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Development and characterization of a graphite-walled ionization chamber as a reference dosimeter for ^{60}Co beams

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AUTHOR-HIGHLIGHTS

- A graphite ionization chamber was assembled and characterized as a reference dosimeter.
- The characterization test results were within recommended limits.
- Monte Carlo simulations were undertaken to obtain the correction factors.
- The air kerma rate of a ^{60}Co source was obtained with satisfactory results.

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ABSTRACT

A graphite-walled ionization chamber with a sensitive volume of 6.4 cm^3 was developed at the Calibration Laboratory of IPEN (LCI) to determine the air kerma rate of a ^{60}Co source. This new prototype was developed to be a simple chamber, without significant nongraphite components and with a simple set-up, which allows the determination of its various required correction factors by Monte Carlo simulations. This new ionization chamber was characterized according to the IEC 60731 standard, and all results were obtained within its limits. Furthermore, Monte Carlo simulations were undertaken to obtain the correction factors involved with the air kerma determination. The air kerma rate obtained with the graphite-walled ionization chamber was compared with that from the reference dosimeter at the LCI, a PTW ionization chamber (model TN30002). The results obtained showed good agreement within the statistical uncertainties.

1. Introduction

The ionization chamber is the most practical and widely utilized dosimeter type for accurate measurements in radiotherapy. It may be used as an absolute or a relative dosimeter. As an absolute dosimeter, it is possible to determine directly the air kerma or absorbed dose. The air kerma rates in ^{137}Cs and ^{60}Co gamma radiation fields are usually determined using thick walled graphite cavity ionization chambers.

The primary standards for air kerma in ^{60}Co beams are usually graphite walled ionization chambers assembled and maintained by primary standard calibration laboratories. These ionization chambers may have different configurations: cylindrical (Büermann and Burns, 2009), spherical (Delaunay et al., 2010) and parallel-plate (Burns et al., 2007a; Büermann and Burns, 2009). Its characterization process involves two methods: experiments and Monte Carlo (MC) simulations. The use of MC simulations has improved the accuracy and consistency of air kerma determinations when graphite ionization chambers are utilized as primary standards (Burns et al., 2007b). The MC simulation is essential to obtain the correction factors related to graphite ionization chambers, and it is the main part of the air kerma determination.

The development and characterization of a reference dosimeter in terms of air kerma in ^{60}Co beams is essential, because gamma radiation from ^{60}Co sources is used as reference radiation in the case of calibration of detectors. At the Calibration Laboratory of IPEN (LCI) some ionization chambers were developed and characterized for diagnostic radiology beams (Perini et al., 2012, 2013a) and radiotherapy beams (Neves et al., 2012; Perini et al., 2013b) for use in radiation dosimetry. They present metrological characteristics following international recommendations, and with the advantage of presenting a low-cost construction and knowledge of all dimensions and materials.

Recently a parallel-plate graphite ionization chamber was characterized as a reference instrument in ^{60}Co beams by Perini et al. (2013b). This ionization chamber presents some differences in relation to that developed and characterized in the present work.

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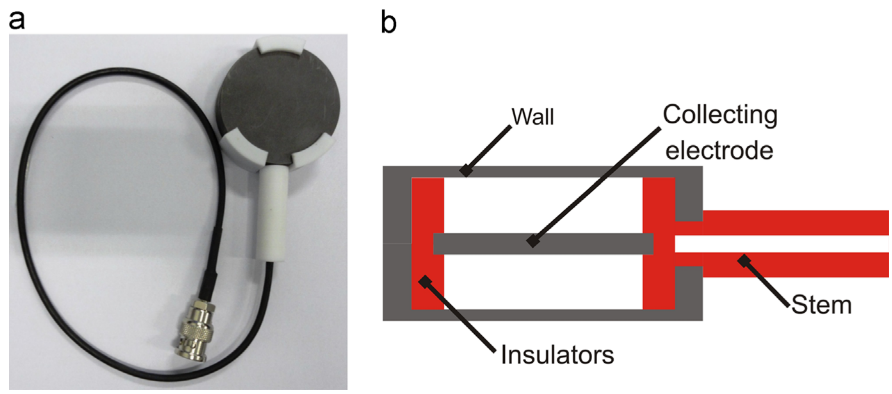

Fig. 1. (a) Photo and (b) scheme of the graphite ionization chamber developed at LCI.

