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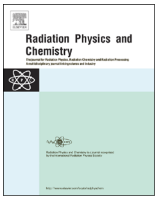

A new standard cylindrical graphite-walled ionization chamber for dosimetry in ^{60}Co beams at calibration laboratories

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HIGHLIGHTS

- A new cylindrical ionization chamber was developed to be used as a reference dosimeter.
- The characterization tests were performed according to the IEC 60731 standard.
- All tests presented results within its recommended limits.
- The correction factors were determined using the EGSnrc Monte Carlo code.
- This dosimeter presents potential use as a primary standard dosimeter.

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ABSTRACT

^{60}Co sources are used mostly at dosimetry laboratories for calibration of ionization chambers utilized for radiotherapy dosimetry, mainly in those laboratories where there is no linear accelerator available. In this work, a new cylindrical ionization chamber was developed and characterized to be used as a reference dosimeter at the Calibration Laboratory of the IPEN. The characterization tests were performed according to the IEC 60731 standard, and all tests presented results within its recommended limits. Furthermore, the correction factors for the wall, stem, central collecting electrode, nonaxial uniformity and the mass-energy absorption coefficient were determined using the EGSnrc Monte Carlo code. The air kerma rate determined with this new dosimeter was compared to the one obtained with the IPEN standard, presenting a difference of 1.5%. Therefore, the new ionization chamber prototype developed and characterized in this work presents potential use as a primary standard dosimeter at radiation metrology laboratories.

1. Introduction

According to IAEA recommendations (IAEA, 2000), the calibration of ionization chambers used for radiotherapy dosimetry follows the substitution method (Lamperti and O'Brien, 2001), which demands the use of a reference ionization chamber. Normally, clinical dosimeters are calibrated against a secondary standard, with traceability to a primary standard system. There are several ionization chamber types employed as primary standard systems, depending in which energy range they are supposed to be used. The most common ionization chamber, used as a primary standard for X-rays in the range of 7.5 kV–400 kV, is the free-air ionization chamber (Grimbergen et al., 1998), and for energies above those, as for instance for ^{137}Cs or ^{60}Co gamma radiation, air cavity ionization chambers (Chung and Yoo, 2007) are used.

The calibration procedure of ionization chambers also relies on the determination of several correction factors using Monte Carlo simulations. As shown by some authors (Sato et al., 2006; Araki et al., 2009), correction factors determined with Monte Carlo simulations differ from those reported in dosimetry protocols, such as those of the AAPM (1999) and IAEA (2000). Several effects that cannot be measured experimentally may be evaluated separately using Monte Carlo techniques for the determination of the correction factors.

At the *Bureau International des Poids et Mesures* (BIPM), the determination of the air kerma rates ($\dot{K}_{air}$) of ^{60}Co beams employs a parallel-plate ionization chamber, and the German primary standards dosimetry laboratory, *Physikalisch-Technische Bundesanstalt* (PTB) employs a set of three ionization chambers: two cylindrical and one parallel-plate, all made of high-purity graphite (Allisy et al., 2005). This is the same approach adopted by other

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Primary Standards Dosimetry Laboratories (PSDLs), though the geometry and sensitive volume sizes may vary (Allisy-Roberts et al., 2004). From these values of $\dot{K}_{air}$ it is possible to determine the absorbed dose in air or water, using the adequate conversion factors.

As in all of Latin America there is no PSDL for the measurement of $\dot{K}_{air}$ for ^{60}Co gamma radiation, all secondary systems have to be calibrated abroad. Therefore, in this work, a new cylindrical graphite ionization chamber was developed and characterized, to be used as a primary standard system for the determination of the $\dot{K}_{air}$ of ^{60}Co sources. This new ionization chamber has a sensitive volume of 2.40 cm^3 and it has walls, collecting electrode and body made of high-purity graphite, and stem and insulators made of Teflon®. The experimental characterization was based on the IEC 60731 (IEC 60731, 2011) standard and the correction factors were determined with the EGSnrc Monte Carlo code (Kawrakow et al., 2011).

2. Materials and methods

The new ionization chamber prototype developed and characterized in this work was of cylindrical shape and entirely made of high-purity graphite, with a sensitive volume of 2.40 cm^3 and a wall thickness of 4.0 mm, to allow electronic equilibrium for ^{60}Co radiation. The central collecting electrode has a diameter of 2.0 mm, and is 16.0 mm long. The support of the collecting electrode and the stem is made of Teflon®. The photo and scheme of this new prototype are shown in Fig. 1 and its physical characteristics are listed in Table 1.

