Biomedical Physics & Engineering Express

RECEIVED
27 February 2017

REVISED
24 July 2017

ACCEPTED FOR PUBLICATION
28 July 2017

PUBLISHED
13 September 2017

PAPER

Development and tests of a 30 cm pencil-type ionization chamber for dosimetry in standard and clinical CT beams

M C Castro[1], N F Silva[1], M Xavier[1], M E A Andrade[2], H J Khoury[2] and L V E Caldas[1]

[1] Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN/SP, Av. Prof. Lineu Prestes, 2242, 05508-000, São Paulo, SP, Brazil

[2] Departamento de Energia Nuclear, Universidade Federal de Pernambuco (DEN/UFPE), Av. Prof. Luiz Freire, 1000, 50740-540, Recife, PE, Brazil

E-mail: maysadecastro@gmail.com

Keywords: pencil ionization chamber, standard CT beams, clinical CT beams

Abstract

The use of computed tomography (CT) for imaging procedures is growing due to advances in the CT equipment technology. To perform the dosimetry in CT beams, the most widely used instrument is the pencil type ionization chamber with a sensitive volume length of 100 mm; however, some studies have shown that this dosimeter has underestimated the dose values. Therefore, in this study an ionization chamber with sensitive volume length of 300 mm was developed at IPEN. The characterization of this chamber was performed, and the results were obtained within the international recommended limits. As an application, the developed ionization chamber was tested in clinical beams of two different hospitals.

1. Introduction

In the recent years, the use of computed tomography (CT) for diagnostic images has been growing due to technological advances of this equipment (Boone 2007). Therefore, there is an increased concern regarding the dose received by the patients undergoing this kind of imaging procedure because it uses higher radiation dose comparing to others fields of conventional radiology.

For the dosimetry of CT beams, the radiation detector is usually a pencil-type ionization chamber. It presents a uniform response to the incident radiation beam from all angles, which makes it suitable for CT equipment, since the x-rays tube executes a circular movement around the table during irradiation (Suzuki and Suzuki 1978). The commercial chamber used to perform the quality control testing of the equipment has usually a sensitive volume length of 100 mm. However this ionization chamber does not make an accurate prediction of the dose in the modern multiple-slice, helical CT scanners, that have a total (nominal) beam widths of 20–30 mm or more and rotation times of 1 s or less (Dixon 2006). An integration range of 300 mm is necessary to, accurately, measure dose under a nominal beam width of 128 mm or more, due to scatter radiation (Mori *et al* 2006).

To contribute for the dosimetry of modern CT equipments, the research group of the Calibration Laboratory of Instruments (LCI) of IPEN has developed over the last years some prototypes of ionization chambers, including a pencil-type (Neves *et al* 2013, Perini *et al* 2013). These homemade chambers present some small differences in relation to the commercial models. The main differences are in relation to the material used in manufacturing the chamber body and in the positioning of the BNC connector. This new configuration provided a low cost construction, and the ionization chamber test results met the internationally accepted standards, as noted in previous studies (Neves *et al* 2013, Perini *et al* 2013). Based on this experience, a pencil ionization chamber with 30 cm long was developed to be used for dosimetry of the new generation of the CT equipment.

The aim of this work is to present the construction of this pencil ionization chamber and its characterization results, obtained in standard metrology laboratory and in clinical CT beams.

2. Methods and materials

2.1. Construction of the ionization chamber

Two pencil ionization chambers, with sensitive volume lengths of 30 cm (called C_{30}) and 10 cm (called

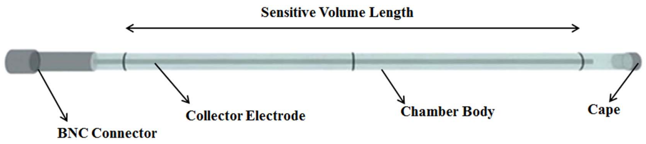

Figure 1. Characteristics and specifications of the developed C_{30} and C_{10} ionization chambers.

