Dosimetric investigation for the new BEBIG cobalt 60 source used in brachytherapy using Monte Carlo N-Particles eXtended code (MCNPX)

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Abstract: The purpose of this work is to calculate the parameters of the 60Co-source model: Co0.A86 newly introduced to the HDR brachytherapy, and to validate the MCNPX code in Monte Carlo investigation, the radial dose function, and function of anisotropy are calculated in water as recommended in the report of HEBD working group (AAPM&ESTRO). The results obtained in this study agree will with the data published in previous studies.

1. Introduction
Brachytherapy is a local irradiation. The dose is delivered by one or several sealed sources. Different kinds of brachytherapy have been defined. Nowadays, Ir-192 and Co-60 are available in devices used in high dose rate HDR brachytherapy, generally for the treatment of gynecological tumors. The dose rate distribution in the formalism of HEBD working group (AAPM&ESTRO) requires calculating different dosimetric parameters of the new BEBIG Eckert & Ziegler 60Co HDR source, using a Monte Carlo code. The dosimetric data given in this study can be useful for the control of TPS calculations.

2. Materials and methods

2.1. Source description and geometry
The HDR brachytherapy source of 60 Co, model Co0.A86, manufactured by BEBIG used in this work was composed of pure cobalt 60 cylindrical active core with a 3.5mm length and 0.5mm in diameter (density:8.09 g/cm³). The active part is covered by an air shell of 0.1 mm of thickness then encapsulated in a cylindrical stainless steel capsule of 0.2mm for thickness and 1mm for the external diameter. For this study, we considered 4mm and 0.9mm for the source cable length and diameter, respectively, figure 1. The density used for the stainless steel, 8.03 g/cm³ for the capsule and the source cable.
Table 1. Elemental composition used in this study (source and phantom) [1].

| Element | Medium | Water (%) | Air (%) | Stainless steel (%) |
|---------|--------|-----------|---------|---------------------|
| H       |        | 11.010    | 0.073   | -                   |
| C       |        | -         | 0.012   | 0.03                |
| N       |        | -         | 75.032  | 0.01                |
| O       |        | 88.900    | -       | -                   |
| Si      |        | -         | -       | 0.75                |
| Na      |        | -         | -       | -                   |
| Mg      |        | -         | -       | -                   |
| Cl      |        | -         | -       | -                   |
| K       |        | -         | -       | -                   |
| Ca      |        | -         | -       | -                   |
| P       |        | -         | -       | 0.045               |
| S       |        | -         | -       | 0.03                |
| Ar      |        | -         | 1.274   | -                   |
| Cr      |        | -         | -       | 17.0                |
| Mn      |        | -         | -       | 2.0                 |
| Fe      |        | -         | -       | 65.543              |
| Ni      |        | -         | -       | 12.0                |
| Mo      |        | -         | -       | 2.5                 |
| Co      |        | -         | -       | -                   |
| Density (g/cm³) | | 0.998    | 0.012   | 8.03                |

Figure 1. Source description (dimensions in mm)
Figure 2. The source and the detectors geometry used to calculate \( g_r(r) \) with MCNPX

2.2. Dose calculation formalism

According to the recommendations of the HEBD, the dose formalism for the measure of dose rate can be defined in a polar coordinate system by the equation (1)[2]:

\[
\hat{D}(r, \theta) = S_{\chi} \frac{C(r, \theta)}{C(r, 0, 0)} g_r(r) F(r, \theta)
\]  

(1)

This formalism required the calculations of dosimetric parameters of the source using Monte Carlo code, such as the air-kerma strength \( S_{\chi} \), the radial dose function \( g_r(r) \), the anisotropy function \( F(r, \theta) \), and the dose rate constant \( \lambda \). The radial dose function and the anisotropy function are calculated using the two following equations:

\[
g_r(r) = \frac{D(r, \theta) C(r, 0, 0)}{D(r, 0, 0) C(r, 0, 0)}
\]  

(2)

\[
F(r, \theta) = \frac{D(r, \theta) C(r, 0, 0)}{D(r, 0, 0) C(r, 0, 0)}
\]  

(3)

