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Characterization of the response of a well chamber to different models of Ir-192 sources for HDR brachytherapy

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Abstract: The determination of the reference *air kerma rate* (K_R) with well chambers calibrated using a different model of source than desired can lead to significant errors, affecting both radiological traceability institutions and healthcare facilities. This study employs the methodology proposed by SHIPLEY *et al.* (2015) with the PTW T33005 well chamber model and six models of HDR brachytherapy sources (microSelectron v.1; microSelectron v.2; Flexisource; GammaMed Plus; BEBIG GI192M11; Varisource VS2000) to derive correction factors for source geometry (K_{SG}). These factors adjust the chamber calibration factor for air kerma (N_K) to the source model under measurement. The methodology relies on simulating the chamber response to sources using the Monte Carlo Method (MC), specifically utilizing the MCNPX code. Both the source and well chamber models were validated by comparing dosimetric parameters from TG-43 and simulated calibration factors ($^{MC}N_K$) with literature-derived reference values. The normalized K_{SG} values, relative to the microSelectron v.1 source, agree with reference values, demonstrating the methodology's applicability across various chamber models, sources, and MC codes. The corrections ranged from 0.984 to 1.001, with the most significant correction observed for the Varisource VS2000 source, yielding K_{SG} = 0.984, corresponding to a -1.6% correction.

Keywords: HDR brachytherapy, Monte Carlo method, Ir-192 sources.

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Caracterização da resposta de uma câmara poço para diferentes modelos de fonte de Ir-192 para braquiterapia

Resumo: A determinação da *taxa de kerma no ar de referência* (K_R) com câmaras poço calibradas usando um modelo de fonte diferente do desejado pode levar a erros significativos, afetando tanto instituições de rastreabilidade radiológica quanto de saúde. Este estudo emprega a metodologia de SHIPLEY *et al.* (2015) na câmara poço modelo PTW T33005 e seis modelos de fontes de braquiterapia HDR (microSelectron v.1; microSelectron v.2; Flexisource; GammaMed Plus; BEBIG GI192M11; Varisource VS2000) para obter fatores de correção para a geometria das fontes (K_{SG}). Esses fatores corrigem o fator de calibração da câmara para kerma no ar (N_K) para o modelo de fonte em medição. A metodologia baseia-se na simulação da resposta da câmara às fontes usando o Método de Monte Carlo (MC), neste caso, o código MCNPX. Os modelos de fontes e câmara poço foram validados comparando parâmetros dosimétricos do TG-43 e fatores de calibração simulados (${}^{MC}N_K$) com valores de referência da literatura. Os valores normalizados de K_{SG}, em relação à fonte microSelectron v.1, concordam com os valores de referência, indicando a aplicabilidade da metodologia em diferentes modelos de câmaras, fontes e códigos de MC. As correções variaram de 0.984 a 1.001, sendo a mais significativa para a fonte Varisource VS2000, com K_{SG} = 0.984, uma correção de -1.6%.

Palavras-chave: braquiterapia HDR, método de Monte Carlo, fontes de Ir-192.

1. INTRODUCTION

High Dose Rate (HDR) brachytherapy is used for treatment most types of the cancer. According to the Instituto Nacional de Câncer (INCA) in its report "ESTIMATE|2023 - Incidence of Cancer in Brazil," it is projected that 704,000 new cases of cancer will occur annually in Brazil during the 2023-2025 period, with the Southern and Southeastern regions accounting for approximately 70% of the incidence [1].

Nationally, non-melanoma skin cancer is the most common malignancy, accounting for 31.3% of all cases, followed by breast cancer in women (10.5%), prostate cancer (10.2%), colorectal cancer (6.5%), lung cancer (4.6%), and stomach cancer (3.1%) had the highest incidences [1], naturally depending on the staging. In Brazil, HDR brachytherapy for treatment of the cervical and endometrial cancers a role in maintaining local control rates [2].

