Simulation Study on Dosimetric Parameters of Domestic High-Dose-Rate Brachytherapy Ir-192 Source

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Abstract

Background Ir-192 brachytherapy source is a high-dose-rate γ-ray source characterized by a high central dose rate and rapid dose fall-off at the edges. In clinical treatment, this dose distribution characteristic enables the Ir-192 source to effectively protect normal tissues and organs surrounding the tumor. Objective Referencing the dosimetric parameters for Ir-192 sources recommended by the American Association of Physicists in Medicine (AAPM) in TG43-U1, a fine-structured model of a domestically-produced high-dose-rate brachytherapy Ir-192 source was established based on Monte Carlo simulation software for simulation calculations. Methods Monte Carlo software was used to establish a fine-structured model of a domestically-produced high-dose-rate brachytherapy Ir-192 source, and dosimetric parameters were simulated and calculated, including: dose rate constant Λ, air kerma strength per unit activity, radial dose function, and anisotropy function. Results The simulated dose rate constant was 1.105 cGy · h-1 · U-1, with a difference within 1.2% compared to literature reports; the air kerma rate per unit activity was 9.788\$×\$10-8 UBq-1, with a difference of 0.23% from literature-reported results. The radial dose function was obtained in the range of 0.5 to 20 cm from the source transverse axis, and an empirical formula was fitted. Conclusion The domestically-produced Ir-192 source model established based on Monte Carlo software shows good consistency with literature-reported data in terms of dosimetric parameters, indicating that the model can be used for clinical practice applications of domestically-produced Ir-192 sources and has certain guiding significance.

Full Text

Simulation Study on the Dosimetric Parameters of Domestically Produced High-Dose-Rate Brachytherapy Ir-192 Source

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Abstract

Purpose: To establish a detailed structural model of a domestically produced high-dose-rate Ir-192 brachytherapy source using Monte Carlo simulation software, based on the dosimetric parameters recommended by the American Association of Physicists in Medicine (AAPM) TG43-U1 report, and to perform comprehensive simulation calculations. **Methods**: A detailed geometric model of the domestically produced high-dose-rate Ir-192 brachytherapy source was constructed using Monte Carlo software. The simulated dosimetric parameters included the dose rate constant Λ, air kerma strength per unit activity S_K, radial dose function g(r), and anisotropy function F(r,). **Results**: The simulated dose rate constant was 1.105 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$, with a difference of less than 1.2% from literature values. The air kerma strength per unit activity was 9.788$×10^{-8}$ $\mathrm{U \cdot Bq^{-1}}$, differing by only 0.23% from reported results. The radial dose function was obtained for distances ranging from 0.5 to 20 cm from the source transverse axis, and an empirical formula was fitted to the data. **Conclusions**: The domestically produced Ir-192 source model established using Monte Carlo software demonstrates good consistency with literature-reported dosimetric parameters, indicating that this model can be used for clinical practice applications of domestically produced Ir-192 sources and provides valuable guidance for their implementation.

Keywords: Ir-192 source; Monte Carlo simulation; dosimetric parameters; brachytherapy

Introduction

Ir-192 brachytherapy sources are high-dose-rate γ-ray emitters characterized by high central dose rates with rapid dose fall-off at the periphery. This distinctive dose distribution profile enables effective protection of surrounding normal tissues and organs during clinical treatment. By precisely controlling the source position and irradiation time, the tumor region can receive a therapeutic dose while minimizing damage to healthy tissue. Consequently, Ir-192 sources have been widely adopted in the treatment of cervical cancer, prostate cancer, and other malignancies [**?**, **?**]. In brachytherapy, accurate dose calculation and distribution are critical for patient outcomes. To ensure treatment efficacy and safety, detailed quantitative evaluation of the dosimetric characteristics of Ir-192 sources is essential. The American Association of Physicists in Medicine (AAPM) recommends in its TG-43 [?] and TG-43U1 [?] reports that at least one complete set of experimental measurements and one complete Monte Carlo simulation should be performed before clinical implementation to obtain the source dosimetric parameters. Although numerous studies have investigated the dosimetric parameters of Ir-192 sources internationally, simulation studies on the HDR Ir-192 source produced by Atomic High-Tech Co., Ltd. remain scarce in China, with only Wu et al. [?] having previously examined this source. To expand the available data, this study systematically investigates the dosimetric parameters of this source using Monte Carlo simulation methods. A detailed geometric model of the source was constructed using Monte Carlo software to calculate photon air kerma strength and absorbed dose in water medium. The simulation results were subsequently compared with existing literature data [?] to validate the accuracy and reliability of this study, providing important theoretical foundation and data support for improving dose calculation precision in brachytherapy.