C_{10}), were manufactured using polymethyl methacrylate (PMMA), coated with graphite, aluminum electrode and coaxial cables. Both ionization chambers were manufactured in the same way. Aluminum was utilized as collecting electrode material due to its high electrical conductivity and mechanical resistance. Initially, the collector electrode and the chamber body were painted with graphite spray. Then, the electrode was welded to the BNC connector to match the working length. In sequence, the same was done with the chamber body so that the electrode was located on the central axis, and finally the ionization chamber cape was installed at its end. Figure 1 shows the design of the ionization chambers and table 1 shows their specifications.

These homemade ionization chambers were constructed using low-cost materials, and present some differences in their manufactures, as the position of the BNC connector. Therefore, this new configuration presents a good effective-cost, and it is performed in accordance with the international recommendations. The C_{30} ionization chamber can provide highest accuracy measurements of scattered radiation because its sensitive volume length is greater.

Two commercial ionization chambers (Physikalisch-Technische Werkstatten (PTW) type 30009 and Radcal type RC3CT) were utilized in the clinical tests to help and confirm the good results obtained for the two homemade ionization chambers (C_{30} and C_{10}).

During all of the measurements, the ionization chamber was connected to an electrometer, model UNIDOS E, PTW Freiburg, Germany, and all measurements were corrected to the standard values of environmental temperature and pressure. The C_{10} ionization chamber was only utilized in this study for the clinical tests.

All tests performed in this work were done considering the uncertainties of type A and type B; in some cases it was necessary to determine the combined uncertainty. Then it was expanded using a factor $k = 2$.

2.2. Characterization tests

The characterization tests performed with the ionization chamber will be presented in this section. For the short- and medium-term stabilities, stabilization time and leakage current test, the check source ($^{90}Sr + {}^{90}Y$) PTW, with nominal activity of 33 MBq (1994) was used, but it was necessary to utilize a support for the check source to be positioned in the ionization chamber. So, it was necessary to make an acrylic support using PMMA to allow the reproducible geometric conditions. For the saturation curve, polarity effect, ion collection efficiency, linearity of response, energy dependence and angular dependence test, the x-ray equipment, Pantak/Seifert, model ISOVOLT 160 HS, operating between 5 and 160 kV, was utilized.

Table 1. Characteristics and specifications of the developed C_{30} and C_{10} ionization chambers. The collector electrode material is aluminum with a layer of graphite and the wall material is PMMA with a layer of graphite.

Characteristics	Specifications	
	C_{30}	C_{10}
Diameter of the central collector electrode (mm)	3.20	3.20
Inside diameter of the ionization chamber (mm)	7.40	7.40
Wall thickness (mm)	0.26	0.26
Sensitive volume length (mm)	300	100
Sensitive volume (cm^3)	10.5	3.50

For the short-term stability test, the ionization chamber was exposed to the check source under reproducible geometric conditions and ten consecutive charge measurements were taken during intervals of 60 s. For the medium-term stability test, measurements over four months were performed, and each measurement corresponding to 10 charge readings produced by the ionization chamber during 60 s exposed, at the same geometry, to the check source.

In the stabilization time test the ionization chamber was connected to the electrometer and was exposed to the check source, positioned at the acrylic support, under reproducible geometric conditions. After irradiation, the ionizing current was measured 15 min and 60 min after switching on the dosimetric system. The difference between results obtained in the two measurements was calculated and compared with the limits established by IEC (International Electrotechnical Commission 2005).

The leakage current was measured using the check source. This test lasted one hour, and was divided into three parts (before, during and after irradiation), each part lasted 20 min. The analysis was made between the measurements obtained before and after irradiation in relation to the case during irradiation. The difference between results obtained in the two measurements was calculated and compared with the limits established by IEC (International Electrotechnical Commission 2005).

Table 2. Characteristics of the CT standard x radiation qualities at the LCI (International Electrotechnical Commission 2005).

