Evaluation and Simulation of a New Ionization Chamber Design for use in Computed Tomography Beams

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***Abstract*—A newly-designed pencil ionization chamber with a sensitive volume of $3.4\ \mathrm{cm}^3$ was evaluated at the Calibration Laboratory of IPEN (São Paulo, Brazil) for use in the dosimetry of computed tomography (CT) medical equipment. The main differences between this CT ionization chamber and the commercial ones are related to the respective design and constituent materials. In the ionization chamber characterized in this work an alternative wall material was tested and a different BNC connector position was evaluated. This novel dosimeter was also designed to have an assembling process as simple and cheap as possible. To estimate the chamber performance, several pre-operational tests were undertaken. The energy dependence test was also evaluated using Monte Carlo simulation with the PENELOPE code system. In addition, Monte Carlo simulations were done to study the influence of various components on the energy deposition in its sensitive volume. The results obtained in the tests showed that the analyzed configuration of the CT ionization chamber is a good alternative for use in CT dosimetry, because it is easy to construct, and it presents a relatively low cost.**

***Index Terms*—Computed tomography (CT), dosimetry, Monte Carlo simulation, pencil ionization chamber.**

I. INTRODUCTION

COMPUTED tomography (CT) is utilized extensively in diagnostic imaging. The fact that CT procedures deliver significant absorbed doses and that the number of CT examinations continues to grow has received much attention in both the scientific literature [1] and the mass media. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has highlighted that the annual frequency of CT examinations has exhibited a dramatic increase since the beginning of its use. UNSCEAR has also estimated that CT examinations constitute approximately 6% of all x-ray examinations worldwide while accounting for about 34% of the resulting collective dose [2]. The radiation doses received by patients submitted to CT procedures are generally in the order of 1 mSv to 24 mSv per examination for adults [2] and 2.0 mSv to 6.5 mSv for children [3].

The extension of CT into medical areas is still increasing because of the emergence of multidetector computed tomography (MDCT). The development of MDCT provided the introduction of a wide range of new applications, many of which are more extensive than the traditional uses of CT. MDCT has enabled CT angiography [4], CT urography [5], and it has contributed significantly to increase the potential of 3D imaging and virtual reality [6]. The application of CT techniques in these areas has allowed good diagnostic imaging, improving the detection of diseases, a significant decrease in surgical-pathologic severity and shortened hospital stay [1]. But although CT clearly provides many clinical benefits, it is important to carry out further systematic studies to determine the absorbed doses delivered to patients.

The objective of the present work was to test a new pencil ionization chamber, recently developed at the Calibration Laboratory of IPEN (LCI), in standard CT radiation qualities. The main motivation for the construction and characterization of this ionization chamber was to develop a dosimeter that fulfills international requirements and that presents new design and construction characteristics in relation to commercial ionization chambers. In the considered detector, polyvinyl chloride (PVC) was tested as wall material and graphite was deposited in the form of a spray in order to generate the necessary electric field between the collecting electrode and the wall. Another difference is the BNC connector that was positioned directly in the ionization chamber body, without an extension cable as in commercial ionization chambers. This assembling process proved to be simpler than using a cable to connect them. In the case of some commercial pencil ionization chambers the wall material is polymethylmethacrylate (PMMA) coated with graphite, but the coating process is not disclosed by the manufacturer. Other wall materials could also be employed in commercial chambers, such as special plastics developed by the manufacturers.

In addition, this novel device was designed to be as simple and cheap as possible, using the resources available at a calibration laboratory. The materials (PVC, PMMA and graphite

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Manuscript received May 30, 2012; revised August 20, 2012; accepted December 06, 2012. Date of publication February 01, 2013; date of current version April 10, 2013. This work was supported in part by the Brazilian agencies CNEN, FAPESP, CAPES, CNPq, MCT: Project INCT for Radiation Metrology in Medicine, and by MRA Electronic Equipment Industry. The work of J. M. Fernández-Varea was supported by a Visiting Professor grant from CAPES, Brazil.

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Digital Object Identifier 10.1109/TNS.2012.2233752

Fig. 1. CT ionization chamber prototype developed at the LCI.

