Dosimetric comparison between the microSelectron HDR 192Ir v2 source and the BEBIG 60Co source for HDR brachytherapy using the EGSnrc Monte Carlo transport code

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ABSTRACT
Manufacturing of miniaturized high activity 192Ir sources have been made a market preference in modern brachytherapy. The smaller dimensions of the sources are flexible for smaller diameter of the applicators and it is also suitable for interstitial implants. Presently, miniaturized 60Co HDR sources have been made available with identical dimensions to those of 192Ir sources. 60Co sources have an advantage of longer half life while comparing with 192Ir source. High dose rate brachytherapy sources with longer half life are logically pragmatic solution for developing country in economic point of view. This study is aimed to compare the TG-43U1 dosimetric parameters for new BEBIG 60Co HDR and new microSelectron 192Ir HDR sources. Dosimetric parameters are calculated using EGSnrc-based Monte Carlo simulation code accordance with the AAPM TG-43 formalism for microSelectron HDR 192Ir v2 and new BEBIG 60Co HDR sources. Air-kerma strength per unit source activity, calculated in dry air are 9.698×10^{-8} ± 0.55% U Bq^{-1} and 3.039×10^{-7} ± 0.41% U Bq^{-1} for the above mentioned two sources, respectively. The calculated dose rate constants per unit air-kerma strength in water medium are 1.116±0.12% cGy h^{-1} U^{-1} and 1.097±0.12% cGy h^{-1} U^{-1}, respectively, for the two sources. The values of radial dose function for distances up to 1 cm and more than 22 cm for BEBIG 60Co HDR source are higher than that of other source. The anisotropic values are sharply increased to the longitudinal sides of the BEBIG 60Co source and the rise is comparatively sharper than that of the other source. Tissue dependence of the absorbed dose has been investigated with vacuum phantom for breast, compact bone, blood, lung, thyroid, soft tissue, testis, and muscle. No significant variation is noted at 5 cm of radial distance in this regard while comparing the two sources except for lung tissues. The true dose rates are calculated with considering photon as well as electron transport using appropriate cut-off energy. No significant advantages or disadvantages are found in dosimetric aspect comparing with two sources.

Key words: BEBIG Co-60 HDR source, comparison of Ir-192 and Co-60, EGSnrc, HDR brachytherapy, microslectron Ir-192, Monte Carlo code

Introduction
This study comprises EGSnrc[1] Monte Carlo based dosimetry in accordance with AAPMTG-43U1[2] protocol for new BEBIG 60Co HDR source model Co0. A86 (Eckert and Ziegler BEBIG GmbH, Germany) and microSelectron HDR 192Ir source model 105.002 “v2” (Nucletron, Netherlands). The aim of this study was to compare the various dosimetry parameters as well as TG-43U1[2] parameters for two sources. Meanwhile, some authors have published the relevant dosimetry data with different methodology for both sources. Richter et al.[3] have reported a comparison of 60Co and 192Ir sources using EGS-Ray[4] Monte Carlo based calculations and only photon emission has been considered for the simulations. Recently Selvam et al.[5] have published EGSnrc[1] Monte Carlo based dosimetry data except anisotropy function for BEBIG 60Co HDR source. Moreover,
Ballester et al. [6] and Granero et al. [7] have reported GEANT4 based Monte Carlo dosimetry data in accordance with TG-43 [2] formalism for the same source. On the other hand, Daskalov et al. [8] have published dosimetry data for microSelectron HDR 192Ir sources using MCPT Monte Carlo transport code. Collision kerma is used to approximate the absorbed dose calculation. Furthermore, Borg et al. [9] and Taylor et al. [10,11] have reported TG-43 dosimetry parameters for same source using BrachyDose [12]. EGSnrc based Monte Carlo transport code.

In this work, the EGSnrc [1] Monte Carlo code system is used to calculate the TG-43 [2] parameters with similar methodology for two sources. The true dose rates are calculated with considering photon as well as electron transport. The calculated radial dose function and anisotropy function values for both sources are compared. The calculated air-kerma strength and dose rate constant are compared with other published data for the sources. The absorbed dose is calculated in different tissues related to the same dose in water for both sources and the results are compared to estimate the relative heterogeneity effect.