Radiation quality	Tube voltage (kV)	Tube current (mA)	Half value layer (mmAl)	Additional filtration (mm)	Air kerma rate (mGy min^{-1})
RQT 8	100	10	6.9	3.2 Al + 0.30 Cu	22.0
RQT 9[a]	120	10	8.4	3.5 Al + 0.35 Cu	34.0
RQT 10	150	10	10.1	4.2 Al + 0.35 Cu	57.0

[a] LCI reference CT radiation quality.

To evaluate the dose response of the C_{30} ionization chamber, the chamber was positioned in a setup, at the distance of 1 m from the focus of the x-rays equipment, used for calibration of radiation detectors. Table 2 shows the characteristics of the CT standard radiation qualities at the LCI-IPEN. The chamber, connected to the electrometer, was irradiated in the RQT-9 quality beam, with different values of air kerma rates, obtained by the variation of the x-rays tube current from 2 to 18 mA, in steps of 2 mA. For each air kerma rate, ten measurements were taken, and the average and standard deviation were calculated.

To determine the optimal voltage for the operation of the ionizing chamber, the saturation curve was obtained varying the voltage applied to the ionizing chamber C_{30} from −400 to +400 V. The measurements were performed during 60 s, with the ionization chamber exposed to the x-rays quality beam RQT-9 with a fixed air-kerma value and for voltage values varying in steps of 50 V.

The polarity effect was estimated by the calculation of the rate between the ionization current values obtained for the positive and negative polarities, for each applied voltage.

To evaluate the ion collection efficiency, values of the collected charges obtained with +200 V and with +100 V were measured. Using the following equation (1) (International Atomic Energy Agency 2000), it was possible to calculate the ion collection efficiency:

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

where: M_1 and M_2 are the measures obtained with the voltages +200 V and +100 V applied to the ionizing chamber, respectively.

The angular dependence test was performed by applying a rotational motion around the axis of the ionization chamber from −180° to +180° (in steps of 30°). The ionization chamber response was normalized for the 0° position. This test was performed using the reference diagnostic radiology quality beam RQT 9.

The energy dependence characterization test was performed using the C_{30} ionization chamber and the commercial pencil-type ionization chamber of the laboratory (Radcal, RC3CT) in all radiation qualities. The substitution calibration method was utilized for the calibration of the ionization chamber. The calibration coefficients for the ionization chamber were determined. The calibration coefficient establishes, under specific conditions, the relationship between the values obtained with a standard measuring system and the values for the measurement obtained; it means that the measurements obtained with this ionization chamber need to be multiplied by the calibration coefficients to obtain the corresponding measurements using the commercial pencil-type ionization chamber RC3CT.

2.3. Clinical tests

The clinical tests were carried out in two different hospitals: Real Hospital de Beneficiência Portuguesa do Recife (Clinic A) and Hospital Israelita Albert Einstein (Clinic B). The CT scanner of Clinic A was a Siemens Somatom Definition AS (64 channels) and the scanner of Clinic B was a Toshiba Aquilion One Vision (320 channels).

Initially, the Computed Tomography Dose Index free-in air (CTDI free-in-air) was measured, in both Clinics, with the C_{30} and C_{10} pencil ionization chambers. The CTDI free-in-air is the air kerma rate measured in clinical beams (Leitz *et al* 1995). The measurements were performed with the ionization chambers, covered by the build-up cap, and positioned at the center of *z*-axis, parallel to the tube axis. The build-up cap was made of PMMA, and it presents the same length of both ionization chambers. At Clinic A the following irradiation parameters were used to measure the CTDI free-in-air: 120 kV, 200 mAs, rotation time of 1.0 s; single axial scan, slice width of 1.2 mm, 32 slices/rotation, corresponding to a total beam collimation of 38.4 mm. Three measurements were taken, and the average and standard deviation were calculated. In Clinic B the following irradiation parameters were used to measure the CTDI free-in-air: 120 kV, 100 mAs, rotation time of 1.0 s; single axial scan, slice width of 0.5 mm, 64 slices/rotation, corresponding to a total beam collimation of 32.0 mm.

