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Performance of a prototype of an extrapolation minichamber in various radiation beams

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Abstract

An extrapolation minichamber was developed for measuring doses from weakly penetrating types of radiation. The chamber was tested at the radiotherapeutic dose level in a beam from a $^{90}Sr+^{90}Y$ check source, in a beam from a plane $^{90}Sr+^{90}Y$ ophthalmic applicator, and in several reference beams from an X-ray tube. Saturation, ion collection efficiency, stabilization time, extrapolation curves, linearity of chamber response vs. air kerma rate, and dependences of the response on the energy and irradiation angle were characterized. The results are satisfactory; they show that the chamber can be used in the dosimetry of $^{90}Sr+^{90}Y$ beta particles and low-energy X-ray beams.

Keywords: Extrapolation chamber; Weakly-penetrating radiations; Saturation curve; Extrapolation curve; Calibration coefficients; Angular dependence

1. Introduction

Ionization chambers are widely used to detect beta and gamma rays. Their sensitivity depends on the inner air volume, geometry, and the construction materials. The most commonly used ionization chambers are cylindrical, spherical and parallel plate (Boag, 1987).

A special type of ionization chamber, the extrapolation chamber, is recommended for weakly penetrating radiation dosimetry. The volume of the gas in such chambers can be varied by means of a micrometer screw. One can make a series of measurements with different distances between the outer and collecting electrodes; when this interelectrode spacing is very small, the Bragg–Gray conditions are satisfied. Thus, the absorbed dose rate can be determined by extrapolating the measured ion current to the null distance. This method makes it possible to determine the surface absorbed dose rate from β-particle sources used in brachytherapy procedures (IAEA, 2002; Dias and Caldas, 1998; Soares et al, 1997; Deasy and Soares, 1994). Extrapolation chambers can be also used in the dosimetry of low-energy X-rays (Böhm and Schneider, 1986; Dias and Caldas, 2001) because the attenuation and scattering of the incident photons are minimal (Dias and Caldas, 2001).

The initial extrapolation chamber model proposed by Failla (1937) was modified through the years for various purposes (Oesterling, 1982; Scannell et al, 1986; Duppreez, 1987; Klevenhagen, 1991; Darley et al, 1991). More recently, De Blois et al. (2002) demonstrated the feasibility of a bone-equivalent extrapolation chamber in absorbed dose measurements, and in the same year, Bambynek (2002) developed a multi-electrode extrapolation chamber to perform calibrations of brachytherapy sources.

At the Calibration Laboratory of Instituto de Pesquisas Energéticas e Nucleares (IPEN), various ionization chambers have been developed for use in the diagnostic and radiotherapy dose ranges (Albuquerque and Caldas, 1989; Dias and Caldas, 1998; De Souza et al., 1996; Costa and Caldas, 2003a, b).

IPEN has also designed and constructed an extrapolation minichamber as a reference system for calibration of

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$^{90}Sr+^{90}Y$ β sources (Oliveira and Caldas, 2005). The geometry of this chamber was optimized specifically for calibrating plane applicators used in brachytherapy procedures.

The aim of this work was to study performance characteristics of this extrapolation minichamber in various radiation beams in order to evaluate the feasibility of its use in the dosimetry of weakly penetrating radiation beams.

2. Materials and methods

The extrapolation minichamber (Fig. 1) was developed in the Calibration Laboratory of IPEN as a reference standard system for calibrations of plane $^{90}Sr+^{90}Y$ applicators. It was described previously in the paper by Oliveira and Caldas (2005). A calibration of the minichamber against a standard ionization chamber or a standard β source is unnecessary. This chamber is 113 mm long; its diameter is 30 mm. A coupled micrometer screw provides the necessary variation of the distance between the collecting electrode (an acrylic plate coated with graphite) and the entrance window (aluminized polyester) with an uncertainty better than 10 μm. The collecting electrode is surrounded by a Teflon insulating cap, while a graphited guard ring surrounds both. The effective area of the collecting electrode is 1.68 mm^2. This small area and the small chamber dimensions make the extrapolation minichamber a very versatile instrument, which can be used to calibrate very small sources and to determine dose distributions of extended β sources. This chamber was used in combination with a PTW electrometer (Model UNIDOS 10001, Physikalisch-Technische Werkstätten, Freiburg, Germany). All results of the measurements were brought to the reference conditions (20 °C and 101.3 kPa).

