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Response and Monte Carlo evaluation of a reference ionization chamber for radioprotection level at calibration laboratories

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HIGHLIGHTS

- A special ionization chamber, inserted in a slab phantom, was designed and evaluated.
- This dosimeter was utilized for the $H_p(10)$ determination.
- The evaluation of this dosimeter followed international standards.
- The PENELOPE Monte Carlo code was used to evaluate the design of this dosimeter.
- The tests indicated that this dosimeter may be used as a reference dosimeter.

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ABSTRACT

A special parallel plate ionization chamber, inserted in a slab phantom for the personal dose equivalent $H_p(10)$ determination, was developed and characterized in this work. This ionization chamber has collecting electrodes and window made of graphite, and the walls and phantom made of PMMA. The tests comprise experimental evaluation following international standards and Monte Carlo simulations, employing the PENELOPE code to evaluate the design of this new dosimeter. The experimental tests were conducted employing the radioprotection level quality N-60 established at the IPEN, and all results were within the recommended standards.

1. Introduction

One of the first steps to maintain an accurate measurement system is to evaluate the performance of the dosimetric equipment (as ionization chambers) and the characteristics of the X-ray qualities utilized at calibration laboratories (IAEA, 2007).

Since body related dose quantities, such as the effective dose, are not directly measurable and cannot be used directly in radiation protection monitoring, operational quantities, such as the "personal dose equivalent" and "ambient dose equivalent" were defined (ICRU, 1993). For purposes of routine radiation protection, it is desirable to characterize the potential exposure of individuals in terms of a single dose equivalent quantity. For individual monitoring, the $H_p(10)$ was created, that is the dose equivalent in tissue at the depth of 10 mm below a specified point in the human body (10 mm is used for strongly penetrating radiation beams).

For calibration of personal dosimeters, different types of phantoms, i.e., phantoms consisting of water, PMMA, ICRU tissue-equivalent material, polycarbonate, among others, are necessary to satisfy the $H_p(10)$ definition. In this scenario, Ankerhold et al. (2001) developed the first prototype of a secondary standard ionization chamber to measure the personal dose equivalent $H_p(10)$ (Ankerhold et al., 2001, 1999) and other quantities such as the H*(10) (Ankerhold, 2006; Hupe and Ankerhold, 2007).

Considering that the calibration of instruments used in radioprotection measurements is essential for monitoring procedures, and that about 20% of the instruments used in those routines present problems during their calibration and may require some adjustments (Green et al., 1999), special methodologies for the calibration of these kinds of instruments were established at the Calibration Laboratory of IPEN (Potiens and Caldas, 2002), as well as the development of new dosimeters to be employed as reference systems (Maia and Caldas, 2005; Perini et al., 2012). The methods may be applied in the calibration procedures of personal

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dosimeters such as those used for radiation protection measurements, instruments utilized in direct beams, and quality control of instruments in many different applications (Hupe and Ankerhold, 2006; Bartlett, 2006).

At the Calibration Laboratory (LCI) of the Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN-SP), a new dosimeter was developed, intended to be used as a reference instrument for the determination of the $H_p(10)$. In this dosimeter, the ionization chamber is inserted in a slab phantom, which allows the direct measurement of the $H_p(10)$, without the use of correction factors. The main differences of this dosimeter and another one recently reported (Silva et al., 2011) are the dimensions, sensitive volume and the use of graphite as collecting electrode material, as well as the guard ring (instead of a PMMA plate coated with graphite). Furthermore, in this work, several operational tests were presented, in order to fully characterize this dosimeter, and the responses compared to international standards (IEC, 1997, 2011).

The objective of this work was to develop and characterize a new plane parallel ionization chamber, to be applied as a reference standard for the determination of the $H_p(10)$ at the LCI. This characterization was carried out employing the IEC 61674 and IEC 60731 standards (IEC, 1997, 2011) and Monte Carlo simulations. The simulations were used to evaluate the influence of the collecting electrode, guard ring and screws on the energy deposition at the sensitive volume.

