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Performance comparison of an extrapolation chamber in computed tomography standard beams of two laboratories

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ABSTRACT

The doses received by the patients during the computed tomography (CT) exams are the highest when compared to other diagnostic radiology procedures. This fact makes it so important to keep the quality control using the correct instrument. For dosimetry in CT, a pencil type ionization chamber is usually utilized with a sensitive volume length of 10 cm. A comparison of the performance of an extrapolation chamber in two different laboratories, at the Instrument Calibration Laboratory (LCI) from Instituto de Pesquisas Energéticas e Nucleares (IPEN, Brazil) and at the National Physical Laboratory (NPL, UK) was undertaken. Two chamber characteristics were determined (zero depth and extrapolation curve), and the main recommended characterization tests were performed (stabilization time, saturation curve, polarity effect, ion collection efficiency, linearity of response, and variation of response with source-detector distance). This extrapolation chamber was calibrated using the standard system of NPL laboratory, and the energy dependence was determined. The results obtained were within the international recommendations of IEC 61674, except for the energy dependence, as already expected. This study also established a reference system for the LCI of the IPEN, using a homemade extrapolation chamber for X-ray CT beams. Using the extrapolation curves obtained in the characterization tests and the correction factors of ionic recombination, and scattering and fluorescence, the air kerma rates were obtained, as a reference system in standard laboratory computed tomography beams. The last correction factor was obtained using computer simulations by the MCNP5 code (Monte Carlo). Moreover, two pencil type ionization chambers were calibrated using the replacement method in relation to the extrapolation chamber.

1. Introduction

Computed tomography (CT) has been used very frequently; this occurs because of the advantages of the image which is very detailed (Bushong, 2010). All over the years, these equipment present a technological advance about reducing exposure time and improvement of the image quality (Boone, 2007; McCollough, 2019; Smith--Bindman et al., 2019). Therefore, the concern with the doses received by the patients has been growing.

The pencil type ionization chamber with a sensitive volume length of 10 cm is the usual detector for CT dosimetry, because of its uniform response to the incident radiation beam from all angles (Suzuki and Suzuki, 1978), showing to be the appropriate and reliable detector in radiation metrology.

The metrological reliability of a dosimetric detector is given by performance tests and its calibration. Therefore, it is very meaningful that the equipment has to be calibrated and traced to a reference instrument. The pencil type ionization chamber is a secondary standard system after a calibration against a primary standard system.

The main idea of this study was to use an extrapolation ionization chamber, developed at the Calibration Laboratory (LCI) of the Instituto de Pesquisas Energéticas e Nucleares (IPEN) to establish a CT reference standard for laboratory beams (Dias, 1996; Dias and Caldas, 1998; Dias and Caldas, 2001).

An extrapolation chamber is a parallel-plate ionization chamber that allows the variation of its sensitive air volume. Usually, this ionization chamber is utilized in beta radiation dosimetry (Antonio et al., 2014; Polo et al., 2017; Hansen et al., 2018), but this chamber has already been used in low-energy X radiation beams too, and it showed results within the international recommended limits (Dias and

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Caldas, 2001; Neves et al., 2012). This homemade extrapolation chamber was already studied using Monte Carlo simulation to obtain the influence of each component and the best materials for the collecting electrode (Castro et al., 2020).

This study aims to test a homemade extrapolation chamber in standard computed tomography beams in two laboratories and to compare their responses at the LCI/IPEN and at the National Physical Laboratory (NPL).

Initially, the extrapolation chamber was tested in relation to its characteristics: zero depth, extrapolation curve, stabilization time, saturation curve, polarity effect, ion collection efficiency, linearity of response, variation of the response of source-detector distance and energy dependence.

To establish an absolute standard system using such an ionization chamber in computed tomography laboratory beams at the LCI/IPEN, it was still necessary to determine two correction factors, being one experimentally (ionic recombination) and the other one using Monte Carlo simulations (scattering and fluorescence). This extrapolation chamber was utilized to calibrate two pencil type ionization chambers.

2. Materials and methods

2.1. Equipment utilized

- A pencil type ionization chamber, Radcal, modelo RC3CT, with a sensitive volume length of 10 cm and a volume of 3 cm^3, called C_{IPEN} of LCI.
- A primary standard free air chamber utilized in the energy range of the laboratory radiation beams from 40 kV to 300 kV, called C_{NPL}, of NPL.
- A homemade extrapolation chamber with an aluminum collector electrode of 30 mm in diameter, an aluminum guard ring, and an entrance window made of aluminized Mylar. Fig. 1 shows the extrapolation chamber and Table 1 shows the specifications of the chamber.
- A homemade pencil type ionization chamber, with a sensitive volume length of 10 cm and a sensitive volume of 3.5 cm^3, called C10, was manufactured at IPEN.

