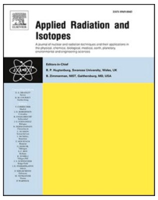
Applied Radiation and Isotopes 225 (2025) 111991

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso



Evaluation of a special parallel-plate ionization chamber in standard mammography beams

Climério S. Soares [a,b,*], Linda V.E. Caldas [a]

[a] Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN), Comissão Nacional de Energia Nuclear, Av. Prof. Lineu Prestes 2242, 05508-000, São Paulo, SP, Brazil
[b] Universidade Federal do Oeste da Bahia, Campus de Luís Eduardo Magalhães, Rua Itabuna, 1278, 47855-218, Luís Eduardo Magalhães, BA, Brazil

ARTICLE INFO

Keywords:
Parallel-plate ionization chamber
Mammography
Dosimetry

ABSTRACT

The aim of this work was to verify the possibility of the application of a special parallel-plate ionization chamber, developed at the Calibration Laboratory (IPEN), for mammography dosimetry. The homemade chamber has a polymethyl methacrylate body, 10 cm of sensitive length, and a sensitive volume of 3.2 cm^3. Its entrance window is a foil of Mylar and its collecting electrode is made of graphite. Some quality control and characterization tests were applied to evaluate the ionization chamber: short- and medium-term stabilities, leakage current, saturation, ion collection efficiency, polarity effect, stabilization time, linearity of response, angular dependence, and energy dependence. The tests were carried out using mammography standard radiation beams and a^{90}Sr + ^{90}Y check source. All the results obtained were within the international recommended limits.

1. Introduction

Currently, mammography is universally accepted as a standard test for the early detection of breast cancer. However, the diagnostic quality of this equipment in a mammography screening program is subject to its periodic monitoring in a quality assurance program (IAEA, 2011). As with any medical imaging system that uses X-rays, mammography image quality must be consistent with acceptable dose levels for the patient.

In the quality control protocols for mammography available in the literature (Bers et al., 2018; EFOMP, 2015; IAEA, 2011), the choice of dosimeter is left to the user's discretion. The practicality of using the ionization chamber makes it the preferred dosimeter in both metrology laboratories and hospitals and clinics. There are several types of ionization chambers; specifically for mammography beams dosimetry, the chamber used it is parallel-plate type (as known as plane-parallel chamber) with a thin entrance window, adequate for measurements of low-energy photons. It should always be used with its entrance window perpendicular to the beam axis (IAEA, 2007).

In Brazil, as in many developing countries, sometimes it is very difficult and expensive to import ionization chambers. Unfortunately, this is one of the reasons that make radiation dose optimization actions unfeasible in institutions that offer mammography services (Mora et al., 2015). This was one of the main motivations for the development of several types of ionization chambers at the Calibration Laboratory of Instruments (LCI) of IPEN for different applications using low-cost materials (Neves et al., 2024). Among these ionization chambers, one has a special design: it is an extended-length parallel-plate ionization chamber (Maia and Caldas, 2005). This chamber has a polymethyl methacrylate (PMMA) body, a sensitive volume of 3.2 cm^3, and a 10 cm sensitive length. Its entrance window is a foil of Mylar, which favors measurements of low-energy photons, such as mammography beams.

In this work, the special chamber was evaluated to verify the possibility of its application for mammography beams dosimetry. For that, the homemade ionization chamber was characterized in standard mammography beams through the following tests proposed by the IEC 61674 standard (IEC, 2012): saturation curve, polarity effects, ion collection efficiency, stabilization time, short- and medium-term stabilities, leakage current, response linearity, angular dependence, and energy dependence. The tests and measurements were performed at the LCI, which is a reference Brazilian dosimetry laboratory, where are offered several services of calibration of radiation detectors.

This article is part of a special issue entitled: Reprolam 2024 published in Applied Radiation and Isotopes.

* Corresponding author. Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN), Comissão Nacional de Energia Nuclear, Av. Prof. Lineu Prestes 2242, 05508-000, São Paulo, SP, Brazil.

E-mail addresses: climerio.soares@usp.br, climerio.soares@ufob.edu.br (C.S. Soares).

https://doi.org/10.1016/j.apradiso.2025.111991
Received 31 January 2025; Received in revised form 2 June 2025; Accepted 3 June 2025

2. Materials and methods

The technical specifications of the special parallel-plate ionization chamber developed at LCI are listed in Table 1. Fig. 1 shows a picture and a schematic diagram of the homemade ionization chamber. During all measurements, the ionization chamber was connected to an IBA electrometer, model DOSE 1, and all charge readings were corrected to atmospheric conditions at 20 °C and 101.3 kPa.

