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A Review of Ionization Chambers Developed for Use at the Brazilian IPEN Calibration Laboratory

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Abstract

Over the past 35 years, the Calibration Laboratory of IPEN (LCI) has seen significant advancements in the development of ionization chambers. This paper highlights the key contributions and achievements in this field. Numerous Master's and PhD students at LCI/IPEN, under the guidance of Linda Caldas, have devoted their careers to advancing the science and education of medical physics. This review showcases some of their work, all of which was made possible through the initial efforts in dosimetry at the IPEN by Prof. Shigueo Watanabe.

Keywords Radiation measurements · Medical physics · Dosimetry · Ionization chambers

1 Introduction

Ionization chambers are essential for clinical use because they provide accurate dosimetric measurements. Although the use of solid-state dosimeters has increased, ionization chambers remain indispensable for calibration laboratories such as IPEN/CNEN-SP.

Wilhelm C. Röntgen, known for discovering X-rays, described a device to measure X-ray intensity in his seminal paper "Über eine neue Art von Strahlen" ("On a new kind of rays") [1]. This apparatus, though not explicitly called an ionization chamber, utilized the principle of ionizing air to gauge radiation levels.

The gold-leaf electroscope, regarded as the most rudimentary form of an ionizing chamber, was employed to detect and measure ionizing radiation by observing the movement of a gold leaf due to air ionization between its plates [2]. As technology advanced and understanding of radiation-matter interactions and radiation transport deepened, thanks to the contributions of Marie Curie and other physicists, more sophisticated instruments were developed.

The concept of the ionization chamber is also linked to British physicist Charles Thomson Rees Wilson, who received the Nobel Prize in Physics in 1927 for inventing the cloud chamber [3]. This invention was also connected to the 1936 Nobel Prize awarded to Carl David Anderson for discovering the positron [4]. Recent publications provide further insights into the cloud chamber and its applications [5, 6].

During the 1920s and 1930s, scientists such as H. Geiger and W. Müller, who are known for the Geiger-Müller counter, led the radiation detector to a more refined design, resembling those used today [7]. Since then, several types of dosimeters were developed, for different applications, and the reader is invited to discover more about these developments in [8] and [9].

Since 1980, the Calibration Laboratory of IPEN (LCI) has offered calibration services for radiation measuring instruments in various medical and scientific fields. The measurement reference systems of the laboratory are traceable to

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esteemed primary standardization laboratories such as the Physikalisch-Technische Bundesanstalt (PTB), the National Physical Laboratory (NPL), the Bureau International des Poids et Mesures (BIPM), and also to the Secondary Standard Dosimetry Laboratory (SSDL) of Brazil, at the Radiation Protection and Dosimetry Institute, Rio de Janeiro, the *Laboratório Nacional de Metrologia das Radiações Ionizantes* (LNMRI). The LNMRI is the Designated Institute for Brazil in Ionizing Radiation Metrology, maintaining a combination of primary and secondary standards. LCI has developed homemade ionization chambers with distinct features, differing from commercial models.

The LCI at IPEN has focused on developing and characterizing radiation detectors, such as thermoluminescent dosimeters (TLDs) and ionization chambers. IPEN patented and commercially produced $CaSO_4$:Dy [10] TLDs for many years, significantly enhancing the country's self-sufficiency in radiation dosimetry. However, the development of ionization chambers did not progress in a similar manner. The goal behind their development was to maintain a self-sustained laboratory capable of producing its own standards for use.

Significant exchange rate fluctuations and a high dependence on foreign technology have underscored the need for developing national devices, especially in a country as vast as Brazil, where other laboratories may arise to meet the country's needs. Numerous devices have been developed to enhance self-sufficiency and expertise in dosimetry, as well as scientific advancements in calibration setups. This pursuit of self-sustainability has driven 40 years of research, which is now compiled in this review paper.

This review will examine some of the ionization chambers developed at LCI, focusing on their main characteristics and their significance in dosimetry and radiation protection. The review encompasses papers published by the LCI group, led by Linda V. E. Caldas, involving the development and characterization of ionization chambers since 1989.

2 Ionization Chamber Types

An ionization chamber is a type of gas detector, consisting of a volume of gas between two electrodes, with a voltage applied between the electrodes. There are several types of ionization chambers, such as parallel-plate, cylindrical, spherical, extrapolation, and monitoring chambers. Each ionization chamber has its applications, although some may be applied in different situations, as described by [11], but care must be taken. The sensitive volume is the region designed to be irradiated, but other components may also be inside the field and influence the responses. Nowadays, the Monte Carlo method is an indispensable tool for evaluating the response of these items, but experimental measurements may also be carried out by irradiating the cable of the ionization chamber [12] and determining the appropriate correction factors.