The CTDI values were calculated by the following equation (2) (International Atomic Energy Agency 2011):

$$\text{CTDI} = M.\, N_k.\, K_{TP}.\, (L/NT)\ , \quad (2)$$

where: M is the average of the three measurements, N_k is the calibration factor, K_{TP} is the correction factor for pressure and temperature for the reference values, L is the active length of the ionization chamber (10 cm or

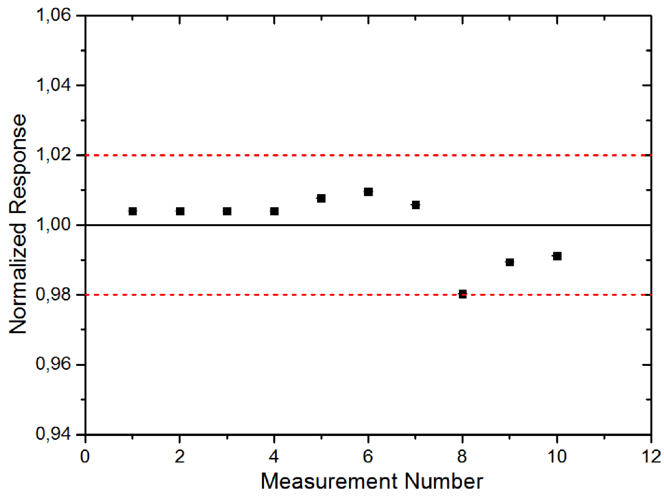

Figure 2. Medium-term stability for the C_{30} ionization chamber; the maximum uncertainty of the measurements was 0.01%, not visible in the figure.

30 cm) and *NT* is the total beam collimation (product of the slice width by the number of slices per rotation).

Measurements were also performed with the CT head and CT body dosimetric phantoms. The phantoms were made of PMMA and they present diameters of 160 mm (head) and 320 mm (body). These phantoms have some cylindrical holes: one in the center and four in the periphery, to insert the C_{10} and C_{30} ionization chambers. The measurements were taken with the ionization chamber at the center of the phantom and using the following irradiation parameters: 120 kV, 100 mAs, rotation time of 1.0 s, in volumetric mode, slice width of 0.5 mm, 128 slices/rotation, corresponding to a total beam collimation of 64.0 mm.

3. Results and discussion

3.1. Characterization tests

The figure 2 shows the results obtained for the test of medium-term stability. The relative response on *y*-axis represents the ratio between the ionizing current measurements and the mean value of the ten measurements. The maximum uncertainty of the measurements of each point was 0.01%, not visible in the figure. The dotted lines represent the recommended limits, that according to International Electrotechnical Commission (2005) need to be lower than 2% of the reference value.

The result obtained for the short-term stability test with the C_{30} ionization chamber showed a coefficient of variation of 0.01%, indicating that the stability of the response of the ionization chamber is in accordance to the international recommendations International Electrotechnical Commission (2005), where the maximum acceptable coefficient of variation is 1% for CT specific chambers.

For the stabilization time test, the results of the ionization current measured 15 and 60 min after switching on the dosimetric system presented a variation of 0.04%, which is within the recommended limit by IEC 61267 (International Electrotechnical Commission 2005), that is ±2%.

In the leakage current characterization test, the current before and after irradiation should not exceed the limit of 5% compared to the ionization current during the irradiation of the ionization chamber (International Electrotechnical Commission 2005). The leakage current obtained for the ionization chamber before and after the irradiation was less than 0.02%. Therefore, the result is within the recommended limit.

The results for dose response to C_{30} is shown in figure 3, exposed to the x-rays quality beam RQT-9. The results show a linear response of the ionization chamber with the air kerma rate, indicated in the graph by the value of the current applied to the x-rays tube. Each point corresponds to the average of 10 measurements and the maximum uncertainty of the measurements was 0.02%, not visible in the graph. The straight line in figure 3 shows the linear fit obtained for the measurements. A linear regression coefficient $R^2 = 1.0$ was obtained; indicating a linearity of response of the ionization chamber.

