.901	0.823	0.9	0.91
9	0.863	0.9	0.886	0.846
10	0.892	0.847	0.849	0.86

Table 3: Radial dose function calculated in water phantom for BEBIGTM ^{60}Co HDR source.
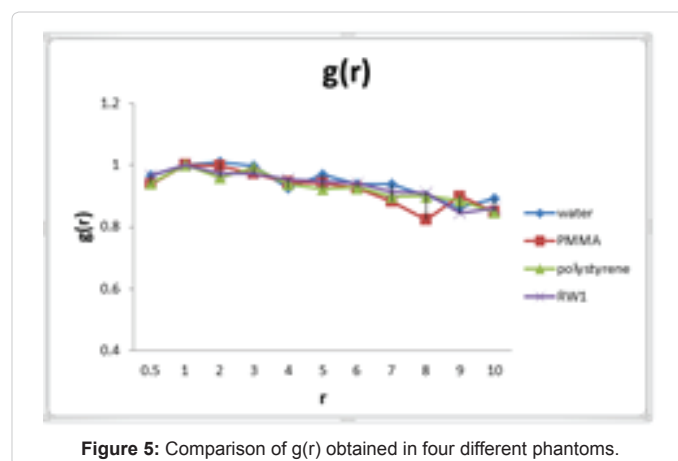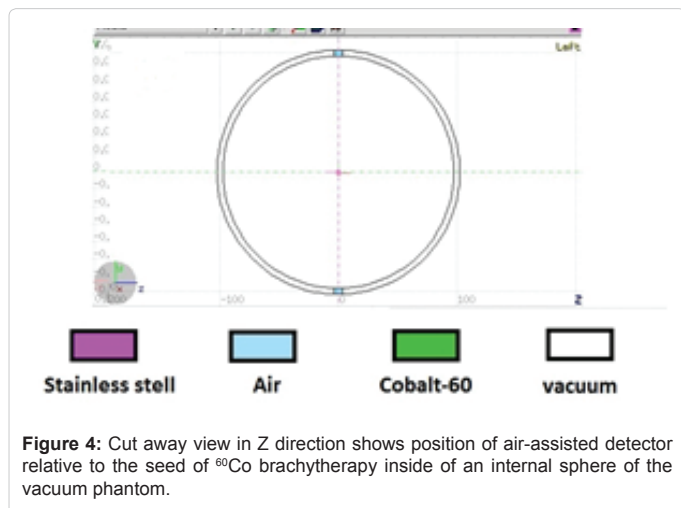
Figure 5: Comparison of g(r) obtained in four different phantoms.

on (Tables 4-7). These data shows that, considering a constant distance and by increasing the angles, the dose rate in the phantom is increased. Conversely, in a constant angel, increasing distance leading to lower dose rates. In this calculation using Fluka simulation, the value of air Kerma Strength per activity was 2.9429×10^{-7}cGy.cm²/h·Bq. Also, the value of dose-rate constant for water phantom was estimated 1.0936 cGy/h·U.

Discussion

Θ (deg)	r (cm)										
	0.5	1	2	3	4	5	6	7	8	9	10
0	6.57E-07	2.78E-07	6.97E-08	2.84E-08	1.76E-08	8.91E-09	8.48E-09	4.00E-09	3.95E-09	3.16E-09	2.40E-09
10	7.38E-07	2.31E-07	6.64E-08	3.11E-08	1.80E-08	1.26E-08	6.51E-09	5.10E-09	4.51E-09	3.44E-09	2.90E-09
20	7.78E-07	2.51E-07	6.88E-08	3.21E-08	1.80E-08	1.04E-08	8.35E-09	4.91E-09	4.36E-09	3.22E-09	2.60E-09
30	8.25E-07	2.59E-07	6.99E-08	3.22E-08	1.76E-08	1.08E-08	8.35E-09	6.29E-09	4.37E-09	3.59E-09	2.70E-09
40	8.59E-07	2.57E-07	7.22E-08	3.21E-08	1.84E-08	1.19E-08	8.12E-09	5.65E-09	4.45E-09	3.42E-09	2.90E-09
50	8.99E-07	2.72E-07	7.16E-08	3.34E-08	1.87E-08	1.18E-08	8.35E-09	5.50E-09	4.68E-09	3.71E-09	2.90E-09
60	9.51E-07	2.77E-07	7.28E-08	3.29E-08	1.99E-08	1.22E-08	7.78E-09	5.88E-09	4.29E-09	3.37E-09	2.60E-09
70	1.00E-06	2.92E-07	7.97E-08	3.50E-08	1.87E-08	1.23E-08	8.47E-09	6.11E-09	4.70E-09	3.38E-09	2.90E-09
80	1.11E-06	3.07E-07	7.74E-08	3.38E-08	1.91E-08	1.25E-08	8.47E-09	6.23E-09	4.63E-09	3.60E-09	2.80E-09
90	1.21E-06	3.22E-07	8.20E-08	3.60E-08	1.88E-08	1.26E-08	8.47E-09	6.23E-09	4.58E-09	3.46E-09	2.90E-09