The charge was obtained for the measurements, and then the current, once it was possible to choose the measurement time in the electrometer, the extrapolation chamber was connected to an electrometer, model UNIDOS E, Physikalisch-Technische Werkstatten (PTW), Germany. All of the measurements obtained were corrected to the standard values of environmental conditions (temperature and pressure), the values obtained from the thermometer and barometer were applied to the expression presented by the IAEA (2007). The uncertainties of type A (for the correction factor of environmental conditions and the standard deviation obtained from the 10 measurements) and type B (all the uncertainties associated with the standard instruments of the laboratory, and that provided for the electrometer) were determined, with the combined uncertainty of factor k = 2.

Table 1
Characteristics and specifications of the extrapolation chamber.

Component	Material	Dimensions (mm)	
		Length	Diameter
Chamber Body	Aluminum	126	31.0
Aluminum Base	Aluminum	10.0	75.0
Screw Control	Aluminum	24.5	11.0
PMMA Cap	PMMA	40.0	Internal 150 External 160
Collecting Electrode Support	PMMA	14.5	60.0
Component	**Material**	**Dimensions (mm)**	
		Thickness	**Diameter**
Collector Electrode	Aluminum	3.50	30.0
PMMA Ring	PMMA	3.50	Internal 30.0 External 38.0
Guard Ring	Aluminum	3.50	Internal 38.0 External 60.0
Entrance Window	Aluminized Mylar	0.008	60.0

The X-ray equipment, Pantak/Seifert, model ISOVOLT 160 HS, operating between 5 kV and 160 kV, was utilized at the LCI, and the characteristics of the CT radiation qualities are presented in Table 2. Table 3 presents the beam characteristics for the X-ray equipment, Comet, model MXR-321, operating up to 320 kV used at the NPL.

2.2. Characterization tests

The following characteristics of the extrapolation chamber were determined: zero depth and extrapolation curve. The characterization tests performed in both laboratories were: stabilization time, saturation curve, polarity effect, ion collection efficiency, linearity of response and variation of response with source-detector distance. This chamber was calibrated using the standard system of NPL laboratory, and the energy dependence was determined.

The zero depth and the extrapolation curve were first obtained in

Table 2
Characteristics of the CT standard X radiation qualities at the LCI, based on IEC (2005).

Radiation Quality	Tube Voltage (kV)	Tube Current (mA)	Additional Filtration (mm)	Air Kerma Rate (mGy/min)
RQT 8	100	10	3.2 Al + 0.30 Cu	22.0
RQT 9[a]	120	10	3.5 Al + 0.35 Cu	34.0
RQT 10	150	10	4.2 Al + 0.35 Cu	57.0

[a] LCI Reference CT radiation quality.

Fig. 1. Homemade extrapolation chamber developed at LCI/IPEN. Reproduced from Castro et al. (2020).

Table 3
Characteristics of the CT standard X radiation qualities at the NPL, based on IEC (2005).

Radiation Quality	Tube Voltage (kV)	Tube Current (mA)	Additional Filtration (mm Cu)	Air Kerma Rate (mGy/min)
RQT 8	100	10	0.20	22.7
RQT 9[a]	120	10	0.25	31.5
RQT 10	150	10	0.30	48.1

[a] NPL Reference CT radiation quality.

order to use the chamber in the correct depth with the constant electric field of 100 V/mm during the characterization tests.

In the stabilization time test of the chamber, the ionization current obtained after 15 min and 60 min were compared and the standard deviation must not exceed ±2% (IEC, 1997).

The saturation curve analyzes the behavior when the electric field applied to the chamber is not constant. Through this curve it is possible to determine the polarity effect and the ion collection efficiency. For the polarity effect test, the ratio of the ionization currents obtained for positive and negative polarities must not exceed ±1% (IEC, 1997); therefore, the results should be in the range 0.99–1.01. To obtain the ion collection efficiency for the extrapolation chamber Equation (1) (IAEA, 2000) was used; the standard deviation must not exceed ± 95% (IEC, 1997).

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

where: M_1 and M_2 are the measured current values obtained with the voltages $V_1 = +200$ V and $V_2 = +100$ V, respectively.

In the linearity of response test of the extrapolation chamber, a linear curve should be obtained, so the correlation factor needs to be close to 1.00 ($R^2 = 1.00$).

The aim of the variation of response of source-detector distance test is to know if the inverse square law applies in the case of the extrapolation chamber response.

The ionization chamber was calibrated in relation to the standard chamber of NPL (C_{NPL}) using the replacement method (IAEA, 1994). The energy dependence was determined through the results obtained, where the standard deviation must not exceed ±5% (IEC, 1997).

2.3. Determination of the air kerma rate

To determine the air kerma rate ($\dot{K}$) of a material, the ionization occurs in the gas sensitive volume:

$$\dot{K}_{ar} = \overline{W} \cdot S_m \cdot p \tag{2}$$

where $\overline{W}$ is the average energy required to form an ion pair, S_m is the ratio between the material and gas stopping powers, and p is the number of ion-electron pairs per mass unit.