The figure 4 shows the curve of the ionization current in function of the applied voltage on the ionization chamber. The results show no significant changes in the saturation current produced by the RQT-8, RQT-9 and RQT-10 x-rays quality beams. Each point corresponds to the average of three measurements at the same condition. The maximum uncertainty of the measurements was 0.01%, not visible in the figure. The uncertainty was determined using the uncertainties of type A and type B, and the coverage factor was $k = 2$.

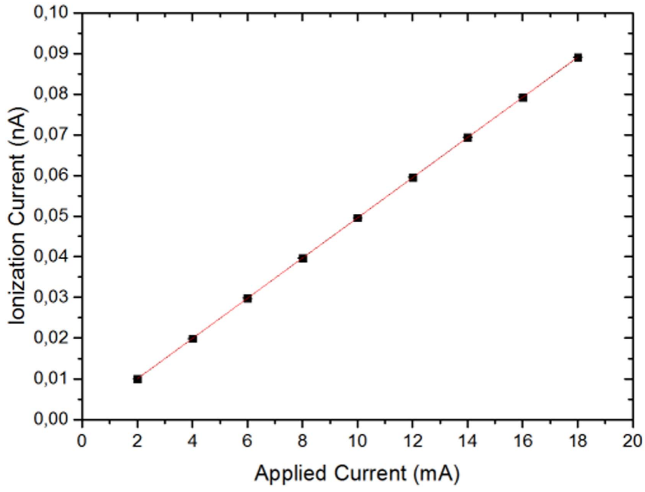

Figure 3. Dose response of the C_{30} ionization chamber in the CT reference quality beam (RQT 9).

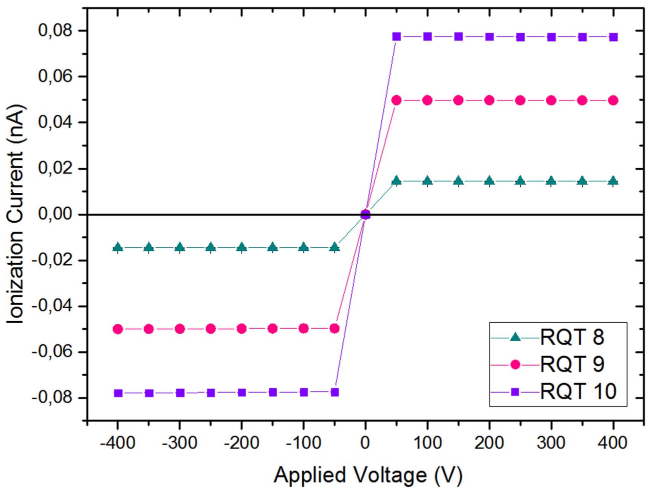

Figure 4. Saturation curves of the C_{30} ionization chamber.

Table 3. The polarity effect for the C_{30} ionization chamber exposed to RQT x-rays quality beams.

Applied voltage (kV)	RQT 8	RQT 9	RQT 10
100	0.991 ± 0.012	1.001 ± 0.002	1.002 ± 0.002
200	0.989 ± 0.012	0.999 ± 0.002	0.999 ± 0.002
300	0.987 ± 0.012	0.996 ± 0.002	0.996 ± 0.002
400	0.985 ± 0.012	0.994 ± 0.002	0.994 ± 0.002

Table 4. Ion collection efficiency for the C_{30} ionization chamber.

Radiation quality	Ion collection efficiency (%)
RQT 8	100.0 ± 0.12
RQT 9	99.98 ± 0.03
RQT 10	99.99 ± 0.03

Table 3 presents the results of the ratio between the ionization current values obtained for the positive and negative polarities for each applied voltage. The values obtained were in the range between 0.994 and 1.002, indicating that the values of the polarity effect are within the recommended limit by IEC 61267 (International Electrotechnical Commission 2005), that is 1%.