The main differences are related to its project, including dimensions, sensitive volume and its design. As the LCI is responsible for a large number of clinical dosimeter calibrations utilizing the ^{60}Co source, the development and maintenance of reference dosimeters is very important for the air kerma determination in this laboratory. Up to now, at the LCI, the reference dosimeter has been a commercial ionization chamber (PTW, model TN30002). As this ionization chamber is a commercial one, its construction project is not well known, and this limits the application of the MC simulations to determine its correction factors.

In this work a new ionization chamber design was developed and characterized as a reference dosimeter for ^{60}Co beams. The main design criterion adopted was the obtaining of a simple chamber, without significant nongraphite components and with a simple design. This is crucial, because it allows the determination of several required correction factors, in particular the MC evaluation of the wall, electrode and stem.

The new ionization chamber was characterized according to the IEC 60731 standard (IEC, 2011). Some MC simulations were undertaken to determine the correction factors associated to the air kerma measurements. Besides the evaluation of a new design ionization chamber for ^{60}Co beam dosimetry, another contribution provided by this work is the development of a new system, composed of two ionization chambers, for the air kerma determination in ^{60}Co beams. With the use of this system, the air kerma rate may be obtained as the mean response of the ionization chamber presented in this work and that characterized in the work of Perini et al. (2013b), improving the accuracy in the calibration procedures. This technique is adopted in calibration laboratories (although with different ionization chambers), as at the German Primary Standard Laboratory Physikalisch-Technische Bundesanstalt (BIPM, 2005).

2. Materials and methods

A new graphite-walled ionization chamber, developed at the LCI, was manufactured using graphite, Teflon and co-axial cables. A photo and a scheme of this new prototype are shown in Fig. 1, and its technical specifications are listed in Table 1.

2.1. Experimental characterization

During all experimental measurements, the graphite-walled ionization chamber was connected to an electrometer, model UNIDOS E, Physikalisch-Technische Werkstätten (PTW) Freiburg, Germany. All measurements were corrected to the standard conditions of environmental temperature and pressure.

The irradiation conditions for the characterization tests were fixed at a reference field of 10 $\times$ 10 cm^2 using a Siemens/Gammatron II S80 irradiator unit. The reference system adopted at the LCI is a PTW Farmer ionization chamber, model TN30002. This reference system has traceability to the Bureau International des Poids et Mesures (BIPM).

Table 1
Technical specifications of the new prototype.

Characteristics	Specifications
Graphite density (g/cm^3)	1.77
Wall thickness (mm)	2.80
Internal diameter (mm)	45.0
Outer diameter (mm)	50.6
Collecting electrode diameter (mm)	41.0
Collecting electrode thickness (mm)	1.00
Chamber volume (cm^3)	6.40

For the angular dependence test, a goniometer, OPTRON, model GN1 200, was utilized.

The uncertainties of all reported results are expanded uncertainties utilizing a coverage factor of 2 (95% of confidence level).

2.2. Monte Carlo characterization

The Monte Carlo simulations were carried out using the EGSnrc code (Rogers et al., 2000) for radiation transport, in order to obtain several terms involved in the air kerma rate determination. The spectrum utilized in the simulations was provided by the Secondary Standard Dosimetry Laboratory of Sweden (Tedgren et al., 2010). At this laboratory there is a ^{60}Co source similar to the ^{60}Co unit at the LCI. The source spectrum of the Swedish laboratory was previously tested in the work of Neves et al. (2013), where experimental and simulation results were compared, indicating that this spectrum may be utilized to represent the spectrum of the LCI source. The actual spectrum of the ^{60}Co source of the LCI was not obtained due to two factors: the blueprints of the machine are not available to simulate the machine, and the LCI does not have a spectrometer suitable for ^{60}Co beams.

The number of histories utilized in each simulation was 10^9. The uncertainties of all MC results are Type A uncertainties utilizing a coverage factor of 2.

3. Results and discussion

3.1. Experimental results

3.1.1. Saturation, ion collection efficiency and polarity effect

From the saturation curve test the optimal voltage was determined for the ionization chamber operation. A saturation curve was obtained varying the voltage from −400 V to +400 V, in steps of 50 V, using the charge collecting time of 15 s. This test was performed using the ^{60}Co source. For all applied voltage values, no significant changes in the collected charge were observed. The chosen applied voltage for this new prototype was +100 V. This voltage was adopted for all further characterization tests.