Three radiation systems were used in this work to study the chamber performance: (i) an Amersham $^{90}Sr+^{90}Y$ plane applicator (nominal activity of 633 MBq, 2004), (ii) a $^{90}Sr+^{90}Y$ check source (nominal activity of 33.3 MBq, 1988) PTW Type 8921, and (iii) an X-ray Rigaku-Denki system (Model Geigerflex) with a Phillips tube (Model PW 2184/00), which has a 1-mm beryllium window and a tungsten target and can operate in the range from 20 to 60 kV (the currents can be varied between 2 and 80 mA). Table 1 lists the characteristics of the latter system.

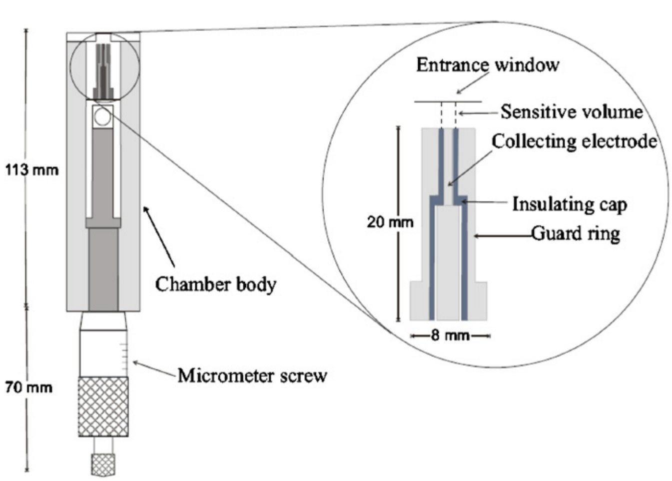

Fig. 1. Diagram of the extrapolation minichamber developed at IPEN.

Table 1
Characteristics of the Rigaku–Denki low-energy X-ray system

Radiation quality	Tube potential (kV)	Tube current (mA)	Half-value layer (mmAl)	Air kerma rate (mGy min^{-1})
RT 25	25	30	0.25	399.21 ± 0.29
RT 30	30	30	0.36	421.30 ± 0.27
RT 40	40	30	0.53	591.91 ± 0.12
RT 45	45	25	0.59	561.78 ± 0.04
RT 50	50	25	0.89	466.69 ± 0.14

The standard system for the calibration of the X-ray beams in the tested energy range was a parallel-plate ionization chamber PTW Model M23342-0709 (0.2 cm^3) and a PTW electrometer (Model UNIDOS 10001). This chamber was calibrated at the Deutscher Kalibrierdienst (DKD) Laboratory (DKD, 1996).

3. Results and discussion

The following characteristics of the extrapolation minichamber were studied: saturation curve, ion collection efficiency, stabilization time, extrapolation curves, linearity of chamber response vs. air kerma rate, dependence of the response on radiation quality, and dependence of the response on the chamber orientation in X-ray beams (angular dependence).

3.1. Saturation and ion collection efficiency

The extrapolation minichamber was irradiated with the plane applicator; the polarizing voltage varied from −100 to +100 V, while the electrode separation remained constant (1 mm). Ten replicate ionization current values were obtained for each polarizing voltage, and the ionization currents were determined as the mean values of these results. The saturation curve (Fig. 2) shows an adequate behavior (Costa and Caldas, 2003a); the selected operational polarizing voltage was ±50 V in the saturation region.