The characterization tests were conducted according to the IEC 60731 standard (IEC 60731, 2011): saturation, ion collection efficiency, polarity effect, stability, leakage current, linearity of response and angular dependence, and all described in the following sections. These tests were undertaken utilizing an electrometer UNIDOS E, Physikalisch-Technische Werkstätten (PTW) Freiburg, Germany, and a ^{60}Co Gammatron II S80 system. The reference system adopted at the Calibration Laboratory of the IPEN (LCI) is a PTW Farmer-type ionization chamber, model TN30002, with traceability to the *Bureau International des Poids et Mesures* (BIPM) trough the Brazilian Secondary Standards Dosimetry Laboratory (SSDL), Instituto de Radioproteção e Dosimetria (IRD), located in Rio de Janeiro. The correction factors were calculated using the Monte Carlo simulations with the EGSnrc code (Kawrakow et al., 2011).

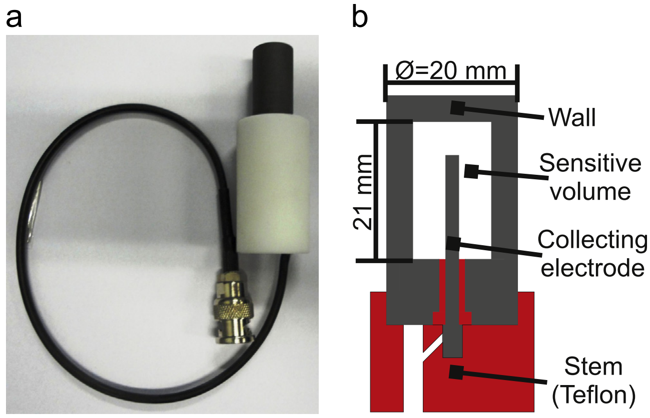

Fig. 1. (a) Photo and (b) schematic diagram of the new cylindrical graphite ionization chamber developed and characterized in this work.

Table 1
Technical specifications of the cylindrical graphite ionization chamber.

Component	Specifications
Collecting electrode and wall materials	Graphite
Body material	Graphite
Stem material	Teflon®
Collecting electrode material	Graphite
Insulator material	Teflon®
Internal diameter	12.0 mm
Wall thickness	4.0 mm
Sensitive volume length	21.0 mm
Connector	BNC
Sensitive volume	2.40 cm^3

The uncertainties associated with all experimental results in this work are expanded uncertainties, obtained by the combination of type A and B uncertainties (taking into account the environmental pressure and temperature, readings and positioning), using a coverage factor of 2. Each measurement was obtained by the mean value of ten consecutive measurements, in the same controlled conditions. In the Monte Carlo simulations, uncertainties arising from limitations of the Monte Carlo code and simplifications of the geometrical arrangement were not taken into account, although all dimensions of this dosimeter were determined prior to its assembly, and these values were used in the simulations. A more comprehensive discussion of the air kerma rate uncertainties is presented in Section 3.8.

3. Results and discussion

3.1. Saturation curve, ion collection efficiency and polarity effect

The saturation curve was obtained by measuring the ionization chamber response with applied voltages from −400 V to +400 V in 50 V steps. For all voltages applied no significant differences were observed in the collected charge, and the saturation was achieved in the whole tested interval, as shown in Fig. 2.

The ion collection efficiency was 99.9% for all applied voltages used in this work. The maximum polarity effect was 0.4% and, therefore, within the recommended limit of 1% (IEC 60731, 2011).

Considering these results, all other tests were performed using an applied voltage of +100 V. This value was also chosen in order to reduce the leakage currents that could be induced by higher voltages.