In brachytherapy, there is a rapid dose decrease with increasing distance from the source, allowing high doses to be delivered while preserving adjacent healthy tissues [3]. However, the benefits of HDR brachytherapy in cancer treatment are achieve if there is consistency between the dose prescribed by the radiation oncologist and the dose delivered to the target volume. Thus, a dosimetric quantity traceable to the International System of Units (SI) is measure for the sources in question. Based on the recommendation of the International Commission on Radiation Units and Measurements (ICRU) - Report 58 [4] used quantity to specify source intensity is the reference air kerma rate (KR).

In clinical practice, the uncertainty of the final result in KR measurements is often difficult to estimate due to various factors includes, potential errors in the relative position between the source and measurement point, of the used ionization chamber low signal intensity collected, and improper contribution of scattered radiation. In this context, a well-type ionization chamber model was proposed, in other words, a well chamber where the source is inserted into the sensitive volume containing gas [5].

The use of such chambers ensures better reproducibility in source positioning relative to the detection volume, provides electrical currents of magnitudes easily measurable by clinical electrometers for all source intensities, reducing the significance of spurious signals such as scattered radiation in the air and room walls/floor, and is extremely practical in its use. However, the use of this type of chamber is subject to the influence of source characteristics that were not significant in measurements with standard ionization chambers, such as the geometry of the active element and its encapsulation [6], [7].

These parameters affect the dose distribution around the source due to the finite size of the active element and the differential absorption of radiation generated within it and within the encapsulation. Without proper characterization of these influences, which depend on the source model used, the uncertainty resulting from them, when added to all other uncertainties involved in brachytherapy treatment, can make it impossible to maintain the total uncertainty below 5%, as recommended by ICRU Report 24 [8], or even below 10%, as estimated in AAPM Report # 51 (American Association of Physicists in Medicine), result of Task Group 43 (TG-43) work [9].

Furthermore, the failure to apply corrections for calibration factor of the well chamber (NK) obtained with one source model and its subsequent utilization with another model, which occurs in many HDR brachytherapy services, becomes a technical problem due to the uncertainties involved in KR measurements.

The main objective of this work is to apply the methodology presented by SHIPLEY et al. (2015) [10] to characterize the response of the well-type ionization chamber, SourceCheck 4 PiTM model – T33005 (PTW-Freiburg), to six models of 192Ir sources for HDR brachytherapy (Flexisource; microSelectron-V1 (classic); microSelectron-V2; GammaMed Plus; Varian VariSource VS2000; BEBIG E SGI192M11) and, from the characterized response, to generate correction factors of its calibration factor according to the source models, KSG.

2. MATERIALS AND METHODS

2.1. Theoretical Synthesis and Present Research

SHIPLEY et al. (2015) [10] presents a methodology for determining the correction factors for source geometry, KSG, utilizing the Monte Carlo method. In this study, KSG values were obtained for the Standard Imaging 1000 Plus well chamber equipped with the 70010HDR adapter (which connects to the HDR device and allows for reproducible source insertion) and six different source models: Nucletron Microselectron v.1, Nucletron Microselectron v.2, BEBIG GI192M11, GammaMed Plus, Isodose Control Flexisource, and Varian VariSource VS2000. The KSG factors are defined as follows.

$$K_{SG} = \frac{[N_{kr}]_{hosp}}{[N_{kr}]_{calib}} \qquad \text{Eq. 1}$$

Where $[N_{kr}]_{hosp}$ and $[N_{kr}]_{calib}$ represent the calibration coefficients for the chamber in question, obtained using the source models available at the hospital and the laboratory, respectively.

To determine the K_{SG} values using the Monte Carlo method, SHIPLEY et al. (2015) first modeled [10], in detail, the chamber with the adapter and each source model using the EGSnrc code. The validation of the source models was achieved by calculating two TG-43 parameters— the radial dose function, g(r), and the dose rate constant, Λ— for each model, and comparing them with the values from the CLRP database and the data published by the HEBD working group. The chamber model was validated by comparing the simulated response curves for three source models with their typical experimental values. Once the models were validated, the K_{SG} values were calculated as follows.

