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A new extended-length parallel-plate ionization chamber

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Abstract

A special parallel-plate ionization chamber was developed. The motivation for the construction of this new chamber was mainly to fulfil the need of a reference system for computed tomography standard beams in the Calibration Laboratory of IPEN. However, the chamber was tested also in standard radiation beams of mammography and conventional diagnostic radiology. The chamber was manufactured at the institute workshop, as simply and cheaply as possible. Its design differs from the common ionization chambers used in dosimetric procedures of computed tomography equipment, because it is a parallel-plate chamber instead of a cylindrical chamber. However, its dimensions and sensitive volume are very similar to those of a commercial pencil ionization chamber. The new ionization chamber was submitted to several characterization and quality control tests, showing its very good performance.

1. Introduction

The ionization chambers used in CT dosimetry are known as pencil ionization chambers (Jucius and Kambic 1977, Suzuki and Suzuki 1978, Pavlicek *et al* 1979, Poletti 1984, Bochud *et al* 2001). These chambers are cylindrical, and they have a sensitive length of 10 cm and a sensitive volume close to 3 cm^3 in most cases.

A reference system is necessary for the calibration of an ionization chamber. This system should be as similar as possible to the chamber under calibration. Any difference in the geometry and dimensions between the reference chamber and the chamber under calibration will increase the uncertainty of the measurements, since the chambers will not be exposed to the same radiation field, and, consequently, to the same field homogeneity.

At the Calibration Laboratory of IPEN, the reference system for diagnostic radiology beams does not resemble a pencil ionization chamber. The difference between the current reference system and a typical pencil ionization chamber would contribute to the uncertainty

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budget with a factor that is estimated as 0.20%. This factor can be even bigger in a less homogeneous radiation field, and may reach values as high as 0.50%. Therefore, this project had the main objective of developing and constructing an ionization chamber, similar to the pencil ionization chamber, which could be used as a reference system for the CT calibration beams. This chamber will be used for the determination of air kerma rates in the standard beams, in the same way as the current reference chamber. However, because of the similarity in its shape to the pencil chambers, the total uncertainty involved in the calibration using the new reference chamber will decrease.

Even though the main application of this new chamber will be in CT reference beams, some tests were performed in a broad range of energy, including low-energy diagnostic radiology and mammography standard beams, to verify its performance in the vicinity of the range of interest too.

The developed chamber has a parallel-plate design. This type of chamber was chosen because it is simple in construction, but also because this type of chamber usually presents flatter energy dependence in the low-energy region than cylindrical chambers (DeWerd and Wagner 1999). Besides, most of the chambers used in diagnostic radiology beams have this design. The developed chamber cannot be used for direct measurements in computed tomography equipment, because of the tube rotation, but it can operate very well at metrology laboratories as a reference system.

Since the Calibration Laboratory of IPEN does not have laboratories specialized for this task, the project was designed to be as simple and cheap as possible. The final result was a home-made ionization chamber that can be constructed without specialized personnel and special materials, but that showed very good results, fulfilling the requisites as a reference system.

2. Materials and methods

For the short- and long-term stability tests, a $^{90}\mathrm{Sr} + {}^{90}\mathrm{Y}$ check source, Physikalisch-Technische Werkstätten (PTW; 5.77 MBq, 2003), was used.

For the majority of the tests, an industrial x-ray system Pantak/Seifert, model ISOVOLT 160HS, was utilized. This equipment operates from 5 to 160 kV. 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 the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB), and it is therefore a secondary standard.

A low-energy x-ray system Rigaku Denki Co. Ltd generator, type Geigerflex, with a Philips tube, model PW 2184/00, was also utilized for the energy-dependence test. This equipment operates from 20 to 60 kV. Mammography qualities similar to those from the National Institute of Standards and Technology (NIST) (Coletti *et al* 1997) were used in this system. The parameters of those qualities are listed in table 2. The direct beams simulate the incident beams at the patient while the attenuated beams simulate the post-patient beams. The reference 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 is 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.

Table 1. Diagnostic radiology qualities of the Pantak/Seifert x-ray equipment.