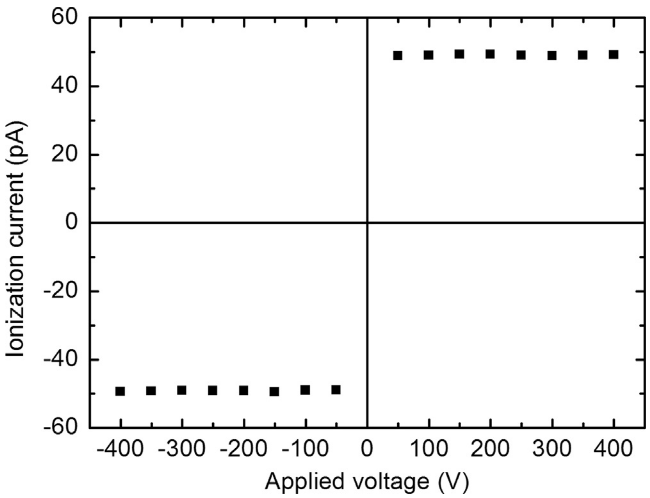

Fig. 2. Saturation curve of the ionization chamber developed in this work.

3.2. Short- and medium-term stabilities

The maximum variation for the short-term stability test was 0.05%, which is within the acceptable limit of 0.3% in accordance with the IEC standard (IEC 60731, 2011). In order to obtain the medium-term stability, the short-term values obtained were normalized to their mean value, for a period of time of three months, as shown in Fig. 3.

As can be seen in Fig. 3, all results were within the recommended limits of 0.5% (IEC 60731, 2011).

3.3. Leakage current

The leakage current was measured before and after all in beam (shutter open) measurements. The maximum value, reported as the percentage of the ionization current with the ionization chamber during the measurements with the shutter open, was 0.1%, satisfying the recommended maximum variation limit of 0.5% (IEC 60731, 2011).

3.4. Stabilization time

In the stabilization time test, the ionization currents measured after 15 min and 120 min of the connection with the electrometer were 99.9% of the value measured after a 60 min irradiation. These results are in accordance with the recommended variation of 0.5% (IEC 60731, 2011).

3.5. Linearity of response

In this test, the absorbed doses were varied from 12 mGy to 150 mGy, and the ionization currents were measured for six different doses. The results are shown in Fig. 4, normalized to the response at 12 mGy.

The correlation coefficient (R^2) of the linear fit was 0.99998, showing that the dosimeter presents a linear response.

3.6. Angular dependence

The ionization chamber response was evaluated as it was rotated around its central axis, from 0° to 360°, and the measurements were taken in 30° steps. A goniometer, OPTRON, model GN1 200, was employed to allow a precise rotation of the dosimeter, and ten measurements were conducted for each position. The results are shown in Fig. 5, and it is possible to observe that the variation was within the recommended limit of 0.5% (IEC 60731, 2011).

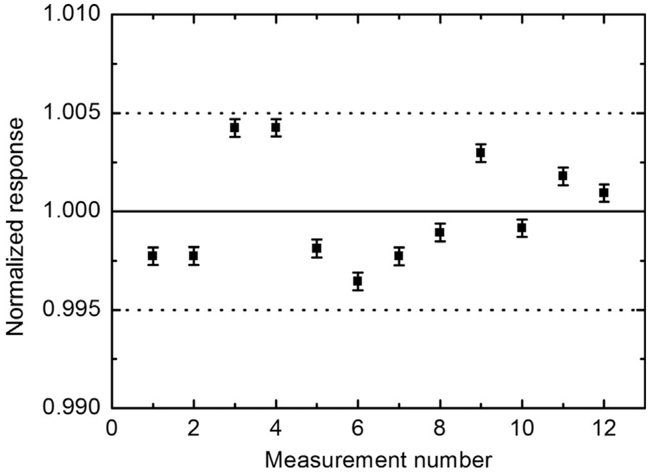

Fig. 3. Stability test of the graphite ionization chamber developed in this work for a period of three months. The dotted lines represent the recommended limit of 0.5% (IEC 60731, 2011).

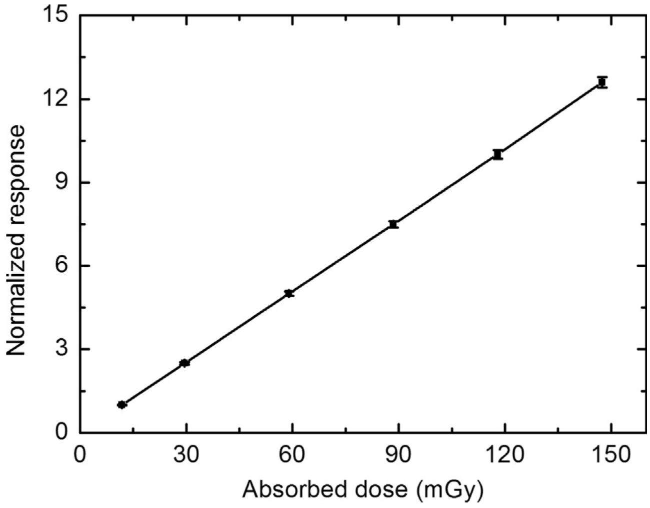

Fig. 4. Linearity of response of the ionization chamber.

