An analytic approach to the dosimetry of a new BEBIG ⁶⁰Co high-dose-rate brachytherapy source

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ABSTRACT

We present a simple analytic tool for calculating the dose rate distribution in water for a new BEBIG high-dose-rate (HDR) ⁶⁰Co brachytherapy source. In the analytic tool, we consider the active source as a point located at the geometric center of the ⁶⁰Co material. The influence of the activity distribution in the active volume of the source is taken into account separately by use of the line source-based geometric function. The exponential attenuation of primary ⁶⁰Co photons by the source materials (⁶⁰Co and stainless-steel) is included in the model. The model utilizes the point-source-based function, f(r) that represents the combined effect of the exponential attenuation and scattered photons in water. We derived this function by using the published radial dose function for a point ⁶⁰Co source in an unbounded water medium of radius 50 cm. The attenuation coefficients for ⁶⁰Co and the stainless-steel encapsulation materials are deduced as best-fit parameters that minimize the different

Key words: Analytic method, brachytherapy, high-dose-rate, monte carlo, treatment planning

Introduction

In clinical practice, high-dose-rate (HDR) ¹⁹²Ir and ⁶⁰Co brachytherapy sources are used. ¹⁹²Ir sources are most commonly used, but the use of ⁶⁰Co sources has increased because of its longer half-life (5.25 years) and its availability in miniaturized forms (with dimensions comparable to those of ¹⁹²Ir HDR sources). The Ralstron remote afterloader which uses type 1, type 2 and type 3 ⁶⁰Co HDR sources, was introduced for intracavitary treatments because of the longer half-life.^[1] Presently, BEBIG HDR ⁶⁰Co brachytherapy sources (old and new designs) are in widespread use for intra-cavitary treatments.^[2,3] In a

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recently published study by Richter *et al.*,^[4] the authors have compared the physical properties of ⁶⁰Co and ¹⁹²Ir HDR sources. They demonstrated that the integral dose due to radial dose fall-off is higher for ¹⁹²Ir than for ⁶⁰Co within the first 22 cm from the source. At larger distances, this relationship is reversed. Their study suggests that no advantage or disadvantage exists for ⁶⁰Co sources compared with ¹⁹²Ir sources with regard to clinical aspects. However, there are potential logistical advantages of ⁶⁰Co sources because only 33% of the activity of ¹⁹²Ir sources is needed to yield an equivalent dose-rate. Further, because of relatively long half life, ⁶⁰Co sources can be used for much longer duration resulting in reduced operating costs.

The use of a brachytherapy source for clinical trials requires an extensive dosimetric data set either in the form of an American Association of Physicists in Medicine (AAPM) TG-43 parameters or in the form of a 2-D doserate lookup table.^[5,6] According to AAPM TG-56, such data are needed for commissioning and verification purposes in radiotherapy treatment planning systems (RTPS).^[7] The dosimetry data are usually generated by use of Monte Carlo methods. For example, Monte Carlo-based dosimetry data for HDR ⁶⁰Co sources are reported in the literature.^[1:3] and ^[8] An EGSnrc-based published study for new and old sources by Selvam and Bhola^[8] demonstrated that the dose-rate data compare well with the GEANT4-based published data^[2] and ^[3] for radial distances larger than 0.5 cm. Selvam and Bhola^[8] have shown differences in dose values up to 9% for regions close to BEBIG ⁶⁰Co sources when compared with GEANT4-based published work for these sources.^[2] and ^[3] It was also demonstrated that the length of stainless-steel cable for the new BEBIG ⁶⁰Co source considered by Granero *et al.*^[3] in their GEANT simulations was 1 mm, although it was mentioned to be 5 mm.^[8]

The Sievert integral algorithm is generally used in RTPS for dose calculation around brachytherapy sources.^[9] For ¹²⁵I, ¹⁶⁹Yb, ¹³⁷Cs and ¹⁹²Ir brachytherapy sources, such analytic methods have already been established.[10-18] Our objective in the present study was to develop a simple analytic tool for calculating the 2D dose-rate distribution in water for the new model (Co0.A86) of a BEBIG 60Co HDR source. Using the analytic model, we calculated AAPM TG-43 dose parameters such as the dose-rate constant, radial dose function and anisotropy function for the above source in a 50-cm radius in an unbounded water medium. We also calculated the dose-rate look-up table in a Cartesian format. A comparison was made with previously published work.^[8] The dose-rate data calculated with the use of the proposed analytic model could be used for verifying the results of treatment-planning systems or directly as input data for RTPS.

Materials and Methods

New BEBIG 60 Co source

Analytic calculations were performed for the new model of the BEBIG ⁶⁰Co HDR (model Co0.A86) brachytherapy source [Figure 1].^[3] The new BEBIG ⁶⁰Co HDR brachytherapy source^[3] is very much similar, both in materials and design, to the old BEBIG ⁶⁰Co HDR brachytherapy source (model GK60M21).^[2] The new source design has a smaller active core of diameter 0.5 mm with a rounded capsule tip, whereas the old design has a more rounded capsule tip. Both sources consist of a central cylindrical active core of length 3.5 mm, which is made of metallic ⁶⁰Co. The active core is covered by a cylindrical stainless-steel capsule with an external diameter of 1 mm.

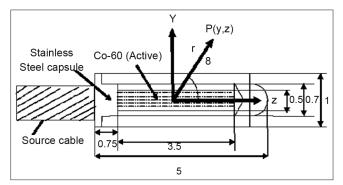


Figure 1: Schematic diagrams of the new BEBIG ⁶⁰Co high-doserate brachytherapy source (model Co0.A86), depicting geometric characteristics and materials. The coordinate axes used in this study are also shown with their origin situated in the geometric center of the active volume. All dimensions are in millimeters. Figures not drawn to scale

TG-43 dose calculation formalism

The TG43 report^[5,6] has recommended the dose calculation algorithm for establishing the 2D dose-rate distribution in a water medium around cylindrically symmetric photon-emitting brachytherapy sources. The dose-rate at polar coordinates (r, θ) is written as

$$\dot{D}(r,q) = S_K \Lambda \frac{G_L(r,q)}{G_L(r_0,q_0)} g_L(r) F(r,q) \qquad \dots \dots (1)$$

Here, the air-kerma strength, S_k , is defined as the product of the air-kerma rate $\dot{K}(r_c)$ measured at a calibration distance r_c along the transverse bisector of the source in free space and the square of the distance r_c . S_k has units of U $(1U=1 \mu Gym^2/h = 1 cGycm^2/h)$.

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

The dose-rate constant, Λ , is defined as the dose-rate per S_k along the transverse source bisector at the reference distance $r_0 = 1$ cm. The reference angle, θ_0 defines the source transverse plane, and is specified to be 90° or p/2 radian. Λ has the units of cGy/h/U, which reduces to cm.

$$\mathbf{\Lambda} = D(\mathbf{r}_0, \mathbf{q}_0) / S_k \,. \tag{3}$$

The radial dose function, $g_L(r)$, accounts for the effect of absorption and scatter in the medium along the transverse axis of the source, defined as follows:

$$g_L(r) = \dot{D}(r, q_0) G_L(r_0, q_0) / \dot{D}(r_0, q_0) G_L(r, q_0) \qquad \dots (4)$$

The anisotropy function, $F(r, \theta)$, accounts for anisotropy of the dose distribution around the source, and is defined as follows:

$$F(r,q) = \dot{D}(r,q)G_L(r,q) / s\dot{D}(r,q)G_L(r,q) . \qquad(5)$$

The geometry function, $G_L(r,q)$, accounts for the spatial distribution of radioactivity within the source, and is defined as follows:

point source approximation,
$$G_L(r,q) = 1/r^2$$
,(6.a)
line-source approximation, $G_L(r,q) = \frac{b}{Lr \operatorname{sing}}$,(6.b)

where β (in radians) is the angle subtended by the source to the point of interest, (r, θ) .^[5,6]

Analytic approach

Monoenergetic point photon source in water

The absorbed dose-rate in water at a distance r (cm) away from a point isotropic monoenergetic photon source is given by,

$$\dot{D}(r) = A k \frac{1}{4pr^2} E \left[\mathfrak{m}_{en}(E) / \mathfrak{r} \right]_{wat} e^{-\mathfrak{m}_w r} B \qquad \dots (7)$$

where A denotes the activity of the source (in Bq), E is the energy emitted by the source (in MeV) per photon, k is the constant converting the unit MeV/gm to Gy, $[m_{en}(E)/r]_{air}^{wat}$ the mass energy absorption coefficient of water in units

of cm²/gm for photon of energy E, and B is the energyabsorption build-up factor.^[19] B is defined as the absorbed dose-rate from both the primary and the scattered photons in an infinite water medium divided by the absorbed doserate from only primary photons. The assumption made in equation 7 is that the energy lost by photons in the scattering and absorption events is absorbed locally in the medium. This means that the range of secondary electrons (photo electrons, compton electrons and delta-rays) is assumed to be negligible. In the energy range relevant to brachytherapy sources, this assumption has little impact on the calculated dose-rate.

