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# Characterization of an extrapolation chamber for low-energy X-rays: Experimental and Monte Carlo preliminary results

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ABSTRACT

The extrapolation chamber is a parallel-plate ionization chamber that allows variation of its air-cavity volume. In this work, an experimental study and MCNP-4C Monte Carlo code simulations of an ionization chamber designed and constructed at the Calibration Laboratory at IPEN to be used as a secondary dosimetry standard for low-energy X-rays are reported. The results obtained were within the international recommendations, and the simulations showed that the components of the extrapolation chamber may influence its response up to 11.0%.

## 1. Introduction

An extrapolation chamber is a special type of parallel-plate ionization chamber where it is possible to vary its sensitive volume air mass, through the variation of the distance between the collecting electrode and the entrance window, or chamber depth (Zankowski and Podgors, 1997). In general extrapolation chambers are used for measuring electron beams where the perturbation effect is more significant. Another application is the measurement of absorbed doses near the surface of a medium.

Nowadays, some correction factors for primary standards for radiation detection have been determined using Monte Carlo techniques (Wulff et al., 2008), which allow results to be more accurate than those obtained by experimental approaches. Moreover, it is possible, through this technique, to get a better knowledge about the physical aspects of each factor utilized in experimental measurements (Burns, 2003; Selvam et al., 2005; Burns, 2006).

At the Calibration Laboratory of IPEN (LCI) some tests were performed in order to calibrate and characterize extrapolation chambers for weakly-penetrating types of radiation (beta- and low-energy X-rays). Recently, a PTW extrapolation chamber model 23391 was calibrated utilizing three $^{90}$Sr+$^{90}$Y sources of different activities (Antonio et al., 2012). Furthermore, in a previous work, a homemade extrapolation chamber designed and constructed at LCI for the calibration of planar beta applicators (Dias and Caldas, 1998) was characterized for low-energy X ray dosimetry (Dias and Caldas, 2001). This homemade extrapolation chamber was tested for low-energy X-rays, utilizing the tube voltage in the interval of 25–50 kV in the following tests: linearity of response, extrapolation curves and energy dependence.

In the present work, this homemade extrapolation chamber was characterized utilizing a tube voltage of 50–100 kV, and some important tests were undertaken as follows: linearity of response, saturation curve, ion collection efficiency and polarity effect. Moreover, this homemade extrapolation chamber was simulated using the MCNP-4C code. This simulation was validated comparing the extrapolation curve determined experimentally and using the Monte Carlo code. This technique was also applied to determine the influence of the component materials of this ionization chamber on its response.

## 2. Materials and methods

The extrapolation chamber presently studied has a collecting electrode (30 mm in diameter and thickness of 3.0 mm) and a guard ring made of graphite. Between the collecting electrode and the guard ring, polymethylmethacrylate (PMMA) was utilized as an insulating material. The entrance window is made of aluminized polyethylene terephthalate (0.84 mg/cm$^2$), the walls are made of PMMA, and atmospheric air fills its interior. The extrapolation chamber is shown in Fig. 1.

The experimental tests were undertaken using an industrial X-ray unit, Pantak Seifert model ISOVOLT 160HS, that operates from 5 to 160 kV. The standard diagnostic radiology beam qualities utilized in this work were RQR3, RQR5 and RQR8. These radiation qualities were established at LCI using the International Electrotechnical Commission IEC 61267 standard (IEC, 2005), and

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a parallel-plate ionization chamber, PTW model 77334, with 1.0 $cm^3$ of sensitive volume. This ionization chamber has traceability to the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB). The characteristics of the established standard beam qualities are listed in Table 1.

A Keithley electrometer 6517A was utilized to measure the electric charge, collected by the extrapolation chamber. This electrometer has a precision of 0.1 pC. All measurements were corrected to the standard environmental conditions of temperature and pressure (20 °C and 101.3 kPa).

The MCNP-4C Monte Carlo code, developed and maintained by Los Alamos National Laboratory (Briesmeister, 2000), that can simulate the transport of electrons and photons with energies ranging from $10^3$ eV up to $10^{11}$ eV, was utilized in this work. The MCNP code presents a great advantage to describe the geometry system in a detailed manner, in relation to other Monte Carlo codes.

The simulation of the extrapolation chamber was carefully modeled, based on its real dimensions, shapes and chemical composition. The simulated extrapolation chamber is shown in Fig. 2. The radiation beam used in the simulation, presenting the spectrum of the RQR5 radiation quality beam (one of the standard radiation qualities at LCI), was obtained experimentally with a spectrometer.