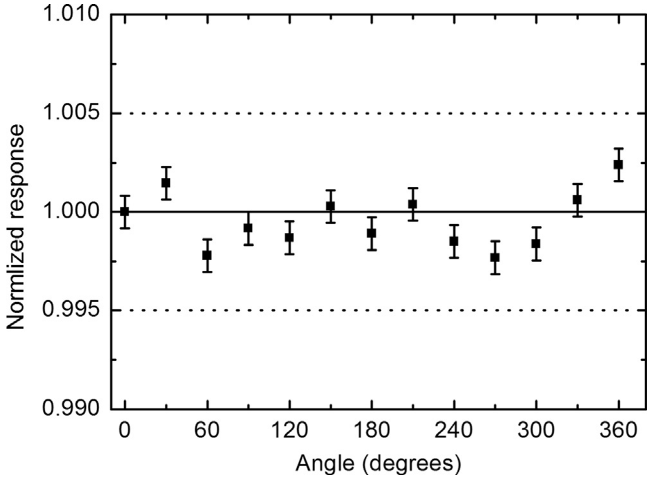

Fig. 5. Angular dependence test of the ionization chamber. The dotted lines represent the recommended limit of 0.5% (IEC 60731, 2011).

3.7. Correction factors

The correction factors were obtained using the EGSnrc Monte Carlo code (Kawrakow et al., 2011). This code is suitable for this task since it has libraries specially developed to calculate certain correction factors, such as wall, nonaxial uniformity and the mass-energy absorption coefficient. Other correction factors such as stem and central collecting electrode were determined as the ratio between the response of the ionization chamber without the studied component to that of the complete ionization chamber. In this work, 1×10^9 histories were simulated. The correction factors determined with the use of Monte Carlo simulations were: wall (k_{wall}), stem (k_{stem}), central collecting electrode (k_{elec}), and nonaxial uniformity (k_{an}). These values and uncertainties will be presented in Section 3.8.

The spectrum of the ^{60}Co Gammatron II S80 system was not available at the LCI, and as there was no access to its blueprints, the spectrum of the ^{60}Co source at the Swedish SSDL was used (Tedgren et al., 2010). This spectrum was already used to simulate this irradiation system, as presented in the work of Neves et al.

(2013). The results showed that it is very suitable for this application, and therefore, it was employed in this work.

3.8. Air-kerma rate determination

Using the ionization chamber developed in this work, the air kerma rate, $\dot{K}_{air}$, was determined for the ^{60}Co Gammatron II S80 system, employing Eq. (1) (Rogers and Kawrakow, 2003):

$$\dot{K}_{\text{air}} = \frac{I_{\text{gas}}}{m_{\text{air}}(1-\bar{g}_{\text{air}})}\left(\frac{W}{e}\right)_{\text{air}}\left(\frac{\bar{L}}{\rho}\right)^{\text{wall}}_{\text{air}}\left(\frac{\bar{\mu}_{\text{en}}}{\rho}\right)^{\text{air}}_{\text{wall}}\times \Pi k_{\text{cf}} \qquad (1)$$

where I_{gas} is the electric current measured in the ionization chamber cavity, with mass of air m_{air}; $\bar{g}_{\text{air}}$ is the fraction of energy dissipated outside the cavity due to Bremsstrahlung produced inside the cavity; W is the mean energy spent by an electron of charge e to produce a pair of ions in dry air; $(\bar{L}/\rho)^{\text{wall}}_{\text{air}}$ is the stopping power ratio between the wall and air; $(\bar{\mu}_{\text{en}}/\rho)^{\text{wall}}_{\text{air}}$ is the mass-energy absorption coefficient ratio of wall to air, and k_{cf} are the correction factors k_{an}, k_{wall}, k_{elec} and k_{stem} listed in Table 2.