Radiation quality	Voltage (kV)	Total filtration (mmAl)	Half-value layer (mmAl)	Effective energy (keV)
		Direct beams		
RQR2	40	2.5	1.44	25.1
RQR3	50	2.5	1.79	27.2
RQR4	60	2.5	2.09	28.8
RQR5	70	2.5	2.35	30.2
RQR6	80	2.5	2.65	31.7
RQR7	90	2.5	2.95	33.1
RQR8	100	2.5	3.24	34.4
RQR9	120	2.5	3.84	37.1
RQR10	150	2.5	4.73	40.8
		Attenuated beams		
RQA2	40	6.5	2.22	29.5
RQA3	50	12.5	3.91	37.3
RQA4	60	18.5	5.34	43.3
RQA5	70	23.5	6.86	49.4
RQA6	80	28.5	8.13	54.8
RQA7	90	32.5	9.22	59.7
RQA8	100	36.5	10.09	64.0
RQA9	120	42.5	11.39	71.2
RQA10	150	47.5	13.20	82.1

Table 2. Mammography qualities of 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 + 2mmAl)			
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

All uncertainties presented in this paper are expanded uncertainties and they were computed by combining the type A and type B uncertainties, as recommended by ISO (1995), using a coverage factor of 2.

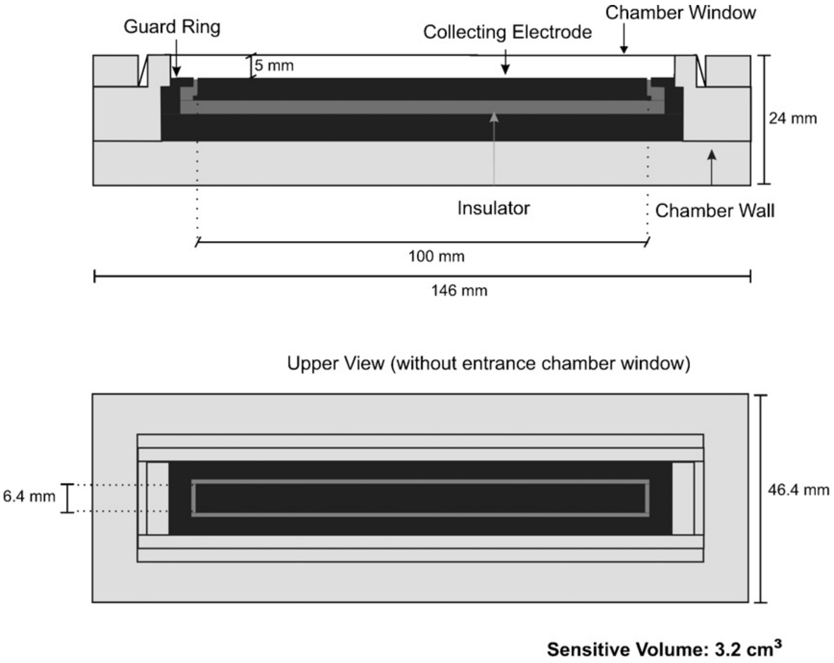

Figure 1. Schematic diagram of a special parallel-plate ionization chamber for CT standard beams.

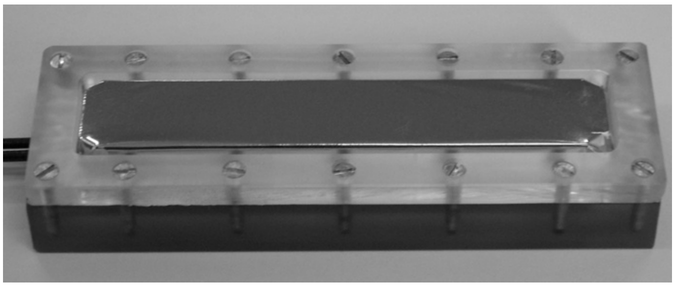

Figure 2. Picture of the new parallel-plate ionization chamber.

3. Results and discussion

The ionization chamber developed in this project has the two most important characteristics similar to those of pencil ionization chambers: 3.2 cm^3 of sensitive volume and 10 cm of sensitive length. However, it is a parallel-plate ionization chamber instead of cylindrical, which is the case of pencil ionization chambers. The reference point of measurement of the new chamber is at the entrance window, not at the geometrical centre as in cylindrical chambers. Figure 1 shows the ionization chamber project. The collecting electrode and the ring guards are made of graphite, the insulator is made of Teflon, the chamber wall is made of PMMA and the chamber window is a Mylar foil. Figure 2 shows the final ionization chamber; and figure 3 shows the chamber during a stability test with the ^{90}Sr + ^{90}Y PTW check source.