Eq. 2

$$K_{SG} = \frac{\left[\frac{K_{air,1m}}{D_{ch,max}}\right]_{hosp}}{\left[\frac{K_{air,1m}}{D_{ch,max}}\right]_{calib}}$$

Where $K_{air,1m}$ is the air kerma at a point on the plane transverse to the longest dimension of the source, passing through its center at 1 meter distance, as calculated per simulated history. $D_{ch,max}$ represents the maximum dose computed across the entire collection volume of the chamber. The indices "hosp" and "calib" refer to the hospital and calibration laboratory sources, respectively. $D_{ch,max}$ is considered equivalent to the charge generated within the sensitive volume of the chamber and is obtained during the process of determining the response curves for each source. $K_{air,1m}$ was determined in a vacuum, thereby eliminating the need to correct for attenuation and scattering effects that would occur in air.

Table 1 provides a comparative analysis between the methodology developed by SHIPLEY et al. (2015) [10] and its application in the present research.

Table 1 : A summarized comparative analysis of the parameters adopted in SHIPLEY et al. (2015)[10] and those utilized in the present study.

	SHIPLEY et al (2015)[10]	**Present Research**
Well Chamber	Standarg Imaging HDR 1000Plus	SourceCheck 4 PiTM – T33005; PTW-Freiburg
Computational code	cavit/EGSnrc (release V4- r2-2-5)	MCNPX
Cut-off energies (ECUT)	Photons – 1 keV Electrons – 5 keV	Photons – 1 keV Electrons – 1 keV
Number of histories	1E9	1E9
Ir-192 sources	Flexisource; microSelectron-V1 (classic); microSelectron- V2; GammaMed Plus; Varian VariSource VS2000; BEBIG E SGI192M11	Flexisource; microSelectron-V1 (classic); microSelectron- V2; GammaMed Plus; Varian VariSource VS2000; BEBIG E SGI192M11
Spectrum used	Decay Data Evaluation Project - DDEP	NuDat (E>10 KeV; sem β)

	SHIPLEY et al (2015)[10]	**Present Research**
Formalism	$K_{SG} = \frac{\left[\frac{K_R}{D_{pos,max}}\right]_{hosp}}{\left[\frac{K_R}{D_{pos,max}}\right]_{calib}}$	$K_{SG} = \frac{\left[\frac{K_R}{D_{pos,max}}\right]_{hosp}}{\left[\frac{K_R}{D_{pos,max}}\right]_{calib}}$
Dpos.máx	Value obtained at the maximum of the second-order polynomial fit curve.	Value obtained at the central position of the chamber (nominal measurement position).
Determination of K_R	Circular plane (1 cm radius) in a vacuum at a distance of 1 meter.	A ring centered on the source, with a thickness of 1.0 cm and a height of 2.0 cm, formed by the intersection of two spheres and a cone.

2.2. Uncertainties

In this research, only the statistical uncertainty associated with the simulation results, stemming from the stochastic nature of the Monte Carlo method, was considered. Other sources of uncertainty, such as those arising from cross-section libraries and geometric uncertainties in the sources and chamber, are not accounted for in the obtained results.

The propagation of statistical uncertainties accompanying the simulation results, when applicable, is performed according to equation 3 given that u = f(x, y), the uncertainty in u, due to uncertainties in x and y, is expressed as:

$$\sigma_u = \left\{\left[\left(\frac{\partial f}{\partial x}\right).(\sigma_x)\right]^2 + \left[\left(\frac{\partial f}{\partial y}\right).(\sigma_y)\right]^2\right\}^{1/2} \quad \text{Eq. 3}$$

Where σ_u represents the uncertainty in variable u, and ∂f/∂x and ∂f/∂y are the partial derivatives of f with respect to x and y, respectively.

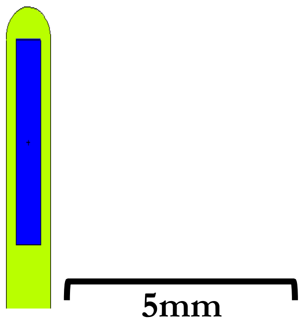
2.3. Modeling

The sources were modeled in MCNPX, meticulously following every geometric detail of their designs, as well as their composition. Assumed for all sources that the distribution of Ir-192 (radioactive) is uniform within the metallic iridium core. The major axis of the sources lies along the z-axis of the coordinate system with the center of the iridium core at the origin (0,0,0).