The spectrometer was manufactured by EG&G Ortec, model NOMAD-PLUS 92X, with a high-purity germanium semiconductor detector (HPGe) model GLP-16195/10P. The entrance window is made of Beryllium (3.0 cm in diameter and 0.5 mm thick). The data acquisition was made by the Maestro™ software provided with the spectrometer system.

All uncertainties displayed in this paper are expanded uncertainties, using a coverage factor of 2 (ISO, 1995).

## 3. Results and discussion

To characterize the homemade extrapolation chamber for low-energy X-rays, the saturation curves, linearity of response and extrapolation curves were obtained. To validate the simulation results, the experimental and simulated extrapolation curves were compared. The influence of the components of the chamber was determined for the RQR5 radiation quality, and a chamber depth of 0.75 mm.

**Fig. 1.** Extrapolation chamber developed at IPEN (Dias and Caldas, 1998).

**Table 1**
Standard diagnostic radiology qualities at the Pantak/Seifert X-ray equipment, using a constant tube current of 10 mA, based on IEC 61267 (IEC, 2005).

| Radiation quality | Voltage (kV) | Additional filtration (mmAl) | Half-value layer (mmAl) | Air kerma rate (mGy/min) |
|---|---|---|---|---|
| RQR3 | 50 | 2.40 | 1.78 | 21.60 ± 0.18 |
| RQR5 | 70 | 2.80 | 2.58 | 37.88 ± 0.32 |
| RQR8 | 100 | 3.20 | 3.97 | 67.45 ± 0.54 |

### 3.1. Saturation curve

The main objective of obtaining the saturation curve is to define the operating region of an ionization chamber. It was obtained measuring the ionization current as a function of the applied voltage between −100 V and +100 V. A saturation curve was obtained for 0.75 mm and 1.25 mm chamber depths. Fig. 3 shows the saturation curve for the RQR5 diagnostic radiology quality beam.

Another objective related to the saturation curve is the possibility to determine the ion collection efficiencies and the recombination factors to be applied to the extrapolation chamber readings. The ion collection efficiency was determined by the two voltage method (IAEA, 2001):

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

where $M_x$ is the collected charge at a $V_x$ voltage, and $V_1/V_2 = 2$. The ion collection efficiency was better than 99.9%.

In the polarity test, the response of the extrapolation chamber was compared, when exposed to radiation, with the same applied voltage in module, but with reversed polarity. In Table 2, the values obtained for the polarity effect, at the RQR5 diagnostic radiology quality beam, are presented. Observing these data, it is possible to conclude that the maximum variation in the polarity

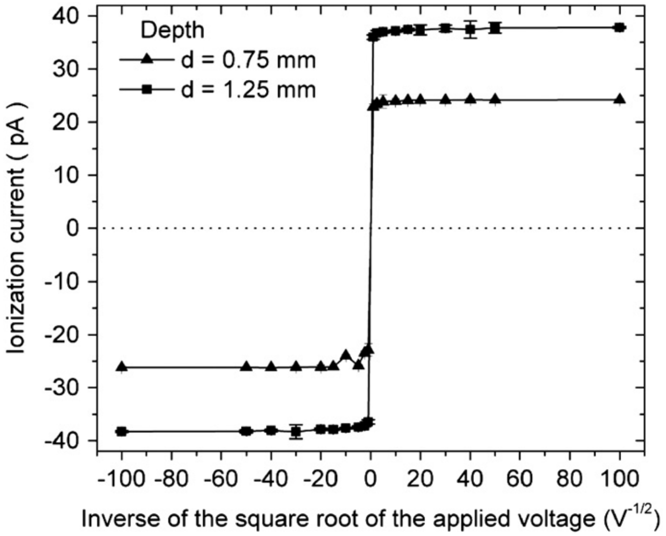

**Fig. 3.** Saturation curves of the extrapolation chamber, measured at the RQR5 diagnostic radiology quality beam. Due to the graph scale, most of the uncertainties are not visible.

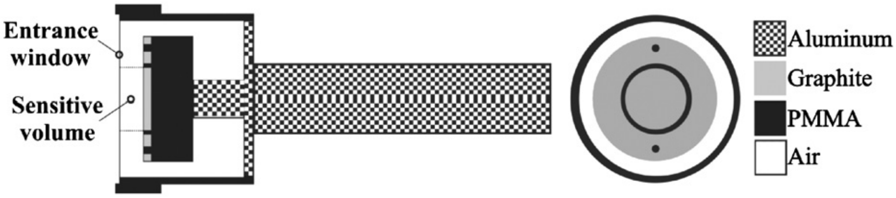

**Fig. 2.** Extrapolation chamber simulated using the MCNP-4C code.

**Table 2**
Polarity effect of the extrapolation chamber tested at the RQR5 diagnostic radiology quality beam.

| Voltage (V) | Collected charge (nC) | Ratio $\|Q+\|/\|Q-\|$ |
|---|---|---|
| +10/−10 | +0.231 ± 0.012/−0.233 ± 0.014 | 0.991 ± 0.079 |
| +25/−25 | +0.233 ± 0.013/−0.234 ± 0.014 | 0.996 ± 0.082 |
| +50/−50 | +0.235 ± 0.015/−0.235 ± 0.014 | 1.000 ± 0.087 |
| +100/−100 | +0.254 ± 0.015/−0.255 ± 0.015 | 0.996 ± 0.083 |