2. Materials and methods

The plane parallel ionization chamber, built at the LCI, has a graphite collecting electrode and a window made of a very thin layer (about 0.032 mm in thickness) of graphite ink. It also has an inner graphite electrode, composed of a ring of 50 mm in diameter and 2 mm in thickness, a guard ring made of graphite with 100 mm in diameter, and a hole in the center with 50.5 mm in diameter (assembled as the ionization chamber developed by Ankerhold et al., 2001). The slab phantom, where the ionization chamber is inserted, was developed with 12 PMMA plates juxtaposed. These plates are all connected with PMMA pins, in order to support the plates and the ionization chamber.

The painting process of the electrode was obtained as follows: the PMMA disk and parts were cleaned, to remove dust, oil and moisture; after that, the material was heated until 35 °C for 5 min (to dry the disk); the plates were inserted in a rotary system (a dish with constant speed) for the application of the graphite spray (Aerodag G™). This technique allows a better homogeneity in the disk. At the end of the painting process the material was dried again, but now with 30 °C, during 15 min. Many initial tests were carried out (with different kinds of inks) until the best ink was selected. A scheme of the ionization chamber developed and characterized in this work is shown in Fig. 1.

A Pantak/Seifert X-ray generator, model ISOVOLT 160HS (160 kV), was utilized for the tests. The X-ray qualities, radioprotection level (ISO, 1997), established in this equipment are listed in Table 1. The air kerma rates were determined using a standard ionization chamber, traceable to the German Primary Dosimetry Laboratory, Physikalisch-Technische Bundesanstalt (PTB). This ionization chamber is a Physikalisch-Technische Werkstätten (PTW), model 32002, with a sensitive volume of 1000 cm^3, and it was connected to a PTW electrometer, UNIDOS 10001. This is a secondary standard dosimeter for X-ray beams, radioprotection level.

The assembled ionization chamber was tested in relation to its operational characteristics according to the recommendations of the IEC 61674 and IEC 60731 standards (IEC, 1997, 2011) depending on the tests. For all tests in this work the ISO N-60 X-ray beam

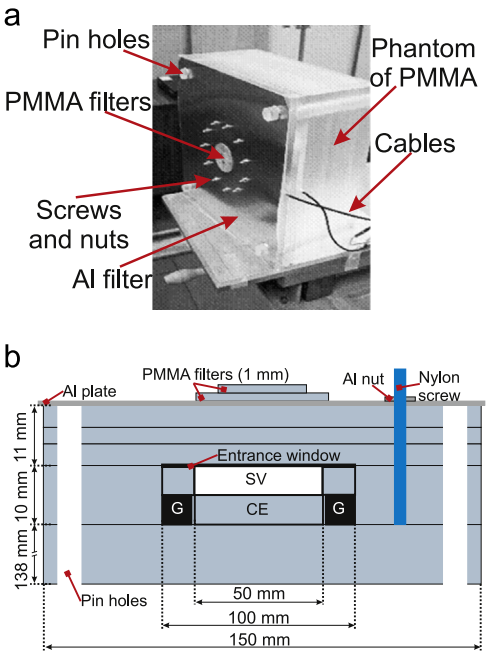

Fig. 1. (a) Photo of the ionization chamber inserted in a slab phantom (PMMA, with dimensions of 300 mm × 300 mm × 150 mm), and (b) detailed scheme where it is possible to observe the ionization chamber and its main components, as the sensitive volume (SV), collecting electrode (CE), and guard ring (G). In (b) some components are out of proportion for a better visualization.

Table 1
Characteristics of the X-ray qualities, radioprotection level, established at the Calibration Laboratory of IPEN, as recommended by ISO (1997).

Radiation quality	Voltage (kV)	Additional filtration[a] (mm)	HVL (mmCu)	Air kerma rate[b] (mGy h^{-1})
N-60	60	0.60(Cu)	0.250	19.90
N-80	80	2.00(Cu)	0.612	10.50
N-100	100	5.00(Cu)	1.14	5.01
N-150	150	2.50(Sn)	2.40	41.50

[a] In all cases, 4.0 mm of Al was added to the Cu and Sn filtration.
[b] Air kerma rates for a focus-chamber distance of 2.5 m, X-ray tube current of 20 mA and a circular field diameter of 42.0 cm.

recommended by ISO 4037-1 (ISO, 1997) was utilized.