TABLE I
TECHNICAL SPECIFICATIONS OF THE TESTED CT IONIZATION CHAMBER

Characteristics	Specifications
Electrode material	Aluminum
Wall material	PVC coated with graphite
Electrode diameter (mm)	1.22±0.02
Chamber inner diameter (mm)	6.72±0.03
Chamber wall thickness (mm)	0.26±0.02
Chamber sensitive length (mm)	100.0±0.2
Chamber sensitive volume (cm^3)	3.4±0.1

TABLE II
RADIATION QUALITIES ESTABLISHED AT THE PANTAK/SEIFERT X-RAY EQUIPMENT, WITH A CONSTANT TUBE CURRENT OF 10 mA, AT THE CALIBRATION LABORATORY OF IPEN

Radiation Quality	Voltage (kV)	Additional Filtration (mm)	Half-Value Layer (mmAl)	Air Kerma Rate (mGy/min)
CT1	100	3.2Al+0.30Cu	6.9	22.0 ± 0.3
CT2	120	3.5Al+0.35Cu	8.4	34.0 ± 0.5
CT3	150	4.2Al+0.35Cu	10.1	57.0 ± 0.9

spray) were chosen for three main reasons: they are readily available with a relatively low cost, and they are resistant and easily machined in order to yield a robust dosimeter. The location of the BNC connector was intended to produce a compact dosimeter, with the ionization chamber and connector in the same body. The choice of a wall made of PVC is related to the fact that this material offers some advantages, such as mechanical resistance, and it is suitable for the coating process. Due to the small thickness of the material that delimits the sensitive volume, the PMMA presented some cracks after the application of the graphite spray layer, but this effect was not observed in the case of PVC, or in thicker PMMA pieces. It is also worthwhile to notice that all components and dimensions are well known, which may be important for calibration laboratories that wish to characterize their dosimeters by means of Monte Carlo simulations.

In this work, the performance of the developed prototype pencil ionization chamber was analyzed through the main operational tests recommended by the IEC standard [7].

Monte Carlo techniques have always played an important role in radiation dosimetry with ionization chambers (see, e.g., reference [8] and references therein). In the present work, simulations were undertaken to investigate the influence of various components on the energy deposition in its sensitive volume. The validation of the results was achieved by comparing the chamber response in radiation fields normally used in CT. It is worth noting that this Monte Carlo study may also be applied to commercial ionization chambers with the pencil-type geometry.

II. MATERIALS AND METHODS

The CT chamber evaluated in this work (Fig. 1) was recently designed and assembled at the LCI. The technical specifications of this dosimeter are listed in Table I; all lengths were measured after the production and graphite-coating process of the pieces. The CT chamber was manufactured with PMMA, graphite-coated PVC, aluminum and co-axial cables.

As a wall material, PMMA presented some problems, such as cracks and deformation, when exposed to the graphite coating process. Besides, it was not possible to machine PMMA with a thickness of 0.5 mm or less to produce an ionization chamber that would fit into any commercial phantom for CT dosimetry. The solution was to use a different material that could be machined to the required thickness, and coated with graphite, while maintaining the low cost of this new dosimeter. One of the materials that fulfills these requirements is PVC.

The thickness of the graphite layer was estimated based on other pieces coated in the same way. Owing to the small inner diameter of the CT chamber, it was not possible to measure it with a high-precision equipment. Furthermore, the process of measuring the piece several times could damage the thin graphite layer. The graphite layer thickness was estimated to be $(10 \pm 1)\ \mu\text{m}$.

For the measurements, the CT ionization chamber was connected to an electrometer, model UNIDOS E, Physikalisch-Technische Werkstätten (PTW), Germany. The stability tests were made using a $^{90}\text{Sr} + ^{90}\text{Y}$ check source device, PTW, model 8921, with nominal activity of 33 MBq (1994), and a special acrylic support to assure reproducible measurement conditions [9]. All other pre-operational tests were conducted utilizing the established CT radiation qualities CT1, CT2 and CT3, summarized in Table II, with the same half-value layers (HVL) defined by the International Electrotechnical Commission, IEC 61267 [10] for the RQT8, RQT9 and RQT10 standard radiation qualities. The CT1, CT2 and CT3 qualities were established in an industrial x-ray unit, Pantak Seifert, model ISOVOLT 160 HS. This unit operates from 5 to 160 kV, has a 0.8 mmBe window and a W-anode angle of 21°. The dosimetric reference system for the considered qualities was a RADCAL pencil ionization chamber, model RC3CT, with traceability to the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB). The IEC 61674 [7] recommendations, specific for dosimeters used in diagnostic radiology, were adopted as reference for all tests.