Two other characteristics were analyzed using the saturation curve data: the polarity effect and ion collection efficiency. The polarity effect was obtained utilizing (IAEA, 2001)

$$K_{pol} = \frac{|M_+| + |M_-|}{2M} \quad (1)$$

where M_+ and M_- are the electrometer readings obtained at positive and negative polarities, respectively, and M is the electrometer reading obtained with the polarity used routinely (positive or negative). For all pairs of voltage values in the saturation test, the polarity effect did not exceed the recommended limit of 1% (IEC, 2011). The highest value obtained in this test was 0.49%.

The ion collection efficiency was obtained taking into consideration the collected charges and the two polarity voltage method, given by (IAEA, 2001)

$$K_s = \frac{(V_1/V_2)^2 - 1}{(V_1/V_2)^2 - (M_1/M_2)} \quad (2)$$

where M_x is the collected charge at a V_x voltage, and $V_1/V_2 = 2$. For $V_1 = 200$ V (or −200 V) and $V_2 = 100$ V (or −100 V), the ion collection efficiency was better than 99.999% for both polarities.

3.1.2. Short- and medium-term stabilities

The chamber response was tested in relation to its stability (short- and medium-term stabilities). The prototype was repeatedly exposed to ^{60}Co source under reproducible geometric conditions. The short-term stability test was obtained by taking ten readings of charge, during time intervals of 15 s. The maximum variation observed was 0.25%, this value is within the limit recommended internationally (0.3%) (IEC, 2011).

The medium-term stability test was obtained by taking the medium value of ten measurements of the short-term stability tests during a period of 2 months (Fig. 2). According to IEC 60731 (IEC, 2011), the value obtained in each test must not differ from the reference value by more than 0.5%. As shown in Fig. 2, all deviations were within the acceptable range.

3.1.3. Leakage current

The leakage current of the graphite-walled ionization chamber was measured in time intervals of 20 min, before and after its irradiation, and the maximum value obtained was 0.39% of the ionization current produced during the irradiations. This value is within the limit recommended internationally of 0.5% of the ionization current during the irradiations (IEC, 2011).

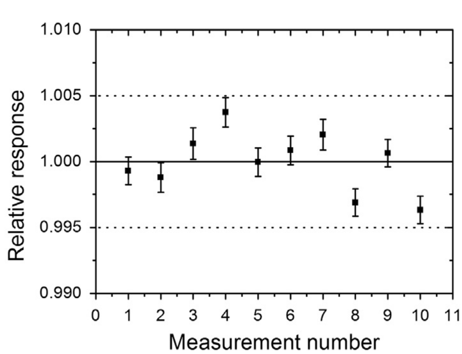

Fig. 2. Medium-term stability of the new prototype obtained with the ^{60}Co source. The dotted lines represent the maximum limit recommended by the IEC 60731 standard (IEC, 2011).

3.1.4. Linearity of response

The linearity of response test of the graphite-walled ionization chamber was studied as the collected charge as a function of the absorbed dose in the ^{60}Co beam. A linear fit of the chamber response versus absorbed dose was obtained, and the uncertainty in the angular coefficient was only 0.01%, with a correlation coefficient R^2 of 1.000. Therefore, the ionization chamber presented a linear behavior.

3.1.5. Angular dependence

In the angular dependence test, the ionization chamber was rotated around its central axis from −5° to +5°, in steps of 1°, utilizing the goniometer. By the IEC 60731 recommendations (IEC, 2011), the value obtained in each angle must not differ from the 0° position by more than 0.5%. The maximum variation obtained was only 0.2%, and therefore within the recommended limit, as shown in Fig. 3.