The simulations of this new dosimeter were carried out with the PENELOPE/penEasy Monte Carlo code for radiation transport (Salvat et al., 2008; Sempau et al., 2011). As this new dosimeter was developed at the LCI, all dimensions and materials are known, and they were used as input for the simulations. The spectrum of the LCI irradiation system was not available, and therefore, the one used in the simulations was obtained experimentally from the PTB (Büermann, 2004).

The industrial X-ray unit, Pantak Seifert, model ISOVOLT 160 HS operates from 5 to 160 kV, has a 0.8 mmBe window and a W-anode angle of 21°. The spectra from PTB were acquired in a 450 kV Yxlon facility with a tube of type "B450-1H450" from Thales, at a distance of 100.0 cm from the X-ray focus. The W-anode angle was 21° and the window was 7.0 mmBe. As shown elsewhere (Perini et al., 2013), for CT radiation qualities, the difference between experimental measurements and simulated results was below 3.0%, but still within the expanded statistical (type A) uncertainties. These results pointed out that the PTB spectra may be employed to represent the LCI equipment. In this work, the spectrum representing the ISO N-60 radiation quality (the standard radiation quality at the LCI), was employed for all the simulations.

Table 2
Parameters used in the PENELOPE code.

Parameter[a]	Value
E_{abs}	1 keV
C_1	0.05
C_2	0.05
W_{CC}	0.1 keV
W_{CR}	1 keV
s_{max}	10^{30} cm
Number of histories	

[a] More details regarding these parameters may be found in Salvat et al. (2008).

The parameters used in the PENELOPE code are listed in Table 2. These parameters were the same for all the materials, including the air in the sensitive volume. In the simulations, photon and electron transport was discontinued below $E_{abs} = 1$ keV. The other parameters for electron tracking were: the average angular deflection (C_1); the maximum average fractional energy loss between consecutive hard elastic events (C_2); cutoff energy loss for hard inelastic collisions (W_{CC}) and the cutoff energy loss for hard Bremsstrahlung (W_{CR}). The maximum allowed step length (s_{max}) was set to 10^{30} cm, to switch off the external step-length control.

The influence of the ionization chamber components was determined as the ratio of the energy deposited to the gas in the sensitive volume, with the different material, to that of the complete ionization chamber. In this work, the influence of the collecting electrode, guard ring and nylon screws were evaluated. The influences of the collecting electrode and guard ring on the chamber response were determined by substituting its constituent materials by air, and scoring the energy deposited in the sensitive volume. For the screws, nylon was substituted by PMMA.

The uncertainties of all experimental studies in this work are expanded uncertainties, obtained by the combination of the type A and B uncertainties, with a coverage factor of 2. The type B uncertainties considered were obtained from the calibration certificates of the equipments: electrometer, thermometer, barometer, monitoring chamber, and error in the equipment positioning at the calibration bench. The same coverage factor was adopted for the uncertainties (type A) of the Monte Carlo simulations.

3. Results and discussion

The experimental characterization tests as well as the simulations with the Monte Carlo code are presented in two different sections.

3.1. Experimental characterization

The ionization chamber was studied in relation to its operational characteristics: saturation curve, polarity effects, ionic recombination, stabilization time, short-term stability, long-term stability, leakage current without irradiation, leakage current after irradiation, and linearity of response.

3.1.1. Saturation curve

Ionization chambers shall be operated in their saturation region to assure that small changes in their bias voltage do not change the collected charge. It is very important to define its initial and final bias voltages, to determine the nominal voltage to be used; in this work, it was chosen as +400 V. At this voltage level, the ionic recombination is very low, and therefore, it does not affect the operation of the dosimeter.

Table 3
Response of the ionization chamber for the saturation test in the ISO N-60 X-ray quality beam. The uncertainties in the results are lower than ±0.3%.