 S_k at a distance r away from a point monoenergetic photon source of energy E and activity A can be obtained analytically:

$$S_k = A \frac{1}{4p} E k \left[m_{en}(E) / r \right]_{air} , \qquad \dots (8)$$

where $[m_{en}(E)/r]_{dir}$ is the mass-energy absorption coefficient of air for the energy E. It should be noted that S_k is expressed in terms of the recommended unit U (= 1 cGycm²/h).

The dose-rate $\dot{D}(r)$ in water per S_k due to a point monoenergetic point photon source of energy E is then given by

$$\frac{D(r)}{S_k} = \left[m_{en}(E) / r \right]_{air}^{wat} f(r) \frac{1}{r^2} \qquad \dots (9)$$

where $f(r) = Be^{-m}w^r$, $[m_{en}(E)/r]_{air}^{wat}$ is the ratio of the mass–energy absorption coefficient of water to air at photon energy E, which is equal to 1.112 at ⁶⁰Co energies.^[20] The value of $[m_{en}(E)/r]_{air}^{wat}$ is constant (=1.112) in the photon energy range between 0.15 MeV and 3 MeV.^[20] As compton scattering is the predominant process in water at ⁶⁰Co energies, one can write $[m_{en}(E)/r]_{air}^{wat} = \left[\frac{\langle Z/A \rangle}{\langle Z/A \rangle}\right]_{air}^{wat} = 1.112$, where $\left[\frac{\langle Z/A \rangle}{\langle Z/A \rangle}\right]_{air}^{wat}$ is the ratio of electrons/g between water and air. The values of $\langle Z/A \rangle$ for water and air are 0.555 and 0.499, respectively.^[20]

The functional form of f(r) for ⁶⁰Co brachytherapy sources has been presented by many authors. Kartha *et al.*^[21] have given an analytical expression, $f(r) = \exp\{[0.73/E^{0.05}s] - 1\}mr$, where E is the photon energy (for ⁶⁰Co, it is 1.25 MeV), μ is the linear attenuation coefficient in water and r is the distance from the source. Meisberger^[22] approximated f(r) by the ratio of the air kerma in water to air kerma in air. He fitted the f(r) data to a third-order polynomial function, $f(r) = A + Br + Cr^2$ +Dr³ (valid up to 10 cm from the source), with coefficients A = 0.99423, B = -5.318x10⁻³/ cm, C=-2.610x10⁻³/cm² and D = 13.27 x 10⁻⁵/cm³. Van Kleffens and Starr^[23] provided an expression, f(r) = (1 + ar²) / (1+br²), with a= 10x10⁻³/cm² and b=14.50x10⁻³/cm². Kornelson and Young^[24] have given a functional form for the build-up factor, $B(r) = 1 + k_a (mr)^{k_b}$ where μ is the linear attenuation coefficient at ⁶⁰Co energies, $k_a = 0.896$ and $k_b = 1.063$. Angelopoulos *et al.*^[25] have provided data for f(r) for distances r = 1–9 cm in a 10-cm-radius water phantom. The most recent published study for a point ⁶⁰Co source in water gives a radial dose function, $g_p(r)$, in an unbounded water medium by Papagiannis *et al.*^[1]

$$g_{b}(r) = -1.418 \times 10^{-4} r^{2} - 1.470 \times 10^{-2} rs + 1.015 \qquad \dots (10)$$

Note that equation 10 is based on water-kerma as it was verified in a previously published work.^[8] From equation 10, f(r) can be derived as follows:

According to the TG-43 protocol, [5,6]

$$g_{p}(r) = \frac{\dot{D}(r)r^{2}}{\dot{D}(r_{0}^{-}r_{0}^{2}} \qquad \dots \dots (11)$$

where $r_{0} = 1$ cm.

By using equation 7 in 11, one obtains

$$g_p(r) = \frac{Be^{-m_w r}}{Be^{-m_w r_0}} = \frac{f(r)}{f(r_0)} \qquad \dots \dots (12)$$

$$f(r) = f(r_0)g_p(r)$$
(13)

Here, $f(r_o) = 0.9864$ is calculated at $r_0 = 1$ cm with the use of Mesiberger's polynomial^[22] for f(r). In our analytical model, we make use of equation 13.

Monoenergetic bare cylindrical source in water

The dose-rate $\dot{D}(r,q)$ at a point (r, θ) in water per S_k for a bare cylindrical source of photon energy, E, can be written as

$$\frac{\dot{D}(r,\mathbf{q})}{S_k} = \left[\mathbf{m}_{en} / \mathbf{r} \right]_{air}^{wat} \frac{1}{N} \sum_{i=1}^{N} f(r_i) \frac{1}{r_i^2} \qquad \dots \dots (14)$$

In the above formalism, the active cylindrical source is divided into N active segments, and each segment is treated as a point source and r_i is the distance between the ith source element to the point (r, θ). The above equation is further simplified as follows:

$$\frac{\dot{D}(r,\theta)}{S_k} = [m_{en} / r]_{air}^{wat} f(r) G_L(r,\theta) \qquad \dots \dots (15)$$

where, r is the distance between the center of the active length and the point of interest (r, θ) . In equation 15, an assumption is made that the entire activity is concentrated at the geometric center of the cylinder. The influence of the activity distribution in the cylindrical volume is taken into account separately by use of the line-source-based geometry function, $G_L(r,q)$. A simple calculation for a cylindrical bare active ⁶⁰Co source of 3.5 mm length and 0.5 mm diameter (these are typical active dimensions of the new BEBIG ⁶⁰Co source) by using equations 14 and 15 give a dose-rate value of 4.23 cGy/h/U at 5 mm along the transverse axis of the source. This suggests that equation 15 can be used for dose calculations.

Papagiannis *et al.*^[26] observed that close to ¹⁹²Ir HDR sources, it is the inherent influence of the "exact" geometry function^[5,18,27] that determines the dose-rate distribution. In order to verify that the use of $G_L(r,q)$ in equation (15) produces reasonably accurate results, we calculated an "exact" geometry function, $G_{ex}(r,q)$, by using the Monte Carlo integration approach as adapted by Karaiskos *et al.*^[18],

$$G_{ex}(r,q) = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{|r'-r|^2} = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{r_i^2} \qquad \dots \dots (16)$$

where $r_i^2 = |\mathbf{r}' - \mathbf{r}|^2$, with r_i being the distance between the ith Monte Carlo generated point and the calculation point (r, θ) . The Monte Carlo values of $G_{ex}(r, \theta)$ at distances 1, 2 and 5 mm from the source center along the transverse axis (q = 90°) are larger only by 1.23%, 0.5% and 0.1%, respectively, when compared with the corresponding values of $G_L(r, \theta)$.