Materials and Methods

Monte Carlo models of microSelectron-HDR 192Ir v2 source and BEBIG 60Co HDR source

The microSelectron HDR 192Ir source consists of pure iridium metal having density 22.39 g cm⁻³. A source cylinder having diameter 0.065 cm and length 0.36 cm contains the radioactive 192Ir material distributed uniformly inside it. The source core is encapsulated with an AISI 304 steel capsule which has outer diameter 0.09 cm, inner diameter 0.065 cm, and length 0.45 cm and is connected to a 0.2 cm long steel cable having diameter of 0.07 cm. The thickness of the capsule on the opposite end of the steel cable is 0.02 cm, and side of the indium core toward the cable is 0.07 cm. Figure 1a shows the geometry of the real microSelectron-HDR 192Ir v2 source whose model used in the Monte Carlo calculations is shown in Figure 1b. The cylindrical geometric model is an approximation of the real geometry of the sources.

The BEBIG 60Co HDR source consists of pure cobalt metal (density of 8.9 g cm⁻³) and is kept inside the source cylinder having diameter 0.05 cm and length 0.35 cm. Radioactive 60Co material is uniformly distributed inside it. As of the previous case the source core is encapsulated, but now with an AISI 316L steel capsule (outer diameter = 0.1 cm, inner diameter = 0.07 cm). The capsule is 0.5 cm long and connected to a 0.2 cm long steel cable. The capsule thickness is 0.075 cm on the longitudinal sides of the 60Co source core and the thickness of axial side is 0.015 cm. There is an air gap of 0.01 cm around the axial side of the active source core. Figure 2(a) shows the geometry of the real BEBIG 60Co HDR source and Figure 2(b) shows the model of it used in the Monte Carlo simulations.

Medium

For the calculation of air-kerma strengths the sources are positioned at the center of a cylindrical container having 200 cm diameter and in dry air of mass density 0.001205 g cm⁻³ (pressure = 1 atm. and temperature = 20°C). Following the recommendation of TG-43 [2] for absorbed dose calculations, the density of water was taken as 0.998 g cm⁻³ at 22°C. Several tissues are used as media for absorbed dose calculations. The ICRU density correction files [13] are used to make the peg4 input files. Some human tissue equivalent materials are shown in Table 1 are simulated to investigate the absorbed dose difference for BEBIG 60Co and microSelectron HDR v2 sources.

Monte Carlo simulations

The EGSnrc code system [1] used in the present work is widely accepted Monte Carlo simulation code for coupled electron-photon transport. Its current energy range of applicability is considered to be 1 keV to 10 GeV. It is an extended and improved version of the EGS4 package [1] originally developed at Stanford Linear Accelerator Center (SLAC). [15] In particular, it incorporates significant improvements in the implementation of the condensed history technique for the simulation of charged particle transport and better low energy cross sections. [14] In this study, the latest version of the code is used for calculations of photon fluence and absorbed dose to water.

The half-life for 192Ir is 73.825 days and as an average one-decay will result in the emission of 1 electron and 2.363 photons. [9] The decay of 192Ir radionuclide occurs through 4.7 % electron capture and 95.3 % β transitions followed by γ transitions and k- and L-shells X-rays. [9] “192Ir_1993” spectrum and “192Ir_beta” spectrum are used as input photon spectrum and as beta spectrum respectively presented by Duchemin et al. [16] for all Monte Carlo calculations of microSelectron HDR 192Ir source. The half-life of 60Co radionuclide is 5.27 years and one-decay will result of emission of two photon spectrums with energy of 1.17 MeV and 1.33 MeV. [15] The “bareco60” spectra file is used for all the subsequent Monte Carlo calculations of BEBIG 60Co HDR source. The number of history used for all calculations is 10⁸. The bound Compton scattering, PE angular sampling, Raleigh scattering and atomic relaxations are considered as transport parameters. Variance reduction techniques are avoided in the calculations.

Calculation of air-kerma strength

Air-kerma strength, $S_k$ is a measure of brachytherapy source strength which is specified in terms of air-kerma rate, at a point along the transverse axis of the source in free space. [12] It is defined as the product of air-kerma rate, $K_{air}$ (d) at a calibration distance, d, in free space, measured along the transverse bisector of the source and the square of the distance, d. [9]
The total air-kerma is related to the photon fluence by

\[
K_{air} = 1.602 \times 10^{-10} \int_{E_{min}}^{E_{max}} \phi(E) \cdot E \cdot \left( \frac{\rho_{air}(E)}{\rho} \right) dE \quad \text{(Gy)} \quad \text{(2)}
\]

where, \( \phi(E) \) [MeV\(^{-1}\) cm\(^2\)] is the photon fluence per unit energy at energy \( E \) [MeV] and \( \rho_{air}(E) \) is the mass energy-absorption coefficient at the same energy \( E \). The factor \( 1.602 \times 10^{-10} \) is required to convert \( K_{air} \) from MeV\(^{-1}\) cm\(^2\) into Gy.

