Characterization and Simulation of a New Design Parallel-Plate Ionization Chamber for CT Dosimetry at Calibration Laboratories

Ana P. Perini, Lucio P. Neves, Ana F. Maia, and Linda V. E. Caldas

***Abstract*—In this work, a new extended-length parallel-plate ionization chamber was tested in the standard radiation qualities for computed tomography established according to the half-value layers defined at the IEC 61267 standard, at the Calibration Laboratory of the Instituto de Pesquisas Energéticas e Nucleares (IPEN). The experimental characterization was made following the IEC 61674 standard recommendations. The experimental results obtained with the ionization chamber studied in this work were compared to those obtained with a commercial pencil ionization chamber, showing a good agreement. With the use of the PENELOPE Monte Carlo code, simulations were undertaken to evaluate the influence of the cables, insulator, PMMA body, collecting electrode, guard ring, screws, as well as different materials and geometrical arrangements, on the energy deposited on the ionization chamber sensitive volume. The maximum influence observed was 13.3% for the collecting electrode, and regarding the use of different materials and design, the substitutions showed that the original project presented the most suitable configuration. The experimental and simulated results obtained in this work show that this ionization chamber has appropriate characteristics to be used at calibration laboratories, for dosimetry in standard computed tomography and diagnostic radiology quality beams.**

***Index Terms*—Computed tomography, dosimetry, Monte Carlo simulation, operational tests, parallel-plate ionization chamber.**

I. INTRODUCTION

COMPUTED TOMOGRAPHY (CT) procedures have experienced a large growth in recent years due to improvements in the technology and new clinical applications. Advances in technology refer to an upgrade in the CT components: tube, detector, slip ring, data acquisition systems and algorithms. Also, it is possible to verify that new CT examinations were added to conventional exams due to the introduction of helicoidal and multislice CT systems.

A very important procedure related to CT examinations is its beam dosimetry, that involves larger radiation doses than the more common, conventional x-ray imaging procedures, as plain radiographs (e.g. chest x-rays) or mammography. For example, in a recent study of Osei and Darko [1] carried out with 94 patients who underwent CT examinations and 338 patients who had conventional radiography examinations, the mean effective dose for an abdomen examination (AP projection) was 0.14 mSv, while a CT abdomen and pelvis examination presented a mean effective dose of 13.6 mSv. Considering a thoracic spine examination (lateral projection), the mean effective dose was 0.32 mSv, while a CT chest examination presented a mean effective dose of 7.9 mSv. Certainly, these results vary for different clinics and machines, but CT exams present larger doses to the patients.

Recently, a research pointed out that CT examinations are responsible for just 6% of all x-ray examinations worldwide, while accounting for about 34% of the resultant collective dose [2]. The most common dosimeter types utilized to undertake dose measurements in CT are: ionization chambers, thermoluminescent dosimeters and radiographic films. Ionization chambers present some advantages in relation to other radiation detectors (as thermoluminescent dosimeters and radiographic films): high precision, measurements with low uncertainties, stable response within a wide range of energies, robustness, easy handling, and the readings are obtained in real time.

For CT dosimetry, a specially designed air filled long pencil-shaped ionization chamber is used. The active length of the ionization chamber is normally 100.0 mm. It can be used to measure absorbed doses free in air or in a phantom. At the Calibration Laboratory of IPEN (LCI) some ionization chambers were developed for CT dosimetry [3]–[5]. Maia and Caldas [3] tested a special parallel-plate ionization chamber for x-ray dosimetry, utilizing the standard x-ray qualities presented in the IEC 61267 (1994) standard [6]. In the present work, this ionization chamber was evaluated in CT radiation qualities, based on the new IEC 61267 (2005) standard [7], which substitutes the IEC 61267 (1994) standard [6]. It is important to note that the IEC 61267 (1994) [6] standard did not present specific CT radiation qualities, as in the newest edition of IEC 61267 (2005) standard [7].

The ionization chamber characterized in this work has the two most important characteristics similar to those of pencil ionization chambers: 3.2 cm^3 of sensitive volume and 10.0 cm of sensitive length. However, it is a parallel-plate ionization chamber instead of cylindrical type, which is the case of pencil ionization chambers. It will be called PPCT (parallel-plate CT) ionization

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chamber throughout this work. The parallel design was utilized because it is possible to define the sensitive volume more accurately. The guard rings provide a better definition of the sensitive volume, and they are useful to reduce the leakage current. The reference point of measurement of the new chamber is at the entrance window, not at the geometrical centre as in cylindrical chambers. Due to its geometrical arrangement, this ionization chamber is not suitable for use in a rotational CT geometry, but it is intended only for fields that are perpendicular to the chamber window.

During the last decades it was possible to observe an improvement of the computer processors and parallel processing, increasing the use of Monte Carlo (MC) techniques for radiation transport simulations, and turning it one of the most common and powerful methods applied to medical physics [8]–[11]. The Monte Carlo code applied to CT has been utilized to assess the impact of different physical design parameters on the overall scanner performance, clinical image quality, absorbed dose delivered in CT examinations and evaluation of detectors utilized in CT dosimetry applications [5]. These characteristics may be difficult or even impossible to estimate by experimental measurements and theoretical studies.

