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Evaluation of the operational characteristics of a CT ionization chamber

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Abstract

The most common ionization chamber used in computed tomography dosimetry is the "pencil ionization chamber". It is a special cylindrical dosimeter developed for attending computed tomography beams particularities. In this study, a Victoreen pencil ionization chamber was submitted to a set of tests for a detailed evaluation of its operational characteristics. Such as many kinds of detectors, especially field instruments, this ionization chamber had originally a preamplifier to keep it electrically more stable. In this study, the performance of the chamber was analyzed with the original preamplifier and after its removal, and the results were compared. The objective of the preamplifier removal was to enable connecting the chamber to other kinds of electrometers available in laboratories. The behavior of the pencil ionization chamber before and after the removal of the preamplifier was very similar, and the results obtained were always within the limits of international recommendations. The results obtained in both situations allow, if necessary, the preamplifier removal of the system without lack of precision in the measurements.

Keywords: Pencil ionization chamber; X-rays; CT beams

1. Introduction

The dosimetry in computed tomography (CT) medical equipments differs from the conventional radiodiagnostic dosimetry mainly because of the tube rotation around the patient. A special ionization chamber, named pencil ionization chamber, is commercially available for CT dosimetric purposes. These chambers have a special design and present some particular properties as their partial volume response, i.e., the chamber reading is proportional to the irradiated length, and their response uniformity around their central axis. Since its introduction, this kind of chamber became very common for the determination of the CT dose descriptor, specially the computed tomography dose index (CTDI) (Jucius and Kambic, 1977; Suzuki and Suzuki, 1978; Pavlicek, 1979; Poletti, 1984; Bochud et al., 2001).

Externally, the pencil ionization chambers look like thimble chambers; however, they are usually longer and thinner. The sensitive length of a typical pencil ionization chamber is about 10–15 cm, its external diameter is about 9 mm, and its sensitive volume is about 3 cm^3 (Suzuki and Suzuki, 1978). As many kinds of ionization chambers, the Victoreen pencil ionization chamber used in this study had originally a signal digitizing preamplifier. The preamplifier is mostly used in field instruments to guarantee a better electrical stability. However, in most cases, the preamplifier can only be coupled to a specific electrometer. Nevertheless, for laboratory instruments it may be interesting to remove the preamplifier to earn more versatility of the instrument.

Even being those kinds of chambers broadly used, information about their operational characteristic are rare in the

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literature. Only a few technical papers can be found, and they usually date from the period when those chambers were introduced in the clinical practice (Jucius and Kambic, 1977; Suzuki and Suzuki, 1978; Pavlicek, 1979; Poletti, 1984).

This paper completes a study aiming a detailed evaluation of operational characteristic of this kind of chamber, and preliminary results were reported elsewhere (Maia and Caldas, 2003a, 2004). In another recent paper, a detailed study of the energetic dependence of this chamber was reported (Maia and Caldas, 2003b). In the present paper, the performance of a Victoreen pencil ionization chamber was analyzed in several tests. The main quality control tests, as saturation, polarity effects, ion collection eficiency, short- and long-term stability, leakage current, linearity of response, angular dependence and energy dependence in diagnostic and mammography calibration beams, were performed with the chamber before and after the original preamplifier removal. The study was realized using the available radiation beams at the laboratory.

2. Materials and methods

A Victoreen pencil ionization chamber, model 660-6, was used in this study in two operational conditions: before the preamplifier removal—when the chamber was tested coupled to a Victoreen electrometer, model 660—and after the preamplifier removal—when the chamber was coupled to a PTW electrometer, model UNIDOS 10001. The chamber is not sealed and presents 3.2 cm^3 of sensitive volume and 10 cm of sensitive length. The measures of this chamber are proportional to the irradiated length. With the preamplifier, the physical quantity measured by this chamber was the exposure in air length product, and the electrometer readout was in the old units R.cm or R.cm/min, with a range from 0.01 R.cm/min (0.001 R.cm) to 999 R.cm/min (99.9 R.cm). Without the preamplifier, the measurements were made directly in units of charge (C), but the results were also proportional to the length.