For radiation detectors with a small sensitive volume, when compared to the range of charged particles connected to radiation, which is the case of the extrapolation chamber, a linear behavior between the ionization current and the interelectrodic distance is expected. Therefore, it is possible to determine the B gradient, as shown in Equation (3).

$$B = \frac{\Delta_i}{\Delta_x} \tag{3}$$

where Δ_i is the variation of the ionization current, and Δ_x is the variation of the interelectrode distance (also called chamber depth). The B gradient is dependent on the electric field measurements since the effective area is not changed during the measurement; so, the B gradient is the angular coefficient of the extrapolation curve. Therefore, the air kerma rate can be obtained using Equation (4).

$$\dot{K}_{ar} = \frac{\overline{W}}{e} \cdot \frac{\Delta_i}{\Delta_x \cdot \rho \cdot A_{ef}} \cdot \prod_1^i k_i = \frac{\overline{W}}{e} \cdot \frac{B}{\rho \cdot A_{ef}} \cdot \prod_1^i k_i \tag{4}$$

where

$\overline{W}$ is the average energy required to form an ion pair;
e is the electron charge;
ρ is the atmospheric air density;
A_{ef} is the effective area of the entrance window;
$\prod_1^i k_i$ is the product of the applied correction factors to determine the air kerma rate.

Table 4 shows the values of the constants utilized in Equation (4) for the determination of the air kerma rate for the extrapolation chamber at the LCI.

2.4. Correction factors

To support the determination of the air kerma rate it is important to obtain two correction factors: one was obtained using Monte Carlo simulation (scattering and fluorescence) and the other one was obtained experimentally (ionic recombination).

To obtain the ionic recombination for the extrapolation chamber, Equation (5) was used (IAEA, 2000).

$$K_s = \frac{(V_1/V_2)^2 - 1}{(V_1/V_2)^2 - (M_1/M_2)} \tag{5}$$

where: M_1 and M_2 are the measures (ionization current) obtained with the voltages $V_1 = +200$ V and $V_2 = +100$ V, respectively.

2.5. MCNP5 model and methodology

To determine the scattering and fluorescence correction factor, the Monte Carlo MCNP5 (MCNP5, 2008) simulation was utilized. This Monte Carlo code has a great flexibility in the design of complex geometries. In the simulation of the ionization chamber geometry, the actual dimensions were used (Table 1). This mechanism is responsible for turning on and turning off the secondary particles during the simulation. More specific information about the methodology used in the analysis:

Description of the source and collimation system: Photons were emitted isotropically, in a solid angle, from a conic punctual source. The source was positioned at 1.0 m distance from the surface of the ionization chamber.

Transport Parameters and variance reduction technique: The cutoff energy for the photons and electrons and variance reduction were not used. 1×10^{12} particle histories were used, aiming to reduce the associated uncertainties.

Calculated quantity: The average energy absorbed in the volume of the ionization chamber was calculated using Tally F8: p,e (MeV/particle-source) of the MCNP5 code.

Table 4
Constants utilized for the determination of the air kerma rate of the standard radiation qualities for computed tomography beams at LCI.

Constant	Description	Value
$\overline{W}$	Average energy required to form an ion pair	33.97 eV
e	Electron charge	1.60×10^{-19} C
ρ	Atmospheric air density [a]	1.2930 kg/m^3
A_{ef}	Effective area of the entrance window	2.83×10^{-3} m^2

[a] Reference conditions: 20°C e 101.325 kPa.

2.6. Calibration of the pencil type ionization chambers

The two pencil type ionization chambers (C_{IPEN} and C10) were calibrated in relation to the extrapolation chamber using the replacement method. Therefore, to determine the calibration factor (N_{KL}) for the pencil type ionization chambers, the ratio was taken between the air kerma rate obtained using the extrapolation chamber and the average of the measurements corrected for the reference environmental conditions of the chambers to be calibrated. Equation (6) shows how to obtain the calibration factor.

$$N_{KL} = \frac{\dot{K}_{ar}}{M \cdot F_{T,P}} \quad (6)$$

where $\dot{K}_{ar}$ is the air kerma rate obtained for the extrapolation chamber, $F_{T,P}$ is the correction factor for the standard environmental conditions and M is the measurement (ionization current) obtained with the chamber under calibration. Then, it is possible to determine the correction factor (K_Q) for each radiation quality using Equation (7).

$$K_Q = \frac{N_{KL}}{N_{KLref}} \quad (7)$$

The correction factor is the ratio between the calibration factor for each radiation quality (N_{KL}) and the calibration factor for the reference radiation quality (N_{KLref}); in the case at the LCI, the reference radiation quality for computed tomography beams is RQT 9.

3. Results and discussion

The results are presented in three sections: characterization tests, air kerma rate determination and calibration of the pencil type ionization chambers.