Real cylindrical source in water

Cassell proposed the quantization method (decomposition of the source into small cells) for brachytherapy dose calculations.^[28] This algorithm is similar to the Sievert integral model described by Williamson.^[10] According to Cassell,^[28] the dose-rate \dot{D} (r, θ) in water at a point P(r, θ), in units of cGy/h can be obtained from the following equation:

$$\dot{D}(r,q) = \dot{K}_{R}[m_{en} / r]_{air}^{wat} e^{m_{s}t_{1} + m_{f}t_{2}} \qquad \dots \dots (17)$$

$$\frac{1}{N} \left[\sum_{j=1}^{N} \exp(-m_{s}r_{s_{j}} - m_{f}r_{f_{j}}) \frac{f(r_{w_{j}})}{r_{j}^{2}} \right]$$

Note that the reference air-kerma rate, \dot{K}_R , is equivalent to S_{μ} of the source.^[6]

In the quantization method, the active part of the cylindrical source is divided into N source elements, which are treated as point sources. For each elemental source, the dose-rate is calculated by multiplying $[m_{en} / r]_{air}^{wat}$ and correcting for the inverse square of the distance, tissue attenuation, self-absorption and filter attenuation by use of an exponential correction over the line between the elemental source and the calculation point. Symbols in equation 17 have the following meaning: μ_s , μ_f and μ_w are the linear attenuation coefficient of the active source, of the filtration material and of water, respectively. t_1 and t_2 are the active radii of the source and the encapsulation thickness, respectively. r_{s_j} , r_{f_j} and r_{w_j} are the distances traveled by photons within the source core, filter material and the water medium, respectively, and r_i is the distance between

the center of the source and the calculation point $P(r, \theta)$. Photon paths in different media are depicted in [Figure 2].

$$r_j = r_{s_j} + r_{f_j} + r_{w_j}$$
(18)

Motivated by our analytic model described for a bare cylindrical source, we consider that the total activity is concentrated at the center of the ⁶⁰Co material instead of being distributed throughout its volume. The influence of the distribution of activity in the source on the dose-rate is taken into account separately by the line-source-based geometry function $G_L(r, \theta)$. According to our simplified model, the dose-rate $\dot{D}(r, \theta)$ per S_k at a point (r, θ) can be written as follows:

$$\frac{\dot{D}(r,\mathbf{q})}{S_k} = \left[\frac{\mathbf{m}_{en}}{\mathbf{r}}\right]_{air}^{wat} e^{(\mathbf{m}_s t_1 + \mathbf{m}_f t_2)} e^{(-\mathbf{m}_s r_s - \mathbf{m}_f r_f)} f(r_w) G_{\mathrm{L}}(r,\theta) \quad \dots (19)$$

where r_s , r_f and r_w (= $r - r_s - r_f$) are the distances traveled by photons within the source core, filter material and water, respectively, as is shown in [Figure 2]. In the calculations, the function f(r) (equation 13) is evaluated at r_w . When $\theta = \theta_0$, $r_s = t_1$, $r_f = t_2$. For the new design of the ⁶⁰Co source, $t_1 = 0.025$ mm, $t_2 = 0.015$ cm and $t_1 + t_2 = 0.04$ cm. Therefore, $r_w = r$ and f(r_w) = f(r) for values of r larger than 2.5 mm. For $\theta = \theta_0$, equation 19 can be written as:

$$\frac{\dot{D}(r,\mathbf{q}_0)}{S_k} = \left[\frac{\mathbf{m}_{en}}{\mathbf{r}}\right]_{air}^{wat} f(r)G_L(r,\mathbf{q}_0) \qquad \dots (20)$$

Equation 20 is same as equation 15 when we set $\theta = \theta_0$ in equation 15. For the calculation of the transverse axis dose-rate distribution, equation 20 is good enough. When we set $\mathbf{r} = \mathbf{r}_0 = 1$ cm in equation 20,

$$\frac{\dot{D}(r_0, \theta_0)}{S_k} = \Lambda = \left[\frac{m_{en}}{r}\right]_{air}^{wat} f(r_0) G_L(r_0, \theta) \qquad \dots (21)$$

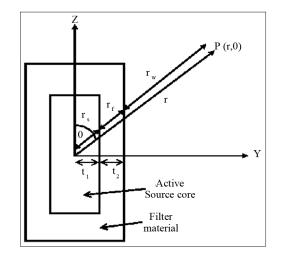


Figure 2: Simplified geometry used in the present analytical model. A point ⁶⁰Co source is positioned at the geometric center of the inactive metallic ⁶⁰Co material

Equation 21 is a general expression for the dose-rate constant of a monoenergetic photon source of active length L.

Dose-rate calculation for BEBIG source by use of the analytic tool

We have adapted the analytical tool described above for calculating dose-rate distributions in water around the new BEBIG ⁶⁰Co HDR source. We used equation 19 for this purpose. The lengths of stainless steel cable considered in the analytical calculations are 1 mm and 5 mm. Doserate calculations are carried out as functions of polar coordinates (r, θ) and Cartesian coordinates (y,z). In the calculations, the radial distance r is varied from 1 mm to 14 cm (in 2.5- mm intervals up to 3 cm and 1-cm intervals from 3 cm to 14 cm), and the polar angle θ is varied from 0° to 179° (in 2° intervals) for each r, with the 180° angle referring to the source cable side.

The analytically calculated dose-rate values for the new BEBIG ⁶⁰Co source with 1 mm and 5 mm cable lengths by use of equation 19 compare well with the published values for regions other than those close to the source axis.^[3,8] For example, for the regions close to the source axis, the analytically calculated dose-rates are higher by up to 10% when compared with the published Monte Carlo-based values.^[3,8] In order to verify whether this disagreement is due to simplifications made in the analytic model, we carried out a test calculation by using equation 17. Yet, the same disagreement was observed. For the analytical calculations, we used $\mu_s = 0.47/\text{cm}$, $\mu_f = 0.43/\text{cm}$ and $\mu_w = 0.063/\text{cm}$, all obtained at ⁶⁰Co energies.^[13]

Most of the currently available RTPS make use of the Sievert algorithm^[9] to generate dose distributions for filtered line sources. Frequently, the RTPS, based on this algorithm, does not produce accurate calculations^[5] for the regions close to the source axis. TG-43^[5] recommends treating the attenuation coefficients as parameters of the best fit for minimizing the deviations between the Sievert model predictions and the other calculated results. Selfabsorption by the source core (μ_{a}) and attenuation by the filtration material (μ_f) to be used in such algorithms are generally derived by comparing the dose results with the Monte Carlo results. For example, Ballester et al.^[13] and Casal et al.^[14] adapted this approach in their Sievert integralbased ¹³⁷Cs dosimetry and derived best-fit parameters for μ_{a} and μ_{a} . Similarly, Pérez Calatayud *et al.*^[16] derived bestfit parameters for μ_{i} and μ_{i} in their quantization methodbased dosimetry study on CDC-type miniaturized ¹³⁷Cs sources^[15] and the best-fit parameter for μ for ¹⁹²Ir wires.