An industrial X-ray unit Pantak/Seifert, model ISOVOLT 160HS with tungsten target, that operates from 5 kV to 160 kV was used in most of the tests. In this X-ray system are established the standard mammography qualities used in this work (listed in Table 2) and other qualities established according to IEC 61267 (IEC, 2005), that are used in the radiation detector calibration services performed at LCI. The reference system for mammography qualities in this equipment was a Radcal parallel-plate ionization chamber, model RC6M, with sensitive volume of 6 cm^3. This chamber has traceability to the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB), and it was used in this work coupled to a PTW electrometer, model UNIDOS E, for determining the air kerma rates in the linearity of response and energy dependence tests. All standard mammography spectra used in this work can be viewed in Corrêa et al. (2012).

A ^{90}Sr + ^{90}Y check source, Physikalisch-Technische Werkstätten (PTW), model 8921, with nominal activity of 33 MBq (1994), was utilized for the stability tests. For the angular dependence test, a commercial goniometer, OPTRON, model GN1 200 was employed.

In all measurements using the X-ray equipment, the chamber was positioned 100 cm from the focal point of the X-ray tube, with a beam diameter of 12 cm. The uncertainties associated with each of the measurements presented in this work were evaluated according to the guide to the expression of uncertainty in measurement (ISO, 2008), using a coverage factor of 2.

3. Results and discussion

3.1. Short-and medium-term stability tests

The aim of these control quality tests is to evaluate the constancy of the chamber response over time. In this case, for the short-term stability test, the ionization chamber was repeatedly exposed to a ^{90}Sr + ^{90}Y PTW check source by taking ten measurements of 1 min in each measurement, in reproducible conditions, as shown in Fig. 2. The highest coefficient of variation observed in this test was 0.15 %. This result complies with standard IEC 61674 (IEC, 2012), which establishes a maximum coefficient of variation of 1 % for this test.

To assess the medium-term stability of the ionization chamber response, the results of the short-term stability tests were plotted as a function of time. In according to IEC 61674 (IEC, 2012), the mean values obtained in each short-term stability test must not differ from the reference value by more ± 3 %. The reference value considered was the mean value of ten measurements of the short-term stability test for six months. As observed in Fig. 3, all deviations were within the recommended limit.

Table 1
Technical specifications of the special parallel-plate ionization chamber studied in this work.

Characteristics	Dimensions/Specifications
Electrode material	Graphite
Entrance window material	Mylar
Insulator material	Teflon
Sensitive volume length	100.0 mm
Connector types	BNC and banana
Sensitive volume	3.2 cm^3

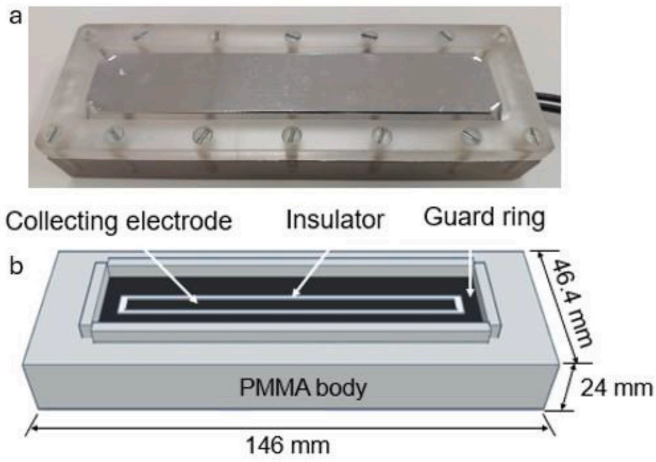


Fig. 1. (a) Picture and (b) three-dimensional drawing schematic of the special parallel-plate ionization chamber without the entrance window.

Table 2
PTB mammography qualities (PTB, 2015) in the Pantak/Seifert equipment.

Radiation quality	Voltage (kV)	Tube current (mA)	Half-value layer (mmAl)	Mean energy (keV)
Direct beams (total filtration: 0.07 mmMo)				
WMV 25	25	10	0.36	15.9
WMV 28	28	10	0.37	16.1
WMV 30	30	10	0.38	16.3
WMV 35	35	10	0.41	16.9
Attenuated beams (total filtration: 0.07 mmMo + 2 mmAl)				
WMH 25	25	10	0.56	18.7
WMH 28	28	10	0.61	19.1
WMH 30	30	10	0.68	19.7
WMH 35	35	10	0.93	22.9

Fig. 2. Ionization chamber with a special PMMA hold and a radioactive stability checking device during stability test.