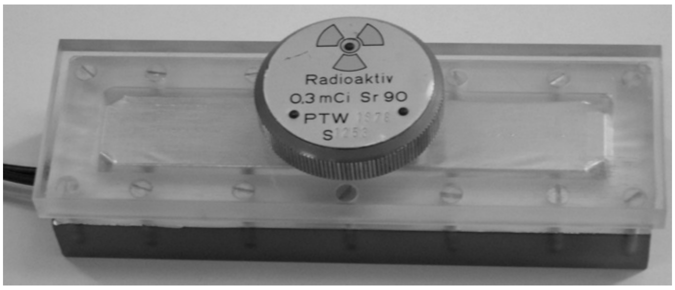

Figure 3. The new parallel-plate ionization chamber during a stability test, with a ^{90}Sr + ^{90}Y check source.

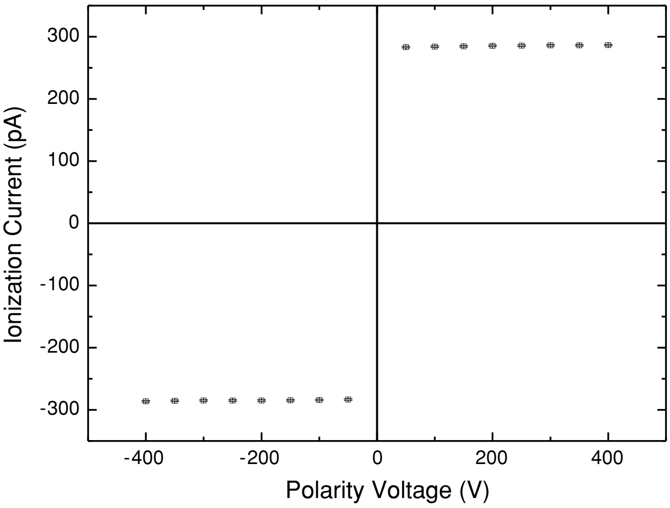

Figure 4. Saturation curve for the new parallel-plate ionization chamber with a diagnostic radiology quality beam (RQR9, air kerma rate of 121.8 mGy min^{-1}).

Several tests were performed to evaluate the operational characteristics of the chamber: saturation, polarity effect, ion collection efficiency, short- and long-term stability, leakage current effect, energy dependence and angular dependence.

3.1. Saturation, polarity effects and ion collection efficiency

The saturation test has the objective of determining the optimal applied voltage for the chamber operation. A saturation curve (figure 4) was obtained for the new parallel-plate ionization chamber by varying the voltage from −400 V to +400 V in steps of 50 V, using an air kerma rate of 121.8 mGy min^{-1} for a diagnostic radiology quality beam (RQR9) of the industrial x-ray equipment, Pantak/Seifert. The mean value for the ionization current measured was 285.11 pA, and the highest coefficient of variation obtained was only 0.66%. So, for all applied voltages, no significant changes were observed in the measured ionization currents, indicating that the chamber saturation was achieved in the whole voltage interval.

Two effects could be analysed from the saturation curve. The polarity effects were determined by comparing the collected charges at similar voltages of opposite signals. For all pairs of voltages tested during the saturation determination, the polarity effects were less

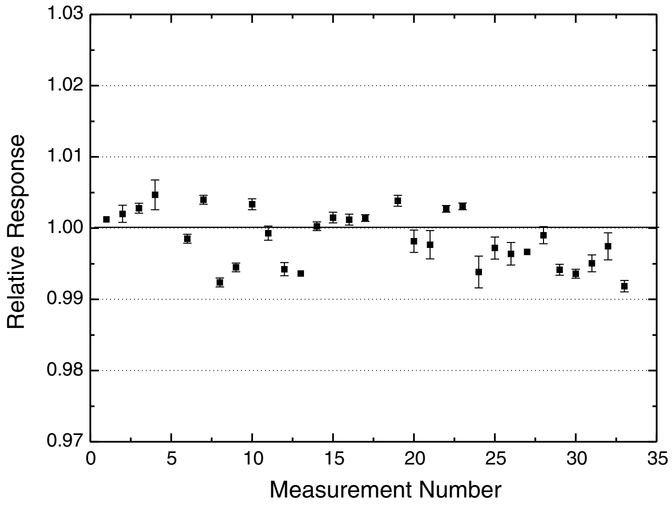

Figure 5. Long-term stability test of the new parallel-plate ionization chamber using a ^{90}Sr + ^{90}Y check source.

than 0.4%, and so below the recommended limit of 1% (IEC 60731 1997). The ion collection efficiency, besides, was determined by the two-voltage method (Boag 1987, IAEA TRS 398 2001), given by

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

where M_x is the collected charge at a V_x voltage and $V_1/V_2 = 2$. For $V_1 = -300$ V and $V_2 = -150$ V, the ion collection efficiency was better than 99.9%. Therefore, the operational voltage chosen was -300 V.