Guided by the above-mentioned published work, we treated the parameters μ_s and μ_f as free-fit parameters. Instead of using the actual values of μ_s (= 0.47/cm) and μ_f (= 0.43/cm) at ⁶⁰Co energies,^[13] we used the fitted values μ_s = 0.25/cm and $\mu_f = 0.25$ /cm for the new BEBIG ⁶⁰Co HDR

source [Table 1]. For the above-described analytic method, computer software has been developed in C_{++} computerprogramming language. The software generates a complete dosimetry dataset around the source. The data include TG-43 parameters and a 2D look-up table. For the calculation of $g_L(r)$ and $F(r,\theta)$, we used $G_L(r,\theta)$. This is consistent with the updated TG-43 formalism.^[6]

Table 1: Actual and fitted values of linear attenuation coefficients for source and filtration materials $\mu_{s \text{ and }} \mu_{f}$, respectively, for the new BEBIG ⁶⁰Co source

| Linear attenuation coefficient | μ _s (/cm) | μ _f (/cm) |
|--------------------------------|----------------------|----------------------|
| Actual value | 0.47 | 0.43 |
| Fitted value | 0.25 | 0.25 |

Table 2: Comparison of dose rate constants of old and new BEBIG ⁶⁰Co sources

| Source model | This work | Puk | olished work |
|----------------------|-----------|--------------------|---------------------------|
| Model GK60M21 (old) | 1.088 | 1.087ª | 1.093 ± 0.002° |
| Model Co0.A86 (new) | 1.088 | 1.084 ^b | $1.097 \pm 0.002^{\circ}$ |
| *Def 2 bDef 2 cDef 0 | | | |

^aRef 2 , ^bRef 3, ^cRef 8

Table 3: Comparison of analytically calculated (this work) and Monte Carlo-based published data of radial dose function, $g_L(r)$, of the new BEBIG ⁶⁰Co HDR source

| Radial distance (cm) | This work | Published (Ref 8) |
|----------------------|-----------|-------------------|
| 0.1 | 0.904 | 0.830 |
| 0.15 | 1.023 | 0.961 |
| 0.2 | 1.022 | 1.037 |
| 0.25 | 1.022 | 1.072 |
| 0.3 | 1.021 | 1.077 |
| 0.35 | 1.020 | 1.066 |
| 0.4 | 1.019 | 1.050 |
| 0.45 | 1.018 | 1.037 |
| 0.5 | 1.018 | 1.028 |
| 0.6 | 1.016 | 1.019 |
| 0.75 | 1.014 | 1.011 |
| 1 | 1.000 | 1.000 |
| 1.5 | 1.002 | 0.991 |
| 2 | 0.994 | 0.983 |
| 2.5 | 0.987 | 0.974 |
| 3 | 0.979 | 0.967 |
| 4 | 0.962 | 0.95 |
| 5 | 0.952 | 0.938 |
| 6 | 0.930 | 0.916 |
| 7 | 0.914 | 0.9 |
| 8 | 0.899 | 0.884 |
| 10 | 0.863 | 0.849 |
| 12 | 0.832 | 0.81 |
| 15 | 0.779 | 0.759 |
| 20 | 0.676 | 0.664 |

| Table 4: Anisotropy function | ι F(r,θ) values for the new (| model Co0.A86 |) BEBIG ⁶⁰ Co HDR source. |
|------------------------------|-------------------------------|---------------|--------------------------------------|
| | | | |

| | | | | ()-) | | Ra | adial dis | tance r | (cm) | | - | | | | | |
|---------------------|-------|-------|-------|-------|-------|-------|-----------|---------|-------|-------|-------|-------|-------|-------|-------|-------|
| θ (deg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 10 | 12 | 15 | 20 |
| 0 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.955 | 0.956 |
| 1 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.955 | 0.956 |
| 2 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.956 |
| 3 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.956 |
| 4 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.956 |
| 5 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.954 | 0.955 | 0.955 |
| 6 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.955 | 0.955 |
| 8 | | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.953 | 0.954 | 0.954 | 0.954 | 0.955 |
| 10 | | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.966 | 0.967 | 0.967 | 0.967 | 0.968 | 0.968 |
| 15 | | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.976 | 0.976 | 0.976 |
| 20 | | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.984 | 0.984 | 0.984 |
| 25 | | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.989 |
| 30 | | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.992 | 0.992 |
| 40 | | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 |
| 50 | | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.998 |
| 60 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| 70 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 1.000 | 1.000 |
| 80 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 90 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 100 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 110 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 1.000 | 1.000 |
| 120 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| 130 | | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 | 0.998 |
| 140 | | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 | 0.995 |
| 150 | | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.991 | 0.992 | 0.992 |
| 155 | | | 0.987 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.988 | 0.989 |
| 160 | | | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.983 | 0.984 | 0.984 | 0.984 |
| 165 | | | - | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.975 | 0.976 | 0.976 | 0.976 |
| 170 | | | - | 0.958 | 0.958 | 0.958 | 0.958 | 0.958 | 0.959 | 0.959 | 0.959 | 0.959 | 0.959 | 0.960 | 0.960 | 0.961 |
| 172 | | - | - | 0.930 | 0.930 | 0.930 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.933 | 0.934 |
| 174 | | - | - | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.932 | 0.933 | 0.933 | 0.934 |
| 175 | | - | - | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.932 | 0.933 | 0.933 | 0.934 |
| 176 | | - | - | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.932 | 0.932 | 0.933 | 0.933 | 0.935 |
| 177 | | - | - | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.932 | | 0.933 | 0.934 | 0.935 |
| 178 | | - | - | 0.931 | 0.931 | 0.931 | 0.931 | 0.931 | 0.932 | 0.932 | 0.932 | 0.932 | 0.932 | 0.933 | 0.934 | 0.935 |
| 179 Missing entr | | - | - | 0.931 | 0.931 | 0.931 | | | | 0.932 | | 0.932 | 0.933 | 0.933 | 0.934 | 0.935 |

Missing entries correspond to the points lying within the source. The length of the stainless-steel cable is 1 mm

Results and Discussion

Table 2 compares the values of the dose-rate constants A of BEBIG sources to published values.^[2,3,8] In the present study, this is 1.088 cGy/h/U (for both new and old designs). The GEANT4-based published values of A are 1.084 cGy/h/U and 1.087 cGy/h/U for the old and new source designs, respectively.^[2,3] When $r_0 = 1$ cm, equation 9 represents the dose-rate constant for a point source, Λ_p . The calculated value of Λ_p for a ⁶⁰Co point source is 1.097 cGy/h/U, which is consistent with the value of 1.094 cGy/h/U reported by Papagiannis *et al.*^[1] and the EDKnrc-based value of 1.107 ± 0.01 cGy/h/U reported by Selvam and Bhola.^[8]

Table 3 compares the values of $g_L(r)$ for BEBIG ⁶⁰C sources calculated in the present study and the EGSnrc-

based published work.^[8] At r = 2.5 mm, the EGSnrc-based published value^[8] is higher by about 6% when compared with the value obtained in the present work. This is because the analytic calculation considers that there is charged particle equilibrium for all calculation points, including for regions close to the source. [Table 4] presents values of the anisotropy function for various radial distances from the source. The source cable length considered in this calculation was 1 mm for comparison with values published by Granero et al.^[3] The analytically calculated data compares with the published data within 3%. [Tables 5 and 6] present the 2-D dose-rate distribution in water (in cGy/h/U) for the new source model with 5-mm and 1-mm-length stainless-steel cable, respectively. For the 1-mm cable length, the analytical data agree with the data published by Granero et al.^[3] within 1%, and for the 5-mm cable length, the agreement is within Table 5: Dose rate distributions per unit air-kerma strength (cGy/h/U) around the new (model Co0.A86) BEBIG ⁶⁰Co HDR source.