3.1. Characterization tests

For all tests, the extrapolation chamber was positioned at the distance of 1 m from the focus of the X-rays equipment used for calibration of radiation detectors. Only in the variation of response of source-detector distance test, the chamber was not fixed in 1 m from the focus of the X-rays. Measurements were taken in the three radiation qualities.

Initially are presented the results obtained for the characteristics of the extrapolation chamber; zero depth was obtained for the chamber in both laboratories in the reference radiation quality (RQT 9) for computed tomography beams. Ten measurements were taken during 30 s in the positive and negative voltages applied to the chamber, varying the depth so that the electric field was always kept constant at 100 V/mm. Fig. 2 shows the zero depth values obtained for the extrapolation chamber in both laboratories (LCI and NPL).

As can be seen in Fig. 2, the curves obtained for both polarities were extended to determine the intersection point that matches with the zero depth, where the curves cut the x-axis. The value obtained in both laboratories was - 0.21 mm. As this result is less than zero, the correct way to use the chamber is by adding 0.21 mm to the depth when utilizing it in the other tests.

For the extrapolation curves, the zero depth was applied to the depth for each voltage applied to the chamber, and the electric field was always kept constant at 100 V/mm. The extrapolation curves can be seen in Fig. 3.

The analysis of the extrapolation curve is given by the linearity of the curve, so the correlation coefficients should be close to 1.000. Table 5 shows the correlation coefficients obtained for the extrapolation chamber in both laboratories.

The correlation coefficients obtained for the extrapolation chamber in the three CT radiation qualities in both laboratories are very close to 1.000. Consequently, it is possible to confirm the linearity of the curve.

For the stabilization time test, the procedure was to irradiate the extrapolation chamber and then measure the ionizing current after 15 min, 30 min, 45 min and 60 min. The difference between the ionizing currents measured after 15 min and 60 min was compared with the limit established by IEC (IEC, 1997) of ±2%. The results are presented in Table 6, and they are within the limit, for both laboratories.

To analyze the variation of the electrical field applied to the extrapolation chamber, the saturation curves were determined, varying the applied voltage from - 250 V to + 250 V, in steps of 50 V. The results are presented in Fig. 4 for the chamber in both laboratories.

As can be observed in Fig. 4, the extrapolation chamber presents the same behavior for both polarities applied to the chamber in all radiation qualities at the LCI and NPL; the only difference is the fact that the ionization current is higher at LCI than at NPL, due to the beam characteristics.

The polarity effect was obtained by taking the ratio of the positive and negative ionization currents obtained in each applied voltage to the extrapolation chamber. The recommended limit is ±1% (IEC, 1997). The results are shown in Table 7 for all CT radiation qualities in both laboratories, and they are all within the limit.

The ion collection efficiency was obtained from the saturation curve considering the values obtained for + 200 V and +100 V in each radiation quality at the LCI and NPL laboratories. The recommended limit is ±95% (IEC, 1997), and the results are shown in Table 8, all within the limit.

For the linearity of response test, the tube current was varied from 2 mA to 20 mA at the LCI and from 1 mA to 15 mA at the NPL. The results can be seen in Fig. 5 for the chamber in both laboratories, and the correlation coefficients (R^2) are shown in Table 9.

All of the correlation coefficients obtained in the three CT radiation

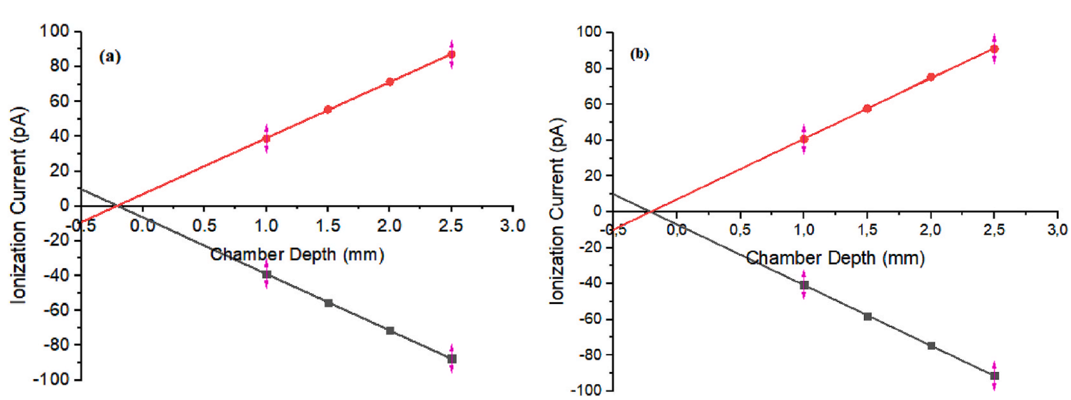


Fig. 2. Zero depth for the extrapolation chamber in the reference radiation quality (RQT 9) for computed tomography beams at the (a) LCI and (b) NPL. The maximum measurement uncertainty was 0.06%, not visible in the figures.