3.2. Leakage current

The leakage of a dosimeter shall not exceed 5.0 % of the minimum effective air kerma rate of the range in utilization for at least 1 min (IEC, 2012). In this work, the leakage current of the ionization chamber was measured in time intervals of 20 min, after its exposure to the check source. The maximum value observed was 0.53 % of the minimum air kerma rate produced.

3.3. Saturation, polarity effect and ion collection efficiency

The optimal voltage for chamber operation is obtained by observing its saturation curve. This curve (Fig. 4) was obtained by varying the voltage from – 400 V to +400 V, in steps of 50 V. For each selected voltage, ten measurements were performed at 15 s intervals, using an X-

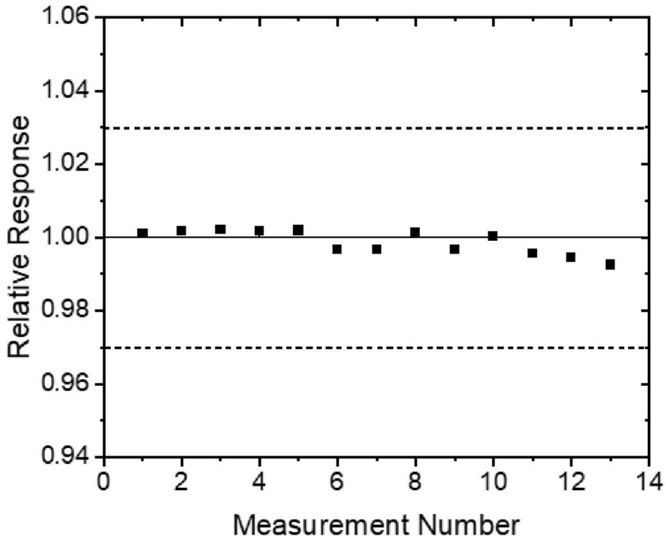


Fig. 3. Medium-term stability of the special parallel-plate ionization chamber during 6 months. The maximum uncertainty was 0.05 %, and therefore not visible in the figure. The dashed lines indicate the tolerance limits.

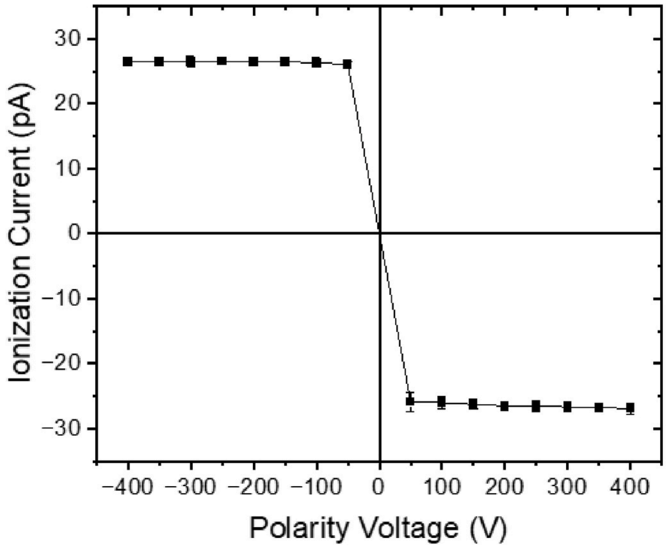


Fig. 4. Saturation curve of the special parallel-plate ionization chamber, in the WMV 28 mammography quality beam.

ray unit, with the WMV 28 (Table 2) mammography quality beam. As represented in Fig. 4, the constancy of the ionization current indicates that chamber saturation has been reached in the tested voltage range. The chosen operational voltage for the ionization chamber was – 300 V.

The data obtained to plot the saturation curve were used to analyze two more parameters: the ion collection efficiency and the chamber polarity effect.

The polarity effect was evaluated by comparing the chamber readings with positive and negative voltages equal in magnitude. Among all pairs of voltage tested, the highest value obtained was 0.87 %, less than ±1 % as recommended by IEC (IEC, 2011).

The ion collection efficiency was evaluated using the following equation (IAEA, 2001):

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

where M_x is the collected charge at a V_x voltage, and $V_1/V_2 = 2$. For $V_1 = -300$ V and $V_2 = -150$ V, the collection efficiency was better than 99.9 %. This result shows that recombination losses are less than 5 %, as recommended by IEC (IEC, 2012).