3.2. Short- and long-term stability tests

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%. The highest coefficient of variation obtained was 0.22%, and so within the recommended limit.

The long-term stability test was obtained by plotting the results of the short-term stability test as a function of time. As stated by IEC (IEC 61674 1997), the mean value obtained in each short-term stability test must not differ from the reference value by more than 3%. Figure 5 shows the results obtained for the new parallel-plate ionization chamber. A total of 33 tests were performed, between June 2004 and February 2005, and the highest coefficient of variation obtained was only 0.82%, thus within the recommended limit.

3.3. Leakage current

The leakage current was measured during 20 min, before and after irradiation. According to international recommendations (IEC 61674 1997), 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

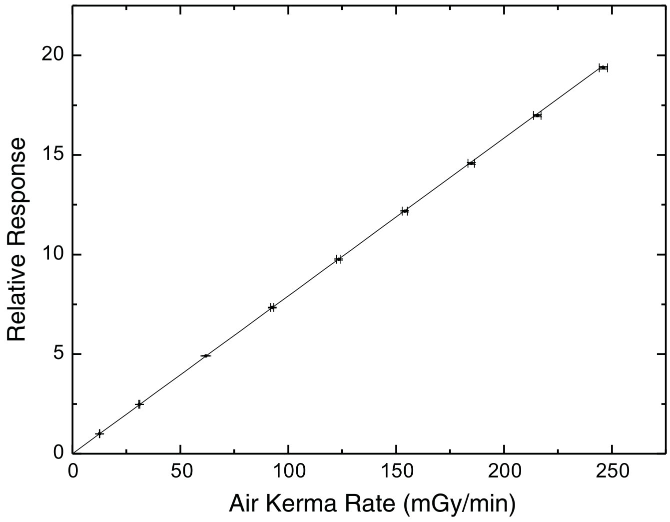

Figure 6. Response linearity of the new parallel-plate ionization chamber in standard x-ray beams (120 kV, HVL of 3.84 mmAl). Normalization of the chamber response was performed in relation to 1 mA.

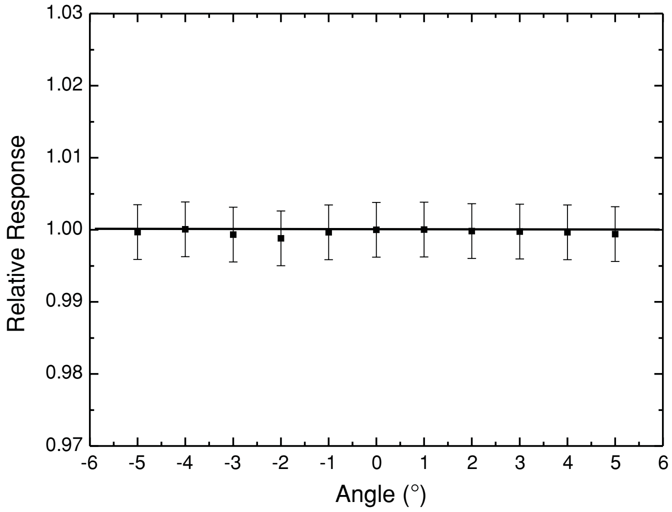

Figure 7. Angular-dependence test results of the new parallel-plate ionization chamber in standard x-ray beams (120 kV, 10 mA, HVL of 3.84 mmAl). Normalization of the chamber response was performed in relation to 0°.

maximum leakage current obtained represented only 0.76% of the ionization current produced by the minimum air kerma rate used in this study (0.534 mGy min^{-1}).

3.4. Linearity of response

In the linearity of response test, the new parallel-plate ionization chamber was exposed to several air kerma rates. In the Pantak/Seifert equipment, nominal currents from 1 to 20 mA