To simulate the ionization chamber characterized in this work, we had recourse to the PENELOPE/penEasy Monte Carlo code [11], [12]. This software comprises a general-purpose subroutine package for the simulation of the coupled electron-photon transport in a wide energy interval and a flexible steering main program. The simulations were based on the actual dimensions of the ionization chamber (Fig. 2 and Table I), and included all its main components: PVC wall, graphite layer, collecting electrode of aluminum, extremities of PMMA and a detailed description of the BNC connector.

As the spectra of the x-ray equipment utilized at the LCI for the CT1, CT2 and CT3 radiation qualities were not available to be employed as input for the simulations, two sets of spectra were used and compared. One set was obtained experimentally

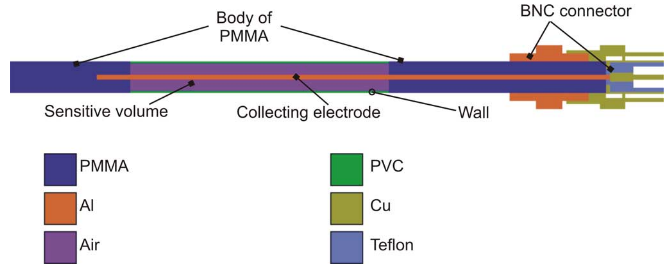

Fig. 2. Geometry and materials of the CT ionization chamber in the MC simulations. In this figure, the sensitive volume length was reduced to 60% of its original size for better visualization of all components. (Color figure available only in the electronic version of this paper).

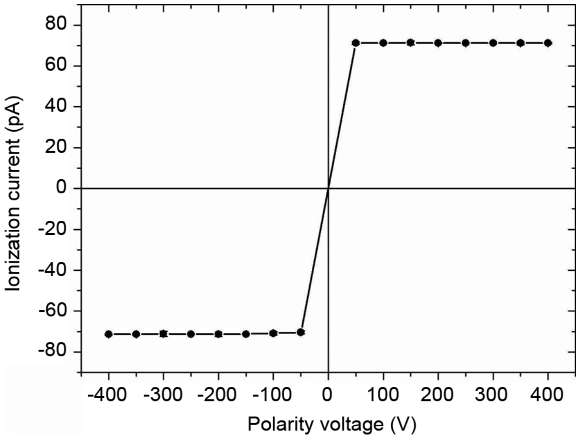

Fig. 3. Saturation curve of the CT ionization chamber.

at the PTB [13] for the RQT8, RQT9 and RQT10 radiation qualities, and the other set was generated with the SpekCalc software [14] with the same characteristics described in Table II.

The spectra from PTB were 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. The W-anode angle was 21° and the window was 7.0 mmBe. Although the x-ray units at PTB and LCI are not from the same manufacturer and there are some differences between the respective filtrations, the HVL values are similar, as defined at IEC 61267 [10].

The SpekCalc spectra [14] were obtained utilizing the characteristics of the x-ray equipment available at LCI, as previously described. The parameters regarding the CT radiation qualities, used as input for the program, were the same established at the LCI (Table II). These spectra were utilized to check whether the results, obtained with the characteristics of the LCI x-ray unit, would be similar to those obtained in another equipment.

The geometry was chosen to be as similar as possible to that of the experimental set-up. The center of the ionization chamber was positioned at 100 cm from the x-ray focus (source), and there was a 5-cm-thick layer of air in the direction of the beam (in front of and behind the ionization chamber) to account for the scattering effects in the vicinity of the ionization chamber. The semi-aperture angle of the x-ray beam was 2.9°, the same as in the experimental measurements.

In all undertaken simulations the scored quantity of interest was the energy deposited in the material (air) of the dosimeter sensitive volume. The influence of some components (central collecting electrode, PMMA body, BNC connector) on that quantity was estimated by replacing each studied component with air but without altering the scoring volume. The simulation results were then divided by the value obtained for the complete ionization chamber. The influence of the wall material was reported as the ratio between the PVC wall and the PMMA wall responses (both with the same thickness).

In the simulations, photon and electron transport was discontinued below $E_{\mathrm{abs}} = 1\ \mathrm{keV}$. Other simulation parameters for electron tracking, specific to the PENELOPE code [11], 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 $W_{\mathrm{CC}} = 0.1\ \mathrm{keV}$; and a cutoff energy loss for hard Bremsstrahlung emission $W_{\mathrm{CR}} = 1\ \mathrm{keV}$. The external electron step-length control was switched off by setting $s_{\max} = 10^{30}\ \mathrm{cm}$. To obtain low statistical uncertainties, 10^{10} histories were simulated in each run.