2.1 Parallel-Plate Ionization Chambers

Parallel-plate ionization chambers have important designs and applications. They are constructed using two parallel plates of material, generally plastic, forming the chamber wall. These walls are coated with a conducting layer, to form the positive and negative electrodes, and the gas between the walls fills the sensitive volume [13]. At the LCI several parallel-plate ionization chambers were developed and characterized for different applications.

In 1989, Albuquerque and Caldas [14, 15] developed the first ionization chambers of the LCI, two plane-parallel ionization chambers for beta and X-ray radiation dosimetry. These chambers had a circular form, sensitive volume of 0.6 cm^3, and entrance windows made of aluminized Mylar©. The electrode materials chosen were graphite and aluminum. The chamber wall material was Lucite. These chambers were submitted to the following tests: short- and long-term stability, leakage, and energy dependence. The ionization chamber with graphite electrode showed metrological characteristics comparable to secondary standard plane-parallel ionization chambers. Caldas [16] developed a tandem system, utilizing these ionization chambers, to be employed for effective energy determination of X radiation beams in the range 6 to 138 keV. This method proved to be simple, easy, and rapid, where absorbers or a special setup are not necessary. Tandem systems were also employed later on, for X-rays, radiotherapy level [17, 18]. Potiens [19] suggested a reference dosimeter based on a tandem system for diagnostic radiology beams, with very good results.

Souza [20, 21] developed two parallel-plate ionization chambers, one constructed with polymethyl methacrylate (PMMA) and another with polystyrene. The PMMA chamber has a nominal collecting volume of 0.056 cm^3, window material of aluminized Mylar©, and collecting electrode material of graphite coating. The polystyrene chamber had a nominal collecting volume of 0.078 cm^3, window material of aluminized Mylar©, and collecting electrode material of graphite coating. Both ionization chambers showed applicability for electron beam dosimetry. Also, for electron beams, Nonato [22, 23] developed an PMMA ionization chamber with a collecting electrode coated with silver paint. Several tests were undertaken, and two different LINACs were used, a Varian model 2100C (6, 9, 12, and 16 MeV) and an Elekta Synergy (4, 6, 9, 12, and 15 MeV). Despite some variations in the polarity effect test, the dosimeter presented suitable results. Besides the study of homemade chambers, commercial ionization chambers were also studied in different calibration methods for electron beams [24].

Costa [25, 26] developed a special double-faced parallel ionization chamber (tandem chamber) for quality control of diagnostic and mammography X-ray equipment. The tandem chamber presents one face with aluminum electrode and the other face with graphite electrode. The chamber body material is Lucite, the entrance windows are made of aluminized polyester foils, and the sensitive volumes are 2.5 cm^3.

Afonso et al. [27] used two ionization chambers initially constructed to be used as a standard system for calibration at radioprotection level [28], to evaluate the operational characteristics of those ionization chambers to establish a control quality program to be applied in mammography beams (other studies characterized commercial ionization chambers as a primary standard for low-energy X-ray beams [29, 30]). These chambers inserted in slab phantoms (30× 30×15 cm^3) have different collecting electrode materials: graphite and aluminum. The sensitive volumes are 10 cm^3, and the results pointed out that the use of two chambers allowed verification of the X-ray beam constancy, in a simple and quick way. Neves et al. [31] characterized the response of this chamber using the PENELOPE Monte Carlo code [32] with radioprotection level radiation qualities. The simulations provided the influence of several components, as described by the authors [31] as the ratio of the *response without the studied component by response of the complete chamber*. The response was measured as the energy deposited in the collecting electrode. The highest influences on the responses of the chamber were for the collecting electrode material (11%) and guard ring (6%).

The ionization chamber developed by Costa and Caldas [26] was also employed for quality control in diagnostic radiology beams [33, 34]. This double-faced ionization chamber was tested in standard conventional diagnostic and computed tomography radiation fields established at LCI. With this tandem system, it was possible to determine the half-value layers of the radiation beams for quality control, and the results pointed out that this double-faced chamber can be used to evaluate the diagnostic radiology qualities established at LCI [33].