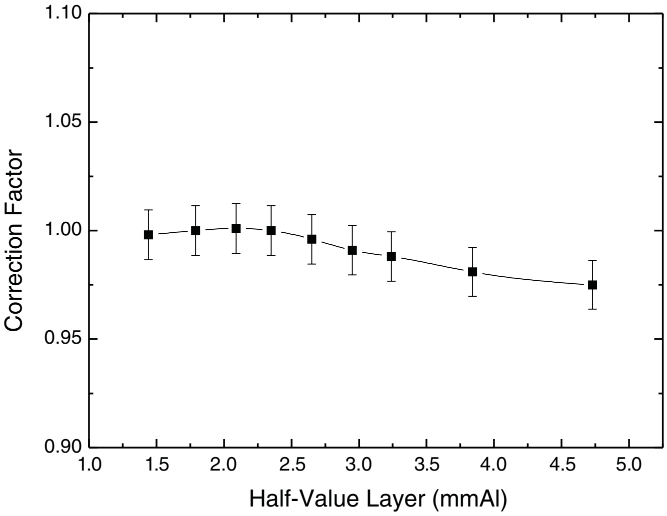

Figure 8. Energy-dependence curve for the new parallel-plate ionization chamber in diagnostic radiology quality direct beams. The calibration coefficients were normalized for the RQR5 quality (HVL of 2.34 mmAl).

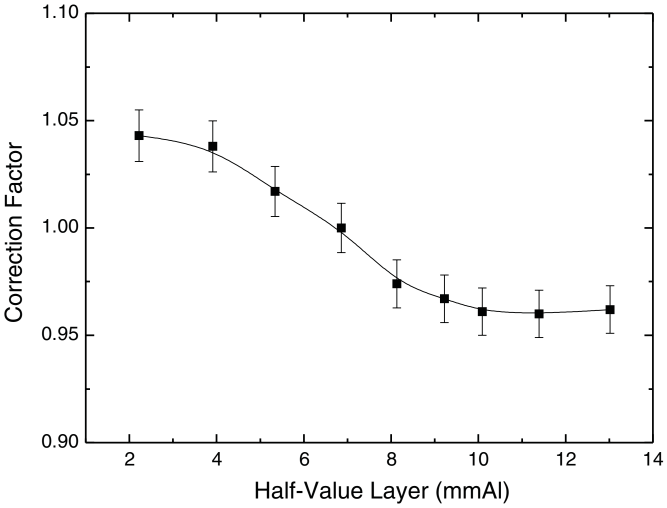

Figure 9. Energy-dependence curve for the new parallel-plate ionization chamber in diagnostic radiology quality attenuated beams. The calibration coefficients were normalized for the RQA5 quality (HVL of 6.78 mmAl).

were used at the fixed voltage of 120 kV (HVL of 3.84 mmAl). The air kerma rates were determined using the reference system for the diagnostic radiology beams. Figure 6 shows the chamber response variation, normalized for the measurement obtained with a current of 1 mA, as a function of the air kerma rate. A linear fit was provided, and the standard uncertainty obtained in the angular coefficient, which is the slope of the fitted curve, was 0.11%.

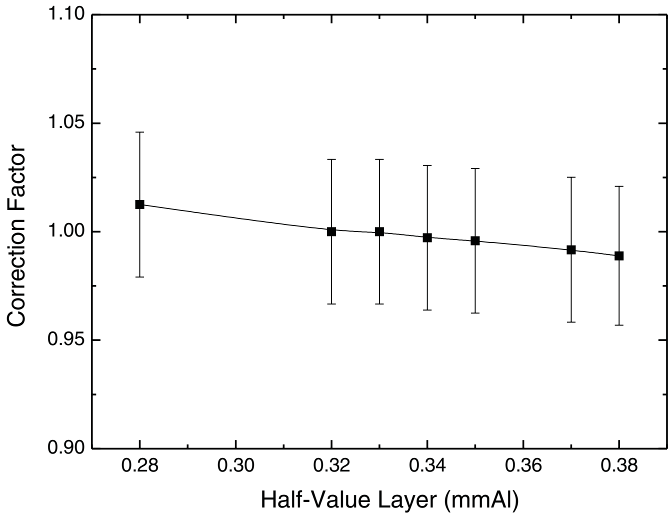

Figure 10. Energy-dependence curve for the new parallel-plate ionization chamber in mammography quality direct beams. The calibration coefficients were normalized for the RXM25 quality (HVL of 0.33 mmAl).

Table 3. Calibration coefficients for the new parallel-plate ionization chamber in diagnostic radiology standard beams. The uncertainties associated with the calibration coefficients were 1.0% for the beams.