| Along, z (cm) 0 0.1 0.25 0.5 0.75 1 z (cm) z (cm) 0.00372 0.00371 0.00377 0.00377 0.00373 0.00373 -14 0.00795 0.00793 0.00793 0.00377 0.00373 0.00373 -6 0.00795 0.00793 0.00793 0.00793 0.00374 0.00337 -6 0.00791 0.01288 0.0237 0.0237 0.02337 0.02336 0.0346 -7 0.0550 0.0553 0.0551 0.0597 0.0597 0.0338 -2.2 0.1416 0.1452 0.1525 0.1588 0.1333 0.1333 -15 0.1414 0.412 0.447 0.429 0.333 0.1451 -15 0.4144 0.412 0.447 0.429 0.333 0.1451 -15 0.4144 0.412 0.447 0.429 0.333 0.1251 -16 0.141 0.412 0.447 0.429 0.149 < | | | | | l | | (| 10 | 14 |
|---|---|------------|-----------------|------------|---------|---------|---------|---------|---------|
| 0.1 0.12 0.23 0.00372 0.00371 0.00781 0.00781 0.00781 0.00781 0.00371 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.00781 0.04114 < | - | | | ٢ | 4 | 7 | | | 14 |
| 0.00372 0.00371 0.00371 0.00371 0.00371 0.00371 0.00371 0.00371 0.00304 0.01291 0.01288 0.01283 0.00341 0.00341 0.00374 0.00374 0.01291 0.01281 0.01281 0.01341 0.0253 0.01341 0.0253 0.00378 0.03348 0.03348 0.03347 0.0374 0.0374 0.0378 0.0237 0.02348 0.0347 0.0374 0.0374 0.0378 0.03348 0.03347 0.0347 0.0374 0.0374 0.0378 0.03348 0.0347 0.0347 0.0374 0.0374 0.0378 0.0347 0.0254 0.0374 0.0374 0.0374 0.03128 0.1452 0.1452 0.1526 0.0374 0.0376 0.414 0.412 0.1429 0.1349 1.737 0.1414 0.412 0.1429 0.333 0.700 | | 2 | <i>2.5</i> | 4 | Ω | 0 | ò | 2 | ţ |
| 0.00795 0.00793 0.00793 0.00793 0.00781 0.00231 0.00233 0.01281 0.00341 0.00341 0.01231 0.02331 0.01231 0.02533 0.01341 0.02533 0.03741 0.02530 0.02341 0.0347 0.03657 0.03743 0.03741 0.03748 0.03441 0.03759 0.03741 0.02533 0.03741 0.03749 0.03471 0.03471 0.03765 0.03741 0.02531 0.03749 0.03471 0.03471 0.03741 0.07781 0.03749 0.03230 0.05531 0.05571 0.03741 0.07811 0.037410 0.1416 0.14152 0.1525 0.16381 0.17331 0.1416 0.1412 0.1417 0.1412 0.14291 0.13331 0.2330 0.22291 0.2447 0.23331 0.23331 0.2414 0.1412 0.1417 0.14291 0.134911 0.1116 0.1412 0.1412 0.17311 0.1116 0.14201 1.0271 0.187911 0.11261 0.16611 0.16111 0.170111 0.11261 0.16112 0.1429111 $0.023311349111331134911311311311311311311341911311311311311311311311311311311311311$ | | 1 0.00397 | 0.00406 0.00401 | 01 0.00389 | 0.00373 | 0.00353 | 0.0031 | 0.00265 | 0.00187 |
| 0.01291 0.01288 0.01288 0.0237 0.0234 0.0253 0.02533 0.02533 0.02533 0.02533 0.02533 0.03744 0.02553 0.02573 0.02573 0.02573 0.02573 0.02573 0.005673 0.05573 0.05573 0.05573 0.05573 0.05573 0.05573 0.05797 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.00779 0.011416 0.1452 0.1525 0.1525 0.1526 0.1078 0.1078 0.1414 0.1412 0.1417 0.417 0.429 0.2333 0.4141 0.412 0.1427 0.2143 0.1736 0.1736 0.1414 0.1412 0.1426 0.233 0.1349 0.700 0.14165 0.1429 0.2143 0.1429 0.233 0.1349 0.14166 0.1426 0.2426 0 | - | 0.00862 | 0.0085 0.00831 | 31 0.00781 | 0.00721 | 0.00658 | 0.00533 | 0.00425 | 0.00266 |
| 0.0238 0.0237 0.0244 0.0255 0.0348 0.0347 0.0355 0.0357 0.0348 0.0347 0.0355 0.0357 0.0550 0.0553 0.0551 0.0557 0.0557 0.0372 0.0553 0.0551 0.0559 0.0374 0.0372 0.0552 0.1525 0.1078 0.1078 0.1416 0.1452 0.1525 0.1628 0.1078 0.1416 0.1422 0.1245 0.1233 0.1738 0.230 0.229 0.247 0.1333 0.1333 0.414 0.412 0.447 0.2333 0.2333 0.9956 1.001 1.027 0.879 0.7303 0.9916 1.027 0.879 0.7337 0.9928 1.230 1.249 1.737 0.9913 1.201 1.241 1.92 0.9913 1.265 1.280 3.941 1.737 </td <td></td> <td>0.01383</td> <td>0.01345 0.01296</td> <td>96 0.0118</td> <td>0.01053</td> <td>0.00929</td> <td>0.00707</td> <td>0.00535</td> <td>0.00312</td> | | 0.01383 | 0.01345 0.01296 | 96 0.0118 | 0.01053 | 0.00929 | 0.00707 | 0.00535 | 0.00312 |
| 0.0348 0.0344 0.0344 0.0345 0.0355 0.0355 0.0357 0.0550 0.0553 0.0551 0.0590 0.0597 0.0979 0.0999 0.1028 0.1078 0.1078 0.1416 0.1452 0.1525 0.1588 0.1536 0.1414 0.1452 0.1245 0.1538 0.1533 0.1414 0.412 0.447 0.429 0.2333 0.230 0.229 0.245 0.1383 0.2333 0.956 1001 1.027 0.879 0.2333 0.956 1001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.1737 4.79 4.50 3.74 1.737 1.067 1.924 15.44 4.24 1.92 1.075 1.926 $1.2.80$ 3.94 1.849 1.075 1.924 15.44 4.24 1.92 1.967 1.924 1.727 0.879 0.700 1.967 1.924 1.737 4.79 1.737 1.075 1.924 1.737 1.949 1.075 0.264 0.1266 0.726 0.1062 0.2166 0.460 0.949 0.700 1.075 0.254 0.276 < | | 0.0246 | 0.0233 0.0219 | 19 0.0188 | 0.0159 | 0.0133 | 0.0093 | 0.0066 | 0.0036 |
| 0.0550 0.0553 0.0550 0.0553 0.0599 0.0079 0.0599 0.0078 0.0536 0.0597 0.0979 0.0999 0.1028 0.1080 0.1078 0.1078 0.1416 0.1452 0.1525 0.1588 0.1536 0.230 0.229 0.2245 0.1688 0.1333 0.414 0.412 0.447 0.429 0.333 0.9566 1.001 1.027 0.879 0.700 0.9566 1.001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.967 12.80 3.49 1.737 1.195 $1.2.80$ 3.94 1.849 1.197 $1.2.80$ 3.94 1.849 1.1967 $1.2.80$ 3.74 1.92 1.1967 1.926 3.74 | | 7 0.0346 | 0.0321 0.0295 | 0.0243 | 0.0197 | 0.0159 | 0.01060 | 0.00728 | 0.00379 |
| 0.0979 0.0979 0.1416 0.1452 0.1525 0.1536 0.1078 0.1416 0.1452 0.1525 0.1536 0.1536 0.230 0.229 0.245 0.233 0.1536 0.414 0.412 0.447 0.429 0.383 0.414 0.412 0.447 0.233 0.233 0.956 1001 1.027 0.879 0.333 0.956 1001 1.027 0.879 0.700 0.412 0.412 0.447 0.429 0.333 0.940 3.74 2.23 1.737 1.258 14.20 4.10 1.886 1.1737 58.83 14.20 4.194 1.925 1.280 3.74 1.92 1.1957 12.80 3.74 1.737 1.1967 1.924 1.737 1.737 1.0567 1.924 1.736 0.776 | | 0 0.0512 | 0.0460 0.0408 | 0.0316 | 0.0244 | 0.0189 | 0.01191 | 0.00792 | 0.00398 |