Silva and Caldas [35] characterized a homemade ionization chamber [26] in radiotherapy beams, using the angular dependence and variation of response with distance. The chamber response variation with distance presented a maximum variation of 11%, and the angular dependence was within 1%. Silva et al. [36, 37] and Honda [38] also successfully used this type of ionization chamber for QA tests in mammography, as previously established at the LCI by Guerra [39]. Perini et al. [40] also developed and evaluated a PMMA graphite-coated ionization chamber, using diagnostic X-ray qualities and the Monte Carlo method. The deposited energies below and above the collecting electrode presented a difference lower than 1.6%, showing that the chamber is suitable for this energy range.

Perini [41] and Perini et al. [42, 43] investigated new graphite ionization chambers for use as reference instruments in measuring air kerma rates for ^{60}Co gamma rays. These ionization chambers are of the graphite parallel-plate type, featuring sensitive volumes of 9.4 cm^3 and 6.4 cm^3. Both prototypes were designed to be straightforward and easy to set up, with the latter lacking significant non-graphite components. Characterization tests were conducted, and Monte Carlo simulations were performed to evaluate the performance of the chambers in ^{60}Co beams and to determine necessary correction factors. The results for both chambers fell within specified limits and showed satisfactory performances, with the graphite-walled ionization chambers' air kerma rate displaying good agreement within statistical uncertainties when compared to the reference dosimeter of the LCI. These sets of chambers were to be used with the one developed by Neves [44] and Neves et al. [45] described later.

2.2 Cylindrical Ionization Chambers

At the LCI, a new set of 4 special pencil ionization chamber types were developed, firstly intended for CT dosimetry, but several tests showed that their applicability goes far beyond, spanning from CT to radiotherapy and field mapping.

Perini et al. [46] characterized the first of these chambers, a new pencil ionization chamber with 3.4 cm^3 for dosimetry of CT equipment, with a wall material of PVC coated with graphite and BNC connector attached directly to the chamber. This innovative dosimeter was also engineered to be straightforward and cost-effective in its assembly process. The impact of various components on the energy deposition in its sensitive volume was assessed using the Monte Carlo method. The results showed no influence of the BNC connector and PMMA body, approximately a 9% influence of the aluminum collecting electrode, and a 50% difference if PMMA was used replacing the PVC forming the collecting electrode. Another chamber of this type, but with a sensitive volume of 1.06 cm^3, was also tested in radiotherapy X-ray beams [47] presenting excellent results.

Neves et al. [48] characterized the second chamber of this set, for radiotherapy beams. This chamber had a cylindrical design, and its difference in relation to commercial ones was their sensitive volume (1.06 cm^3), geometry, and employed materials used in its construction. It was intended to be used in clinical and metrological applications.

Perini et al. [49] characterized the smallest chamber of the set for radiation field mapping. This CT chamber has a sensitive volume of 0.34 cm^3 and a sensitive length of 10.0 mm. The radiation field mapping made with this CT chamber was comparable with those from a commercial chamber. Castro [50], Castro et al. [51], Castro [52] characterized the latest and larger chamber of the set, with a sensitive volume length of 30 cm in standard and clinical CT beams, specially designed to accurately measure the doses from CT scanners that may present beam widths of 20–30 mm [53]. Given the promising results of these new chambers, Neves et al. [45, 54] developed and characterized new cylindrical ionization chambers for dosimetry of ^{60}Co beams, to be used with those developed by Perini et al. [42, 43].

2.3 Extrapolation Ionization Chambers

This type of ionization chamber allows adjustment of the sensitive volume by varying the distance between the electrodes. For several measurements, it is possible to obtain the dose values for a zero distance through extrapolation curves [55].

Dias and Caldas [56] constructed an extrapolation chamber for the calibration of beta-ray applicators. This ionization chamber features interchangeable electrodes. The chamber body was made of Lucite material, and the collecting electrodes were made of graphite. This chamber was also characterized as a reference standard in a CT radiation field, in the work of Castro et al. [57]. This extrapolation chamber was evaluated at IPEN and at NPL, UK. Key characteristics and various tests were conducted, with the chamber calibrated at NPL. Neves et al. [58] evaluated this extrapolation chamber for low-energy X-rays, using an experimental study and the Monte Carlo method.