Table 4: Dose rate in water phantom for the new BEBIG™ ^{60}Co source based (cGy^2·cm^2/h^2·Bq·U).

Θ (deg)	r (cm)										
	0.5	1	2	3	4	5	6	7	8	9	10
0	6.57E-07	2.38E-06	3.70E-08	1.96E-08	1.59E-08	9.50E-09	5.18E-09	4.43E-09	3.32E-09	3.09E-09	2.20E-09
10	7.38E-07	2.39E-06	6.53E-08	2.93E-08	1.68E-08	9.02E-09	7.65E-09	4.97E-09	3.89E-09	3.30E-09	2.70E-09
20	7.65E-07	2.34E-06	6.60E-08	2.98E-08	1.76E-08	1.10E-08	7.41E-09	6.03E-09	4.43E-09	3.41E-09	2.80E-09
30	7.93E-07	2.55E-06	6.76E-08	3.09E-08	1.77E-08	1.11E-08	7.43E-09	5.40E-09	4.09E-09	3.24E-09	2.20E-09
40	8.42E-07	2.50E-06	7.06E-08	3.19E-08	1.74E-08	1.09E-08	7.92E-09	5.91E-09	4.55E-09	3.43E-09	2.60E-09
50	8.64E-07	2.57E-06	6.98E-08	3.20E-08	1.80E-08	1.17E-08	7.54E-09	5.56E-09	4.38E-09	3.24E-09	2.50E-09
60	9.23E-07	2.69E-06	7.26E-08	3.19E-08	1.82E-08	1.11E-08	8.16E-09	5.63E-09	4.54E-09	3.20E-09	2.60E-09
70	9.68E-07	2.82E-06	7.45E-08	3.34E-08	1.86E-08	1.15E-08	8.08E-09	5.66E-09	4.46E-09	2.95E-09	2.80E-09
80	1.05E-06	2.96E-06	8.02E-08	3.53E-08	1.93E-08	1.19E-08	8.01E-09	5.49E-09	4.03E-09	3.20E-09	2.50E-09
90	1.15E-06	3.14E-07	7.90E-08	3.42E-08	1.87E-08	1.20E-08	8.15E-09	5.70E-09	4.08E-09	3.52E-09	2.70E-09

Table 5: Dose rate in PMMA phantom for the new BEBIG™ ^{60}Co source based (cGy^2·cm^2/h^2·Bq·U).

Θ (deg)	r (cm)										
	0.5	1	2	3	4	5	6	7	8	9	10
0	8.29E-07	2.55E-07	6.86E-08	2.40E-08	1.46E-08	9.69E-09	7.53E-09	4.49E-09	4.26E-09	3.01E-09	2.40E-09
10	7.26E-07	2.17E-07	6.52E-08	2.93E-08	1.66E-08	1.09E-08	7.81E-09	5.03E-09	4.07E-09	3.00E-09	2.80E-09
20	7.53E-07	2.33E-07	6.80E-08	2.93E-08	1.79E-08	1.06E-08	7.26E-09	4.69E-09	4.56E-09	3.52E-09	2.40E-09
30	7.75E-07	2.58E-07	7.00E-08	3.24E-08	1.82E-08	2.30E-08	7.78E-09	5.48E-09	4.39E-09	3.11E-09	2.40E-09
40	8.33E-07	2.54E-07	6.90E-08	3.15E-08	1.82E-08	1.16E-08	7.49E-09	5.93E-09	4.09E-09	3.46E-09	2.70E-09
50	8.71E-07	2.65E-07	7.15E-08	3.31E-08	1.73E-08	1.16E-08	7.66E-09	5.76E-09	4.51E-09	3.22E-09	2.40E-09
60	9.20E-07	2.70E-07	7.41E-08	3.16E-08	1.83E-08	1.15E-08	8.11E-09	5.60E-09	4.25E-09	3.40E-09	2.90E-09
70	9.71E-07	2.83E-08	7.64E-08	3.32E-08	1.95E-08	1.16E-08	7.91E-09	5.64E-09	4.41E-09	3.44E-09	2.70E-09
80	1.05E-06	2.98E-07	7.55E-08	3.38E-08	1.88E-08	1.18E-08	8.35E-09	6.03E-09	4.59E-09	3.33E-09	2.70E-09
90	1.16E-06	3.15E-07	7.65E-08	3.51E-08	1.87E-08	1.18E-08	8.21E-09	5.84E-09	4.48E-09	3.49E-09	2.70E-09