Table 4 presents the results of the ion collection efficiency that was obtained using equation (1). The voltage values applied to the ionization chamber were +200 and +100 V, for the RQT x-rays quality beams. The results show that the values are higher than 95% that is the recommended limit by IEC 61267 (International Electrotechnical Commission 2005).

The results of the angular dependence response of the ionization chamber C_{30} are presented at figure 5. The ionization chamber response was normalized for the 0° position. According to the international recommendations, the angular dependence should not exceed the limit of 3% (International Electrotechnical Commission 2005). As can be observed in figure 5, the results obtained for the angular dependence are within the recommended limit.

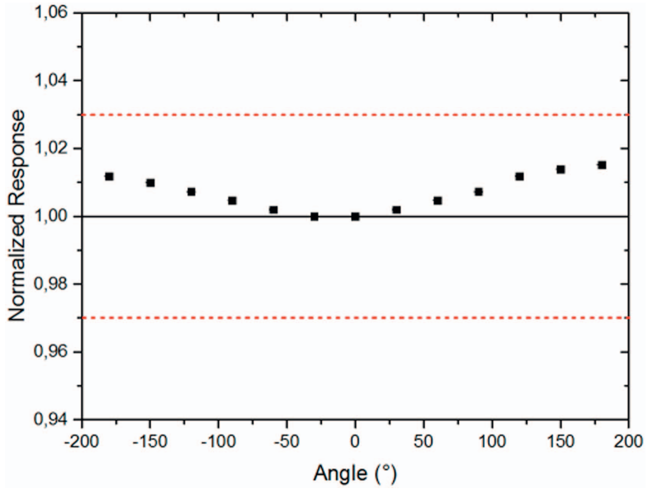

Figure 5. Angular dependence of the C_{30} ionization chamber response in the RQT 9 reference quality beam; the maximum uncertainty of the measurements was 0.01%, not visible in the graph.

Table 5. Energy dependence of the C_{30} ionization chamber response.

Radiation quality	Calibration coefficient (mGy pC^{-1})	Correction factor
RQT8	0.0109 ± 0.0001	0.9505 ± 0.0009
RQT 9	0.0114 ± 0.0001	1.0000 ± 0.0001
RQT 10	0.0120 ± 0.0001	1.0480 ± 0.0006

Table 6. Values of $CTDI_{10air}$ and $CTDI_{30air}$ in air measured with the ionization chambers C_{10} and C_{30}, previously calibrated. The values correspond to the average results and their standard deviations obtained in the clinics A and B.

CTDI air kerma (mGy mAs^{-1})	Clinic A	Clinic B
$CTDI_{30air}$	0.191 ± 0.03%	0.230 ± 0.04%
$CTDI_{10air}$	0.197 ± 0.03%	0.228 ± 0.04%

The energy dependence test analyzes the ionization chamber response in function of the effective energy of the x-rays beams (table 5). The correction factor was obtained by normalizing the calibration coefficients for the reference quality RQT 9, for a better visualization of the energy dependence of the chamber response. The calibration coefficients need to be normalized to obtain the correction factors, and the deviation of the RQT 8 and RQT 10 response in relation to RQT 9. Finally the energy dependence could be determined. The variation in energy dependence should not exceed the recommended limit of ±5% in relation to the reference quality (International Electrotechnical Commission 2005).

The energy dependence obtained for the ionization chamber is within the internationally acceptable limits.

Table 7. CTDI values measured at the center of the phantoms using the ionization chambers with sensitive volume lengths of 300 mm (C_{30}) and 100 mm (C_{10}). The coverage factor is $k = 2$.