A ^{90}Sr+^{90}Y check source, Physikalisch-Technische Werkstätten (PTW; 5.77 MBq, 2003), was used to perform the short- and long-term stability tests. For most types of ionization chambers, supports for those tests are commercially available. However, this is not the case of supports for pencil ionization chambers. Therefore, a homemade acrylic support was utilized for those two tests (Maia and Caldas, 2003b).

It was not possible to measure the leakage current before the preamplifier removal, because of its manual zero adjustment. After the removal, the leakage current was measured before and after irradiation with the PTW check source.

Three X-ray systems were used in this study. The first one was a diagnostic radiology level equipment, Medicor Mövek Röntgengyara, model Neo-Diagnomax, that operates from 40 to 125 kV at the radiographic mode and from 45 to 100 kV at the fluoroscopic mode. Diagnostic qualities defined by the International Electrotechnical Commission, IEC 61267 (1994), were used in this system, and their parameters are listed in Table 1. The reference system for these qualities was a parallel plate ionization chamber with 1 cm^3 of sensitive volume, PTW, model 77334, with a PTW electrometer, model UNIDOS 10001. This chamber was calibrated by PTW, with traceability to the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB).

The second X-rays system was a low energy system Rigaku Denki Co. Ltd. Generator, Geigerflex type, and a Phillips tube, model PW 2184/00. This equipment operates from 20 to 60 kV. Mammography qualities similar to those from the National Institute of Standards and Technology (NIST), defined by International Atomic Energy Agency (IAEA TRS 381, 1997) were used in this system. In Table 2 the parameters of these qualities are listed. The reference

Table 1
IEC diagnostic radiology qualities in the Medicor Mövek Röntgengyara X-ray equipment

Radiation quality	Voltage (kV)	Total filtration (mmAl)	Half-value layer (mmAl)	Effective energy (keV)
Direct beams				
RQR3	52	2.5	1.82	27.4
RQR5	70	2.5	2.45	30.7
RQR7	90	2.5	3.10	33.8
Attenuated beams				
RQA3	52	12.5	4.0	38.8
RQA4	63	18.5	5.7	45.6
RQA5	70	23.5	7.1	51.8
RQA6	80	29.5	8.4	57.9
RQA7	90	32.5	9.1	62.9

Table 2
Mammography qualities in the Rigaku Denki X-ray equipment

Radiation quality	Voltage (kV)	Half-value layer (mmAl)	Effective energy (keV)
Direct beams (total filtration: 0.06 mmMo)			
RXM20	20	0.28	13.6
RXM23	22.5	0.32	14.8
RXM25	25	0.33	15.1
RXM28	27.5	0.34	15.3
RXM30	30	0.35	15.6
RXM32	32.5	0.37	16.0
RXM35	35	0.38	16.2
Attenuated beams (total filtration: 0.06 mmMo+2 mmAl)			
RXM20x	20	0.52	18.5
RXM23x	22.5	0.56	18.7
RXM25x	25	0.58	18.8
RXM28x	27.5	0.61	19.0
RXM30x	30	0.67	19.5
RXM32x	32.5	0.72	19.7
RXM35x	35	0.85	21.6

system utilized for these qualities was a parallel plate ionization chamber Radcal Corporation, Model 10×5-6M, with a Radcal Corporation electrometer, model 9015; its sensitive volume was $6\,cm^3$. This chamber has a calibration certificate from the Center for Devices and Radiological Health, Food and Drug Administration, USA, and its calibration is traceable to NIST.

Another X-ray system, therapy level, Pantak, model HF320, which operates up to 320 kV, was used for the linearity of response and angular dependence tests of the pencil ionization chamber with the preamplifier. That equipment could not be used after the preamplifier removal for technical reasons. For the linearity of response test, the air kerma rates were determined using a reference ionization chamber. This reference system was a cylindrical ionization chamber NE, model 2505/3 ($0.6\,cm^3$ sensitive volume) with a PTW electrometer, model UNIDOS 10001. This chamber was calibrated in air kerma by the Brazilian National Laboratory for Ionizing Radiation Metrology, Rio de Janeiro, Brazil; the calibration is traceable to the Bureau International des Poids et Mesures (BIPM).