The total air-kerma is calculated from the equation below\([9]\):

\[
K'_{air} = 1.602 \times 10^{-10} \sum_{E_{min}}^{E_{max}} \phi(E) \cdot E \cdot \left( \frac{\rho_{air}(E)}{\rho} \right) \Delta E, \text{[Gy/phonon]} \quad \text{.....(3)}
\]

Here, \( E_i \) is the mid-point of each energy bin and \( \Delta E \) is the bin size. The air-kerma rate \( K_{air} \) in [Gy/s] of source activity \( \Lambda \) in [Bq] and number of photon per decay, \( N_p \) is determined from:

\[
K_{air} = K'_{air} \cdot N_{photon} = K'_{air} \cdot \Lambda \cdot N_p \quad \text{[Gy/s]} \quad \text{.....(4)}
\]

The air-kerma strength per unit source activity is then calculated using equation (1) and dividing it by the activity \( \Lambda \):

\[
S_k = \frac{K_{air}}{\Lambda} \cdot d^2, \quad \text{[\muGy m}^2\text{h}^{-1}] \quad \text{.....(1)}
\]

The point of 100 cm distance. The cut-off energy for photon and electron transport are 0.001 MeV and 2 MeV. In the present work, bare iridium source data (Ir192_bare_1993 spectrum) is used as spectra file for simulation to calculate the differential fluence spectrum for microSelectron HDR v2 source. The beta spectrum is not considered in the calculation of air-kerma strength in accordance with the TG-43 protocol.\([2]\) But both the spectra are used in the dose rate calculations for the source. Similarly, bare cobalt-60 spectrum (bareco60. spectrum) is used to simulate for the BEBIG \(^{60}\)Co source in the calculation of air-kerma strength and also dose rate.

To estimate the air-kerma strength, the source is kept in a 2 \( \times \) 2 \( \times \) 2 m\(^3\) air cylinder and kerma is scored for a 0.2 cm thick and 0.1 cm high cylindrical ring cell, located along the transverse source axis. The number of 10\([9]\) histories is simulated to obtain air-kerma strength for both sources. Whereas Borg et al.\([9]\) calculated air-kerma strength as same methodology for 50 cm distance for microSelectron HDR \(^{192}\)Ir v2 source. Selvam et al.\([9]\) have calculated using same user code with photon fluence spectrum in 10 keV interval at 100 cm distance in a 1 cm thick and 0.5 cm height of voxel size for new BEBIG \(^{60}\)Co HDR source. Moreover, Sahoo et al.\([13]\) calculated the air-kerma strength at 100 cm distance using MCNP code for new BEBIG \(^{60}\)Co HDR source.

### Calculations of absorbed dose rate

For the absorbed dose rate calculation the source is positioned at the centre of a cylindrical water phantom of volume \( \pi \times 1 \times 2 \) m\(^3\). In order to provide adequate spatial resolution, the cells are 0.01 cm thickness for \(<2\) cm, 0.05 cm for 2 cm < \( r \) < 5 cm, 0.1 cm for 5 cm < \( r \) < 10 cm and 0.2 cm for \( r \) > 10 cm from the source.\([11]\) The dose rate values are calculated in different positions of the water phantom with polar co-ordinate for different position of the water phantom. The user-code DOSRZ\([13]\) is used to calculate \( D_{\text{photon}} \) and \( D_{\text{electron}} \) for subsequent calculation of the true dose \( D_{\text{true}} \) is using the equation (6):\([18]\)

\[
D_{\text{true}} = 3.6 \times 10^5 \left( N_p \times D_{\text{photon}} + D_{\text{electron}} \right) \left( \frac{S_k}{\Lambda} \right) \quad \text{[cGy h}^{-1}\text{U}^{-1}] \quad \text{.....(6)}
\]

where \( D_{\text{photon}} \) is the total dose produced by photons, \( D_{\text{electron}} \) is that due to electrons, \( S_k/\Lambda \) is air-kerma strength per unit source activity in [U Bq\(^{-1}\)]. The factor \( 3.6 \times 10^5 \) is required to convert the dose rate per unit air-kerma