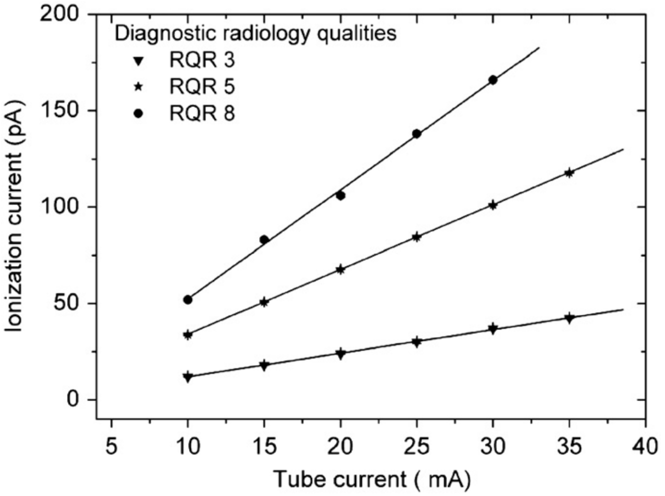

**Fig. 4.** Linearity of response of the extrapolation chamber at the RQR3, RQR5 and RQR8 diagnostic radiology quality beams. The maximum uncertainty was 2.4% for the RQR3, 0.9% for the RQR5 and 1.1% for the RQR8 diagnostic radiology quality beams.

effect was 0.9% (for ± 10 V), and therefore it did not exceed the recommended limit of 1.0% of IEC 60731 (IEC, 1997).

### 3.2. Linearity of response

For the linearity test, the ionization chamber response was investigated by varying the air-kerma rate. The X-ray tube current was varied from 10 to 35 mA, keeping fixed the chamber depth at 1.25 mm. For tube voltages above 100 kV (RQR8) it was not possible to apply currents greater than 30 mA. In Fig. 4 it is possible to verify the linearity of response for RQR3, RQR5 and RQR8 diagnostic radiology quality beams. The minimum correlation coefficient $R^2$ obtained was 0.99921 for the RQR5 radiation quality beam.

### 3.3. Extrapolation curve

The main advantage of an extrapolation chamber is that it is possible to change its sensitive volume by varying the distance between the collecting electrode and the entrance window (chamber depth). The extrapolation curve was obtained by measuring the ionization current for each chamber depth, keeping fixed the electric field. The slope of this curve is related to the air-kerma rate of the incident radiation. Fig. 5 shows the extrapolation curves for the extrapolation chamber at the RQR3, RQR5 and RQR8 diagnostic radiology quality beams.

The ratio between the air-kerma rate and the curve slope for each diagnostic radiology quality provides the calibration factor, listed in Table 3 for all radiation qualities. Therefore, the home-made extrapolation chamber may be used as a reference system for the calibration of other instruments such as work standards.

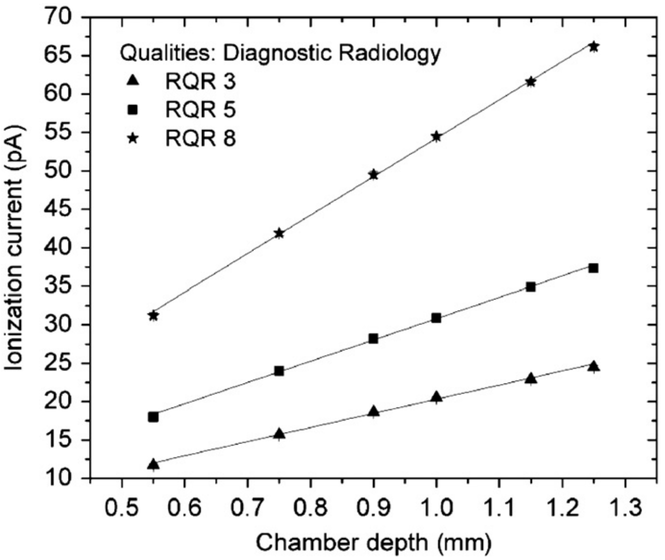

**Fig. 5.** Extrapolation curves of the IPEN extrapolation chamber in the RQR3, RQR5 and RQR8 standard diagnostic radiology direct beams. The maximum uncertainties were 1.7%, 1.2% and 1.2% for the RQR3, RQR5 and RQR8 qualities, respectively.