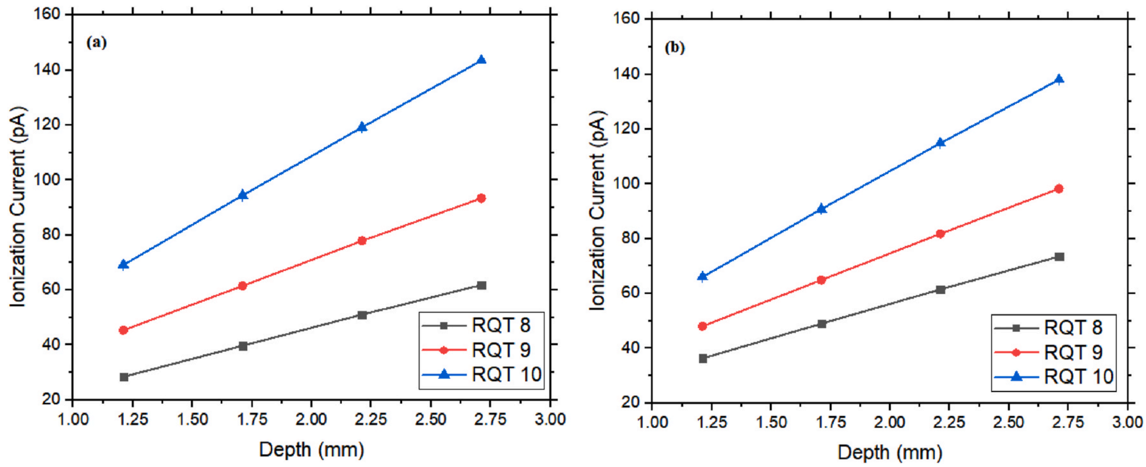


Fig. 3. Extrapolation curves of the extrapolation chamber in the three CT radiation qualities at the (a) LCI and (b) NPL. The maximum measurement uncertainty was 0.03%, not visible in the figures.

Table 5
Correlation coefficients (R^2) were obtained for the extrapolation curves of the extrapolation chamber in the three CT radiation qualities at LCI and NPL.

Radiation Quality	LCI	NPL
RQT 8	0.9997	0.9997
RQT 9	0.9998	0.9998
RQT 10	0.9998	0.9998

Table 6
Stabilization time test for the extrapolation chamber in the CT radiation qualities in both laboratories (LCI and NPL). Δ: Difference between the ionization current values obtained 15 min and 60 min after irradiation.

Radiation Quality	LCI Δ (%)	NPL Δ (%)
RQT 8	0.51	0.19
RQT 9	0.04	0.31
RQT 10	0.01	0.07

qualities in both laboratories (LCI and NPL) are very close to 1.000. Therefore, it is possible to confirm the linearity of the response of the extrapolation chamber.

For the variation of response with the source-detector distance test, measurements were collected changing the distance between the extrapolation chamber and the X-ray tube focus in both laboratories, in all three radiation qualities for computed tomography beams. Figs. 6 and 7 show the curves obtained at the LCI and the NPL.

The deviation of the results obtained for the variation of response with the source-detector distance in relation to the inverse square law can be observed in Table 10.

Table 10 shows the maximum deviation obtained for each radiation quality in CT beams. At the LCI, these maximum deviations occurred at a distance of 1.25 m in the three radiation qualities. At the NPL all the maximum deviations occurred at a distance of 1.50 m. Consequently, the maximum deviation might be due to a positioning problem of the extrapolation chamber.

Table 7
Polarity effect for the extrapolation ionization chamber in the CT radiation qualities at LCI and NPL.

Applied Voltage (V)	LCI			NPL		
	Radiation Quality					
	RQT 8	RQT 9	RQT 10	RQT 8	RQT 9	RQT 10
50	1.009	1.013	1.007	1.006	1.003	1.010
100	1.014	1.013	1.009	1.007	1.005	1.006
150	1.014	1.005	1.009	1.004	1.003	1.006
200	0.997	1.010	1.004	1.005	1.005	1.004
250	1.009	1.007	0.999	1.010	1.002	1.003