1. Structure of the Atomic High-Tech HDR Ir-192 Source

[Figure 1: see original paper] presents a schematic diagram of the HDR Ir-192 source manufactured by Atomic High-Tech Co., Ltd. According to manufacturer specifications, the radioactive core consists of a cylindrical pure iridium metal pellet with a diameter of 0.6 mm and length of 3.5 mm, with a density of 22.56 g/cm^3. Ir-192 is a radioactive isotope with a half-life of approximately 73.8 days, emitting on average one electron and 2.36 photons per decay, with the radioactive material uniformly distributed throughout the cylinder. The source is encapsulated in a 06Cr19Ni10 (304 stainless steel) cylinder measuring 6.5 mm in length, with an inner diameter of 0.8 mm and outer diameter of 1.1 mm. One end of the source is attached to a 170 cm long 06Cr19Ni10 (304 stainless steel) source cable, though only 6 cm is shown in the diagram; the other end features a hemispherical tip with a radius of 0.55 mm. The space between the radioactive core and encapsulation is filled with air. The 304 stainless steel encapsulation provides excellent mechanical strength and corrosion resistance, effectively protecting the radioactive material and preventing leakage during use. details the composition and density of materials used in the calculation model [?, ?], providing fundamental data for subsequent Monte Carlo simulations. These parameters are crucial for accurately simulating the dose distribution and ensuring reliable calculation results.

2. Dosimetric Parameter Calculation Formulas

The AAPM recommends in its TG43-U1 report that dosimetric parameters must be calculated for each new brachytherapy source before clinical use in treatment planning [?]. According to the AAPM TG-43U1 protocol, these dosimetric parameters include: the dose rate constant Λ, air kerma strength per unit activity S_K, radial dose function g(r), and anisotropy function F(r,). Following the TG-43 dose calculation formalism, the absorbed dose rate $\dot{D}(r,\theta)$ at a point in medium is expressed in polar coordinates as:

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G(r,\theta)}{G(r_0,\theta_0)} \cdot g(r) \cdot F(r,\theta)$$

where r is the radial distance from the source center,   is the polar angle relative to the source longitudinal axis, G(r,) is the geometry factor, S_K is the air kerma strength of the source (units of U or cGy • cm^2 • h^{-1}), calculated as:

$$S_K = \dot{K}_\delta(d) \cdot d^2$$

where $\dot{K}_\delta(d)$ is the air kerma rate in vacuum at distance d cm from the source transverse axis (units of cGy • h^{-1}), and d is the distance from the detection point to the source center, taken as 100 cm.

When S_K is known, Λ can be calculated using the formula. The dose rate constant Λ is defined as the ratio of water absorbed dose rate to air kerma strength at the reference position, calculated as:

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K}$$

where $\dot{D}(r_0,\theta_0)$ is the absorbed dose rate at the reference position (r_0 = 1 cm, $_0$ = 90°), with units of cGy • h^{-1} • U^{-1}.

The radial dose function g(r) and anisotropy function F(r,) are calculated as:

$$g(r) = \frac{\dot{D}(r,\theta_0) \cdot G(r_0,\theta_0)}{\dot{D}(r_0,\theta_0) \cdot G(r,\theta_0)}$$

$$F(r,\theta) = \frac{\dot{D}(r,\theta) \cdot G(r,\theta_0)}{\dot{D}(r,\theta_0) \cdot G(r,\theta)}$$

G(r,) is the line source geometry factor, whose value depends on the source geometry and represents the influence of the source itself on the surrounding dose rate. The geometry factor is calculated as:

$$G(r,\theta) = \frac{\beta}{L \cdot r \cdot \sin\theta}$$

where L is the effective active length of the source, and β is the angle subtended by the source ends at the point of interest.

3. Monte Carlo Simulation

This study employed Monte Carlo simulation software to establish a computational model for calculating Ir-192 source dosimetric parameters in polar coordinates, as illustrated in [Figure 2: see original paper]. The photon cross-section library McpLib04 was selected to ensure simulation accuracy. The source was defined using source cards, with sample code: SDEF POS=-0.195 0 0 ERG=D1 PAR=2 AXS=1 0 0 RAD=D2 EXT=D3. The simulation calculated air kerma strength through the source encapsulation and absorbed dose in water medium.

Water Absorbed Dose Calculation: The source model was positioned at the center of a cylindrical water phantom measuring 50 cm in length and 25 cm in radius, assuming charged particle equilibrium within the water medium. Water absorbed dose at various positions was recorded using either the F4 tally card with mass energy absorption coefficients for water from the NIST XCOM database or the F6 energy deposition tally. To minimize voxel size effects on the radial dose function g(r), different voxel sizes were employed at various distances: spherical voxels with 0.035 cm radius for $r \leq 5$ cm, 0.055 cm radius for 5 cm $< r \leq 9$ cm, 0.06 cm radius for 9 cm $< r \leq 15$ cm, and 0.075 cm radius for 15 cm $< r \leq 20$ cm [?]. To reduce angular effects of voxel size on the anisotropy function F(r,), point detector F5 cards were used at different radial distances r and angles from 0° to 180°. Photon and electron transport modes were enabled (mode: p, e), considering contributions from primary photons and secondary electrons. The particle history was set to 1×10^{8}, with cutoff energies of 10 keV for photons and 2 MeV for electrons [?].