Table 6: Dose rate in Polystyrene phantom for the new BEBIG™ ^{60}Co source based (cGy^2·cm^2/h^2·Bq·U).

As seen in (Figures 6-9), the obtained values of radial dose function of four different phantoms in this study were compared to the achieved data using MCNP code.

The air Kerma Strength per activity value using Fluka has been estimated 2.9429×10^{-7}cGy.cm^2/h·Bq and the value estimated by MCNP code [13] was $3.04 \times 10^{-7} \pm 0.05\%$ cGy·cm^2/h·Bq. It can be seen that the air-Kerma strength in Fluka differs a bit from the MCNP code because of the differences in the programming language of each code, possible differences in the geometry definition for brachytherapy seeds and detectors, as well as differences in the method of calculating the Kerma strength either from calculations or simulations method. Also, the dose-rate constant value for water phantom was estimated 1.0936 cGy/h·U. Using MCNP code [9] the value was reported $1.086 \pm 0.06\%$ cGy/h·U and using GEANT code [9] the value was reported $1.017 \pm 0.011\%$ cGy/h·U

Considering the presented values come from Fluka simulation and comparison with the results of MCNP and GEANT codes, it can be concluded that the new BEBIG™ ^{60}Co source can be a good replacement for 192 Irin after loading brachytherapy since it has higher half time which results in more economical application.

Θ (deg)	r (cm)										
	0.5	1	2	3	4	5	6	7	8	9	10
0	8.46E-07	2.33E-07	6.46E-08	2.33E-08	1.54E-08	9.76E-09	7.40E-09	4.54E-09	4.07E-09	3.01E-09	2.40E-09
10	7.36E-07	2.30E-07	6.11E-08	2.93E-08	1.66E-08	1.08E-08	7.50E-09	4.70E-09	4.10E-09	3.01E-09	2.40E-09
20	7.63E-07	2.47E-07	6.46E-08	2.94E-08	1.79E-08	1.06E-08	7.54E-09	5.04E-09	4.16E-09	3.04E-09	2.40E-09
30	7.84E-07	2.54E-07	6.66E-08	3.12E-08	1.82E-08	1.08E-08	7.56E-09	5.54E-09	4.17E-09	3.07E-09	2.50E-09
40	8.38E-07	2.58E-07	6.82E-08	3.23E-08	1.82E-08	1.09E-08	7.58E-09	5.61E-09	4.20E-09	3.13E-09	2.50E-09
50	8.76E-07	2.69E-07	7.08E-08	3.27E-08	1.82E-08	1.13E-08	7.67E-09	5.65E-09	4.25E-09	3.19E-09	2.60E-09
60	9.25E-07	2.74E-07	7.34E-08	3.31E-08	1.83E-08	1.15E-08	7.93E-09	5.68E-09	4.26E-09	3.23E-09	3.20E-09
70	9.79E-07	2.88E-07	7.57E-08	3.32E-08	1.85E-08	1.17E-08	8.13E-09	5.76E-09	4.30E-09	3.24E-09	2.60E-09
80	1.06E-06	3.02E-07	7.66E-08	3.38E-08	1.87E-08	1.19E-08	8.20E-09	5.78E-09	4.42E-09	3.25E-09	2.70E-09
90	1.18E-06	3.14E-07	7.68E-08	3.42E-08	1.89E-08	1.20E-08	8.29E-09	5.90E-09	4.51E-09	3.31E-09	2.70E-09