| 0.1416 0.1452 0.1525 0.1588 0.1536 0.230 0.229 0.245 0.248 0.233 0.414 0.412 0.447 0.429 0.233 0.714 0.412 0.447 0.429 0.333 0.700 0.720 0.879 0.700 0.956 1.001 1.027 0.879 0.700 0.766 1.001 1.027 0.879 0.700 0.756 1.001 1.027 0.879 0.700 \cdots 21.66 9.40 3.49 1.737 \cdots 58.83 14.20 4.10 1.886 \cdots 58.83 14.20 4.19 1.876 \cdots 58.83 14.20 4.19 1.737 \cdots 58.83 14.20 4.19 1.849 \cdots 28.84 15.44 4.24 1.92 \cdots 28.83 14.20 | | 8 0.0802 | 0.0682 0.0575 | 75 0.0409 | 0.0297 | 0.0221 | 0.01316 | 0.00849 | 0.00414 |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$ | | 0.1026 | 0.0838 0.0683 | 33 0.0462 | 0.0324 | 0.0236 | 0.01372 | 0.00873 | 0.00421 |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$ | | 0.132 | 0.1029 0.0806 | 0.0517 | 0.0351 | 0.0250 | 0.01422 | 0.00894 | 0.00426 |
| 0.956 1.001 1.027 0.879 0.700 4.59 3.74 2.23 1.349 21.66 9.40 3.49 1.737 21.66 9.40 3.49 1.737 21.66 9.40 3.49 1.737 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1.849 58.83 14.20 4.19 1.849 58.83 14.20 4.192 1.92 21.66 9.40 3.49 1.737 21.66 9.40 3.49 1.737 21.66 9.40 3.49 1.737 21.66 1.796 | | 0.171 | 0.1247 0.0935 | 35 0.0568 | 0.0375 | 0.0263 | 0.01462 | 0.00911 | 0.00431 |
| 4.59 3.74 2.23 1.349 21.66 9.40 3.49 1.737 47.65 12.80 3.94 1.349 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.349 1.967 1.924 1.736 0.700 0.700 1.075 1.924 1.737 2.23 0.700 0.459 0.459 3.744 2.23 0.700 0.1075 0.257 0.254 0.276 0.700 0.1637 0.1638 <td< td=""><td></td><td>0.214</td><td>0.1467 0.1056</td><td>0.0612</td><td>0.0394</td><td>0.0272</td><td>0.01493</td><td>0.00924</td><td>0.00434</td></td<> | | 0.214 | 0.1467 0.1056 | 0.0612 | 0.0394 | 0.0272 | 0.01493 | 0.00924 | 0.00434 |
| 5 21.66 9.40 3.49 1.737 47.65 12.80 3.94 1.849 58.83 14.20 4.10 1886 58.84 15.44 4.24 1.92 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 21.66 9.40 3.94 1.849 21.65 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.737 4.79 1.924 1.796 1.368 0.700 1.075 1.924 1.796 1.368 0.700 0.466 0.463 0.459 0.700 0.700 0.457 0.257 0.254 0.233 0.7038 0.1637 0.1 | | 0.253 | 0.1640 0.1144 | 4 0.0641 | 0.0406 | 0.0278 | 0.01512 | 0.00931 | 0.00436 |
| 47.65 12.80 3.94 1849 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.10 1886 58.83 14.20 4.19 1.92 58.83 14.20 4.19 1.849 21.66 9.40 3.94 1.849 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.737 4.79 4.59 3.74 2.23 1.737 4.79 4.59 3.74 2.23 1.737 4.79 1.924 1.796 1.368 0.700 1.967 1.927 0.459 0.7303 0.700 0.456 0.459 0.254 0.238 0.1538 0.1637 0.0619 0.0611 <td></td> <td>0.264</td> <td>0.1689 0.1168</td> <td>8 0.0649</td> <td>0.0409</td> <td>0.0279</td> <td>0.01516</td> <td>0.00933</td> <td>0.00436</td> | | 0.264 | 0.1689 0.1168 | 8 0.0649 | 0.0409 | 0.0279 | 0.01516 | 0.00933 | 0.00436 |
| 58.83 14.20 4.10 1.886 58.84 15.44 4.24 1.92 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.349 1.967 1.924 1.796 1.368 0.700 0.466 0.463 0.459 0.429 0.383 0.459 0.257 0.254 0.248 0.233 0.259 0.257 0.254 0.248 0.1536 0.1637 0.1632 0.1618 0.1588 0.1536 0.1126 0.1123 0.1116 0.1109 0.1078 0.0623 0.0621 0.0619 0.0611 0.0607 0.0392 0.0391 0.0380 0.0387 0.0388 0.0267 0.0267 0.0266 0.0265 0.0266 0.01449 0.01446 0.01445 0.01445 0.01433 | | 0.267 | 0.1700 0.1173 | 3 0.0650 | 0.0410 | 0.0280 | 0.01517 | 0.00934 | 0.00436 |
| 58.84 15.44 4.24 1.92 58.83 14.20 4.10 1.886 58.83 14.20 4.10 1.886 47.65 12.80 3.94 1.849 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.349 1.967 1.924 1.796 1.368 0.976 1.075 1.062 1.027 0.879 0.700 0.466 0.463 0.459 0.429 0.733 0.259 0.257 0.254 0.233 0.233 0.1637 0.1632 0.1618 0.1388 0.1536 0.1126 0.1116 0.1116 0.1009 0.0077 0.0523 0.0619 0.0387 0.0387 0.0388 0.0267 0.0267 0.0266 0.0266 0.0266 0.0266 0.01446 | | 0.268 | 0.1704 0.1175 | 5 0.0651 | 0.0410 | 0.0280 | 0.01518 | 0.00934 | 0.00436 |
| 58.83 14.20 4.10 1886 47.65 12.80 3.94 1.849 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.349 1.967 1.924 1.796 1.368 0.976 1.075 1.027 0.879 0.700 0.466 0.463 0.459 0.429 0.383 0.259 0.257 0.254 0.248 0.233 0.1637 0.1618 0.1588 0.1536 0.1126 0.1116 0.1109 0.1078 0.0623 0.0611 0.0611 0.0607 0.0322 0.0267 0.0266 0.0265 0.0262 0.01449 0.01446 0.01445 0.01433 | | 0.268 | 0.1706 0.1176 | 6 0.0651 | 0.0412 | 0.0280 | 0.01518 | 0.00934 | 0.00436 |
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| 21.66 9.40 3.49 1.737 4.79 4.59 3.74 2.23 1.349 1.967 1.924 1.796 1.368 0.976 1.075 1.062 1.027 0.879 0.700 0.4666 0.463 0.459 0.429 0.383 0.259 0.257 0.254 0.233 0.1637 0.1632 0.1618 0.1538 0.1536 0.1126 0.1116 0.1116 0.1109 0.1078 0.0623 0.0611 0.0611 0.0607 0.0392 0.0267 0.0266 0.0266 0.0266 0.01449 0.01446 0.01445 0.01433 | | 0.267 | 0.1700 0.1173 | 3 0.0650 | 0.0410 | 0.0280 | 0.01517 | 0.00934 | 0.00436 |
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| 0.0392 0.0391 0.0390 0.0387 0.0388 0.0267 0.0267 0.0266 0.0265 0.0262 0.01449 0.01446 0.01445 0.01433 | | 0.0512 | 0.0460 0.0408 | 0.0316 | 0.0244 | 0.0189 | 0.01191 | 0.00792 | 0.00398 |
| 0.0267 0.0267 0.0266 0.0265 0.0262 0.01449 0.01446 0.01445 0.01433 | | 7 0.0346 | 0.0321 0.0295 | 0.0243 | 0.0197 | 0.0159 | 0.01060 | 0.00728 | 0.00379 |
| 0.01449 0.01446 0.01445 0.0144 0.01433 | | 5 0.0246 | 0.0233 0.0219 | 19 0.0188 | 0.0159 | 0.0133 | 0.00932 | 0.00662 | 0.00358 |
| | _ | 1 0.01383 | 0.01345 0.01296 | 96 0.0118 | 0.01053 | 0.00929 | 0.00707 | 0.00535 | 0.00312 |
| 10 0.00892 0.0089 0.0089 0.00888 0.00885 0.0088 | 5 | 33 0.00862 | 0.0085 0.00831 | 31 0.00781 | 0.00721 | 0.00658 | 0.00533 | 0.00425 | 0.00266 |
| 14 0.00417 0.00416 0.00416 0.00415 0.00415 0.00414 | | 0.00413 | 0.00398 0.00401 | 01 0.00389 | 0.00373 | 0.00353 | 0.0031 | 0.00265 | 0.00187 |