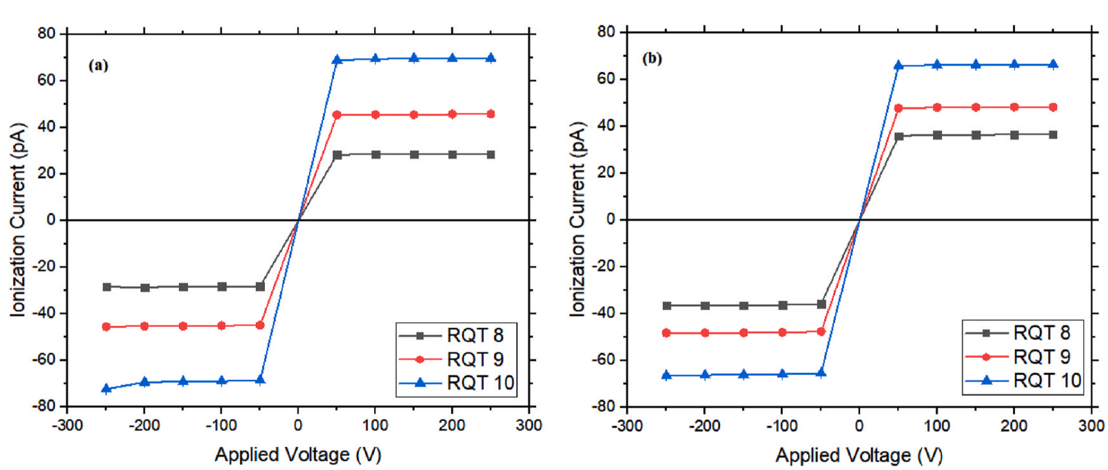


Fig. 4. Saturation curves for the extrapolation chamber in the three standard CT radiation qualities at the (a) LCI and (b) NPL. The maximum measurement uncertainty was 0.04%, not visible in the figures.

Table 8
Ion collection efficiency (%) for the extrapolation chamber in the CT radiation qualities at the LCI and NPL laboratories.

Laboratory	Radiation Quality		
	RQT 8	RQT 9	RQT 10
LCI	99.84	99.96	99.80
NPL	99.63	99.45	99.53

Table 9
Correlation coefficients (R^2) obtained for the linearity of the response test for the extrapolation chamber in the three CT radiation qualities at the LCI and NPL laboratories.

Radiation Quality	Laboratory	
	LCI	NPL
RQT 8	0.9999	0.9999
RQT 9	0.9999	0.9998
RQT 10	0.9999	0.9998

The energy dependence was also determined for the extrapolation chamber at the NPL laboratory. It was obtained by the ratio of the correction factor of the radiation qualities and the reference radiation quality (RQT 9). Table 11 shows the results obtained at the NPL.

The results obtained for the RQT 10 radiation quality at the NPL laboratory are not in agreement with the international recommendations IEC 61674 (IEC, 1997), due to the differences between the extrapolation chamber and the reference chamber (free air chamber). As known, the reference chamber for CT beams is a pencil type ionization chamber. Therefore, the geometry, volume and operation are different. However, to determine the air kerma rate with the extrapolation chamber, the study needs to be expanded, using experimental measurements and Monte Carlo simulations for the correction factors.

3.2. Air kerma rate determination

The air kerma rate was obtained for the extrapolation chamber at the LCI. To determine the air kerma rate using Equation (4) it was necessary to obtain the gradient B, which is the angular coefficient of the extrapolation curve (Fig. 3a). Table 12 shows the angular coefficient obtained for each extrapolation curve in the three radiation qualities for computed tomography beams at the LCI.

These values will be applied to Equation (4) to obtain the air kerma rate, but the correction factors have to be determined before.

The ionic recombination factor (k_s) was determined experimentally for the extrapolation chamber in the three radiation qualities for CT beams at the LCI using Equation (5). Table 13 shows the results obtained for ionic recombination.

The results obtained for the ionic recombination are very close to 1.000, with the highest difference among them of only 0.1%.

The scattering and fluorescence correction factor was determined to turn on and turn off the secondary particles during the simulation using MCNP5 code. This correction factor was obtained for the three radiation qualities for CT beams at the LCI. Table 14 shows the results obtained for the scattering and fluorescence correction factor.

The results obtained for the scattering and fluorescence correction factor are very close to 1.000, with the highest difference among them of only 0.4%.

Finally, with the gradient B and the two correction factors determined (ionic recombination, and scattering and fluorescence) and the constant values showed in Table 4, it was possible to obtain the air kerma rate for the extrapolation chamber in all radiation qualities for computed tomography beams at the LCI using Equation (4).

The results for the air kerma rate can be seen in Table 15, and it was possible to determine the difference between the air kerma rates obtained with the extrapolation chamber and the nominal air kerma rates of the LCI.

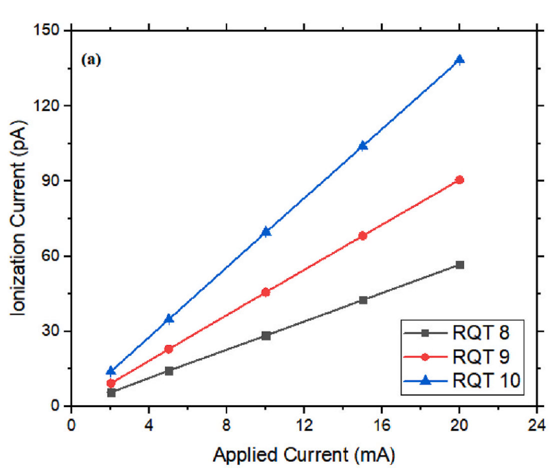
As can be observed in Table 15, it was possible to obtain the air kerma rate using the extrapolation chamber for laboratory computed tomography beams at the LCI; therefore this chamber can be considered as a reference system for this kind of laboratory radiation beams. Moreover, a comparison between the obtained air kerma rates using the extrapolation chamber and the nominal air kerma rates for the LCI showed that the highest deviation was obtained for the RQT 8 radiation quality.