The uncertainties of all experimental studies in this work are expanded uncertainties, obtained by the combination of the type A and B uncertainties, with a coverage factor of 2. The same coverage factor was adopted for the type A uncertainties of the Monte Carlo simulations.

III. RESULTS AND DISCUSSION

Following the recommendations of the International Electrotechnical Commission IEC 61674 [7], the CT ionization chamber was submitted to a number of tests: saturation curve, polarity effect, ion collection efficiency, short- and medium-term stabilities, stabilization time, effective length and spatial uniformity of the response of the ionization chamber, leakage current and energy dependence.

A. Saturation, Polarity Effect and Ion Collection Efficiency

The saturation test determines the optimal voltage for the chamber operation. A saturation curve (Fig. 3) was generated by varying the voltage from -400 V to $+400$ V, in steps of 50 V, choosing a charge collecting time of 15 s. This test was performed for the diagnostic beam quality CT2 (Table II). The mean absolute value of the measured electric current produced by the ionization chamber was 71.15 pA, and the maximum variation was 0.8%. This result shows that for all voltage values applied, no significant changes were observed in the collected charge, indicating that the chamber saturation was achieved in the entire voltage interval. The applied voltage chosen for this ionization chamber was $+100$ V and, therefore, it was utilized for all subsequent tests in this work.

The polarity effect was determined by comparing the collected charges at identical voltages of opposite sign. For all pairs of voltage values in the saturation test, the polarity effect did not exceed 0.6% while the limit recommended by IEC 60731 [15] is 1%.

Fig. 4. Radioactive check source positioned at the special acrylic support into which the CT ionization chamber was inserted.

The ion collection efficiency was obtained taking into consideration the collected charges and the two-voltage method [16], according to

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

where M_i is the collected charge at a voltage V_i. We took $V_1 = \pm 300$ V and $V_2 = \pm 150$ V so that $V_1/V_2 = 2$. The ion collection efficiency was better than 99.9% for both polarities, in agreement with the value of at most 5% of ionic recombination losses recommended by IEC 61674 [7].

B. Short- And Medium-Term Stabilities

The stability tests (short- and medium-term) were done with the help of a radioactive check source and the special acrylic support, as depicted in Fig. 4.

The short-term stability test was conducted by ten readings of the collected charge, during time intervals of 60 s, under reproducible conditions. The highest variation was 0.2%. According to the international recommendations of IEC 61674 [7], the maximum acceptable variation is 1% for CT-specific ionization chambers.

The medium-term stability test was carried out by taking the mean values of ten measurements of the short-term stability tests during a period of 3 months (Fig. 5). According to the IEC 61674 standard [7], the value obtained in each test must not differ from the reference value by more than 3%. As Fig. 5 shows, the deviations were well within the recommended limits.

C. Stabilization Time

For the stabilization time test, the check source was positioned in the same acrylic support as in the stability tests, and then the CT ionization chamber was connected to the electrometer. The ionization current was measured 0.5, 1, 5, 10, 15, 60 and 120 min after connecting the ionization chamber to the electrometer. The results are shown in Table III. The ionization current obtained 15 min after switching on the measuring system is 99.9% of the 1 h stabilization current. This result complies with the limits of $\pm 2\%$ of response variation [7].

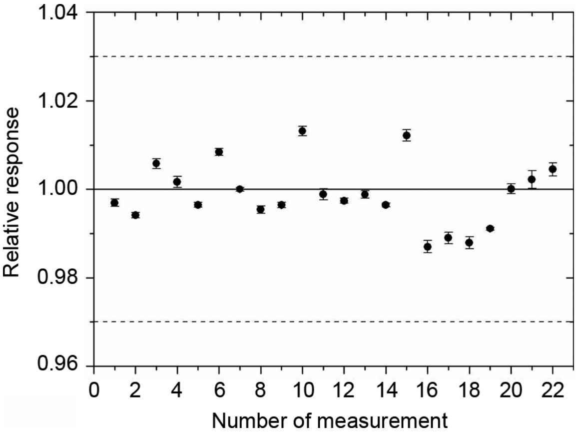

Fig. 5. Medium-term stability of the CT ionization chamber. The dashed lines represent the recommended limits.