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| Table 6: | |

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| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | Distance | | | | | | | Dis | Distance away, y (cm) | y (cm) | | | | | | |
|---|------------------|---------|---------|---------|---------|---------|---------|---------|-----------------------|---------|---------|---------|---------|---------|---------|---------|
| 0.00411 0.00407 0.00460 0.00460 0.00460 0.00460 0.00460 0.00751 <t< th=""><th>along, z (cm)</th><th>0</th><th>0.25</th><th>0.5</th><th>0.75</th><th>1</th><th>1.5</th><th>2</th><th>2.5</th><th>ς</th><th>4</th><th>2</th><th>6</th><th>8</th><th>10</th><th>14</th></t<> | along, z (cm) | 0 | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 | 2.5 | ς | 4 | 2 | 6 | 8 | 10 | 14 |
| 0.00877 0.00877 0.00867 0.00864 0.00864 0.00864 0.00864 0.00864 0.00864 0.00864 0.00781 0.00781 0.00781 0.00781 0.00781 0.00751 0.00754 0.00547 0.01547 <t< td=""><td>- 14</td><td>0.00411</td><td>0.00407</td><td>0.00407</td><td>0.00406</td><td>0.00405</td><td>0.00402</td><td>0.00405</td><td>0.00404</td><td>0.00401</td><td>0.00389</td><td>0.00373</td><td>0.00353</td><td>0.00310</td><td>0.00265</td><td>0.00187</td></t<> | - 14 | 0.00411 | 0.00407 | 0.00407 | 0.00406 | 0.00405 | 0.00402 | 0.00405 | 0.00404 | 0.00401 | 0.00389 | 0.00373 | 0.00353 | 0.00310 | 0.00265 | 0.00187 |
| 0.01424 0.01414 0.01402 0.01391 0.01345 0.01345 0.01345 0.01054 0.01054 0.01054 0.00133 0.0283 0.0325 0.0325 0.0326 0.0356 0.0356 0.0354 0.0153 0.01594 0.01534 0.01593 0.01594 0.01534 0.01594 0.01534 0.01594 0.01534 0.01594 0.01534 0.01594 0.01534 0.01594 0.01534 0.01234 0.02534 | - 10 | 0.00877 | 0.00871 | 0.00869 | 0.00866 | 0.00861 | 0.00867 | 0.00863 | 0.00850 | 0.00831 | 0.00781 | 0.00721 | 0.00658 | 0.00533 | 0.00425 | 0.00266 |
| 0.0223 0.0261 0.0259 0.0254 0.0254 0.0381 <th0.0281< th=""> <th0.0281< th=""> <th0.0281< td="" th<=""><td>8-</td><td>0.01424</td><td>0.01414</td><td>0.01410</td><td>0.01402</td><td>0.01391</td><td>0.01407</td><td>0.01384</td><td>0.01345</td><td>0.01296</td><td>0.01180</td><td>0.01054</td><td>0.00929</td><td>0.00707</td><td>0.00535</td><td>0.00312</td></th0.0281<></th0.0281<></th0.0281<> | 8- | 0.01424 | 0.01414 | 0.01410 | 0.01402 | 0.01391 | 0.01407 | 0.01384 | 0.01345 | 0.01296 | 0.01180 | 0.01054 | 0.00929 | 0.00707 | 0.00535 | 0.00312 |
| 0.0385 0.0387 0.0384 0.0384 0.0384 0.0384 0.0394 0.0197 0.01984 0.0611 0.0606 0.0598 0.0666 0.0566 0.0566 0.0554 0.0334 0.0334 0.0334 0.0334 0.0110 0.1092 0.1097 0.1047 0.1047 0.1048 0.0334 0.0236 0.0236 0.0236 0.0234 0.0236 0.454 0.459 0.333 0.3322 0.2344 0.333 0.1447 0.1457 0.1447 0.1467 0.0468 0.0449 0.0449 0.0449 0.0449 0.0246 0.0236 1.055 1.024 0.349 0.331 0.447 0.244 0.1467 0.1467 0.1467 | -6 | 0.0263 | 0.0261 | 0.0259 | 0.0257 | 0.0260 | 0.0256 | 0.0246 | 0.0233 | 0.0219 | 0.01883 | 0.01591 | 0.01332 | 0.00932 | 0.00662 | 0.00358 |
| 0.0011 0.0060 0.0598 0.0506 0.0596 0.0506 0.0597 0.0440 0.0277 0.0214 0.1106 0.1022 0.1098 0.1079 0.1040 0.1397 0.0440 0.0277 0.0231 0.1007 0.1590 0.1590 0.1637 0.1432 0.1440 0.0375 0.0231 0.0234 0.1567 0.248 0.248 0.2333 0.2132 0.1697 0.0351 0.0375 0.0375 0.0231 0.457 0.454 0.430 0.543 0.703 0.1325 0.1747 0.0561 0.0375 0.0231 0.0235 0.457 0.458 0.707 0.747 0.1325 0.1747 0.1666 0.0375 0.0231 0.457 0.349 0.349 0.331 0.342 0.332 0.1447 0.1666 0.0375 0.0231 0.458 0.440 0.343 0.342 0.332 0.1447 0.166 0.0469 0.0409 0.0246 0.0249 0.0249 | <u> </u> | 0.0385 | 0.0382 | 0.0378 | 0.0381 | 0.0380 | 0.0367 | 0.0346 | 0.0322 | 0.0295 | 0.0243 | 0.0197 | 0.01594 | 0.01060 | 0.00728 | 0.00379 |
| 0.1106 0.1092 0.1093 0.1092 0.1093 0.1093 0.1094 0.1094 0.1094 0.1094 0.1094 0.1094 0.0297 0.0297 0.0231 0.1607 0.1583 0.1590 0.1537 0.1452 0.1241 0.1096 0.0683 0.0462 0.0375 0.0263 0.254 0.248 0.238 0.3384 0.3385 0.1703 0.1325 0.1096 0.0617 0.0375 0.0253 1055 10247 0.430 0.534 0.332 0.2345 0.3355 0.0256 0.0375 0.0256 1055 10247 0.430 0.544 0.332 0.2457 0.2467 0.0479 0.0499 0.0470 0.0275 9.40 3.49 1.737 1.021 0.447 0.1469 0.1469 0.0461 0.0409 0.0234 0.0237 9.40 3.49 1.737 1.021 0.447 0.268 0.1469 0.0461 0.0409 0.0234 <td< td=""><td>-4</td><td>0.0611</td><td>0.0606</td><td>0.0598</td><td>0.0606</td><td>0.0596</td><td>0.0560</td><td>0.0512</td><td>0.0460</td><td>0.0408</td><td>0.0316</td><td>0.0244</td><td>0.01893</td><td>0.01191</td><td>0.00792</td><td>0.00398</td></td<> | -4 | 0.0611 | 0.0606 | 0.0598 | 0.0606 | 0.0596 | 0.0560 | 0.0512 | 0.0460 | 0.0408 | 0.0316 | 0.0244 | 0.01893 | 0.01191 | 0.00792 | 0.00398 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | က | 0.1106 | 0.1092 | 0.1098 | 0.1079 | 0.1040 | 0.0928 | 0.0803 | 0.0682 | 0.0575 | 0.0409 | 0.0297 | 0.0221 | 0.01316 | 0.00849 | 0.00414 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | -2.5 | 0.1607 | 0.1583 | 0.1590 | 0.1537 | 0.1452 | 0.1241 | 0.1027 | 0.0838 | 0.0683 | 0.0462 | 0.0324 | 0.0236 | 0.01372 | 0.00873 | 0.00421 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | -2 | 0.254 | 0.248 | 0.248 | 0.233 | 0.213 | 0.1703 | 0.1325 | 0.1029 | 0.0806 | 0.0517 | 0.0351 | 0.0250 | 0.01422 | 0.00894 | 0.00426 |