3.3. Calibration of the pencil type ionization chambers

A homemade pencil type ionization chamber (C10) and a commercial pencil type ionization chamber (C_{IPEN}) from the LCI were calibrated using the replacement method against the extrapolation chamber.

The calibration factors were determined using Equation (6) and the correction factors were obtained using Equation (7) for all radiation qualities for standard computed tomography beams. Tables 16 and 17 show the calibration factors and the correction factors obtained for the pencil type chambers utilized in this work.

As can be seen in Tables 16 and 17, the determination of the calibration factors and the correction factors for the pencil type ionization chambers using an extrapolation chamber was simple, utilizing only two equations (6) and (7), once the air kerma rates were obtained by the extrapolation chamber in absolute terms, i e, without any previous calibration.



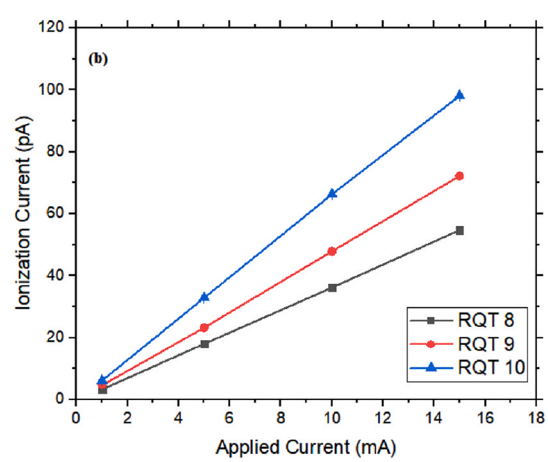


Fig. 5. Linearity of response for the extrapolation chamber in the three standard CT radiation qualities at the (a) LCI and (b) NPL laboratories. The maximum measurement uncertainty was 0.05%, not visible in the figures.

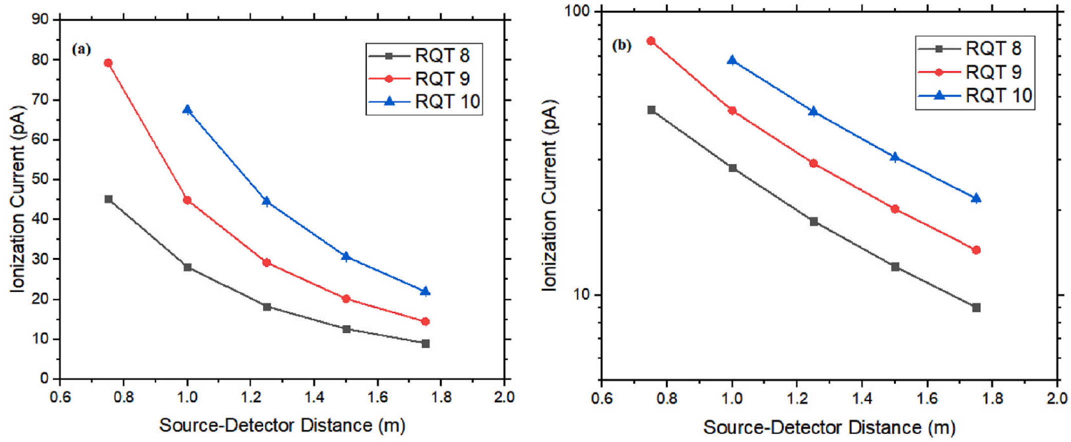


Fig. 6. Variation of the response with the source-detector distance of the extrapolation chamber in the three CT radiation qualities (a) linear scale and (b) logarithmic scale, at the LCI. The maximum measurement uncertainty was 0.05%, not visible in the figures.