Silva [59] and Silva and Caldas [60] also evaluated this extrapolation chamber [56] for low-energy X-rays as reference systems. These results showed that this extrapolation chamber may be useful as a reference system for this energy range. As a final step to characterize this chamber as a primary standard, Polo et al. [61] and Polo [62] used the Monte Carlo method to determine the correction factors for backscattering from the collecting electrode and the guard ring, for Bremsstrahlung in beta secondary standard radiation beams. The values found in their work were compared with reference values, presenting differences up to 2% for the backscatter factors and 1% for the Bremsstrahlung factors.

Oliveira [63] and Oliveira and Caldas [64] developed a mini-extrapolation chamber for the calibration of ^{90}Sr+^{90}Y beta-ray applicators. This ionization chamber has a 3.0 cm outer diameter and is 11.3 cm in length. The entrance window was made of aluminized polyester foil, and the collecting electrode was made of graphite-coated PMMA. It was tested with beta-ray applicators and with a plane ophthalmic applicator, obtaining adequate results. Following the establishment of primary and secondary standards at the LCI, Antonio [65] and Antonio et al. [66, 67] made several tests to establish a commercial Böhm extrapolation chamber as a primary standard system, for the dosimetry and calibration of beta radiation sources. They found that aluminized Mylar© or Hostaphan® entrance windows are suitable to be used as part of beta radiation field detectors, in primary standard systems. The transmission factors and absorbed dose rates of the ^{90}Sr+^{90}Y sources presented, in a great extent, differences comparable to those found in primary standards laboratories, as discussed in [66, 67].

2.4 Monitoring Ionization Chambers

Monitoring ionization chambers are widely used to check the constancy of radiation beam intensity and provide corrections for potential power-line fluctuations [8].

At the LCI, some monitoring ionization chambers were developed and characterized by Yoshizumi [68] and Yoshizumi and Caldas [69]. One of these was the first to be evaluated with the Monte Carlo method at the LCI and had a ring-shaped format with an entrance window made of aluminized polyester foil and electrodes made of graphite-coated PMMA plates. The results indicated that this ionization chamber can be effectively used to monitor X-ray beams without attenuating the beam.

Recently, more studies were carried out using the Monte Carlo method to evaluate the angular and energy dependence of commercial and homemade monitoring chambers as those by Xavier Filho [70].

2.5 Special Types of Ionization Chamber

At LCI, various ionization chambers with unique shapes were developed for specific measurement tasks. In this context, Maia [71] and Maia and Caldas [72] created a parallel-plate ionization chamber designed as a reference system for CT dosimetry. This chamber shares the same sensitive volume (3.2 cm^3) and length (10 cm) as conventional pencil ionization chambers. It features a graphite collecting electrode and guard rings, a Teflon insulator, a PMMA chamber wall, and a Mylar© chamber window.

Eight years after its initial development, this device was reassessed for consistency, and further studies were carried out to enhance its usage by determining correction factors using the Monte Carlo method. Perini et al. [73] compared the results of this chamber with those from a commercial pencil ionization chamber, demonstrating satisfactory consistency. Simulations using the Monte Carlo code evaluated the impact of various components, such as cables, insulators, the PMMA body, collecting electrode, guard ring, and screws, as well as different materials and geometric configurations, on the energy deposited in the sensitive volume of the chamber. The observed differences were 0.4% for cables, 3.0% for the insulator, 10.7% for the PMMA body, 13.3% for the collecting electrode, 4.0% for the guard ring, and 0.5% for the screws. Additionally, the evaluation of different materials and designs confirmed the original design as the most suitable.

3 Conclusion

In conclusion, the extensive development and characterization of ionization chambers at LCI, including parallel-plate, pencil, extrapolation, and monitoring types, have significantly improved the development and characterization of ionization chambers in Brazil. These chambers have demonstrated adaptability and versatility across various applications, from beta and X-ray radiation dosimetry to CT equipment and radiotherapy beam monitoring. Innovative designs, materials, and rigorous testing, including Monte Carlo simulations, have ensured their effectiveness and reliability in different settings. The continuous exploration of new materials and designs, along with the successful application of these chambers in metrological contexts, highlights their importance in ensuring accurate dosimetry and quality assurance in radiation measurement. The ongoing development and evaluation of these ionization chambers at LCI will undoubtedly continue to contribute to further advancements in the field, providing reliable and accurate tools for radiation measurement and quality assurance.

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Data Availability No datasets were generated or analyzed during the current study.

Declarations

Ethical Approval The authors utilized ChatGPT 4.0 (https://chat.openai.com) to enhance their writing and correct English grammar.

Competing Interest The authors declare no competing interests.

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