Besides the experimental analysis, MC simulations were employed to evaluate the influence of the cables, insulator, poly(methyl methacrylate) (PMMA) body, central electrode, guard ring and screws on the energy deposited on the sensitive volume. These types of analyses are, so far, unpublished for this type of dosimeter (parallel-plate) using CT radiation qualities. Furthermore, MC simulations were employed to evaluate the design and materials of this new dosimeter. This study was conducted evaluating the thickness and materials used for the collecting electrode and insulator, the entrance window and wall thickness material as well as the cable distribution. All these analyses can not be conducted experimentally, since several prototypes would be necessary, and several parameters would have to be controlled. The main objective of these analyses is to fully evaluate the chamber components and verify which configuration presents the lowest influence on the radiation beam.

In this work, an ionization chamber (PPCT) was evaluated for CT dosimetry, for use at calibration laboratories, according to the IEC 61674 [12], and the results were compared to those of a commercial pencil ionization chamber Victoreen, model 660-6. The results of these tests were compared with the international recommended limits [12]. Furthermore, this PPCT ionization chamber was also characterized using MC calculations, and the experimental and simulated results were combined to fully characterize and describe this dosimeter in CT standard beams.

II. MATERIALS AND METHODS

A. Experimental Study

The ionization chamber utilized for experimental and simulations analyses was a new type of parallel-plate ionization chamber developed at the LCI by Maia and Caldas [3], shown in Fig. 1. The main technical specifications of this ionization chamber are listed in Table I. The scheme and dimensions are shown in Figs. 2(a) and (b).

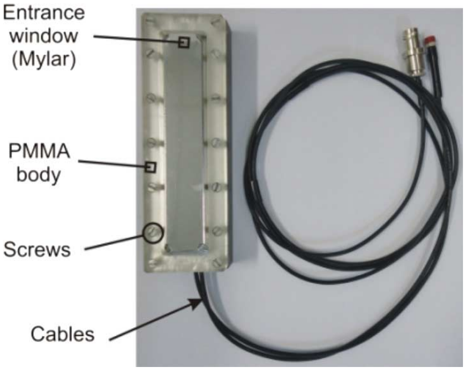


Fig. 1. PPCT ionization chamber developed at the LCI [3] and characterized in this work at CT and diagnostic radiology standard qualities.

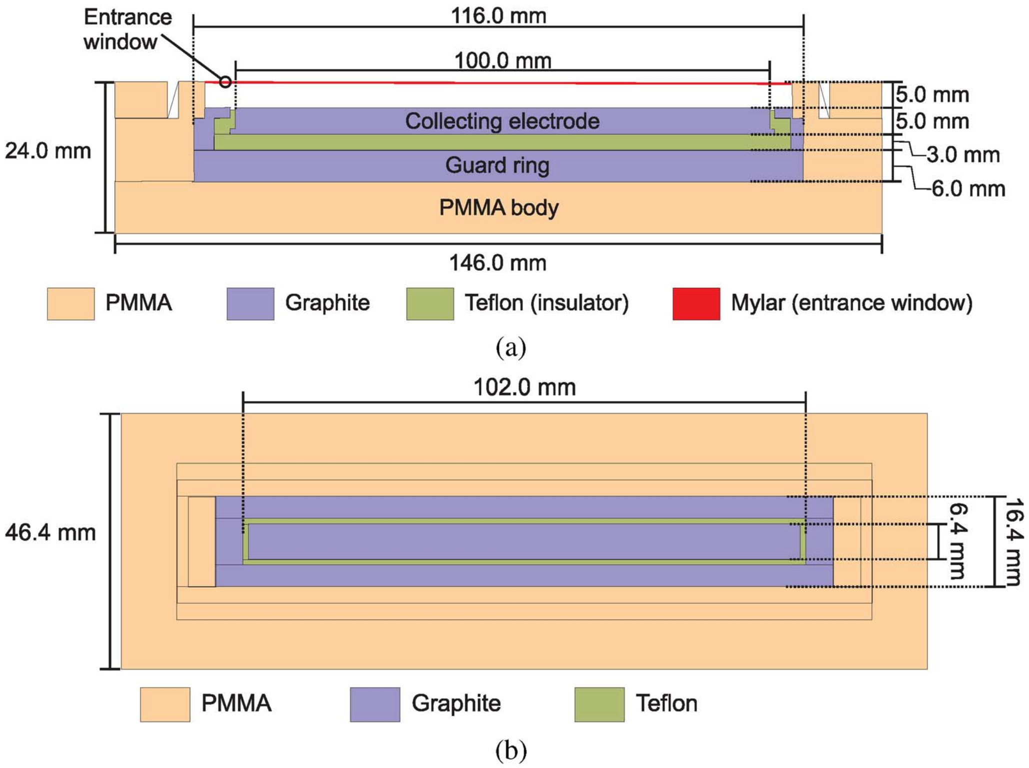
TABLE I
IONIZATION CHAMBER TECHNICAL SPECIFICATIONS

Characteristics	Dimensions/specifications
Collecting electrode material	Graphite
Window material	Mylar
Wall material	PMMA
Chamber outer diameter	146.0 mm
Insulator material	Teflon
Chamber sensitive length	100.00 mm
Connector	BNC and banana pin
Chamber sensitive volume	3.2 cm^3

In order to evaluate the performance of the ionization chamber studied in the present work some operational tests, following the IEC 61674 standard recommendations [12], were performed: saturation curve, ion collection efficiency, polarity effect, stability of response, leakage current, linearity of response and energy dependence for CT and diagnostic radiology qualities (RQR and RQA).