The geometry function \( G(r, \theta) \) is calculated using the following expression:

\[
G(r, \theta) = \frac{\tan^{-1} \left( \frac{\cos \theta - \frac{1}{2}}{\sin \theta} \right) - \tan^{-1} \left( \frac{\cos \theta - \frac{1}{2}}{\sin \theta} \right)}{\tan \theta} \quad \text{for } \theta \neq 0
\]  

(4)

\[
G(r, \theta) = \left( r^2 \frac{\pi}{4} \right)^{-1} \quad \text{for } \theta = 0
\]  

(5)

Where \( r \) is the distance to the point of interest and \( \theta \) is the polar angle with the longitudinal axis of the source (Z axis). The point \((r, \theta) = (1\text{cm}, 90^\circ)\) is chosen as a reference located in the transverse axis of the source.

2.3. Monte Carlo calculation

For this study, we use the MCNPX version: 2.70 (license: C00810MNYP), with the visual Editor VisedX_24E, this edition includes several tools for geometry modeling, particles transport, and a 3D viewing of the defined geometry of the source. To define the dosimetric parameters, MCNPX has different tallies for each chosen calculation. For the simulation, we consider the source composed of two gamma-rays with energies: 1.17 MeV and 1.332 MeV [3].
Monte Carlo code fulfills all the recommendations of the report, “Dosimetric prerequisites for routine clinical use of photon emitting Brachytherapy sources” of the AAPM.

The physics “low energy” models of MCNPX have been used. These physics models use the xdata/mcplib84 cross-sections library for photons and the xdata/el03 for electrons.

The gamma spectrum used in this work was obtained from the database NuDat. A cutoff energy of 10 keV was used. 2×10⁸ photon history was simulated to calculate the dose with an Intel® Xeon (R) CPU E5620@2.40GH×16, HP-Z600. The methodology used for the Monte Carlo simulation follows the HEBD report. In order to obtain the radial dose and anisotropy function in water, the source has been located in the center of a spherical water phantom of 40 cm in radius it acts as an unbounded phantom up to a distance of 20 cm from the source center. HEBD recommended liquid water with a density of 0.998 g cm⁻³ at 22 °C. A grid system of cylindrical rings 0.05 cm thick and 0.05 cm high concentric to the longitudinal source axis, was used to obtain the radial dose function and, to obtain the anisotropy function in the form given by the HEBD report a system of 400×180 concentric spherical sections with a variable thick: (0.1mm)³ for r≤1cm, (0.5mm)³ for 1cm< r ≤ 5cm, (1mm)³ for 5cm< r ≤ 10cm, and (2mm)³ for 10cm< r ≤ 20cm, with an angular width of 1° in the polar angle was used[4]. The coordinate axes used are shown in Figure1.

Table 2. Radial dose function values calculated by MCNPX.

| r (cm) | This work | H. Badry et al. | Guerrero et al. | Granero et al. |
|-------|-----------|----------------|----------------|--------------|
| 0.25  | 1.0143    | 1.06898        | 1.0707         | 1.007        |
| 0.5   | 0.9977    | 1.02743        | 1.0291         | 1.036        |
| 0.75  | 1.0046    | 1.0151         | 1.0102         | 1.015        |
| 1     | 1         | 1              | 1              | 1            |
| 1.5   | 0.9926    | 0.99312        | 0.9894         | 0.992        |
| 2     | 0.9874    | 0.97814        | 0.9794         | 0.984        |
| 3     | 0.9689    | 0.96728        | 0.9638         | 0.968        |
| 4     | 0.9539    | 0.95048        | 0.9471         | 0.952        |
| 5     | 0.9378    | 0.93074        | 0.9335         | 0.939        |
| 6     | 0.9205    | 0.91969        | 0.915          | 0.919        |
| 7     | 0.9035    | 0.90192        | 0.898          | 0.902        |
| 8     | 0.8867    | 0.88179        | 0.883          | 0.884        |
| 9     | 0.8683    | 0.86489        | -----          | -----        |
| 10    | 0.8513    | 0.84412        | 0.847          | 0.849        |
| 12    | 0.8156    | 0.81113        | 0.813          | 0.813        |
| 15    | 0.7593    | 0.75372        | 0.756          | 0.756        |
| 20    | 0.6628    | 0.66381        | 0.661          | 0.665        |
Table 3. Elemental composition of media used to compare $g_0(r)$ [5].