### Table 1: Human equivalent tissue materials which are used in Monte Carlo simulation for the calculation of tissue dependent absorbed dose for the sources

| Tissue       | Water | Compact bone | Breast | Blood | Lung | Thyroid | Muscle | Soft tissue | Testis |
|--------------|-------|--------------|--------|-------|------|---------|--------|-------------|--------|
| Density g/cm\(^3\) | 1.00  | 1.85         | 1.02   | 1.06  | 0.26 | 1.05    | 1.12   | 1.0         | 1.04   |

\[
S_k = \frac{K_{air}}{\Lambda} \cdot d^2, \quad \text{[\muGy m}^2\text{h}^{-1}] \quad \text{.....(1)}
\]
strength per unit source activity in [cGy U⁻¹] to the dose rate per unit air-kerma strength. The values of Nₜ for ¹⁹²Ir and ⁶⁰Co are 2.563 ± 0.3%⁹ and 2, respectively. The true dose rate is calculated for all points of interest and these values are used to calculate TG-43 parameters e.g., dose rate constant, radial dose function and anisotropy function. The cut-off energy for photon and electron transport are 0.001 MeV and 0.521 MeV, respectively, as maintained in the dose rate calculations for all radial distances. Daskalov et al.⁸ simulated for new microSelectron HDR ¹⁹²Ir source using MCPT based Monte Carlo transport code and collision kerma is used to approximate the absorbed dose, whereas secondary electron transport was not considered for calculation. Taylor et al.¹⁰,¹¹ have reported TG-43 parameter’s value for same source using EGSnrc based BrachyDose¹² Monte Carlo transport code without considering electron transport. Granero et al.⁷ and Richter et al.⁵ calculated the dosimetry parameters using Monte Carlo based transport code GEANT4 and EGS-Ray¹⁴ respectively, for new BEBIG ⁶⁰Co HDR source and the authors used 10 keV cut-off energy in the simulation for photon and electron. Selvam et al.⁵ obtained the value of air-kerma strength per unit source activity for BEBIG ⁶⁰Co HDR source is found to be 3.039 ± 0.51% cGy h⁻¹ U⁻¹ whereas Sahoo et al.¹³ obtained 3.043 ± 0.4% cGy h⁻¹ U⁻¹ ) using same code with 10 keV interval of fluence spectrum. The value is about 0.13% higher than the value obtained from this study probably due to higher size of calculation grid. In this case also the results are again in good agreement with Monte Carlo based MCNP results of Borg and Rogers⁹ for air-kerma strength per unit source activity for the microSelectron HDR ¹⁹²Ir v2 source at 50 cm distance from the source centre. It’s worth mentioning that thier methodology has been adopted in the present cases also.

The value of air-kerma strength per unit source activity for BEBIG ⁶⁰Co HDR source is found to be 3.039 × 10⁻² ± 0.41% U Bq⁻¹. All the parameters are set as like the previous case of calculation of the microSelectron HDR ¹⁹²Ir v2 source. Selvam et al.⁵ obtained the value (3.043 × 10⁻² U Bq⁻¹) using same code with 10 keV interval of fluence spectrum. The value is about 0.13% higher than the value obtained from this study probably due to higher size of calculation grid. In this case also the results are again in good agreement with Monte Carlo based MCNP results of 3.04 × 10⁻² ± 0.05% U Bq⁻¹ by Sahoo et al.¹³.

Dose rate constant, Λ

Dose rate constants, Λ, are calculated by dividing the dose to water per unit source activity in a (0.1 mm)³ voxel centred at the reference position, (1 cm, 90°), in the π × 100² × 200 cm³ cylindrical water phantom, by the air-kerma strength per unit source activity. The contribution of primary electron is accounted for in all the calculations related to microSelectron HDR ¹⁹²Ir v2 source. The value of Λ for microSelectron HDR ¹⁹²Ir v2 source is found to be 1.116 ± 0.12% cGy h⁻¹ U⁻¹. This result agrees well with the result of Taylor et al.¹⁰ (1.109 ± 0.18% cGy h⁻¹ U⁻¹) and Hong et al.¹⁸ (1.112 ± 0.51% cGy h⁻¹ U⁻¹).

The calculated value of Λ for BEBIG ⁶⁰Co HDR source is found to be 1.097 ± 0.12% cGy h⁻¹ U⁻¹ whereas...
Selvam et al.\textsuperscript{[5]} have reported the dose rate constant value (\(=1.097\) cGy h\(^{-1}\) U\(^{-1}\)) using FLURZnc-based\textsuperscript{[4]} calculation of collision kerma to approximate the dose. This is also in good agreement with GEANT4 Monte Carlo based published results of \(1.087 \pm 0.011\%\) cGy h\(^{-1}\) U\(^{-1}\) by Granero et al.\textsuperscript{[7]}

**Radial dose function, \(g_L(r)\) and anisotropy function, \(G_L(r, \theta)\)**

The radial dose function, \(g_L(r)\) accounts for dose fall-off on the transverse-plane due to photon scattering and attenuation in water medium. The function is also influenced by the geometry factor, \(G_L(r, \theta)\) and the anisotropy factor, \(F(r, \theta)\). The geometry factor depends on the physical parameters of the source, i.e., the length and the radius of the source. An identical construction of of the sources can ensure same geometry factors. The isodose curve is influenced by the anisotropy factor in clinical dose distribution. These two functions are essential for comparing different brachytherapy sources.