Polarizing voltage (V)	Mean value of measurements (pA)	Polarizing voltage (V)	Mean value of measurements (pA)
+50	386.01	−50	−380.93
+100	386.33	−100	−381.50
+150	387.63	−150	−379.36
+200	387.64	−200	−383.81
+250	389.37	−250	−380.08
+300	388.94	−300	−383.27
+350	389.00	−350	−383.85
+400	389.50	−400	−384.50

In this test, the ionization chamber was exposed to the standard X-ray beam quality N-60. The bias voltage was varied from −400 V to +400 V, in steps of 50 V. The saturation was reached at ±50 V. The ionization currents were always obtained from the mean values of ten consecutive measurements. The IEC 60731 (IEC, 2011) standard recommends for this test a maximum variation in the response of the ionization chamber in the range of the initial bias voltage (50 V) until the maximum bias voltage applied to the chambers of 1% (maximum response change). Table 3 and Fig. 2 show that the ionization chamber complies the limits recommended by the IEC 60731 (IEC, 2011) standard.

3.1.2. Polarity effect

For the test of polarity effect, the ratio between the positive and negative charges collected from the ionization chamber should not be greater than 1%, or the ratio should be between 0.99 and 1.01 (IEC, 2011). The bias voltage applied to the ionization chamber for this test was from ± 50 V to ± 400 V (in 50 V steps), and the respective electric charge was collected for 60 s. The ionization current was then obtained from the average of ten consecutive measurements of electric charge, divided by the charge collecting time.

In Table 4, the results obtained agree with the maximum variation recommended by the IEC 60731 standard (IEC, 2011), except for the voltages of ±150 V and ±250 V. As a result, the voltage of +400 V was chosen as the standard voltage.

3.1.3. Ionic recombination

The ion collection efficiency shall be better than 99%, as recommended by the IAEA-TRS 398 report for ionization chambers

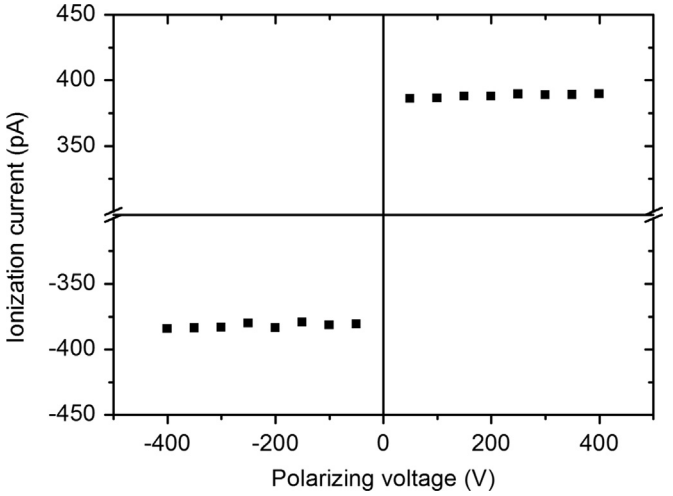

Fig. 2. Saturation curve of the ionization chamber. A break was inserted in the *y*-axis between −300 pA and 300 pA for better visualization. The uncertainties in the results are lower than ±0.3%, and therefore not visible in the figure.

Table 4
Response of the ionization chamber for the polarity effect test in X-ray beams (ISO N-60). Q^+ and Q^- are the collected charges with application of the positive/negative polarizing voltages. The uncertainties in the results were all lower than ±0.3%.

Polarizing voltage (V)	Ratio (Q^+/Q^-)
+50/−50	1.01
+100/−100	1.01
+150/−150	1.02
+200/−200	1.01
+250/−250	1.02
+300/−300	1.01
+350/−350	1.01
+400/−400	1.01

(IAEA, 2009). The ion collection efficiency for the ionization chamber was determined by Eq. (1), and using the electric charges obtained in the tests of polarity effects for the selected bias voltage of ±200 V and ±400 V:

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

where K_s is the ion collection efficiency, M_1 and M_2 are the measurements at the polarizing voltages of V_1 and V_2 ($V_1/V_2=2$).