3.1 Dose Rate Constant and Air Kerma Strength per Unit Activity

Monte Carlo simulations were performed to calculate air kerma strength at 100 cm from the source in vacuum and absorbed dose rate at 1 cm in water. Through formula calculation and unit conversion, the dose rate constant was determined to be 1.105 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$. This value shows a deviation of 0.72% compared to 1.113 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ reported in literature [?], and deviations of 0.90% and 1.09% compared to 1.115 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ and 1.117 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ from literature [?, ?], respectively. The air kerma strength per unit activity was calculated as 9.788×10^{-8} $\mathrm{U \cdot Bq^{-1}}$, showing deviations of 0.069% and 0.023% compared to values of 9.781×10^{-8} $\mathrm{U \cdot Bq^{-1}}$ and 9.790×10^{-8} $\mathrm{U \cdot Bq^{-1}}$ reported in literature [?, ?].

3.2 Radial Dose Function

Based on the simulation environment established in Section 2, data were calculated at various radial positions from the source. To improve accuracy and resolution, the number of detectors was increased along the radial direction. The simulated data were substituted into equation (4) to calculate the radial dose function g(r), which characterizes dose rate attenuation with increasing distance from the source. The results were compared with literature data [?, ?]

and summarized in [Figure 3: see original paper].

Within 20 cm radial distance, the relative error between this study and literature [?] ranged from 0.26% to 3.76%, while comparison with literature [?] showed relative errors from 0.27% to 3.79%, demonstrating good agreement. The radial dose function exhibited an increasing trend from r = 0.05 cm to 5 cm, consistent with literature [?]. Within 3 cm, minor fluctuations were observed, showing a slight decrease followed by an increase. For r < 6 cm, the radial dose function remained approximately constant across all studies. When r > 6 cm, the radial dose function gradually decreased. Beyond 15 cm, differences between this study and literature [?, ?] gradually increased.

Using the simulated data, a fifth-order polynomial fit was performed on the radial dose function with respect to distance r using Origin software [?], yielding the following empirical formula:

$$g(r) = a_0 + a_{1r} + a_{2r}^2 + a_{3r}^3 + a_{4r}^4 + a_{5r}^5$$

The fitted coefficients were 0.98206, 0.00877, -5.31377\$×10$^{\{-4\}, -1.72573\times 10}$\{-4\}, 1.14432×10$^{\{-5\}, and - 2.37093\times 10}$\{-7\}\$. The fitted curve is shown in [Figure 4: see original paper].

3.3 Anisotropy Function

In this study, simulation data were obtained at various distances from the source (0.5 cm, 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, 7 cm, 8 cm, 9 cm, 10 cm, 15 cm, 20 cm) and angles (0°–180°). These data were substituted into equation (5) to derive the two-dimensional anisotropy function, compiled in . The anisotropy functions at 1 cm, 3 cm, 5 cm, and 7 cm from this study were compared with literature [?, ?] and plotted in [Figure 5: see original paper]. Comparison revealed that at r = 10 cm and = 180°, the anisotropy function showed significant deviation due to differences in the source cable structure modeled in the simulation. Within 180°, the maximum relative error between this study and literature [?, ?] was 3.35%, demonstrating good consistency.

Conclusion

This study utilized Monte Carlo simulation software to establish a computational model in polar coordinates for calculating dosimetric parameters of Ir-192 sources. Based on the dose calculation formulas from the TG-43U1 report, the dosimetric parameters of the Atomic High-Tech Co., Ltd. HDR Ir-192 source were simulated. First, the air kerma strength per unit activity was calculated, yielding a dose rate constant of 1.105 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$. This value deviates by 0.72% from 1.113 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ in literature [?], and by 0.90% and 1.09% from 1.115 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ and 1.117 $\mathrm{cGy \cdot h^{-1} \cdot U^{-1}}$ in literature [?, ?], respectively—acceptable deviations considering structural differences between sources. Second, the radial dose function was calculated and fitted with a fifth-order polynomial using Origin software. Comparison with literature [?, ?] showed consistent overall trends, though deviations increased with radius, likely due to geometric differences. Finally, the anisotropy function was investigated, showing agreement with published literature within error margins, validating the reliability of the simulation method and accuracy of results. This study provides a reliable method for calculating the dose rate constant for domestic Ir-192 sources, offering data support for advancing dosimetry of domestic sources and improving clinical treatment accuracy in brachytherapy.

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Note: Figure translations are in progress. See original paper for figures.