**Table 3**
Calibration coefficients of the extrapolation chamber, in standard diagnostic radiology direct beams.

| Radiation quality | Calibration coefficient (mGy/s mm/pA) | Normalized calibration factor |
|---|---|---|
| RQR3 | 19.87 ± 0.62 | 0.918 |
| RQR5 | 21.63 ± 0.38 | 1.000 |
| RQR8 | 22.49 ± 0.37 | 1.039 |

### 3.4. Monte Carlo simulation and influence of the extrapolation chamber components

The extrapolation chamber developed at IPEN was simulated using the MCNP-4C Monte Carlo code, and the calculated extrapolation curve was compared to the experimental data of the RQR5 standard diagnostic radiology direct beam for chamber depths of 0.5, 0.6, 0.75, 0.9 and 1.0 mm; the results were normalized to that obtained with a chamber depth of 0.75 mm, and are shown in Fig. 6. The experimental curve presented a slope of $(1.309 \pm 0.009)\ \mathrm{mm}^{-1}$, and the simulated curve a slope of $(1.319 \pm 0.005)\ \mathrm{mm}^{-1}$, differing in 0.8%, which means that the extrapolation chamber was properly simulated.

The influence of the chamber components on its response was determined by simulating the energy deposition in the ionization chamber sensitive volume, which is the volume of air delimited by the collecting electrode and the entrance window, as shown in Fig. 2, with and without their components. The removed components were collecting electrode, PMMA support, entrance window, aluminum support, PMMA walls and the chamber stem, as illustrated in Fig. 7. The number of histories was $2.1 \times 10^9$, and the deposited energy was obtained using *tally* F6.

The removal of chamber components can lead to a net reduction in the deposited energy up to 11.0%, mainly due to the backscattered radiation from the aluminum stem, the PMMA support and walls. Therefore, in order to characterize this type of ionization chamber as a standard system for low-energy X-rays, the correction factor for each component has to be determined, to obtain an accurate response.

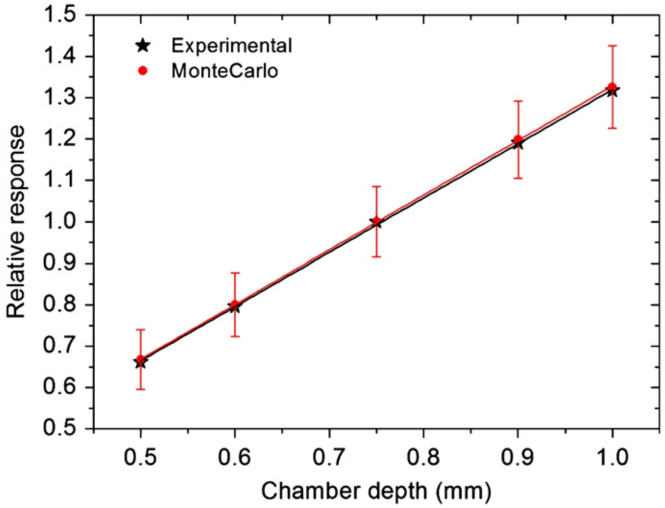

**Fig. 6.** Experimental and simulated extrapolation curves obtained with an extrapolation chamber at the RQR5 diagnostic radiology quality beam. The measurements were normalized for a chamber depth of 0.75 mm. The maximum uncertainty was 1.2% for the experimental results.

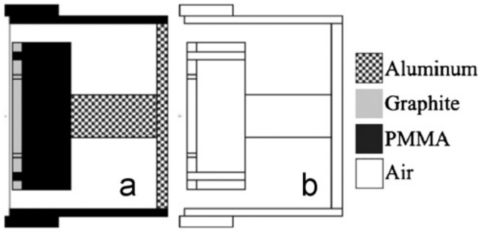

**Fig. 7.** Simulated extrapolation chamber with (a) all components and (b) without its components.

## 4. Conclusions

The results obtained experimentally for the homemade extrapolation chamber used in low-energy X radiation levels were in good agreement with the international recommendations. The extrapolation curves obtained using the Monte Carlo technique presented a good agreement with the experimental results. Therefore, the ionization chamber response may be accurately simulated by the MCNP-4C Monte Carlo code. It was shown that the chamber components influence the response of the ionization chamber up to 11.0%.

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