TABLE III
STABILIZATION TIME TEST

Time (min)	Ionization Current (pA)
0.5	17.84±0.07
1.0	17.82±0.05
5.0	17.79±0.04
10.0	17.78±0.04
15.0	17.76±0.04
60.0	17.77±0.04
120.0	17.77±0.04

D. Effective Length and Spatial Uniformity of the Response of the CT Chamber

The effective length is defined by the IEC [7] as the "full-width-half-maximum (FWHM) of the plot of the response against distance along the axis of the detector". The spacial uniformity of the response of the CT chamber is the region in which its response has a maximum variation of $\pm 3.0\%$. This region will determine the rated length of the chamber. Following the IEC standard [7] recommendations, during these tests a lead diaphragm with an aperture of 2.0 mm was placed 4.0 cm in front of the ionization chamber, and it was moved along its axis from $-5.1\ \mathrm{cm}$ to $+5.1\ \mathrm{cm}$ in relation to its center.

The response of the dosimeter characterized in this work, in relation to the distance along its axis, is displayed in Fig. 6. The tests revealed that the effective length is 0.6% smaller than the active length (10.0 cm), and that the rated length of the ionization chamber is 9.0 cm, with a maximum variation for this region of 2.6% (position of $+4.5\ \mathrm{cm}$).

E. Leakage Current

The leakage current was measured in time intervals of 20 min, before and after the irradiation, and the highest value obtained was 0.06% of the ionization current produced at the minimum air kerma rate applied in this work. This value is within the 5% limit recommended internationally [7].

TABLE IV
CORRECTION FACTORS, AS WELL AS THE COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED RESPONSE, OF THE CT IONIZATION CHAMBER IN STANDARD CT QUALITIES

		Experimental	**MC Simulation**	
Radiation Quality	**Half-Value Layer (mmAl)**	**Correction Factors**	**Normalized Response (PTB spectra)**	**Normalized Response (SpekCalc spectra)**
CT1/RQT8	6.9	0.979± 0.021	1.002± 0.015	1.008± 0.015
CT2/RQT9	8.4	1.000± 0.021	1.000± 0.015	1.000± 0.015
CT3/RQT10	10.1	1.026± 0.019	0.998± 0.015	1.001± 0.015

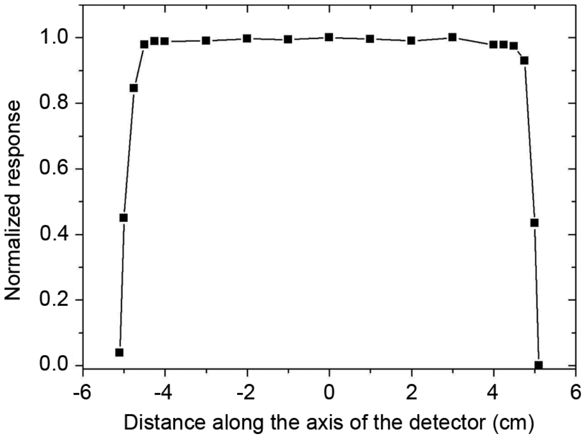

Fig. 6. Response of the ionization chamber characterized in this work in the chamber axis direction. All values were normalized to the response at the center of the sensitive volume. The positive displacement was considered in the direction of the BNC connector.

F. Energy Dependence and Monte Carlo Validation

The energy dependence was evaluated to obtain the correction factors. This test was also made to compare the simulated and experimental results. The experimental correction factors were determined utilizing a reference system consisting of a pencil ionization chamber (RADCAL, model RC3CT) and an electrometer (PTW, model UNIDOS E). The standard system and the dosimeter characterized in this work were irradiated in the CT1, CT2 and CT3 radiation qualities, under identical conditions. The calibration coefficients were determined as described by Meghzifene and Shortt [17]. The correction factors were calculated by dividing the calibration coefficients obtained in each quality by the calibration coefficients of the CT2 radiation quality.

In order to validate the simulation results of the CT ionization chamber characterized in this work, the experimental energy dependence was compared with the simulations, utilizing the experimental spectra from PTB and those generated with the SpekCalc software. The Monte Carlo normalized response was set as the ratio between the values obtained from the simulations for the RQT8, RQT9 and RQT10 radiation qualities normalized for the RQT9 radiation quality. The results are displayed in Table IV. The largest differences observed are 2.8% (CT3) and 2.9% (CT1) for the PTB and the simulated spectra, respectively, but they are still within the expanded statistical (type A) uncertainties. The Monte Carlo results are affected too by type B uncertainties arising from simplifications in the simulated geometry and limitations in the physics interaction models implemented in the code. Among the latter it should be mentioned that existing tabulations of photoeffect cross sections differ by around 2% at low energies [18]. However, since here we compare only normalized responses the systematic (type B) uncertainties cancel out to a great extent.