For the linearity of response and dependence angular tests after the preamplifier removal, the low energy system Rigaku Denki was used. One of the mammography qualities (RXM30, Table 2) was used for these tests and the mammography reference system was used for the determination of different air kerma rates.

For most of the tests realized in this study, the IEC 61674 (1997) recommendations, which are specific for dosimeters used in diagnostic radiology, were used as reference. However, for the linearity test, which is not in this publication, recommendations for dosimeters used in other applications, such as radiotherapy, were used.

3. Results and discussion

The majority of the tests were performed with the pencil ionization chamber before and after the preamplifier removal. However, some tests could only be performed after the preamplifier removal, such as saturation, polarity effects, ion collection eficiency and leakage current effect tests. The last test could not be performed due to the limitation in the preamplifier operation; the other tests, because of the limitation in the electrometer operation that did not allow voltage variations.

The *saturation test* determines the optimal voltage for the chamber operation. A saturation curve (Fig. 1) was obtained for the Victoreen pencil ionization chamber after the preamplifier removal by varying the voltage from −400 to +400 V in steps of 50 V, using an air kerma rate of 31.7 mGy/min at a mammography quality beam (RXM30) of the low-energy X-ray equipment, *Rigaku Denki*. For all voltage values applied, no significant changes in the collected charge were observed, indicating that the chamber saturation was achieved in the entire voltage interval.

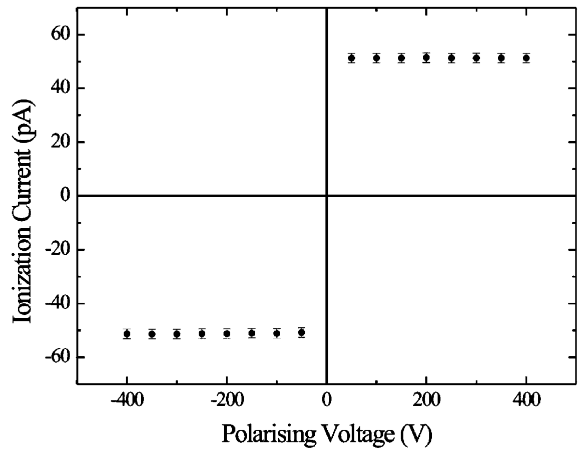


Fig. 1. Saturation curve for the Victoreen pencil ionization chamber, without the preamplifier, at a mammography quality beam (RXM30, air kerma rate of 31.7 mGy/min).

From the saturation curve, two effects could be analyzed. The *polarity effects* should be measured by comparing the collected charges at similar voltages of opposite signals. For all pair of voltage values in the saturation test, the polarity effects did not exceed the recommended limit of 1% by IEC 60731 (1997). The *ion collection efficiency*, besides, could be determined by the two voltage method (Boag, 1987; IAEA TRS 398, 2001), given by

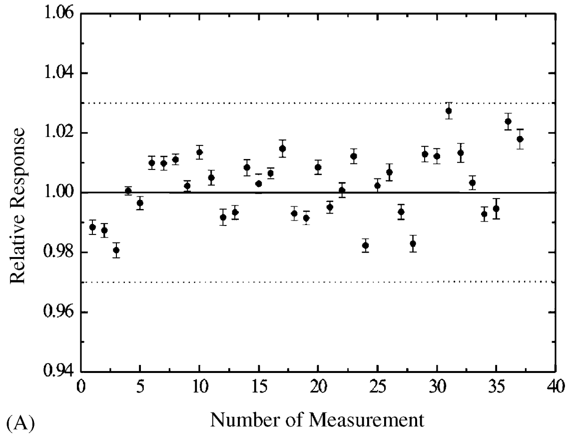
$$k_s = \frac{(V_1/V_2)^2 - 1}{(V_1/V_2)^2 - (M_1/M_2)}, \quad (1)$$

where M_x is the collected charge at a V_x voltage, and $V_1/V_2 = 2$. For $V_1 = 300$ V (or −300 V) and $V_2 = 150$ V (or −150 V), the ion collection efficiency was better than 99.7%. Therefore, the operational voltage chosen was −300 V.