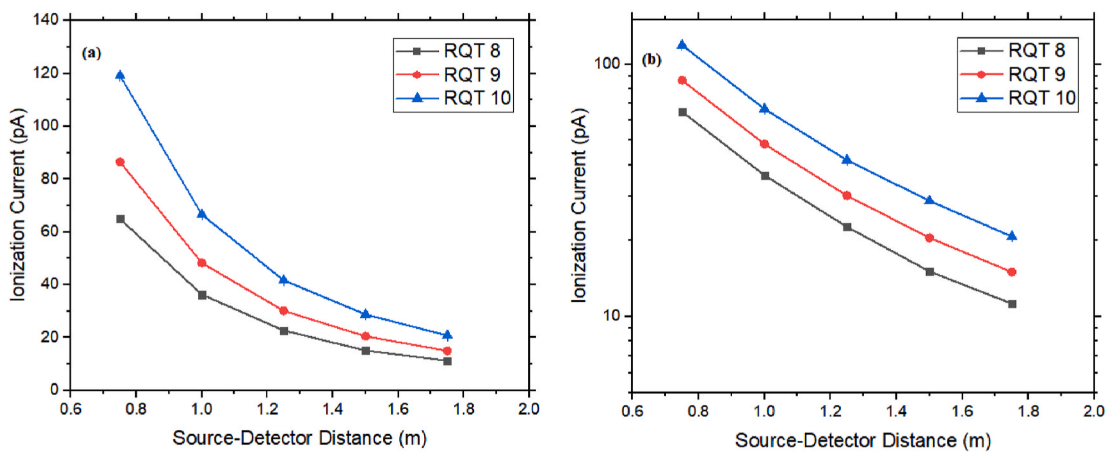


Fig. 7. Variation of the response with the source-detector distance of the extrapolation chamber in all three CT radiation qualities (a) linear scale and (b) logarithmic scale, at the NPL. The maximum measurement uncertainty was 0.05%, not visible in the figures.

4. Conclusion

The extrapolation chamber was tested in computed tomography beams at the LCI and the NPL. The characteristics of the chamber were determined and the characterization tests were undertaken, obtaining results within the international recommendations (IEC 61674), except for the energy dependence as already expected, because of the differences in geometry and volume of the chambers used during the calibration.

The air kerma rates were obtained using an extrapolation chamber in standard laboratory computed tomography beams in absolute terms. In

Table 10
Maximum deviations obtained for the variation of response with the source-detector distance test in relation to the inverse square law for the extrapolation chamber response in the three CT radiation qualities at the LCI and NPL laboratories.

Radiation Quality	Deviation (%)	
	LCI	NPL
RQT 8	2.70	8.06
RQT 9	3.68	5.48
RQT 10	6.48	4.73

Table 12
Angular coefficient obtained for each extrapolation curve in all three radiation qualities for computed tomography beams at the LCI.

Radiation Quality	Angular Coefficient (pA/mm)
RQT 8	22.29 ± 0.19
RQT 9	32.08 ± 0.26
RQT 10	49.51 ± 0.30

Table 11
Calibration factor, correction factor and energy dependence of the extrapolation chamber for the CT radiation qualities at NPL.

Radiation Quality	Calibration Factor (10^7 Gy/C)	Correction Factor	Energy Dependence (%)
RQT 8	1.17 ± 0.01	0.973	2.7
RQT 9	1.21 ± 0.01	1.000	–
RQT 10	1.34 ± 0.01	1.113	11.3

Table 13
Ionic recombination correction factors for the extrapolation chamber in the three radiation qualities for CT beams at the LCI.

Radiation Quality	Ionic Recombination Correction Factor
RQT 8	0.998 ± 0.001
RQT 9	0.999 ± 0.001
RQT 10	0.998 ± 0.001

Table 14
Scattering and fluorescence correction factor for the extrapolation chamber in the three radiation qualities for CT beams at the LCI.

Radiation Quality	Scattering and Fluorescence Correction Factor
RQT 8	0.999 ± 0.006
RQT 9	1.003 ± 0.007
RQT 10	1.002 ± 0.007

Table 15
Deviation between the air kerma rate values for the extrapolation chamber and those of the LCI in the three radiation qualities for CT beams.

Radiation Quality	Air Kerma Rate Extrapolation Chamber (mGy/min)	Nominal Air Kerma Rate at LCI (mGy/min)	Deviation (%)
RQT 8	24.8 ± 0.4	22.0 ± 0.1	10.2
RQT 9	35.8 ± 0.5	34.0 ± 0.1	4.07
RQT 10	55.2 ± 0.6	57.0 ± 0.1	2.30

Table 16
Calibration factors and correction factors for all radiation qualities of CT beams for the pencil type ionization chamber C10.

Radiation Quality	Calibration Factor (10^7 Gy/C)	Correction Factor
RQT 8	6.50 ± 0.07	1.061
RQT 9	6.12 ± 0.07	1.000
RQT 10	5.74 ± 0.07	0.938

Table 17
Calibration factors and correction factors for all radiation qualities of CT beams for the pencil type ionization chamber C_{IPEN}.

Radiation Quality	Calibration Factor (10^7 Gy/C)	Correction Factor
RQT 8	10.04 ± 0.06	1.053
RQT 9	9.53 ± 0.06	1.000
RQT 10	8.98 ± 0.06	0.942

comparison with the nominal air kerma rates at LCI, the highest deviation was 10.2%, for the RQT 8 radiation quality.

The two pencil type ionization chambers (C10 and C_{IPEN}) were calibrated against the extrapolation chamber, and the maximum deviation between the correction factor obtained for each pencil type ionization chamber was 0.8%, showing that the methodology used is adequate when the extrapolation chamber is utilized as a reference system at a calibration laboratory.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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