The irradiations were undertaken utilizing an industrial x-ray system Pantak/Seifert, model ISOVOLT 160 HS. An electrometer, Physikalisch-Technische Werkstätten (PTW) UNIDOS-E, was utilized for the measurements. The standard CT radiation qualities established based on the half-value layers defined by the IEC 61267 [7] were used during the characterization tests (Table II). For the energy dependence tests, two more kinds of radiation qualities were used, the direct and attenuated diagnostic radiology qualities (RQR and RQA), also defined by the IEC 61267 [7] (Table III). The CT radiation qualities were established with a RADCAL RC3CT reference ionization chamber, and the diagnostic radiation qualities with a RADCAL RC6 reference ionization chamber. These dosimeters were initially calibrated at the German primary standard laboratory, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig.

The stability tests (short- and medium-term stability) were performed using a $^{90}\text{Sr}+^{90}\text{Y}$ radioactive check source (PTW;



(a)

(b)

FIg. 2. Schematic diagram and dimensions of the PPCT ionization chamber characterized in this work, in (a) lateral view, and in (b) top view, but without the entrance window for better visualization.

TABLE II
COMPUTED TOMOGRAPHY RADIATION QUALITIES ESTABLISHED AT THE LCI BASED ON THE HALF-VALUE LAYERS DEFINED BY THE IEC 61267 STANDARD RECOMMENDATIONS [7]

Radiation quality	**Tube voltage (kV)**	**Tube current (mA)**	**Additional filtration (mmCu)**	**Additional filtration (mmAL)**	**Half-value layer (mmAl)**	**Air kerma rate† (mGy/min)**
CT 1	100	10	0.30	3.2	6.9	21.79 ± 0.22
CT 2	120	10	0.35	3.5	8.4	33.05 ± 0.33
CT 3	150	10	0.35	4.2	10.1	56.13 ± 0.56

† Measured with a RADCAL RC3CT ionization chamber calibrated at the PTB.

33 MBq, 1994) and an acrylic holder [3], [13] to achieve reproducible geometric conditions.

In order to compare the results obtained in the experimental tests, a Victoreen pencil ionization chamber, model 660-6, was utilized. This ionization chamber is not sealed and presents 3.2 cm^3 of sensitive volume and 10.0 cm of sensitive length.

B. Simulation Study

All calculations were carried out using the PENELOPE/penEasy Monte Carlo code for radiation transport [14], [15]. As the PPCT ionization chamber characterized in this work was made at the LCI, all dimensions were known to set up the geometry, and the simulations were based on its actual dimensions.

The spectrum, utilized in the simulations, was obtained experimentally from the PTB [16] because the spectrum of the LCI irradiation system was not available. The spectrum from PTB was acquired in a 450 kV Yxlon facility with a tube of type "B450-1H450" from Thales, at a distance of 100.0 cm from the x-ray focus; it was obtained with a filtration of 3.7 mmAl+0.25 mmCu, a tube voltage of 120 kV, and the half-value layer of this radiation quality is 8.48 mmAl. This spectrum was used to represent the CT 2 radiation quality at the LCI. The x-ray spectra measured at the PTB are suitable for this study, since the radiation qualities available at the PTB and LCI have the same half-value layers, as recommended by the IEC 61267 [7], and the reference dosimeter used to establish this quality at the LCI was calibrated at the PTB.

Furthermore, in a recent publication of Perini *et al.* [5] the energy dependence of a cylindrical ionization chamber was

TABLE III
DIRECT (RQR) AND ATTENUATED (RQA) DIAGNOSTIC RADIOLOGY QUALITIES ESTABLISHED AT THE LCI BASED ON THE IEC 61267 STANDARD RECOMMENDATIONS [7]

Radiation quality	Tube voltage (kV)	Tube current (mA)	Additional filtration (mmAl)	Half-value layer (mmAl)	Air kerma rate† (mGy/min)
Direct beams					
RQR 3	50	10	2.4	1.78	21.96 ± 0.22
RQR 5	70	10	2.8	2.58	38.70 ± 0.39
RQR 9	100	10	3.2	3.97	69.42 ± 0.69
RQR 10	150	10	4.2	6.57	117.43 ± 1.17
Attenuated beams					
RQA 3	50	20	12.4	3.8	3.83 ± 0.04
RQA 5	70	20	23.8	6.8	3.60 ± 0.04
RQA 8	100	20	37.2	10.1	5.67 ± 0.06
RQA 10	150	20	49.2	13.3	13.33 ± 0.12

† Measured with a RADCAL RC6 ionization chamber calibrated at the PTB.

evaluated with MC simulations using the x-ray spectra measured at the PTB and another obtained with the use of the SpeckCalc software [17] (using the geometry and configuration of the LCI x-ray facility). The results of this paper pointed out no statistical differences between these two spectra (considering Type A uncertainties). In this sense, the spectra of the PTB may simulate in an adequate manner the LCI equipment. Type B uncertainties are related mainly to the simplification of the geometry and limitation of the physical models implemented in the PENELOPE code. As in this work only normalized responses are compared, the systematic, or Type B uncertainties, cancel out to a great extent.