- **MicroSelectron-v1 (classic) [11]**

This source consists of a cylindrical core of metallic Iridium (Ir) with a density of 22.42 g/cm³, a length of 3.5 mm, and a diameter of 0.6 mm, enclosed in an AISI 316L steel capsule (by weight: Mn - 2%, Si - 1%, Cr - 19%, Ni - 10%, Fe - 68%) with an outer diameter of 1.1 mm. The distal (upper) part of the encapsulation is modeled as a hemisphere with a radius of 0.55 mm, offset 1.755 mm from its center. The source cable is modeled as an extension of the capsule, 4.5 mm from the center of the source. Both the encapsulation and cable were modeled with a density of 8.02 g/cm³. Figure 1 below shows the representation of this source in MCNP.

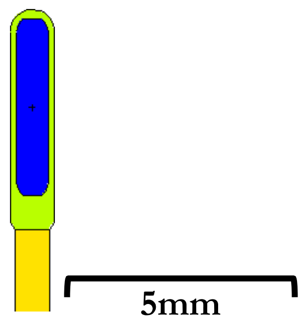
Figure 1: Representation of the microSelectron v.1 source model built in MCNPX (Blue: Metallic iridium core Ir-192 and Green: Stainless steel encapsulation (AISI 316L)).



- ## MicroSelectron-v.2 [12]

This source consists of a cylindrical core of metallic Iridium (Ir) with a density of 22.42 g/cm³, a total length of 3.6 mm, and a diameter of 0.65 mm, enclosed in an AISI 316L steel capsule (by weight: Mn - 2%, Si - 1%, Cr - 17%, Ni - 12%, Fe - 68%) with an outer diameter of 0.9 mm. DASKALOV et al. (1998) [12] modeled the rounded edges of the core using the intersection of the main cylinder with a circular cone. In this research, the Iridium core was modeled with rounded edges, using spheres instead of cones, as described by DASKALOV et al. (1998) [12]. The distal (upper) end of the source is modeled as a hemisphere with a radius of 0.45 mm, offset 1.55 mm from its center, resulting in an upper encapsulation thickness of 0.2 mm. The proximal (lower) part of the encapsulation extends 0.7 mm from the lower face of the core and is modeled with an internal cone angle of 67.4°. The cable, also made of AISI 316L stainless steel, has an outer diameter of 0.7 mm and was modeled with an extension of 2 mm. The encapsulation and cable have densities of 8.02 g/cm³ and 4.81 g/cm³, respectively. Figure 2 below shows the representation of this source in MCNP.

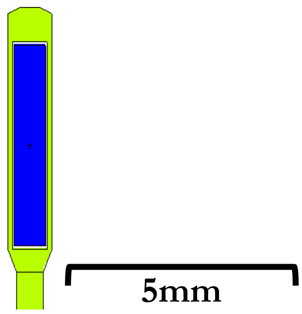
Figure 2: Representation of the microSelectron v.2 source model built in MCNPX (Blue: Metallic Iridium Core (Ir-192), Green: Stainless Steel Encapsulation (AISI 316L), and Yellow: Source Cable) .



- ## Flexisource [13]

This source consists of a cylindrical core of metallic Iridium (Ir) with a density of 22.42 g/cm³, a total length of 3.5 mm, and a diameter of 0.6 mm, enclosed in an AISI 304 steel capsule (by weight: Mn - 2%, Si - 1%, Cr - 19%, Ni - 10%, C - 0.08%, Fe - 67.92%) with an outer diameter of 0.85 mm. The core was modeled inside a hollow cavity within the capsule, with a 0.05 mm gap between the core and the encapsulation. The distal (upper) part of the encapsulation was modeled as a cylinder with a diameter of 0.85 mm and a height of 0.65 mm, with its edge formed by the intersection with a cone at an internal angle of 132.8°, with the vertex 2.476 mm above the center. The proximal (lower) part of the encapsulation was modeled as a conical section with a height of 0.4 mm and an internal angle of 48°. The source cable was modeled as a cylinder with a diameter of 0.5 mm and a length of 5 mm, also made of AISI 304 stainless steel. Both the capsule and cable have a density of 8.0 g/cm³. Figure 3 below shows the representation of this source in MCNP.