Table 7: Dose rate in RW1 phantom for the new BEBIG™ ^{60}Co source based (cGy^2·cm^2/h^2·Bq·U).
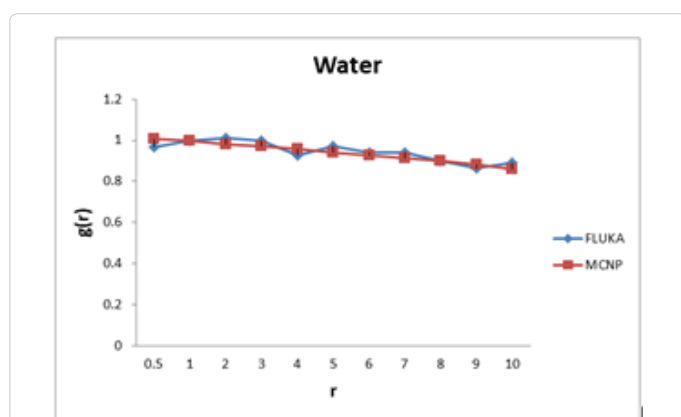

Figure 6: Comparison of g(r) for the new BEBIG™ ^{60}Co source in water phantom using MCNP code [12] and Fluka code.
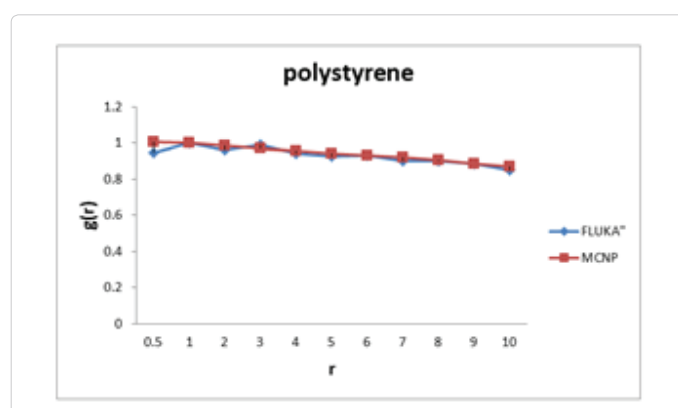

Figure 8: Comparison of g(r) for the new BEBIG™ ^{60}Co source in Polystyrene phantom using MCNP code [12] and Fluka code.
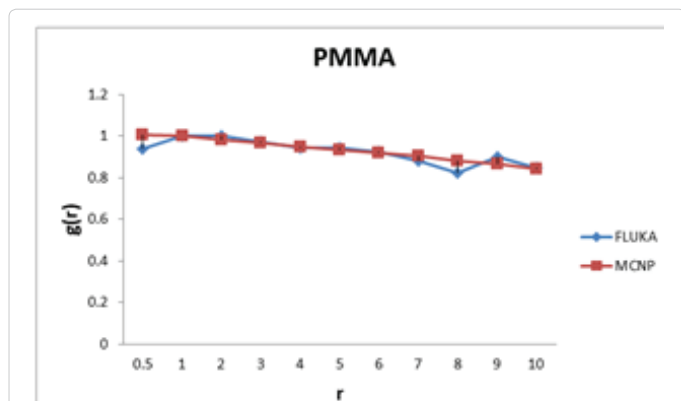

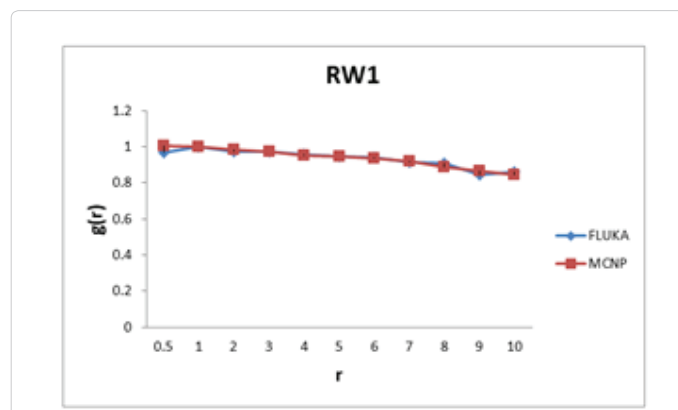**Figure 7:** Comparison of g(r) for the new BEBIG™ ^{60}Co source in PMMA phantom using MCNP code [12] and Fluka code.

Figure 9: Comparison of g(r) for the new BEBIG™ ^{60}Co source in RW1 phantom using MCNP code [12] and Fluka code.

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