| Elemental Composition (% by mass) | Medium          |
|----------------------------------|-----------------|
|                                  | Adipose tissue  | Breast | Muscle | Bone |
| H                                | 11.4            | 10.6   | 10.2   | 3.4  |
| C                                | 59.8            | 33.2   | 14.3   | 15.5 |
| N                                | 0.7             | 3.0    | 3.4    | 4.2  |
| O                                | 27.8            | 52.7   | 71     | 43.5 |
| Na                               | 0.1             | 0.1    | 0.1    | 0.1  |
| Mg                               |                 |        |        | 0.2  |
| P                                | 0.1             | 0.2    |        | 10.3 |
| S                                | 0.1             | 0.2    | 0.3    | 0.3  |
| Cl                               | 0.1             | 0.1    | 0.1    |      |
| K                                |                 |        | 0.4    |      |
| Ca                               |                 |        |        | 22.5 |
| Density (g cm$^{-3}$)            | 0.95            | 1.02   | 1.05   | 1.92 |
Figure 4. Comparison between $g_y(r)$ obtained in water with MCNPX and $g_y(r)$ obtained in different media with EGS5 [7].

3. Results and discussion

The results presented in the table 2 refer to the calculated radial dose function $g_y(r)$ equation (2), calculated with MCNPX, which present a good consistency with the results given in other published data calculated with GEANT4, PENELOP, and EGS5 Monte Carlo codes, the little difference appears in the value of $g_y(r)$ in the radial distance near to the source, and this may depend to the difference in the geometry simulated of the source, the calculated $g_y(r)$ in water was compared to the radial dose function calculated in different medium with EGS5[6] (table 2), the results (figure 4) appears logical, and presents the effect of medium density for the dose deposed, $g_y(r)$ in bones decrease fast compared to the other tissues because the density of bone is the higher (1.92 g cm$^{-3}$) and it has a high attenuation coefficient, for the adipose tissue the density is the lowest (0.95 g cm$^{-3}$) that is why its $g_y(r)$ has a lower decreases. For the other media, the densities are near to the density of water (breast and Muscle) that is why their curves are superposed.

The table 4 summarizes the results of the Anisotropy Function calculated with MCNPX used for this work, with the same coordinates system in figure 1.
| Radial distance (cm) | 0.25 | 0.5 | 0.75 | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 10  | 12  | 15  | 20  | 25  | 30  |
|---------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( \Theta \) (°)  |      |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 0                   | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 8                   | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 10                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 15                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 20                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 25                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 30                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 40                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 50                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 60                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 70                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 80                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 90                  | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 100                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 110                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 120                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 130                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 140                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 150                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 160                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 170                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 180                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 190                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 200                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 210                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 220                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 230                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 240                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 250                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 260                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 270                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 280                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 290                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |
| 300                 | _    | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   | _   |

Table 4. Anisotropy function obtained with MCNPX.

The results of the anisotropy function (equation 3) are compared with other published data, figure 5, the function has a little difference in some values and this is because of the lower number of photon histories simulated with our workstation that limits the number in \( 2 \times 10^5 \) photons histories. Moreover, the curve of the anisotropy function has the same form especially for the polar angle between 10 and 160 degrees, a little different for \( \theta < 10^\circ \) and \( \theta > 160^\circ \) can be attributed to the difference of the geometry simulated, the physic models, and also the code used in the calculations.
Figure 5. Values of the Anisotropy Function for different radial distances: A (r=0.75cm), B (r=2cm), C (r=7cm), D (r=15cm)
Conclusions
The curves of the radial dose function and anisotropic function obtained by MCNPX show good agreement with the published data, calculated with other Monte Carlo codes, such as Geant4, EGS5, Fluka and PENELOPE. To validate the pattern, a comparison of radial dose function was made in different medium, the results obtained are satisfying. Finally the MCNPX code can be used to investigate the dosimetric parameters for different types of sources used in brachytherapy.

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