TABLE V
INFLUENCE OF THE IONIZATION CHAMBER COMPONENTS ON THE ENERGY DEPOSITION IN THE SENSITIVE VOLUME FOR THE RQT9 RADIATION QUALITY

Studied Component	**Ratios of the energy deposition**
BNC connector	1.00±0.01[†]
Collecting electrode	0.91±0.01[†]
PMMA body	1.00±0.01[†]
PMMA instead of PVC	0.51±0.01[‡]

[†] (response without the studied component) / (response of the complete chamber).
[‡] (response with PMMA) / (response with PVC).

The set-up configuration evaluated for this comparison can be used for other purposes, such as for the investigation of the influence of the CT ionization chamber components on the energy deposition in its sensitive volume. Considering that: (1) the reference system utilized to establish the CT qualities at LCI was calibrated at PTB; (2) the CT radiation qualities available at PTB and the CT were both established using the same HVL values recommended by the IEC 61267 standard [10]; the PTB spectra were employed for the analysis presented in the next section. There is good agreement between simulation results for the PTB and SpekCalc x-ray spectra in spite of the differences in the hardness of the respective spectra.

G. Study of the Ionization Chamber Components—A Monte Carlo Approach

In this section we address the influence of the components of the ionization chamber on the energy deposition in the sensitive volume, using the RQT9 radiation quality (120 kV of tube voltage, 3.7 mmAl + 0.25 mmCu of total filtration). These components are: the BNC connector; the PMMA body; the collecting electrode; and the wall material, as illustrated in Fig. 2. The results obtained are shown in Table V as the ratios between the responses of the chamber without the studied components to the response of the complete chamber. For the wall material study, the ratio is between the response with the PMMA wall and with the PVC wall.

It is possible to observe that the BNC connector and the body of PMMA barely affect the energy deposited in the sensitive volume of the ionization chamber and, as a consequence, have a negligible influence (within the quoted statistical uncertainties) on the chamber charge readings. On the other hand, the aluminum collecting electrode has a sizable influence. This is justified by the fact that Compton recoil electrons and photoelectrons produced by interactions of photons with the central electrode contribute significantly to the energy deposited in the sensitive volume.

The last component studied was the wall material. There is no reference in the literature reporting on the suitability of PVC as wall material for ionization chambers, except for the pencil-type ionization chambers (albeit with different sensitive volumes) [19], [20] developed at the LCI. However, no attempt has been made so far to study with Monte Carlo simulation the influence of a PVC wall in dosimeters for diagnostic x-ray beams. To determine the differences between this wall material and the commercially available PMMA, the response of this ionization chamber was compared for an equal thickness of the two considered materials (both coated with 10 $\mu\mathrm{m}$ of graphite). The simulated response for the ionization chamber with a PMMA wall was about 50% lower than that corresponding to the same device but with a PVC wall. This might be caused by the substantially higher effective atomic number of PVC for photon interactions.

Although the influence of the BNC connector and PMMA body is very small, the application of a pencil ionization chamber in calibration procedures requires a lead diaphragm to irradiate just a fraction of the sensitive volume. The effect of these components would be of some importance in dosimetric procedures where the radiation beam is not collimated by a diaphragm, as in those investigated by Maia and Caldas [9]. In their work, a commercial CT ionization chamber was characterized for $^{137}\mathrm{Cs}$ and $^{60}\mathrm{Co}$ beams, in direct and attenuated diagnostic radiology qualities, mammography qualities, and BIPM radiotherapy qualities [21]. Nevertheless, care must be taken in such procedures to avoid the irradiation of regions beyond the sensitive volume of the ionization chamber.

IV. CONCLUSIONS

In this work, a new CT ionization chamber was characterized for use in CT dosimetry. The main motivation to manufacture this ionization chamber was the development of a detector with different characteristics related to its design and construction, as well as a relatively easy and low-cost assembling. Several operational characteristics of this chamber were evaluated and compared with international recommended limits. The undertaken tests achieved very satisfactory results. Although there are some differences between the ionization chamber characterized in this work and the commercial ones, all experimental characterization results were within international recommendations. Moreover, Monte Carlo simulations helped to estimate the influence of different parts of the ionization chamber on the energy deposition in the sensitive volume. The simulations showed that there is no influence in the new BNC connector position while the wall made of PVC coated with graphite presented a considerable influence. Considering the results obtained, it is possible to conclude that the studied ionization chamber may be a good alternative for laboratory or clinical use, because it is simple and easy to manufacture, with the utilization of available commercial materials.

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