3.2. Monte Carlo results

The EGSnrc MC code was utilized to determine the terms involved in the air kerma determination (IAEA, 2009):

$$K_{air} = \frac{Q_{gas}}{m_{air}(1-\overline{g}_{air})}\left(\frac{W}{e}\right)_{air}\left(\frac{\overline{L}}{\rho}\right)^{wall}_{air}\left(\frac{\overline{\mu}_{en}}{\rho}\right)^{air}_{wall} \times \prod K_i \quad (3)$$

where Q_{gas} is the charge released in the air of mass m_{air} ; $\overline{g}_{air}$ is the fraction of the energy of an electron lost in radioactive events while slowing in air; $(W/e)_{air}$ is the energy lost in dry air per Coulomb of charge released; $(\overline{L}/\rho)^{wall}_{air}$ is the Spencer Attix collision mass stopping-power ratio for the wall material to dry air; $(\overline{\mu}_{en}/\rho)^{air}_{wall}$ is the ratio of mass energy absorption coefficients averaged over the spectrum for dry air to the wall material and K_i are the correction factors: K_{elec} the electrode correction factor; K_{wall} the wall correction factor; K_{an} corrects for the axial non-uniformity due to the point source nature of the beam instead of the photon beam being parallel, and K_{stem} the stem correction factor.

The correction factor for the wall (K_{wall}) was determined utilizing the `cavrznrc` code; the $(\overline{L}/\rho)^{wall}_{air}$ was calculated using the `sprrznrc` code; the $(1-\overline{g}_{air})^{-1}$ was calculated by the user code `g` and the $(\overline{\mu}_{en}/\rho)^{air}_{wall}$ was calculated using the `dosrznrc` code (Rogers et al., 2000).

To determine K_{elec} and K_{stem}, the C++ advanced EGSnrc application user code `cavity` was employed. In this case, the correction factors were determined as the ratio of the dose to the gas in the ionization chamber without the studied component (stem and electrode) to that with the studied component.

The MC results obtained are shown in Table 2. The air kerma rate obtained with the graphite-walled ionization chamber was

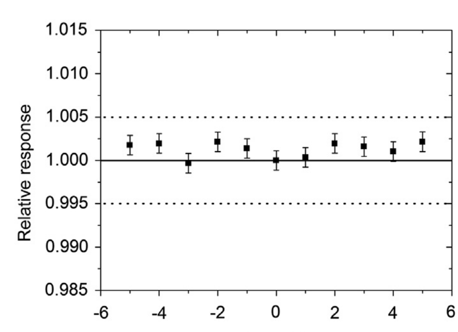

Fig. 3. Angular dependence of the new prototype obtained with the ^{60}Co source. The dotted lines represent the maximum limit recommended by the IEC 60731 standard (IEC, 2011).

Table 2
Results obtained with Monte Carlo simulation of the terms for the air kerma determination.

Correction factor	Value
$(\overline{\mu}_{en}/\rho)^{air}_{wall}$	0.9994 ± 0.0014
$(1-\overline{g}_{air})^{-1}$	1.0024 ± 0.0004
$(\overline{L}/\rho)^{wall}_{air}$	1.0018 ± 0.0002
K_{an}	0.9978 ± 0.0017
K_{wall}	1.0051 ± 0.0001
K_{elec}	0.9998 ± 0.0008
K_{stem}	0.9993 ± 0.0024

compared to the air kerma rate determined with the reference ionization chamber (PTW, model TN30002), currently utilized at the LCI. The air kerma rate values were obtained on March 2013, and the measured values were (0.596 ± 0.012) mGy/s and (0.589 ± 0.018) mGy/s obtained with the graphite-walled ionization chamber and the PTW ionization chamber, model TN30002, respectively. These results show that these values present an excellent agreement within the statistical uncertainties.

4. Conclusion

In this work, a new graphite-walled ionization chamber was designed, assembled and tested. This new prototype was developed to be a simple chamber, without significant nongraphite components and with a simple design, which allows the determination of its various required correction factors by MC simulations. Furthermore, it has a different project, dimensions and sensitive volume size of another ionization chamber previously developed at the LCI. This fact enables the determination of the air kerma as the mean value between two different standard dosimeters. Several characterization tests of this chamber were evaluated and compared to international recommended limits, with very satisfactory results. The Monte Carlo simulations were utilized to determine the correction factors involved in the air kerma determination. All correction factors obtained are near the unity, showing that the material (graphite) and dimensions of the ionization chamber are adequate to characterize it as a reference dosimeter for ^{60}Co beams. The air kerma rate obtained with the graphite-walled ionization chamber was also satisfactory, when compared with that obtained with the commercial ionization chamber (PTW, model TN30002). Therefore, the graphite ionization chamber projected, assembled and characterized in this work presents potential use as a reference dosimeter at calibration laboratories.

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