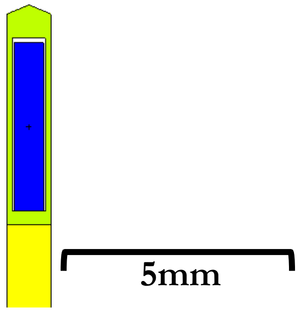
Figure 3: Representation of the Flexisource source model built in MCNPX (Blue: Metallic Iridium Core (Ir-192), Green: Stainless Steel Encapsulation (AISI 316L), and Yellow: Source Cable).



- ## GammaMed Plus [14]

This source consists of a cylindrical core of metallic Iridium (Ir) with a density of 22.42 g/cm³, a total length of 3.5 mm, and a diameter of 0.6 mm, enclosed in an AISI 316L stainless steel capsule (by weight: Mn - 2%, Si - 1%, Cr - 17%, Ni - 12%, Fe - 68%) with an outer diameter of 0.9 mm and a density of 7.8 g/cm³. The core was modeled inside a hollow cavity within the capsule, with gaps of 0.1 mm and 0.05 mm, respectively, in its distal (upper) and lateral sections. The distal part of the encapsulation consists of a cone with an internal angle of 136°, followed by a cylinder with a diameter of 0.9 mm, totaling 0.62 mm from the cone's vertex to the cavity. The proximal part of the encapsulation is a cylinder with a diameter of 0.9 mm and a length of 0.3 mm. The source cable was modeled as a cylinder with a diameter of 0.9 mm and a length of 6 cm, made of AISI 304 stainless steel with a density of 5.6 g/cm³. Figure 4 below shows the representation of this source in MCNPX.

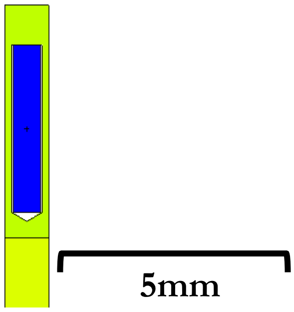
Figure 4: Representation of the GammaMed Plus source model built in MCNPX (Blue: Metallic Iridium Core (Ir-192), Green: Stainless Steel Encapsulation (AISI 316L), and Yellow: Source Cable).



- **BEBIG GI192M11 [15]**

This source was initially modeled with a cylindrical core of metallic Iridium (Ir) with a density of 22.42 g/cm³, but it should have been modeled as an alloy of 70% Ir and 30% Pt, with a density of 21.76 g/cm³. However, this difference did not lead to significant variations, as will be evident in the results. The core, with a total length of 3.5 mm and a diameter of 0.6 mm, is enclosed in an AISI 316L stainless steel capsule (by weight: Mn - 2%, Si - 1%, Cr - 17%, Ni - 12%, Fe - 68%) with an outer diameter of 1.0 mm and a density of 7.8 g/cm³. The hollow interior, housing the core, consists of a cylinder 3.5 mm in length and 0.7 mm in diameter, juxtaposed proximally (inferior side) to a cone with an internal angle of 120° and a height of 0.2 mm. The cylindrical core was modeled adjacent to the distal (upper) part of the cavity. The upper encapsulation measures 0.84 mm in length, and the lower section is 0.55 mm, both measured from the start of the conical section. The source cable was modeled as a cylinder with a 1.0 mm diameter and a length of 6 cm, made of AISI 316L stainless steel with a density of 6.9 g/cm³. Figure 5 below shows the representation of this source in MCNPX.

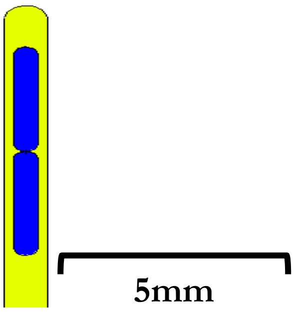
Figure 5: Representation of the BEBIG GI192M11source model built in MCNPX (Blue: Metallic Iridium Core (Ir-192), Green: Stainless Steel Encapsulation (AISI 316L), and Yellow: Source Cable).