The ion collection efficiency was determined using the equation

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

where M_1 and M_2 are the ionization currents measured at the polarizing voltages V_1 (operational polarizing voltage) and $V_2=V_1/2$ (IEC, 1997). The ion collection efficiency

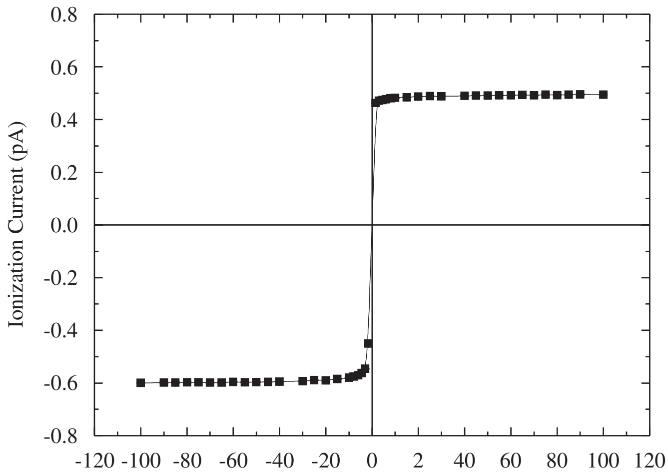

Fig. 2. Saturation curve for the extrapolation minichamber.

determined in this way for the operational polarizing voltage of 50 V exceeds 99.7%. This result proves that the losses by ionic recombination are below 1%, as recommended by IEC (1997).

3.2. Short-term stability

In the short-term stability (repeatability) test of the extrapolation chamber, 10 consecutive measurements of the $^{90}Sr+^{90}Y$ check source were taken. To guarantee the reproducibility of the geometry, a special acrylic cap to hold the chamber and source was designed. The variation of the chamber response was less than 0.24%, as already published (Oliveira and Caldas, 2005). According to IEC (1997), variations of a chamber response to a check source radiation should not exceed 0.3%.

3.3. Stabilization time

Ionization currents were measured for each polarity 15, 60, and 120 min after the application of the polarizing voltage. The chamber was irradiated with the plane applicator located 1 mm away from the chamber window. Table 2 lists the results. Ionization currents measured 15 and 120 min after the voltage application differ from the 60-min value by less than 0.5%, as recommended by IEC (1997). Table 2 also shows the combined overall uncertainties of the measurements ($k=2$). As the predominant contribution to the uncertainty is from the electrometer (0.5% + 1 count), all the quoted values are the same.

3.4. Extrapolation curves

Extrapolation curves, published in the previous paper (Oliveira and Caldas, 2005), were obtained by plotting the ionization currents as a function of the electrode separation. For each separation and polarizing voltage, the charge was collected for 2 min. The maximal standard deviation for 10 such measurements was 0.40%. The extrapolation curves are linear for separations between 0.4 and 1.0 mm (Fig. 3); the correlation coefficient is 0.9992. Measurements performed on consecutive days with the chamber and the source repositioned before each session showed a maximal discrepancy of 2.3%.

3.5. Linearity of the dependence of the chamber current on air kerma rate

The chamber was positioned at a distance of 50 cm from the focal spot in the center of the X-ray field. The distance between the electrodes was 1 mm, and polarizing voltages ±50 V were applied. The charge was collected for 120 s in each of the 10 replicate measurements. The tube current was varied from 2 to 30 mA to provide different air kerma rates.

The air kerma rate for each X-ray quality was measured with the standard PTW parallel-plate ionization chamber coupled to the PTW electrometer. The calibration certificate related ionization currents to air kerma rates at the radiotherapy level for all of the X-ray qualities used in this work.

The dependences of the ionization currents on the air kerma rates have been found linear for all the beam qualities described in Table 1. Fig. 4 shows the results for two beam qualities, namely, RT 40 and RT 45. The high degree of linearity is evident from the correlation coefficients as high as 0.99997.

Table 2
Stabilization time test: relative ionization currents as a function of time

Time after voltage application (min)	Voltage polarity	
	Positive	Negative
15	0.999 ± 0.012	1.001 ± 0.012
60	1	1
120	1.000 ± 0.012	0.999 ± 0.012