3.4. *Linearity of response*

In this test, the special parallel-plate ionization chamber was exposed to different air kerma rates, varying the nominal current of the X-ray system from 2 to 30 mA. The WMV 28 beam quality for mammography (Table 1) was employed, and the air kerma rates were determined using the reference system mammography quality beam. Fig. 5 shows the chamber response as a function of the air kerma rate. The ionization chamber presented a linear behavior within the tested range of air kerma rate. The uncertainty obtained in the linear fit was only 0.04 %, with a correlation coefficient R^2 of 0.999.

3.5. *Stabilization time test*

This test was performed by observing the response of the ionization chamber at time intervals of 15, 30, 45, and 60 min after polarization of the chamber, using the operational voltage of – 300 V. Under the same calibration conditions, the ionization chamber was irradiated using the mammography quality beam WMV 28 (Table 1). The ionization current obtained 15 min after the chamber polarization was 99.1 % of the stabilization current obtained after 60 min. This result is within the recommended limit of ±2 % of response variation (IEC, 2012).

3.6. *Angular dependence test*

For a parallel-plate ionization chamber, the IEC 61674 (IEC, 2012) standard recommends verifying the angular dependence of response varying the incidence radiation direction of ±5° from normal incidence. The chamber was exposed to the same standard beams used in the linearity of the response test and at each angular position, ten readings were taken in 15 s intervals. For the rotation angle to be accurately controlled, the chamber was placed on a goniometer at the calibration distance.

Fig. 6 shows that all values obtained at each angle were within 3 % from 0° (radiation field center), as stated by IEC (IEC, 2012).

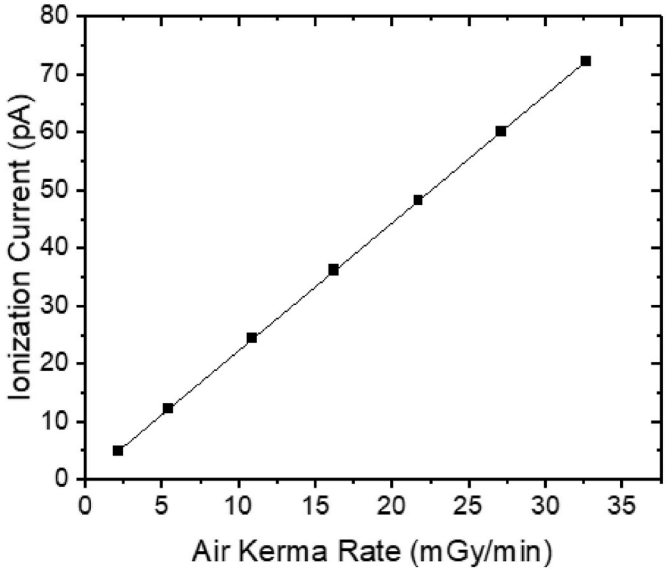


Fig. 5. Linearity of the response of the special parallel-plate ionization chamber in the WMV 28 mammography quality beam. The maximum uncertainty was 1.2 %, so it was not visible in the figure.

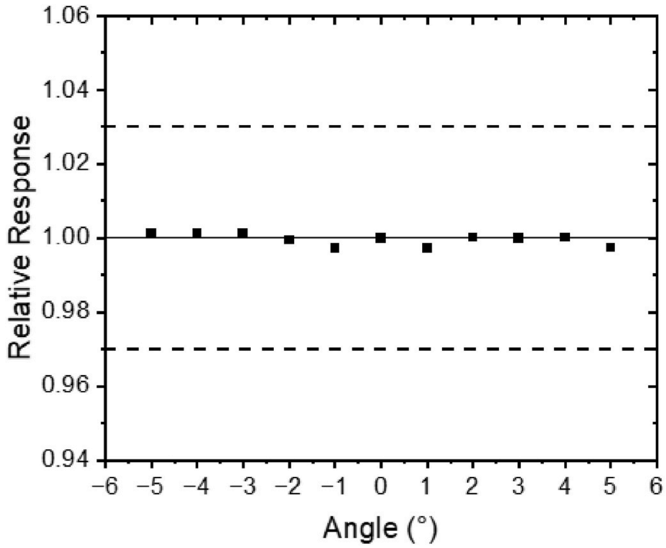


Fig. 6. Angular dependence test of the homemade ionization chamber exposed to a reference WMV 28 mammography quality beam. The responses were normalized to 0° position. As the uncertainties were less than 0.05 %, they are not seen in the figure.