- **Varisource VS2000 [16]**

This source consists of two juxtaposed cylindrical segments of metallic Ir-192 (density of 22.42 g/cm³), each with a diameter of 0.34 mm and a length of 2.5 mm, encapsulated in a Ni/Ti alloy with a mass percentage of 55.6% and 44.4%, respectively. The edges of the segments are modeled as hemispheres with the same diameter as the cylindrical part. The encapsulation has an outer diameter of 0.59 mm, with the distal (upper) edge also composed of a hemisphere of equal diameter. The distance from the distal edge of the encapsulation to the nearest segment is 1.0 mm. The cable is modeled with the same composition and density as the encapsulation and extends 5.0 cm from the center of the source. The total active length is 5.0 mm. Figure 6 below shows the representation of this source in MCNPX.

Figure 6: Representation of the Varisource VS2000 source model built in MCNPX Blue: Metallic Iridium Core (Ir-192) and Green: Stainless Steel Encapsulation (AISI 316L)).



2.4. Validation of the source models constructed in MCNPX

The source models were validated in MCNPX by comparing simulated values with reference data. TG-43 parameters, such as the dose rate constant (Λ), radial dose function (g(r)), and anisotropy function (F(r,θ)), were calculated using simulations. For the radial dose function, sources were modeled at the center of water spheres, and circular toroids were defined to calculate the absorbed dose. In these simulations, photons were tracked using the Tally F6:P. The dose rate constant was derived from air sphere models with linear regression of $K.R^2$ vs. R, while the anisotropy function was obtained by modeling water spheres and computing energy deposition in toroids.

3. RESULTS AND DISCUSSIONS

3.1. Validation of Source Models

The source models constructed in MCNPX were validated by calculating the dosimetric parameters according to the TG-43 protocol and comparing them with reference values. The parameters include the radial dose function, dose rate constant, and anisotropy function.

Radial Dose Function (g(r)): The radial dose function was simulated using circular toroids centered on the sources and was compared with reference values from the literature. The function showed excellent agreement with the reference data, with uncertainties within acceptable ranges.

Dose Rate Constant – Λ: The dose rate constants calculated for each source model are presented in Table 2. The calculated values agree well with the reference values, with the largest observed difference being -1.63% for the Varisource VS2000 model compared to the values reported by Angelopoulos et al. (2000) [16]. Other models, such as microSelectron v.1

and Flexisource, also showed strong concordance with reference values, further validating the models used in this research.

Table 2 : Dose rate constants obtained in this work and their reference values.

Source model	**Λ – This research ($cGy.h^{-1}.U^{-1}$)**	**Λ – Reference (cGy.h-1.U-1)**	**Error (%)**
microSelectron v.1	1.114	1.115 [11]	-0.06
microSelectron v.2	1.110	1.108 [12]	0.16
Flexisource	1.106	1.109 [13]	-0.31
GammaMed Plus	1.108	1.118 [14]	-0.90
BEBIG GI192M11	1.114	1.108 [15]	0.55
Varisource VS2000	1.083	1.101 [16]	-1,63

3.2. Correction Factor for Calibration – K_{SG}

The K_{SG} values calculated in this study, normalized to the microSelectron v.1 source model. The excellent agreement between the calculated values and the reference values highlights the reliability of the developed methodology. For instance, the K_{SG} values for the GammaMed Plus and Flexisource models were within 0.1% of the reference values, indicating a high degree of precision.

The significance of these results is especially relevant for calibration laboratories. The minimal corrections required for most models (within 0.4%) suggest that the method developed in this study can be reliably applied for accurate determination of calibration correction factors (K_{SG}) across various source models used in HDR brachytherapy. For practical clinical applications, only corrections of 1.6%, such as those required for the Varisource VS2000 model, are significant.

4. CONCLUSIONS

In this study, the response of the PTW T33005 well chamber was characterized for six different Ir-192 brachytherapy source models using Monte Carlo simulations. The results showed variations in correction factors (K_{SG}) ranging from 0.984 to 1.001, indicating the importance of applying geometry correction factors to ensure accurate dosimetry in clinical settings. The methodology can be extended to other chamber and source models, ensuring higher reliability in the determination of air kerma rates and improving the effectiveness of brachytherapy treatments.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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