The Figure 3 shows the comparison of radial dose functions from 0.06 cm to 100 cm radial distance and the Figure 4 does the same for distance from 0.06 cm to 2 cm. The values of radial dose function for \(^{60}\)Co source is about 2.4\% lower than \(^{192}\)Ir at 2 cm radial distance (Manchester Point A) and the values are also found to be lower 7.5\%, 9.3\% and 10.5\% for the point of 5 cm, 7.5 cm and 10 cm respectively. The values of radial dose function of \(^{60}\)Co source are also lower than that of the \(^{192}\)Ir source in the range from 0.06 cm - 0.17 cm. The values are, however, found higher in the range from 0.18 cm - 1 cm and above 22 cm of radial distance. The higher values of radial dose function are found for \(^{192}\)Ir source at the distance shorter than 0.17 cm may be the dose by electron contribution. The values are found to be less by 7\% averagely using ECUT \(=2\) MeV.\textsuperscript{[19]} The radial dose function for \(^{60}\)Co source is linearly fall-off from 1 cm to 7.5 cm of radial distances.

The anisotropy factors of BEBIG \(^{60}\)Co HDR source are comparatively higher at the longitudinal side of the source with the values of microSelectron HDR \(^{192}\)Ir source. It is also sharply increases with the radial distances to the longitudinal side of the BEBIG \(^{60}\)Co source comparatively with the value of microSelectron \(^{192}\)Ir v2 source. These factors for the cable connecting side of the BEBIG \(^{60}\)Co source are quite low compared to that of the other side and the values show an increase with the radial distance. The Figures 5 to 8 compare the anisotropy factors for 2 sources at radial distances 1 cm, 3 cm, 5 cm and 10 cm.

**Absorbed dose difference**

A cylindirical phantom was constructed with the respective tissue equivalent materials [Table 1] for simulation. The absorbed doses are calculated at different radial distances. The absorbed dose of water at discrete distances has been used as reference dose for the calculation of relative dose differences. The Figure 9 shows the relative absorbed dose differences between \(^{60}\)Co and \(^{192}\)Ir sources. Significant dose differences are noted for compact bone tissue up to 8 cm and more than 10 cm radial distances. Maximal absorbed dose differences are, however, observed in lung tissue: The results being about 30.8\% at 0.2 cm, and 12.45\% at 1 cm. As is expected the difference decreases with increase in radial distances. Tissue dependence of absorbed dose has been calculated with vacuum phantom for water, breast, compact bone, blood, lung, thyroid, soft tissue, testis and muscle. No significant tissue dependence in absorbed dose is noted at 5 cm of radial distance by comparing BEBIG \(^{60}\)Co HDR to microSelectron HDR \(^{192}\)Ir v2 sources except for the lung tissues. Figure 10 shows the differences comparing them with the absorbed dose of water.

The investigations of \(^{60}\)Co and \(^{192}\)Ir sources have shown approximately identical dose distribution. Negligible differences are noted in radial dose distribution as well as negligible absorb dose differences with various tissues. A significant difference appears in absorbed dose at the close surface of the iridium source (132 times higher than...
the dose of 1 cm of radial distance from the source centre)\(^{[19]}\) probably due to the contribution of primary electron. These differences are minimal when the calculation is done with KERMA approximation.\(^{[19]}\) In case of \(^{60}\)Co source, the absorbed dose is about 74 times higher\(^{[19]}\) than the dose of 1 cm of radial distance.

**Conclusions**

The values of anisotropy function at the longitudinal sides
of the BEBIG $^{60}$Co HDR source are relatively higher than microSelectron HDR $^{192}$Ir source and the isodose lines will be not exactly identical due to this effect for these region. Treatment planning system performs to adjust the isodose distribution using dwell time positioning technology in clinical relevant situation. The radial dose function characterize the dose fall-off on the transverse plane of the source. The higher dose region for $^{192}$Ir source and lower dose region for $^{60}$Co source ($<0.17$ cm from the source centre) may be situated inside the applicators and rest of the region up to 1 cm, the radial dose fall-off will be dependent on the nature of the applicator. The applicators commonly use for cervical site; these region again may be situated inside the applicators. The differences of the radial dose function $<1$ cm for 2 sources may be effectual for narrow catheter based intracavitary or interstitial brachytherapy. The small difference of radial dose function (within the therapeutic range of radial distance) has a possibility to make a negligible difference in isodose distribution in clinical applications.

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