The *short-term stability test* was performed by taking several measurements with the chamber exposed to the check source under reproducible conditions. According to international recommendations (IEC 61674, 1997), the maximum acceptable coefficient of variation is 1% for CT specific chambers. The highest coefficient of variation obtained was 0.32%, before the preamplifier removal, and 0.22%, after the preamplifier removal; both values are within the recommended limit.

The *long-term stability test* was obtained by plotting the results of the short-term stability test, before and after the preamplifier removal, in function of time. As stated by the IEC 61674 norm, the mean value obtained in each short-term stability test must not differ from the reference value more than 3%. Fig. 2 shows the results obtained for the pencil ionization chamber. All values obtained in this work were within the recommended limit.

The *leakage current* was measured during 20 min, before and after irradiation, and the maximum leakage current obtained was 0.34% of the measurement obtained in the



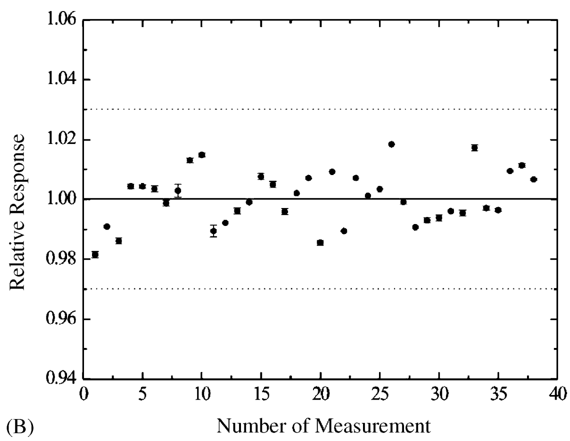


Fig. 2. Long-term stability test of the Victoreen pencil ionization chamber using a ^{90}Sr+^{90}Y check source: (A) with the preamplifier; and (B) without the preamplifier.

short-term stability test. According to the IEC 61674 norm, the leakage current of a dosimeter shall not exceed 5% of the minimum effective air kerma rate of the range in use for at least 1 min. The maximum leakage current obtained before irradiation represented only 1.4% of the ionization current produced by the minimum air kerma rate used in this study (0.534 mGy/min).

For the *energy dependence test*, the chamber was calibrated in the beam qualities described in Tables 1 and 2. The calibration coefficients (Meghzifene and Shortt, 2002) obtained are shown in Tables 3 and 4. The energy dependence (difference between the highest and the lowest calibration coefficients in percentage) of the pencil ionization chamber for those qualities is shown in Table 5 for both cases (with and without preamplifier). Figs. 3 and 4 show the energy dependence curves of the chamber in those qualities. The values were normalized for the highest energy qualities in each case. The results were similar in most of the cases for the condition of use and without use of the preamplifier, but for the attenuated diagnostic beams the lowest energy

Table 3
Calibration coefficients for a Victoreen pencil ionization chamber in IEC diagnostic radiology standard beams, with and without the use of its original preamplifier

Radiation quality	Calibration coefficients	
	With preamplifier (dimensionless)	Without preamplifier ($\times 10^8$ Gy/C)
RQR3	1.04 ± 0.05	1.03 ± 0.05
RQR5	1.06 ± 0.06	1.02 ± 0.05
RQR7	1.05 ± 0.05	1.04 ± 0.06
RQA3	1.03 ± 0.07	1.08 ± 0.06
RQA4	1.15 ± 0.06	1.11 ± 0.06
RQA5	1.20 ± 0.07	1.10 ± 0.06
RQA6	1.19 ± 0.06	1.11 ± 0.06
RQA7	1.20 ± 0.06	1.12 ± 0.06

Table 4
Calibration coefficients for a Victoreen pencil ionization chamber in mammography standard beams, with and without the use of its original preamplifier