Ionization chamber	CTDI—head (mGy mAs^{-1})	CTDI—abdomen (mGy mAs^{-1})
C_{30}	0.219 ± 0.04%	0.110 ± 0.04%
C_{10}	0.173 ± 0.04%	0.073 ± 0.04%

3.2. Clinical tests

The results obtained for $CTDI_{10air}$ and $CTDI_{30air}$ in air are presented in table 6. In the Clinic A the values of $CTDI_{10air}$ were obtained using as auxiliaries the 10 cm long pencil commercial ionization chamber PTW type 30009 and in the Clinic B the $CTDI_{10air}$ were obtained using as auxiliaries the commercial ionization chamber Radcal (RC3CT). Both chambers were previously calibrated at the metrology laboratory. In each condition three measurements were taken, and the average and the standard deviation were calculated. The results indicate that the CTDI free-in-air values present a good correspondence between $CTDI_{30air}$ and $CTDI_{10air}$, that means the both ionization chambers have the same sensitive volume length irradiated and present very close results. The difference of the results obtained with both ionization chambers in Clinic B are lower than 1%, and in Clinic A 3%.

The results for the CTDI air kerma in both clinics was obtained in different conditions, and in the same clinic the results for both ionization chambers presented good correspondence as already informed.

The results of CTDI at the center of the head and abdomen phantoms, obtained with the homemade pencil ionization chamber C_{10} and C_{30} were performed in the Clinic B. The results are shown in table 7.

The results show that the CTDI values obtained with the C_{10} ionization chamber are different from those obtained with the C_{30} ionization chamber. It is known that the radiation dose profile from a single axial CT scan extends beyond the limits of the collimated scan width, due to penumbral and scatter effects. The results show that the C_{30} measured the contribution of the scatter radiation, that is not measured by the C_{10} pencil ionization chamber.

4. Conclusions

The results obtained of the characterization tests of the developed ionization chamber used in this work are within the internationally recommended limits, showing that the construction of the C_{30} ionization chamber was successful. The clinical tests demonstrated that the ionization chamber with the greater sensitive volume length (300 mm) can detect more scattered radiation than the ionization chamber (100 mm).

Acknowledgments

The authors acknowledge the financial support received from the Brazilian agencies: CNEN, CNPq, FAPESP and MCTIC (Project: INCT—Radiation Metrology in Medicine), and the clinics that allowed the experiments for the clinical tests.

References

Boone J M 2007 The trouble with CTDI100 *Med. Phys.* **34** 1364–71

Dixon L R 2006 Restructuring CT dosimetry—a realistic strategy for the future, requiem for the pencil chamber *Med. Phys.* **33** 3973–6

International Atomic Energy Agency (IAEA) 2000 *Calibration of Radiation Protection Monitoring Instruments* (Vienna: IAEA)

International Atomic Energy Agency (IAEA) 2011 *Implementation of an International Code of Practice on Dosimetry in Diagnostic Radiology (TRS n° 457): Review of Tests Results (Human Health Reports n° 4)* (Vienna: IAEA)

International Electrotechnical Commission (IEC) 2005 *IEC 61267:2005 Medical Diagnostic X-ray Equipment. Radiation Conditions for Use in the Determination of Characteristics* 2nd edn (Genève: IEC)

Leitz W, Axelsson B and Szendro G 1995 Computed-tomography dose assessment—a pratical approach *Radiat. Prot. Dosim.* **2** 377–80

Mori S, Nishizawa K, Ohno M and Endo M 2006 Conversion factor for CT dosimetry to assess patient dose using a 256-slice CT scanner *Br. J. Radiol.* **79** 888–92

Neves L P, Perini A P and Caldas L V E 2013 Development and characterization of a new cylindrical ionization chamber for dosimetry of ^{60}Co beams *IEEE Trans. Nucl. Sci.* **60** 712–5

Perini A P, Neves L P, Fernández-Varea J M, Büermann L and Caldas L V E 2013 Evaluation and simulation of a new ionization chamber design for use in computed tomography beams *IEEE Trans. Nucl. Sci.* **60** 768–73

Suzuki A and Suzuki M N 1978 Use of a pencil-shaped ionization chamber for measurement of exposure resulting from a computed tomography scan *Med. Phys.* **5** 536–9