Radiation quality	Calibration coefficient ($\times 10^6$ Gy C^{-1})	Radiation quality	Calibration coefficient ($\times 10^6$ Gy C^{-1})
RQR2	7.315	RQA2	7.451
RQR3	7.328	RQA3	7.416
RQR4	7.331	RQA4	7.266
RQR5	7.327	RQA5	7.143
RQR6	7.299	RQA6	6.955
RQR7	7.263	RQA7	6.908
RQR8	7.241	RQA8	6.863
RQR9	7.185	RQA9	6.856
RQR10	7.141	RQA10	6.872

3.5. Angular dependence

In the angular-dependence test, the new parallel-plate ionization chamber was exposed to the same standard beams used in the linearity of response test. The chamber was rotated around its central axis from −5° to +5°, in steps of 1°. According to IEC (IEC 61674 1997), the value obtained in each angle must not differ from 0° by more than 3%. The maximum variation obtained was only 0.12%, as shown in figure 7.

3.6. Energy dependence

For the energy-dependence test, the chamber was calibrated in the beam qualities described in table 1. The calibration coefficients (Meghzifene and Shortt 2002) obtained are shown in table 3. Figures 8 and 9 show the energy-dependence curves of the chamber in those qualities.

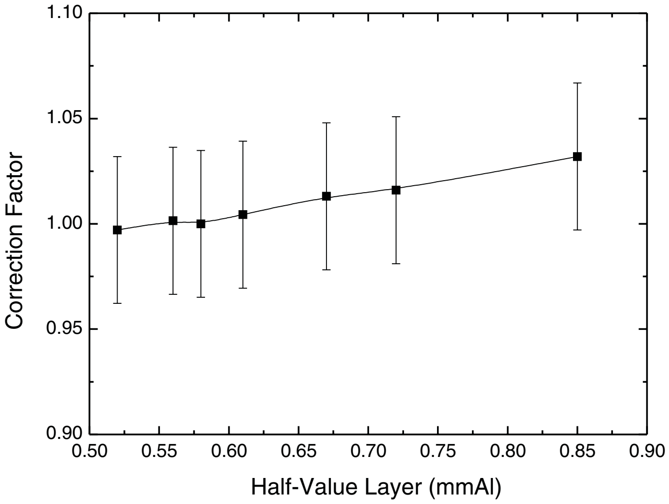

Figure 11. Energy-dependence curve for the new parallel-plate ionization chamber in mammography quality attenuated beams. The calibration coefficients were normalized for the RXM25x quality (HVL of 0.58 mmAl).

Table 4. Calibration coefficients for the new parallel-plate ionization chamber in mammography standard beams. The uncertainties associated with the calibration coefficients were 3.3% for the direct beams and 3.45% for the attenuated beams.

Radiation quality	Calibration coefficient ($\times 10^6$ Gy C^{-1})	Radiation quality	Calibration coefficient ($\times 10^6$ Gy C^{-1})
RXM20	7.278	RXM20x	6.864
RXM23	7.195	RXM23x	6.891
RXM25	7.188	RXM25x	6.880
RXM28	7.165	RXM28x	6.909
RXM30	7.161	RXM30x	6.966
RXM32	7.129	RXM32x	6.994
RXM35	7.114	RXM35x	7.098

The correction factors were obtained by dividing the calibration coefficients obtained in each quality by the calibration coefficients of the RQR5 and RQA5 qualities depending on whether the beams were direct or attenuated. The energy dependence (difference between the highest and the lowest calibration coefficients in percentage) obtained in those diagnostic radiology qualities were 2.6% for the direct beams and 8.0% for the attenuated beams. Considering only the radiation qualities close and adjacent to the CT calibrations beams (RQR9 and RQA9)—RQR7 to RQR10 and RQA7 to RQA10—the energy dependence behaviour improves greatly: 1.7% for the direct beams and 0.7% for the attenuated beams.

The chamber was also calibrated in the beams described in table 2 (mammography qualities), and the calibration coefficients obtained are shown in table 4. Figures 10 and 11 show the energy-dependence curves of the chamber in these qualities. The correction factors were obtained by dividing the calibration coefficients obtained in each quality by the calibration coefficients of the RXM25 and RXM25x qualities, depending on whether the radiation beams were direct or attenuated. The energy dependence obtained in those mammography qualities was 2.3% for the direct beams and 3.3% for the attenuated beams.

4. Conclusions

The developed parallel-plate ionization chamber presented excellent performance in all tests. The main objective of its construction was achieved, and the Calibration Laboratory of IPEN has now an adequate reference system for standard computed tomography beams.

The results obtained show that it is possible to construct a specially designed ionization chamber that presents a performance good enough to operate as a reference system for standard beams. Besides, the chamber was built in a very simple way, using low-cost materials, which makes it accessible to any metrology laboratory or user.

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