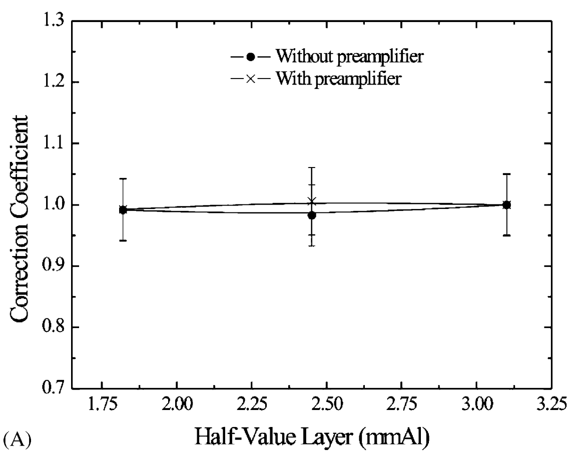
Radiation quality	Calibration coefficients	
	With preamplifier (dimensionless)	Without preamplifier ($\times 10^8$ Gy/C)
RXM20	1.054 ± 0.036	1.060 ± 0.035
RXM23	1.039 ± 0.034	1.048 ± 0.035
RXM25	1.027 ± 0.034	1.044 ± 0.035
RXM28	1.025 ± 0.034	1.040 ± 0.034
RXM30	1.022 ± 0.034	1.037 ± 0.034
RXM32	1.017 ± 0.033	1.031 ± 0.034
RXM35	1.009 ± 0.033	1.027 ± 0.034
RXM20x	0.991 ± 0.038	1.013 ± 0.036
RXM23x	0.996 ± 0.040	1.010 ± 0.035
RXM25x	0.992 ± 0.034	1.006 ± 0.035
RXM28x	1.000 ± 0.034	1.008 ± 0.035
RXM30x	1.001 ± 0.035	1.010 ± 0.035
RXM32x	1.004 ± 0.034	1.014 ± 0.035
RXM35x	1.012 ± 0.034	1.023 ± 0.038

dependence was obtained after the preamplifier removal. Probably these results are due to the interference of the manual zero adjustment of the preamplifier in the measures that were close to the inferior display limit of the electrometer. However, the performance of the pencil ionization chamber with and without the preamplifier was similar and satisfactory for most diagnostic and mammography qualities.

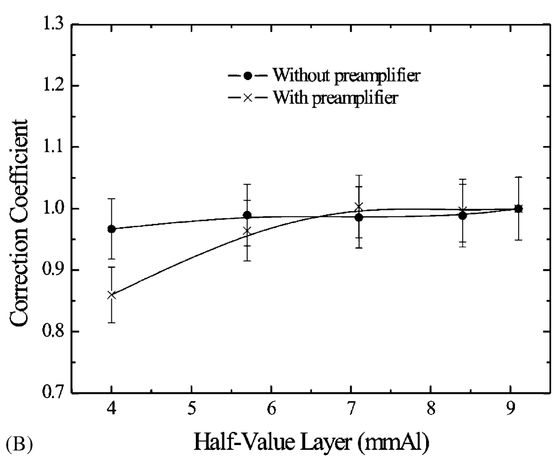
In the case of the *linearity of response test*, the pencil ionization chamber was exposed to several air kerma rates. This test and the angular dependence test were realized at two different X-rays equipments: at the Pantak X-ray system before the preamplifier removal and at the low-energy X-ray system, Rigaku Denki, after the preamplifier removal. In order to provide the air kerma rate variation, nominal

Table 5
Energy dependence of the pencil ionization chamber for several radiation qualities

Radiation quality	Energy dependence	
	With preamplifier (%)	Without preamplifier (%)
IEC diagnostic radiology qualities direct beams	1.9	2.0
IEC diagnostic radiology qualities attenuated beams	16.5	3.7
Mammography qualities direct beams	4.5	3.2
Mammography qualities attenuated beams	2.1	1.7

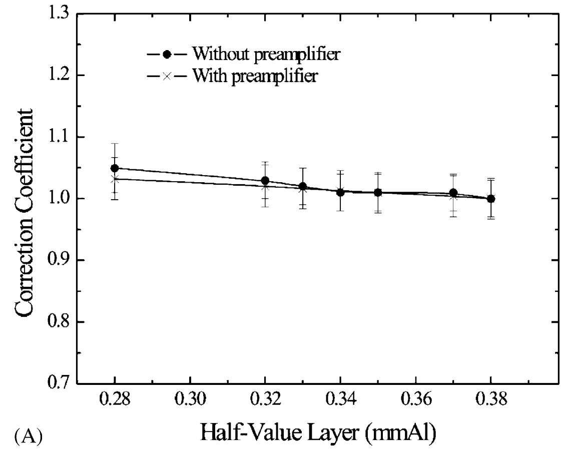


(A)