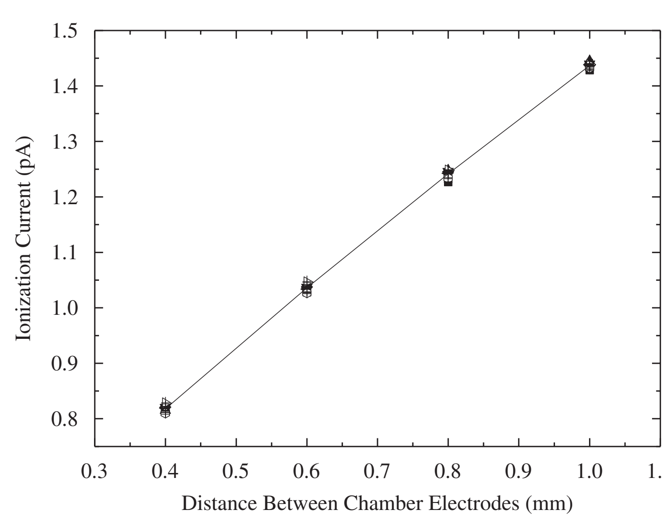

Fig. 3. Extrapolation curves of the minichamber at the $^{90}Sr+^{90}Y$ plane applicator (the line represents the average data).

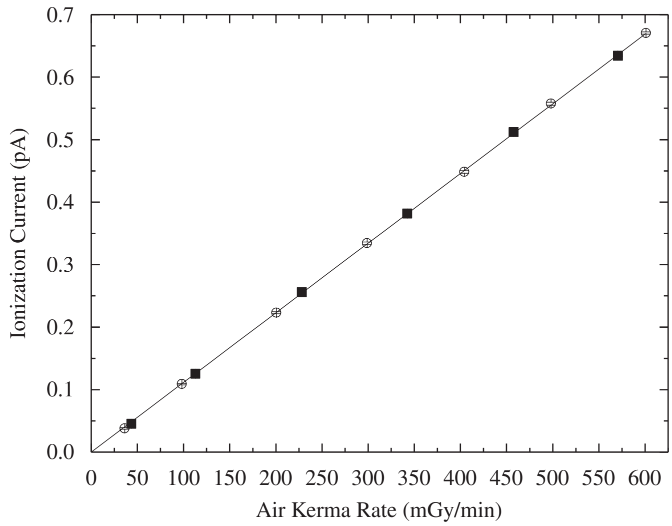

Fig. 4. Linearity of the chamber response vs. air kerma rate for two different beam qualities: RT 40 (open circles) and RT 45 (squares).

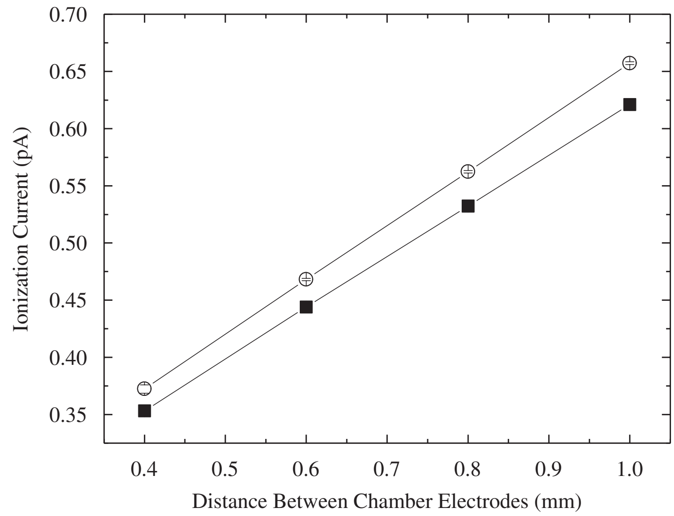

Fig. 5. Extrapolation curves obtained with the minichamber for two different beam qualities: RT 40 (open circles) and RT 45 (squares). The correlation coefficients of the linear fit obtained were 0.99999 and 0.99997 for RT 40 and RT 45, respectively.

3.6. Energy dependence

The beam qualities listed in Table 1 were used. The chamber was always irradiated in the position 50 cm away from the focal spot of the X-ray tube. Extrapolation curves were obtained for each X-ray beam quality (the electrode separation was varied from 0.4 to 1.0 mm). Two of these curves are shown in Fig. 5 as examples. The slopes of the lines were used to evaluate the energy dependence of the chamber response as described below.

1. The air kerma calibration coefficients (Meghzifene and Shortt, 2002) were determined from the measurements obtained with the reference chamber.
2. Identical measurements were performed with the extrapolation chamber under the same geometrical conditions.
3. The calibration coefficient is the ratio of the measurement performed with the reference chamber and the slope of the extrapolation curve obtained in the same X-ray quality.