The uncertainties of the physical constants and correction factors entering in the determination of the air kerma and their estimated relative uncertainties are presented in Table 2.

Some of the uncertainties in the Monte Carlo correction factors were already discussed in the literature. Since these values were higher than those calculated in this work, the non-statistical uncertainties were considered more significant. A brief discussion of these uncertainties (Type B uncertainties) is presented as follows:

- $(\bar{\mu}_{en}/\rho)^{air}_{wall}$: The choice of cross section data is the major source of uncertainty for this correction factor. Considering this, the value used by Burns (2006) of 0.04% was employed in this work.
- $(1-g_{ar})^{-1}$: Burns (2006) used a value of 0.02%, based on the uncertainty in the Bremsstrahlung cross section. The same value was utilized in this work.
- The uncertainty of the product $(\frac{\bar{L}}{\rho})^{wall}_{air}(\frac{W}{e})_{air}$ used by Burns (2006) for the BIPM ionization chamber was 0.11%, and it was similar to that used by Rogers and McCaffrey (2003) (0.12%). The highest value, 0.12%, was considered in this work.
- k_{an}: This correction factor was determined as a ratio of cavity doses, therefore, it is invariant with electron transport parameters. The source model may introduce errors as reported by Rogers and Kawrakow (2003), and the same uncertainty value (0.06%) was adopted in the present work.
- k_{wall}: As shown by Rogers and Kawrakow (2003), this correction factor is relatively insensitive to transport and interaction data. Rogers and Kawrakow (2003) and Burns (2006) determined this correction factor uncertainty, employing two different Monte Carlo codes, and the value adopted in this work (0.03%) was based on their considerations.

Table 2
Physical constants and correction factors entering in the determination of the air kerma rate and their estimated relative uncertainties.

Physical constants/correction factors	Values	Uncertainty (%)	
		Type A	Type B
Ionization current (pA)	–	0.07	0.05
Sensitive volume (cm^3)	2.40	–	1.04
Dry air density (kg/m^3)	1.293	–	0.01
$(1-g_{ar})^{-1}$	1.0024	–	0.02
$\left(\frac{W}{e}\right)_{air}$	33.97	–	0.12
$\left(\frac{\bar{L}}{\rho}\right)^{wall}_{air}$	1.0018		
$\left(\frac{\bar{\mu}_{en}}{\rho}\right)^{air}_{wall}$	0.9994	–	0.04
k_{an}	1.0011	–	0.06
k_{wall}	1.0167	–	0.03
k_{elec}	0.9976	0.11	–
k_{stem}	1.0058	0.57	–
Quadratic summation		0.58	1.05
Combined uncertainty		**1.18**	

Table 3
Air-kerma rates determined with the new cylindrical ionization chamber developed in this work and the LCI standard, a PTW TN 30002 ionization chamber with traceability to the BIPM, through the Brazilian SSDL. Both uncertainties are expanded uncertainties using a coverage factor of 2.

Ionization chamber	Air kerma rate (mGy/s)
New ionization chamber	0.590 ± 0.014
LCI standard (PTW TN 30002)	0.581 ± 0.018

The $\dot{K}_{air}$ value obtained with Eq. (1) and that obtained using the LCI standard are listed in Table 3. The uncertainty of the LCI standard was determined in accordance with the calibration certification that follows it.

Comparing the data presented in Table 3, it is observed that the air kerma rate determined with the new ionization chamber differs by 1.5% from that of the LCI standard, which was calibrated at the Brazilian SSDL, with traceability to the BIPM.

4. Conclusion

In this work, a new cylindrical ionization chamber was developed and characterized to be used as a reference dosimeter at the Calibration Laboratory of the IPEN. The characterization tests were conducted according to the IEC 60731 standard, and all tests yielded results within the specified tolerance limits. The correction factors for the wall, stem, central collecting electrode, nonaxial uniformity and the mass-energy absorption coefficient were determined using the EGSnrc Monte Carlo code. With these results, the air kerma rate could be determined with this new dosimeter, and it was compared to the one obtained with the LCI standard, presenting a difference of 1.5%. Therefore, the new ionization chamber prototype developed and characterized in this work has potential use as a primary standard dosimeter at calibration laboratories.

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