The results obtained for the ionization chamber were 1.002 for the polarizing voltage of +400 V and 1.001 for the polarizing voltage of −400 V. These results are in agreement with the value of at most 5% of ionic recombination losses recommended by IEC 61674 (IEC, 1997), presenting an ion collection efficiency better than 99%. The uncertainties in the measurements were lower than ±0.3% (corresponding mainly to the electrometer uncertainties).

3.1.4. Response stabilization time

In this test, the ionization chamber was irradiated (continuously) during 2 h, after the bias voltage application, in a X-ray beam, ISO N-60. The measurements were taken after time intervals of 15 min, 1 h and 2 h. The charges obtained were normalized to the values measured after 1 h. The IEC 61674 standard (IEC, 1997) recommends that the maximum response variation of the ionization chamber should not be greater than ±2.0% of the measurements, which was observed.

3.1.5. Short-term stability

Ten successive measurements, corrected to the environmental reference conditions, were taken with the ionization chamber exposed to the X-ray beam quality ISO N-60. The experimental standard deviation was 0.3% for the tested ionization chamber. This result meets the IEC 61674 (IEC, 1997) requirement, which states that the variation shall not exceed ±1.0% of the mean output value.

3.1.6. Long-term stability

Ten successive measurements were taken in X-ray beam qualities ISO N-60, during 25 weeks. The long-term stability test checks the reproducibility of the ionization chamber response. The variations on the responses were not greater than 3.0%, which meets the IEC 61674 (IEC, 1997) requirements. Fig. 3 presents these results.

3.1.7. Leakage current

The leakage current was measured in time intervals of 20 min, before and after the irradiation. The highest value obtained was 0.4% of the ionization current produced at the minimum air kerma rate applied in this work. This value is within the 5% limit recommended internationally (IEC, 1997).

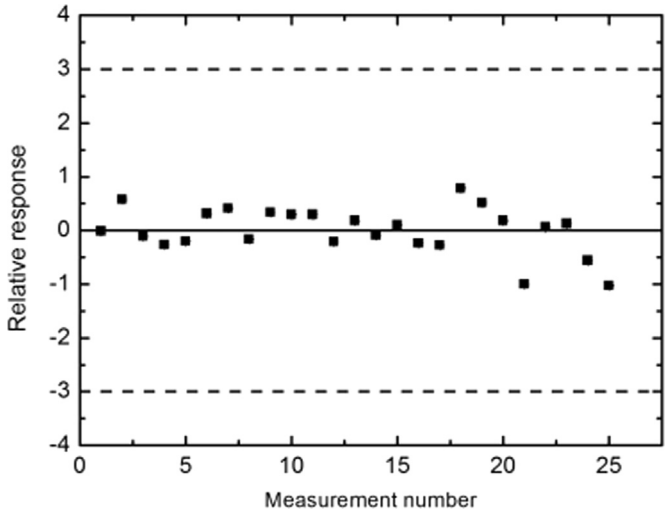

Fig. 3. Long-term stability of the ionization chamber. The dashed lines represent the limits of ±3.0% (IEC, 1997).

3.1.8. Linearity of response

The linear relationship between the ionization current and the air kerma rate was determined by irradiating sequentially the ionization chamber in the X-ray beam quality ISO N-60, and varying the tube current from 0.5 mA to 45 mA. The ionization chamber was positioned in the radiation field at a distance of 2.5 m from the focal spot of the X-ray tube, taking the center of the sensitive volume of the ionization chamber as the reference point. The air kerma rates were determined by utilizing the reference standard ionization chamber (PTW 32002, 1000 cm^3).

The obtained data are presented in Fig. 4. The straight line is the result of a linear fit to these data. The ionization chamber shows good results, i.e., it presents a linear response as a function of the air kerma rate.