In order to obtain a more detailed simulation, the parameters used in the PENELOPE code were the same for all materials. Photon and electron transport was discontinued below $E_{\rm abs} = 1$ keV. Other simulation parameters chosen for electron tracking were: an average angular deflection $C_1 = 0.05$; a maximum average fractional energy loss between consecutive hard elastic events $C_2 = 0.05$; a cutoff energy loss for hard inelastic collisions $W_{\rm CC} = 0.1$ keV; and a cutoff energy loss for hard bremsstrahlung $W_{\rm CR} = 1$ keV. The external electron step-length control was set to $s_{\max} = 10^{30}$ cm, in order to switch it off, and 10^{10} histories were simulated in each run to obtain low statistical uncertainties (below 1.0%).

Furthermore, as the geometry is very complex, and the sensitive volume is small, the variance reduction technique `interaction forcing`, already implemented in the PENELOPE code was employed on the sensitive volume of the ionization chamber. The *tally* utilized was the `energy deposition`, to obtain the average energy deposited in the cavity material (air).

The variance reduction technique `interaction forcing` can effectively reduce the statistical uncertainties of some simulation results, particularly the energy deposition in very thin volumes. Due to this characteristic, it is a good variation reduction technique to be utilized in simulations of the ionization chambers. In this case, the gas (that composes the sensitive volume) occupies a small volume, where photon interactions occur with a probability much smaller than in the walls of the ionization chamber. In this sense, most of the time is utilized to simulate interactions within the walls, which transfer insignificant energy to the sensitive volume. This technique consists of artificially increasing the probability of occurrence of a given process and the result is a net gain in efficiency, i.e., a reduction of the statistical uncertainty for a given calculation time. More details regarding the use of this technique may be found elsewhere [14].

The influence of the chamber components on its response was determined as the ratio of the dose to the gas in the ionization chamber without the studied component $(R_{\rm WC})$ to that of the PPCT ionization chamber $(R_{\rm PPCT})$, as shown in (1).

$$\text{Influence} = \frac{R_{\rm WC}}{R_{\rm PPCT}} \tag{1}$$

For the studies of different materials and components, the influence was determined as the ratio of the dose to the gas in the ionization chamber with the different material or geometrical arrangement $(R_{\rm DMG})$ to that of the PPCT ionization chamber $(R_{\rm PPCT})$ described in Section II-A, as shown in (2).

$$\text{Influence} = \frac{R_{\rm DMG}}{R_{\rm PPCT}} \tag{2}$$

Using (1) and (2) it is possible to evaluate the change in the response due to the different components, and different mate-

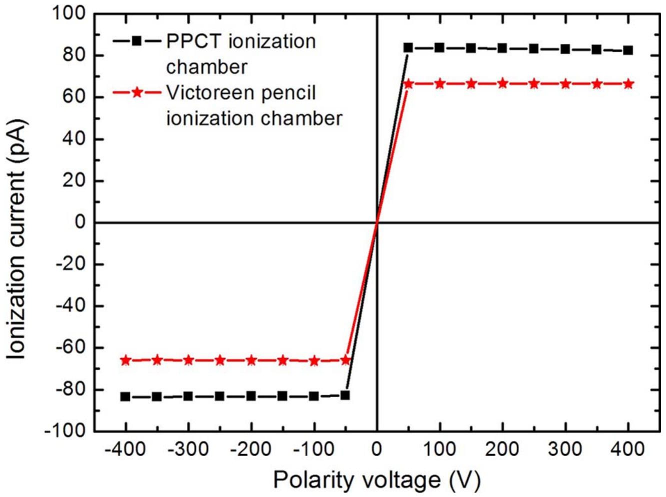


Fig. 3. Saturation curves of the PPCT and the Victoreen 660-6 ionization chambers, obtained for the CT 2 computed tomography radiation quality. The maximum uncertainty was 0.2%, and, therefore, not visible in the figure.

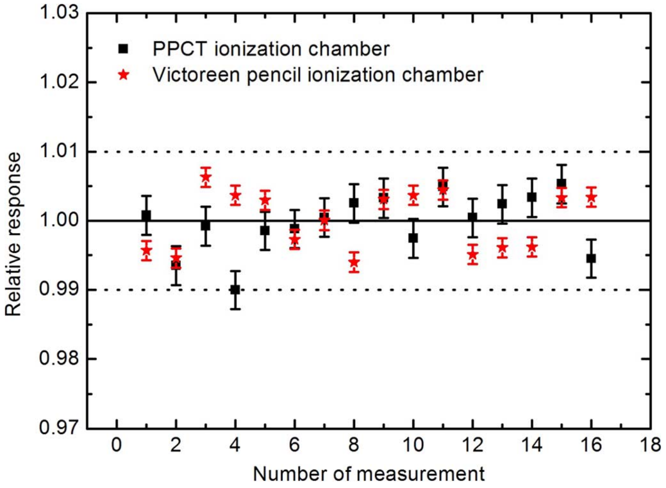


Fig. 4. Medium-term stability test of the PPCT and the Victoreen 660-6 ionization chambers, obtained utilizing a ^{90}Sr+^{90}Y radioactive check source. The dashed lines represent a variation of 1% on the chamber response (1/3 of the recommended limit [12]).

rials and geometrical arrangements. As the "perfect" dosimeter would have no influence in the medium (air where the measurements are being taken), lower influences represent better designed dosimeters.