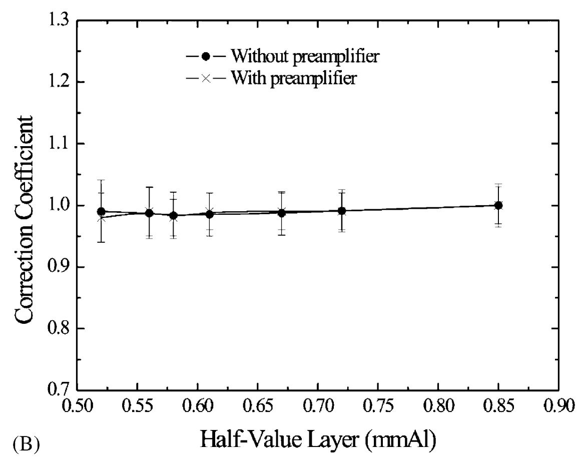


(B)

Fig. 3. Energy dependence curves for the Victoreen pencil ionization chamber, before and after the preamplifier removal, in IEC diagnostic radiology qualities: (A) direct beams; and (B) attenuated beams. The calibration coefficients were normalized for the highest half-value layer qualities: (A) 3.10 mmAl; and (B) 9.1 mmAl.



(A)



(B)

Fig. 4. Energy dependence curves for the Victoreen pencil ionization chamber, before and after the preamplifier removal, in mammography qualities: (A) direct beams; and (B) attenuated beams. The calibration coefficients were normalized for the highest half-value layer qualities: (A) 0.38 mmAl; and (B) 0.85 mmAl.

currents were varied in both X-rays systems. In the Pantak equipment, nominal currents between 1 and 25 mA were used at the fixed potential of 100 kV and half-value layer (HVL) of 4.027 mmAl. The air kerma rates were determined using the reference system calibrated for this quality beam. Fig. 5A shows the chamber response variation, normalized for the reading using a current of 1 mA, in function of the air kerma rate. A linear fit was provided, and the uncertainty obtained in the angular coefficient was ±0.07%. In the Rigaku Denki equipment, the nominal current between 5 and 35 mA were used at the fixed potential of 30 kV and HVL of 0.35 mmAl. The air kerma rates were determined using the mammography reference system. Fig. 5B shows the chamber response variation, normalized for the reading using a current of 5 mA, in function of the air kerma rate. A linear fit was provided, and the uncertainty obtained in the angular coefficient was ±0.11%.

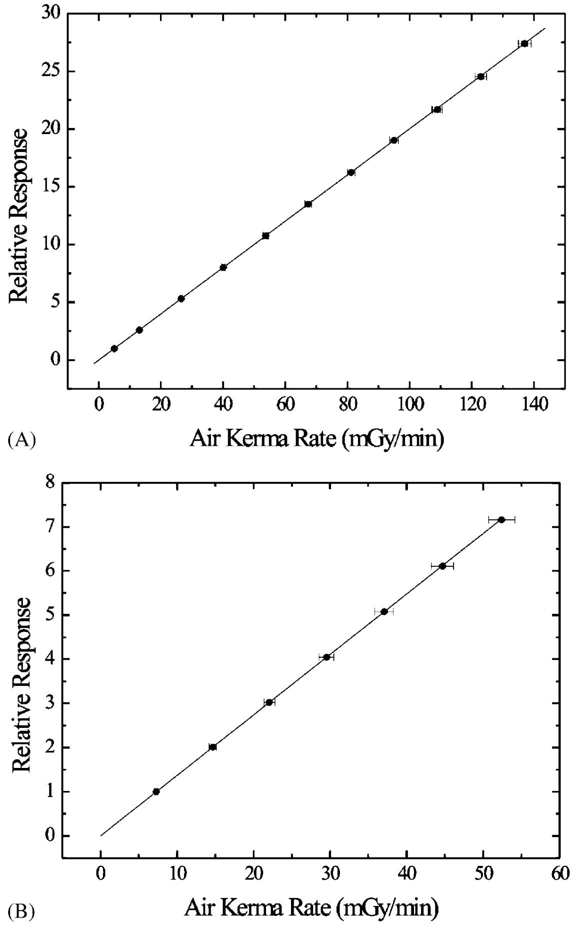


Fig. 5. Linearity of response tests of the Victoreen pencil ionization chamber: (A) with the preamplifier, in standard X-ray beams (100 kV, HVL of 4.027 mmAl); and (B) without the preamplifier, in standard X-ray beams (30 kV, HVL of 0.35 mmAl). Normalization of the chamber response was performed in relation to the minor current: (A) 1 mA; and (B) 5 mA.