The results with the respective standard deviations are presented in Table 3, as well as in Fig. 6. The measurement uncertainties were below 3.6% (coverage factor $k = 2$). The maximal variation in the chamber response was 8.5% over the whole energy range studied.

Table 3
Calibration coefficients for the extrapolation minichamber

Radiation quality	Half-value layer (mmAl)	Calibration coefficient ($Gy\,min^{-1}\,A^{-1}\,mm$)
RT 25	0.25	1.183 ± 0.018
RT 30	0.36	1.198 ± 0.016
RT 40	0.53	1.251 ± 0.009
RT 45	0.59	1.260 ± 0.005
RT 50	0.89	1.294 ± 0.009

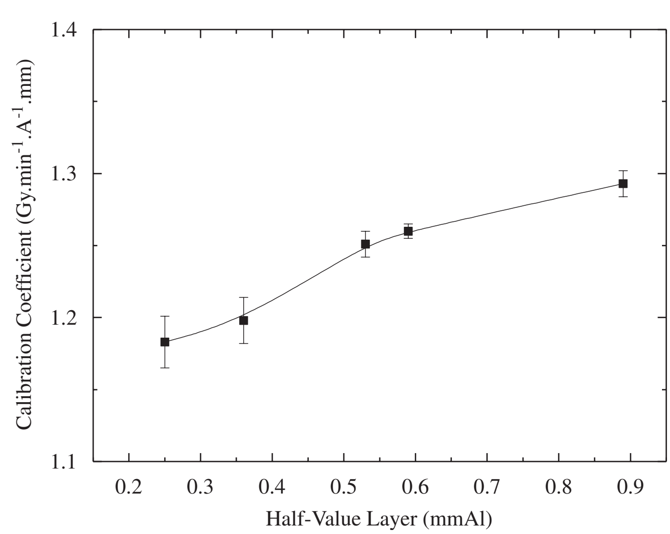

Fig. 6. Energy dependence of the response of the extrapolation minichamber.

3.7. Angular dependence

In order to evaluate the effect of small inaccuracies in the chamber positioning on the response, a series of measurements were performed at various orientations of the chamber in the RT 40 beam. The chamber was positioned in the center of the radiation field, at 50 cm from the center of the X-ray tube, in the reference orientation (perpendicular to the central axis of the X-ray beam). It was then rotated in steps of 1° in the range of angles from -5° to $+5^\circ$ with respect to the initial orientation. The electrode separation was kept constant at 1 mm, and the applied voltage was 50 V. All irradiations were performed.

The chamber response at each orientation was normalized to the response obtained at the reference orientation (0°). The angular variations thus obtained were within 1% of unity.

4. Conclusions

Response of an extrapolation minichamber developed at the Calibration Laboratory of IPEN for use in radiotherapy level radiation beams was studied in various weakly penetrating radiation beams. The chamber performs adequately in terms of the saturation curve, stability, stabilization time, leakage current and extrapolation curves. Moreover, the chamber is useful in measuring doses from low-energy X-rays, as demonstrated by the excellent linearity of the chamber response as a function of the air kerma rate. After a calibration against an appropriate secondary standard system, this chamber can be used instead of the conventional parallel-plate ionization chambers. Unlike the latter, it can be used for measurements in very small radiation fields (e.g., in determining HVL) and in non-uniform fields, as long as the sensitive volume of the chamber is completely irradiated.

As shown in the previous work (Oliveira and Caldas, 2005), this chamber makes it possible to measure dose rates from plane $^{90}Sr+^{90}Y$ β sources. Although extrapolation chambers can be used as primary standards in measuring air kerma rates of low-energy X-rays, the materials of this particular chamber are not appropriate for this purpose. (Unlike this one, a commercial extrapolation chamber has an aluminum collecting electrode for X-rays measurements and a graphite-collecting electrode for beta particles.) Besides these construction details, the electron equilibrium of secondary electrons should be taken into account in choosing adequate distances between the chamber electrodes (Böhm and Schneider, 1986). However, the excellent results obtained with this chamber indicate that it is possible to construct a similar chamber for absolute air kerma measurements in low-energy X-ray beams without a preliminary calibration.

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