III. Results and Discussion

A. Experimental Results

This section presents the results of the characterization tests, following IEC 61674 standard [12], for the PPCT ionization chamber characterized in this work and the commercial Victoreen pencil ionization chamber, model 660-6. The results were compared in order to evaluate the PPCT ionization chamber performance in relation to a commercial pencil type ionization chamber.

1) Saturation Curve, Ion Collection Efficiency and Polarity Effect: The saturation test was made to verify the optimal applied voltage for the chamber operation. As can be observed in Fig. 3, the ionization chambers presented no significant changes in the measured ionization currents. The graph represented in Fig. 3 was obtained varying the voltage applied to the ionization chamber from -400 V to $+400$ V, in steps of 50 V, for the CT 2 computed tomography radiation quality. Each measurement was repeated ten times and the charge was accumulated each time during 15 s.

As seen at Fig. 3, the PPCT ionization chamber presents a higher ionization current than the Victoreen 660-6 ionization chamber for the same conditions. There are several differences between these two dosimeters that may account on the measured ionization current. The PPCT ionization chamber has an entrance window with a larger area than the commercial one, which allows more electrons to be generated (at least for radiation beams at calibration laboratories). Furthermore, the geometrical components of the PPCT ionization chamber, as the PMMA walls, have also some influence on the energy deposited on the sensitive volume, and consequently, in the chamber readings. More details regarding these analyses will be presented in Section III-B.

The polarity effect and the ion collection efficiency were also evaluated utilizing the results obtained in the saturation curve.

The polarity effect was calculated from the saturation curves as defined in IAEA TRS-398 [18] and AAPM TG-61 [19] protocols. The maximum values obtained for the polarity effect were 0.23% and 0.50% for the PPCT and the Victoreen 660-6 ionization chambers, respectively. According to the IEC 60731 [20], the maximum limit acceptable for this test is 1.0%, and therefore the obtained result was within this recommendation.

The ion collection efficiency was obtained taking into consideration the collected charges and the two polarity voltages method as defined in IAEA TRS-398 [18] protocol.

The ion collection efficiency was better than 99.99% for polarities evaluated (-150 V and -300 V) for both ionization chambers. This result presents agreement with the value of 5% of ionic recombination losses, recommended by IEC 61674 [12]. Based on these tests, the operational voltage utilized for these ionization chambers was chosen as -300 V, and it was used during all tests.

2) Short- and Medium-Term Stability: In the stability tests, the PTW radioactive check source was positioned with a source holder [3], [13], to obtain reproducible readings. This test is a continuation of the stability test presented previously [3].

The short-term stability test was obtained by ten readings of charge, during a time interval of 60 s, under reproducible conditions. The highest variation coefficients obtained were 0.28% and 0.14% for the PPCT and the Victoreen 660-6 ionization chambers, respectively. According to the recommended international limits, the maximum variation acceptable is 1% [12].

Ten measurements of charge, collected in a fixed integration time of 60 s, were taken for the ionization chambers and normalized by their mean values in order to obtain the medium-term stability tests.

The mean charge was converted to current to observe the stability of the ionization chambers over a period of time. Fig. 4 shows the relative response of the ionization chambers normalized to the their respective mean values as a function of the

TABLE IV
CALIBRATION COEFFICIENTS AND CORRECTION FACTORS OF THE PPCT AND THE VICTOREEN 660-6 IONIZATION CHAMBERS IN CT RADIATION QUALITY BEAMS

		PPCT ionization chamber		**Victoreen 660-6 ionization chamber**	
Radiation quality	**Half-value layer (mmAl)**	**Calibration coefficient ($\times 10^7$ GyC^{-1})**	**Correction factor**	**Calibration coefficient ($\times 10^7$ GyC^{-1})**	**Correction factor**
CT 1	6.9	6.714 ± 0.074	1.020 ± 0.015	8.297 ± 0.091	1.008 ± 0.015
CT 2	8.4	6.581 ± 0.066	1.000 ± 0.014	8.235 ± 0.082	1.000 ± 0.014
CT 3	10.2	6.687 ± 0.066	1.016 ± 0.014	8.153 ± 0.081	0.990 ± 0.014

number of measurements. According to IEC 61674 [12], the maximum limit recommended for this test is 3.0%, and therefore, the ionization chambers are within this limit, as shown in Fig. 4.

3) Leakage Current: The leakage current of the ionization chambers was measured in time intervals of 20 minutes, before and after their irradiations, and it contributed with less than 0.07% and 0.2% to the ionization current measured, for the PPCT and the Victoreen 660-6 ionization chambers, respectively. These values are within the limit recommended internationally of 5% of the minimum effective air kerma rate of the range in use for at least 1 min [12]. The main reason for a lower leakage current of the PPCT ionization chamber is the presence of a guard ring around the whole sensitive volume, which is not possible on pencil type ionization chambers.