| 1.055 1.028 0.879 0.700 0.544 0.332 0.214 0.1467 0.1056 0.0612 0.0394 0.0275 1.797 1.368 0.976 0.6976 0.698 0.384 0.235 0.1640 0.1144 0.0641 0.0400 0.0278 1.797 1.368 0.976 0.698 0.384 0.255 0.1640 0.1144 0.0409 0.0279 1.77 1.247 1.021 0.467 0.264 0.1689 0.1168 0.0409 0.0279 1.797 1.349 1.737 1.021 0.467 0.2649 0.0409 0.0279 1.797 1.349 1.737 1.021 0.467 0.2649 0.0409 0.0279 1.797 1.368 0.976 0.871 0.487 0.258 0.1649 0.0449 0.0279 1.797 1.368 0.976 0.698 0.384 0.2253 0.1649 0.1144 0.0409 0.0279 1.074 1.028 0.976 0.6798 0.871 0.487 0.2389 0.7162 0.0279 1.074 1.028 0.7162 0.7163 0.1168 0.0649 0.0409 0.0279 0.450 0.976 0.6798 0.871 0.7166 0.7649 0.0409 0.0279 1.074 1.028 0.7169 0.7168 0.7168 0.7168 0.0409 0.0279 0.1052 0.729 0.7169 0.7169 0.7169 0.7169 | -1.5 | 0.457 | 0.454 | 0.430 | 0.384 | 0.332 | 0.2385 | 0.1707 | 0.1247 | 0.0936 | 0.0568 | 0.0375 | 0.0263 | 0.01462 | 0.00911 | 0.00431 |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | ÷. | 1.055 | 1.028 | 0.879 | 0.700 | 0.544 | 0.332 | 0.214 | 0.1467 | 0.1056 | 0.0612 | 0.0394 | 0.0272 | 0.01493 | 0.00924 | 0.00434 |
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| 9.40 3.49 1.737 1.021 0.467 0.264 0.1689 0.1168 0.0449 0.0409 0.0279 15.44 4.24 1.917 1.083 0.480 0.268 0.1706 0.1176 0.0499 0.0280 9.40 3.49 1.737 1.021 0.467 0.2644 0.1649 0.0409 0.0279 9.40 3.49 1.737 1.021 0.457 0.2644 0.1649 0.0401 0.0239 4.78 3.77 2.23 1.349 0.871 0.432 0.235 0.1647 0.0611 0.0401 0.0239 1.074 1.028 0.879 0.7384 0.3322 0.7147 0.1963 0.0467 0.0261 0.0213 0.1652 0.480 0.384 0.3322 0.7147 0.1953 0.0257 0.0236 0.1655 0.1620 0.7610 0.7682 | -0.5 | : | 3.75 | 2.23 | 1.349 | 0.871 | 0.432 | 0.253 | 0.1640 | 0.1144 | 0.0641 | 0.0406 | 0.0278 | 0.01512 | 0.00931 | 0.00436 |
| 15.44 4.24 1.917 1.083 0.480 0.268 0.1706 0.1176 0.0651 0.0410 0.0230 9.40 3.49 1.737 1.021 0.467 0.264 0.1689 0.1168 0.0649 0.0409 0.0279 4.78 3.77 2.23 1.349 0.871 0.432 0.253 0.1640 0.1144 0.0641 0.0406 0.0276 1.96 1.797 1.368 0.976 0.698 0.384 0.235 0.1563 0.1162 0.0612 0.0374 0.0275 1.074 1.028 0.879 0.700 0.544 0.332 0.214 0.1467 0.0612 0.0376 0.0275 0.465 0.4197 0.332 0.2385 0.1707 0.1467 0.1467 0.0612 0.0374 0.0275 0.465 0.4199 0.732 0.2384 0.2332 0.2144 0.1467 0.0612 0.0376 0.0275 0.465 0.4590 0.732 0.2243 0.1247 0.0928 0.0275 0.0275 0.0224 0.0224 0.1112 0.1111 0.1079 0.1232 0.1247 0.1246 0.0256 0.0224 0.0224 0.0224 0.1620 0.0612 0.0612 0.0602 0.0233 0.0246 0.0234 0.0234 0.0234 0.0234 0.1625 0.1118 0.1111 0.1072 0.0246 0.0246 0.0243 0.0124 0.0 | -0.25 | : | 9.40 | 3.49 | 1.737 | 1.021 | 0.467 | 0.264 | 0.1689 | 0.1168 | 0.0649 | 0.0409 | 0.0279 | 0.01516 | 0.00933 | 0.00436 |
| $ \begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$ | 0 | : | 15.44 | 4.24 | 1.917 | 1.083 | 0.480 | 0.268 | 0.1706 | 0.1176 | 0.0651 | 0.0410 | 0.0280 | 0.01518 | 0.00934 | 0.00436 |
| 4.78 3.77 2.23 $1:349$ 0.871 0.432 0.253 0.1640 0.1144 0.0641 0.0406 0.0278 1.96 1.797 $1:368$ 0.976 0.698 0.384 0.235 0.1563 0.1105 0.0628 0.0401 0.0275 1.074 1.028 0.879 0.700 0.544 0.332 0.2385 0.1467 0.1056 0.0612 0.0394 0.0273 0.465 0.430 0.700 0.544 0.332 0.2385 0.1707 0.1447 0.0936 0.0517 0.0375 0.0263 0.465 0.2430 0.384 0.332 0.2385 0.1703 0.1247 0.0936 0.0375 0.0276 0.635 0.1620 0.1590 0.1452 0.1452 0.1427 0.1247 0.0936 0.0517 0.0256 0.1635 0.1620 0.1620 0.1452 0.1452 0.1421 0.1027 0.0838 0.0683 0.0244 0.0271 0.1125 0.1118 0.1111 0.1079 0.1452 0.1421 0.1027 0.0232 0.0256 0.0275 0.0622 0.0620 0.0512 0.0612 0.0612 0.0612 0.0740 0.0274 0.0274 0.1125 0.1118 0.1111 0.1079 0.1027 0.0292 0.0293 0.0294 0.0274 0.00522 0.0620 0.0612 0.0612 0.0612 0.0246 0.0274 0.01974 0.027 | 0.25 | : | 9.40 | 3.49 | 1.737 | 1.021 | 0.467 | 0.264 | 0.1689 | 0.1168 | 0.0649 | 0.0409 | 0.0279 | 0.01516 | 0.00933 | 0.00436 |
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| | 14 | 0.00416 | 0.00417 | 0.00416 | 0.00415 | 0.00414 | 0.00411 | 0.00414 | 0.00407 | 0.00401 | 0.00389 | 0.00373 | 0.00353 | 0.00310 | 0.00265 | 0.00187 |

3%. For regions where charged-particle equilibrium exists, a comparison of these data with the corresponding EGSnrcbased published data^[8] suggests that the analytically calculated values are comparable to within 0.5% for most points, and the maximum deviation is about 3%.

Conclusions

We have proposed a point-source-based simple analytic method for calculating the dose-rate distribution in water in units of cGy/h/U for a BEBIG 60Co HDR source. Using this method, we calculated TG-43 parameters such as the dose-rate constant, radial dose function and anisotropy function. We also calculated a 2-D dose-rate table in Cartesian format. The proposed analytic method needed best-fit parameters for linear attenuation coefficients of source and filtration materials for regions close to the source axis. The analytic model proposed is easy to implement in radiotherapy treatment-planning dose calculations. For regions where electronic equilibrium exists, a comparison between the analytically calculated and published Monte Carlo-based data shows good agreement (for most calculation points, agreement was within 0.5%, and the maximum deviation was about 3%). The dose-rate data calculated with this method could be used for verifying the results of RTPS or directly as input data for radiotherapy treatment-planning dose calculations.

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