3.7. *Energy dependence*

To evaluate the energy dependence – the ratio between the lowest and the highest calibration coefficients in percent – in mammography energy range, the special ionization chamber initially was calibrated against the reference ionization chamber in the beams described in Table 2. The calibration was carried out by using the substitution method. The calibration coefficients and correction factors obtained are shown in Table 3. The correction factors were obtained by dividing the calibration coefficient in each quality by the reference calibration coefficients WMV 28 (direct beams) and WMH 28 (attenuated beams). Figs. 7 and 8 show the energy dependence curves of the chamber in those qualities.

The results presented in Table 3, Figs. 7 and 8 for energy dependence of the ionization chamber were within the variation limits of ±5 %, as recommended by IEC (IEC, 2012).

Patient safety is guaranteed as long as the necessary and sufficient conditions for dose optimization exist. The acquisition of instruments to establish quality assurance programs (or quality control) is one of the main difficulties for most countries. In general, these instruments are imported and expensive. The homemade ionization chamber presented in this work demonstrates the possibility of building with metrological quality robust dosimeter using low-cost materials, easily found in the local market. This makes it accessible to any user who wants to contribute to dose optimization, and consequently ensure that the dose for the patient is within acceptable limits.

Table 3
Calibration coefficients and correction factors for the special parallel-plate ionization chamber at WMV and WMH radiation qualities.

Radiation quality	Calibration coefficient (x10^6 Gy/C)	Correction factor	Energy dependence (%)
Direct beams (total filtration: 0.07 mmMo)			
WMV 25	7.006 ± 0.013	0.9928 ± 0.0032	0.7
WMV 28	7.057 ± 0.019	1.0000 ± 0.0038	
WMV 30	7.031 ± 0.014	0.9963 ± 0.0033	
WMV 35	7.056 ± 0.010	0.9999 ± 0.0030	
Attenuated beams (total filtration: 0.07 mmMo + 2 mmAl*)*			
WMH 25	6.69 ± 0.24	0.972 ± 0.047	4.6
WMH 28	6.88 ± 0.22	1.000 ± 0.045	
WMH 30	7.01 ± 0.18	1.019 ± 0.042	
WMH 35	6.98 ± 0.11	1.015 ± 0.036	

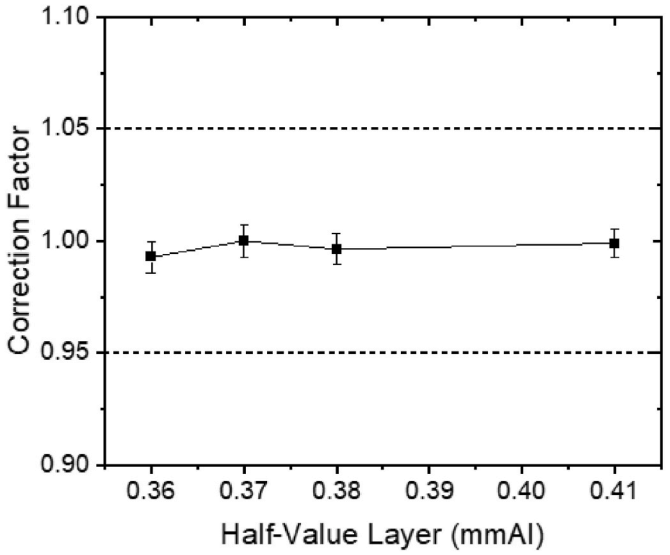


Fig. 7. Energy dependence of the response of the special parallel-plate ionization chamber for WMV radiation qualities (direct beams).

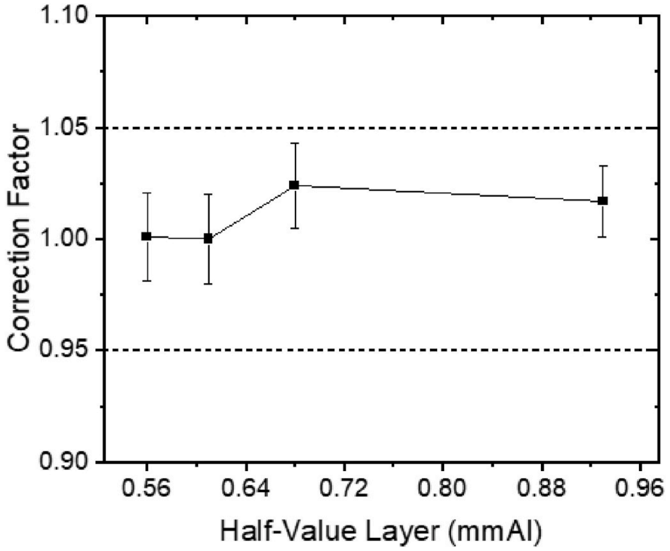


Fig. 8. Energy dependence of the response of the special parallel-plate ionization chamber for WMH radiation qualities (attenuated beams).