4) Linearity of Response: The relation between the ionization current and the air kerma rate was obtained by sequential irradiations of the ionization chambers in the CT 2 computed tomography radiation quality (Table II), with a variable tube current from 2 mA to 25 mA. The ionization chambers were positioned at a distance of 100.0 cm from the x-ray focus, taking the entrance window surface center as reference for the PPCT ionization chamber, and the center of the Victoreen pencil ionization chamber as its reference. The air kerma rates were determined using the reference ionization chamber for computed tomography (RADCAL RC3CT). Fig. 5 shows the data obtained normalized for the measurements obtained with a tube current of 2 mA, as a function of the air kerma rate. A linear fit was obtained with a correlation coefficient (R^2) of 1.000 for both ionization chambers, showing that both dosimeters present a linear response.

5) Energy Dependence: In order to obtain the energy dependence of the ionization chambers, they were calibrated against the reference ionization chambers for diagnostic radiology (RADCAL RC6) and computed tomography (RADCAL RC3CT). The calibration coefficients were determined according to the procedure given by Meghzifene and Shortt [21]. The correction factors were obtained by dividing the calibration coefficients in each radiation quality by the calibration coefficients of the CT 2, RQR 5 and RQA 5 radiation qualities, depending on whether the beams were related to computed tomography, direct or attenuated diagnostic radiology, respectively. The results obtained are shown in Tables IV and V.

The energy dependence (difference between the highest and the lowest calibration coefficients in percentage) are listed in Table VI. The results show that the PPCT ionization chamber presented a better performance to diagnostic radiology qualities (RQR and RQA) when compared with the commercial one. For CT radiation qualities both dosimeters presented similar results, which may be observed from the fact that the correction factors presented (Table IV) for the PPCT and the Victoreen 660-6 ionization chambers presented no statistical differences. These results indicate that the PPCT ionization chamber characterized in this work may be used as a multipurpose dosimeter, with application for CT and diagnostic radiology qualities, at calibration laboratories.

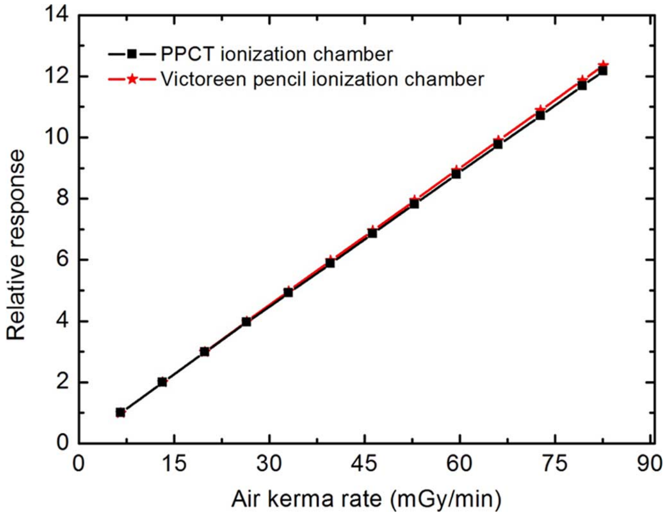


Fig. 5. Linearity of response of the PPCT and Victoreen 660-6 ionization chambers in CT 2 computed tomography radiation quality beam. Normalization was performed in relation to a tube current of 2 mA. The maximum uncertainty was 0.2%, and therefore, not visible in this figure.

B. Simulation Results

The PPCT ionization chamber has several differences among those normally used for CT dosimetry, as already stated. With the impossibility to evaluate those differences experimentally, in this work, Monte Carlo simulations, with the PENELOPE/penEasy code [14], were employed to study the influence on the chamber response of the following components: cables, insulator, PMMA chamber body, collecting electrode, guard ring and screws. Besides that, the thickness and materials for the collecting electrode and insulator; the entrance window material and wall thickness and material and cable distribution were also evaluated.

TABLE V
CALIBRATION COEFFICIENTS AND CORRECTION FACTORS OF THE PPCT AND THE VICTOREEN 660-6 IONIZATION CHAMBERS IN CONVENTIONAL RADIOLOGY QUALITY BEAMS (RQR AND RQA)

		PPCT ionization chamber		**Victoreen 660-6 ionization chamber**	
Radiation quality	**Half-value layer (mmAl)**	**Calibration coefficient ($\times 10^6$ GyC^{-1})**	**Correction factor**	**Calibration coefficient ($\times 10^6$ GyC^{-1})**	**Correction factor**
Direct beams					
RQR 3	1.78	7.246 ± 0.072	1.004 ± 0.028	18.033 ± 0.180	1.014 ± 0.029
RQR 5	2.58	7.218 ± 0.072	1.000 ± 0.028	17.779 ± 0.178	1.000 ± 0.028
RQR 8	3.97	7.206 ± 0.072	0.998 ± 0.028	17.358 ± 0.174	0.976 ± 0.028
RQR 10	6.57	7.040 ± 0.070	0.975 ± 0.028	17.272 ± 0.173	0.971 ± 0.027
Attenuated beams					
RQA 3	3.8	7.126 ± 0.071	1.029 ± 0.015	17.963 ± 0.180	1.112 ± 0.016
RQA 5	6.8	6.925 ± 0.069	1.000 ± 0.014	16.156 ± 0.162	1.000 ± 0.014
RQA 8	10.1	6.596 ± 0.066	0.953 ± 0.013	16.025 ± 0.160	0.992 ± 0.014
RQA 10	13.3	6.630 ± 0.066	0.957 ± 0.014	16.590 ± 0.166	1.027 ± 0.015