3.2. Monte Carlo evaluation

As a second characterization study, Monte Carlo simulations were carried out, to evaluate the influence of the different constituent materials of this new ionization chamber. This evaluation

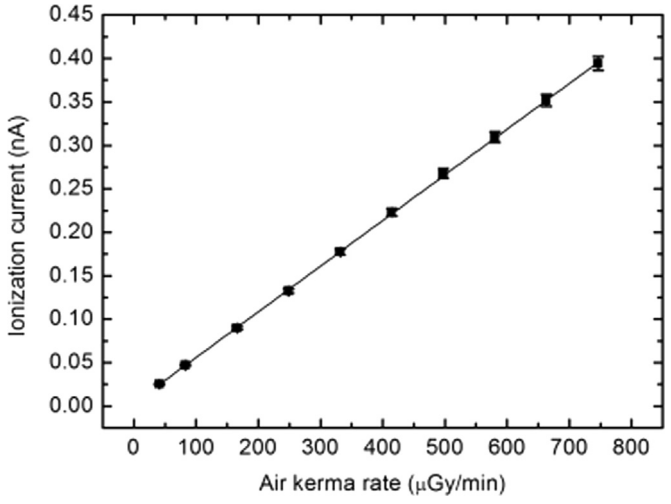

Fig. 4. Response linearity of the ionization chamber as a function of the air kerma rate, for the X-ray quality, radioprotection level, ISO N-60.

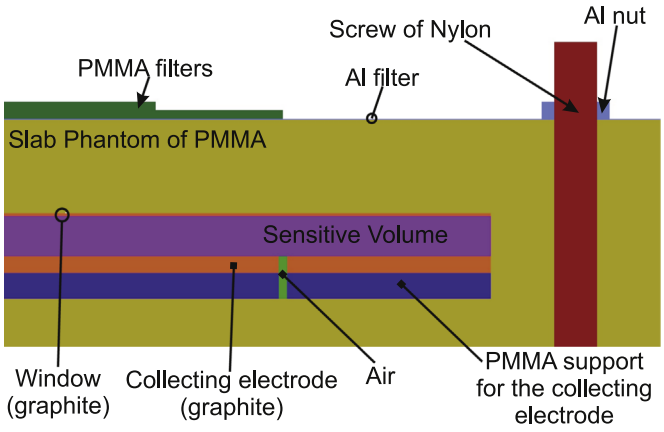

Fig. 5. Geometry employed in the PENELOPE/penEasy code. In order to allow a better visualization of the details in the simulation, this figure is a cut of the whole chamber – the middle upper right portion of the dosimeter.

Table 5
Influence of the studied components on the ionization chamber response.

Component evaluated	Ratio of the energy deposition[a]	Influence (%)
Collecting electrode	0.06 ± 0.01	6.0
Guard ring	0.11 ± 0.02	11.0
Screws	0.009 ± 0.001	0.9

[a] Determined as: (response without the studied component)/(response of the complete chamber).

was important to determine if the components and materials could be reorganized or substituted in order to produce a lower influence on the measurements. This type of evaluation would be time consuming and, in some cases, impossible to realize experimentally.

The PENELOPE/penEasy code was employed to study the influence on the chamber response of the collecting electrode and guard ring, as well as the use of PMMA as the material for the screws instead of nylon. The geometry of the ionization chamber is shown in Fig. 5. The influences of the evaluated components are shown in Table 5.

There are no data in the literature for the evaluation of the ionization chamber presented in this work, but one may consider that the electrode influence was considerably low, comparing with the values from the literature, which may be up to 50.0%, as presented in the work of Muir and Rogers (2011). The same conclusion applies for the guard ring, which is undoubtedly important to delimit the sensitive volume and reduce the leakage current. The use of PMMA screws instead of nylon presents the advantage of a more homogeneous phantom, but they are more fragile than the nylon ones. Besides that, its influence was of just 0.9%.

4. Conclusions

An ionization chamber was tested in accordance to the international recommendations at the Calibration Laboratory of Instituto de Pesquisas Energéticas e Nucleares, employing radioprotection level beam qualities. It showed a satisfactory performance in the X-ray standard beams ISO N-60. The results obtained show that the ionization chamber can be used as a work reference system, including intercomparison programs among laboratories. The Monte Carlo simulations showed that this new ionization chamber project was optimized for $H_p(10)$ measurements, because it presents robustness and a suitable choice of materials that composes the dosimeter.

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