4. Conclusions

A dosimeter is considered suitable for mammography beam dosimetry if it meets all the requirements set out in IEC 61674 (IEC, 2012). It was verified that the special parallel-plate ionization chamber tested in this work satisfied all the requirements demanded by the standard.

Thus, it was demonstrated that a homemade chamber can be built using low-cost materials, with a sufficient level of quality to integrate quality control programs, in a calibration laboratory or in hospitals and clinics.

CRediT authorship contribution statement

Climério S. Soares: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Linda V.E. Caldas:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Climerio Santos Soares reports financial support was provided by National Council for Scientific and Technological Development. Linda Viola Ehlin Caldas reports financial support was provided by State of Sao Paulo Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the Brazilian agencies CNPq (Projects 403664/2022-5, 305142/2021-6, and 406303/2022-3) and FAPESP (Project 2018/05982-0) for partial financial support.

Data availability

Data will be made available on request.

References

Bers, E.A., Pfeiffer, D.E., Butler, P.F., et al., 2018. Digital Mammography Quality Control Manual. American College of Radiology, Reston, Va.

Corrêa, E.L., Vivolo, V., Potiens, M.P.A., 2012. Quality control methodology and implementation of X-radiation standards beams, mammography level, following the standard IEC 61267. Appl. Radiat. Isot. 70 (16), 1396–1399. https://doi.org/10.1016/j.apradiso.2012.01.012.

EFOMP, Europen Federation of Organizations for Medical Physics, 2015. Quality Controls in Digital Mammography: Protocol of EFOMP Mammo Working Group, 2015.

IAEA, International Atomic Energy Agency, 2001. Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water. IAEA Technical Report Series N° 398. IAEA, Vienna.

IAEA, International Atomic Energy Agency, 2007. Dosimetry in diagnostic radiology: an international code of practice. Technical Report Series N° 457. IAEA, Vienna.

IAEA, International Atomic Energy Agency, 2011. Quality Assurance Programme for Digital Mammography. IAEA, Vienna.

IEC, International Electrotechnical Commission, 2005. Medical Diagnostic X-ray Equipment—radiation Conditions for Use in the Determination of Characteristics. Standard IEC 61267. IEC, Geneva.

IEC, International Electrotechnical Commission, 2011. Medical electrical equipment: dosimeters with ionization chambers as used in radiotherapy. Standard IEC 60731. IEC, Geneva.

IEC, International Electrotechnical Commission, 2012. Medical electrical equipment—dosimeters with ionization chambers and/or semi-conductor detectors as used in X-ray diagnostic imaging. Standard IEC 61674. IEC, Geneva.

ISO, International Organization for Standardization, 2008. Evaluation of Measurement data—Guide to the Expression of Uncertainty in Measurement - GUM 2008, Geneva.

Maia, A.F., Caldas, L.V.E., 2005. A new extended-length parallel-plate ionization chamber. Phys. Med. Biol. 50 (16), 3837–3847. https://doi.org/10.1088/0031-9155/50/16/012.

Mora, P., Blanco, S., Khoury, H., Leyton, F., Cárdenas, J., Defaz, M.Y., Garay, F., Telón, F., Aguilar, J.G., Roas, N., Gamarra, M., Blanco, D., Quintero, A.R., Nader, A., 2015. Latin American dose survey results in mammography studies under IAEA programme: radiological protection of patients in medical exposures (TSA3). Radiat. Protect. Dosim. 163 (4), 473–479. https://doi.org/10.1093/rpd/ncu205. Epub 2014 Jul 3. PMID: 24993012.

Neves, L.P., Perini, A.P., Caldas, L.V.E., 2024. A review of ionization chambers developed for use at the Brazilian IPEN Calibration Laboratory. Braz. J. Phys. 54 (5), 1–7. https://doi.org/10.1007/s13538-024-01533-8.

PTB (Physikalisch-Technische Bundesanstalt), 2015. Radiation qualities used for studies in radiation protection ISO-PTB. Available from: www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.2/6.25/ptb_rad_qual_2015_01_07.pdf. (Accessed 8 May 2025).