TABLE VI
ENERGY DEPENDENCE VALUES OF THE PPCT AND THE VICTOREEN 660-6 IONIZATION CHAMBERS IN CT, RQR AND RQA RADIATION QUALITY BEAMS

Ionization	**Energy dependence (%)**		
Chamber	**CT**	**RQR**	**RQA**
PPCT	1.98	2.84	7.44
Victoreen 660-6	1.74	4.22	10.8

As the CT2 radiation quality is the standard quality for CT at the LCI, all MC evaluations were carried out for this quality. Furthermore, as these simulations took a long time to be completed, due to the complexity of the geometrical arrangement of the ionization chamber, no further MC analyses to other radiation qualities were carried out, but the results for CT2 are representative for the other radiation qualities too.

The geometry used for the simulations is shown in Figs. 6, 7 and 8, and the results, obtained with (1) are shown in Table VII. The uncertainties (type A) were below 0.8% (with a coverage factor k of 2) for all simulated results.

The collecting electrode presented the highest effect (13.3%), but it is still lower than the effect from aluminum electrodes, that may come up to 50.0% in some dosimeters [22]. Even for smaller electrodes, as in the work of Perini *et al.* [5], the influence of the collecting electrode on the ionization chamber response was 9.0%. In the dosimeter studied in the present work, the collecting electrode covered the whole sensitive volume bottom area, and its influence is mainly due to the backscattered radiation. This is the same case for the other components that surround the sensitive volume, as the insulator, PMMA body and guard-rings. As the cables are behind the collecting electrode, their influence is smaller, as well as from the screws.

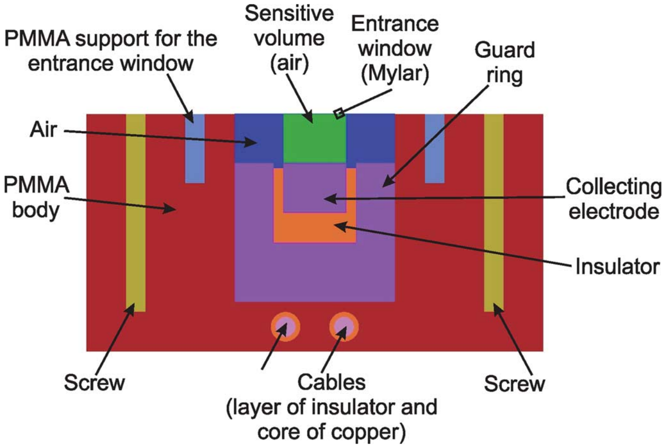


Fig. 6. Axial view of the PPCT ionization chamber geometry used in the Monte Carlo simulations.

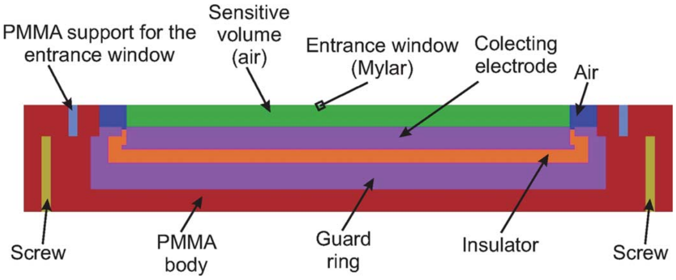


Fig. 7. Lateral view of the PPCT ionization chamber geometry used in the Monte Carlo simulations.

In order to study different constituent materials, MC simulations were employed to evaluate the use of Al as an collecting electrode material, bakelite and PMMA as insulators, entrance

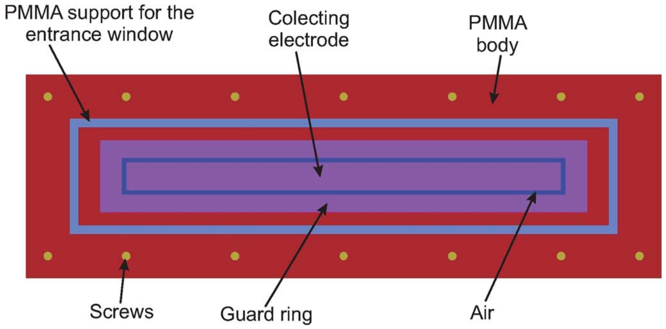


Fig. 8. Top view of the PPCT ionization chamber geometry used in the Monte Carlo simulations.