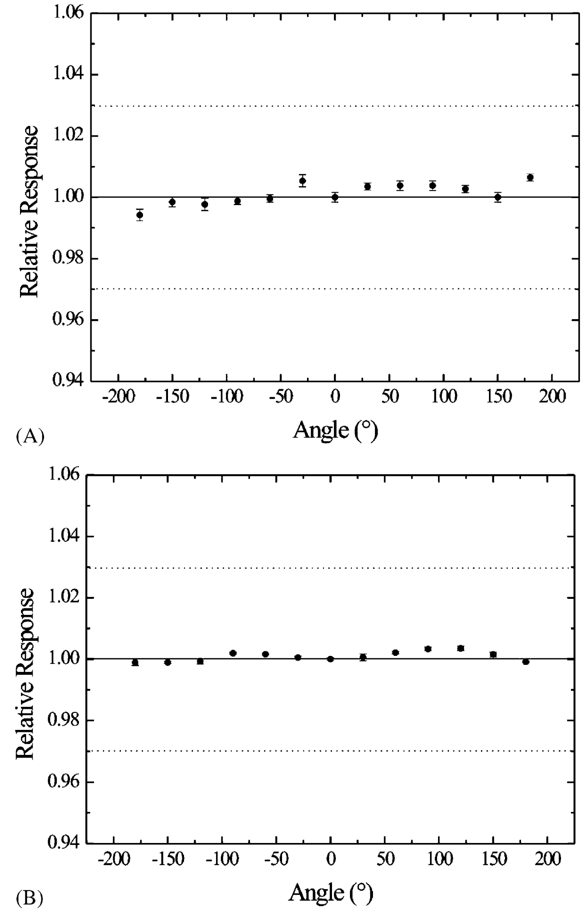


Fig. 6. Angular dependence tests of the Victoreen pencil ionization chamber: (A) with the preamplifier, in standard X-ray beams (100 kV, 5 mA, HVL of 4.027 mmAl); and (B) without the preamplifier, in standard X-ray beams (30 kV, 30 mA, HVL of 0.35 mmAl). Normalization of the chamber response was performed in relation to 0°.

For the *angular dependence tests*, the pencil ionization chamber was exposed to the same standard beams used in the linearity of response tests. The chamber was rotated around its central axis from −180° to +180°, in steps of 30°. By the IEC 61674 recommendations, the value obtained in each angle must not differ from 0° more than 3%. The maximum variation obtained was only 0.65% before the preamplifier removal, as shown in Fig. 6A, and 0.35% after the preamplifier removal, as shown in Fig. 6B.

4. Conclusions

Several operational characteristic of a Victoreen pencil ionization chamber were evaluated and compared with international recommended limits. Except in one case, all results obtained were within the acceptable limits. Even though the results were satisfactory, it is also important to keep the pencil ionization chambers in a quality control program to assure the maintenance of their proper performance and, consequently, the high reliance of the measurements.

An inadequate result was observed, however, for one radiation quality (RQA3) at the energy dependence test for the chamber with its original preamplifier. Once this result was not observed in the other radiation qualities, this accentuated energy dependence is probably due to the effect of the manual zero adjustment of the preamplifier than a real characteristic of the chamber. This result alerts for the possibility of erroneous measurements in consequence of the incorrect adjustment of the preamplifier zero. So, the user must be very careful, especially when dealing with very low dose rates.

This study shows, also, that it is possible to easily adapt a pencil ionization chamber, originally with a preamplifier, to be used with other kinds of electrometers than its original Victoreen one. The results obtained before and after the preamplifier removal were similar in behavior, showing that the adaptation did not imply in lose if precision in the measurements.

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