TABLE VII
INFLUENCE OF THE COMPONENTS OF THE PPCT IONIZATION CHAMBER ON ITS SENSITIVE VOLUME MATERIAL (AIR) RESPONSE

Studied component	Influence (%)
Cables	0.4
Insulator	3.0
PMMA body	10.7
Central electrode	13.3
Guard ring	4.0
Screws	0.5

TABLE VIII
STUDY OF THE INFLUENCE OF DIFFERENT CONSTITUENT MATERIALS ON THE SENSITIVE VOLUME MATERIAL (AIR)

Substitution material	Material used for the PPCT ionization chamber	Influence (%)
Collecting electrode made of Al	Graphite	98.4
Insulator made of Baquelite	Teflon	1.1
Insulator made of PMMA		2.3
Window made of Al	Mylar	137.9
Body made of PVC	PMMA	58.8

window of Al and body of polyvinyl chloride (PVC). Each influence was determined employing (2), and the results are presented in Table VIII.

The results showed that aluminum employed as collecting electrode material or entrance window will have a large influence on the chamber response. This is mainly caused by the Compton recoil electrons and photoelectrons, generated by interactions of photons with aluminum, that significantly contribute to the energy deposition in the sensitive volume. In the work of Muir and Rogers [22] the influence of the central collecting electrode was up to 50.0% for an 200 kVp incident beam. In the case of the PPCT ionization chamber characterized in this paper, however, the collecting electrode is not just a wire, but a plate covering the whole sensitive volume bottom area. In this sense, it is expected that the material selection will play a much more important role. The same applies for the entrance window material.

The PVC body also generates a higher influence in relation to the case of the PMMA body. It is caused by the higher effective atomic number of PVC in relation to PMMA for photon interactions. The use of different insulator materials did not present such a larger influence on the response, but it is important to note that Teflon is a better insulator material than PMMA. Bakelite presented an influence of just 1.1% lower than Teflon, but as it is more difficult to be machined, for this project Teflon was a more suitable choice.

Different geometrical arrangements were also evaluated with MC simulations, as the collecting electrode thickness, PMMA body, insulator thickness and number of cables inside the ionization chamber body. All results were evaluated with (2), and they are listed in Table IX.

The PMMA body presented the highest influence among all geometrical variations evaluated. As the irradiation beam covers the whole dosimeter, the use of a small PMMA body reduced the influence of the backscattered radiation over the sensitive volume material. This new configuration will be considered for future projects of this new type of ionization chamber, but the use of smaller radiation fields, employing e.g. a lead diaphragm, will reduce the influence of the PMMA body on the sensitive volume material.

The use of a thinner collecting electrode had a reduction of just 0.5% on the chamber response, and as graphite may easily break and this dosimeter must be resistant, the use of a thicker collecting electrode is necessary. The use of a thinner insulator material around the sensitive volume also reduced the influence of the insulator on the sensitive volume, but this effect may have a significant drawback: the increase of the leakage current over the surface of the insulator (parasite currents). Therefore, the use of an insulator with 1.0 mm thickness is justified. The use of 3 banana pins (that have a smaller amount of copper per cable than the BNC) instead of 1 BNC and 1 banana pin is also unnecessary, since it would produce a slightly higher influence, mainly due to the higher amount of copper.

IV. CONCLUSION

A newly designed parallel-plate ionization chamber (PPCT) was evaluated for computed tomography and diagnostic radiology dosimetry at a calibration laboratory. Several experimental tests, as proposed by the international standards, were undertaken, and all results were considered satisfactory and within the international recommendations. These results were compared with those obtained with a commercial pencil ionization chamber (Victoreen 660-6), showing good agreement. Monte Carlo simulations were carried out in order to evaluate the different design of the ionization chamber characterized in this work in relation to the pencil type ionization chambers generally utilized in CT beam dosimetry. With the PENELOPE Monte Carlo code, the influence of the cables, insulator, collecting electrode, guard ring, screws, as well as different materials and geometrical arrangements on the energy deposited on the chamber sensitive volume was evaluated. The

TABLE IX
STUDY OF THE INFLUENCE OF DIFFERENT GEOMETRICAL ARRANGEMENTS ON THE SENSITIVE VOLUME MATERIAL (AIR)

Geometrical variation studied	**PPCT ionization chamber geometry**	**Modifications on the PPCT geometry**	**Influence (%)**
Thinner collecting electrode	Thickness of 5.0 mm	Thickness of 2.5 mm	-0.5
Smaller body of PMMA	Lateral length of 46.4 mm	Lateral length of 30.8 mm	-4.3
Thinner insulator around the sensitive volume	Thickness of 1.0 mm	Thickness of 0.2 mm	-2.3
Number of cables	2 cables were used (1 BNC and 1 banana pin)	3 cables were used (BNC was divided into 2 banana pins)	0.3

maximum influence (13.3%) of the chamber component on its sensitive volume was from the central collecting electrode.

According to the simulated results obtained varying the materials and geometrical arrangements of the PPCT ionization chamber, it is possible to conclude that it is suitable as a reference dosimeter for CT radiation qualities, as its components present influences compatible to those from other radiation dosimeters [5], [22]. These results show also that the dosimeter is optimized for CT radiation fields, because its project presents: robustness and a suitable choice of the materials and dimensions of the chamber components. The main advantage of this parallel-plate dosimeter design is related to the fact that it has a well defined sensitive volume, mainly due to the presence of the guard rings (not present on the pencil types). These guard rings also reduced the leakage currents. Furthermore, all components and dimensions are known, which is very important for calibration laboratories. The characterized 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 and as a multipurpose dosimeter for CT, RQR and RQA radiation qualities.

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