# Application of a Pencil Ionization Chamber ($0.34\ \mathrm{cm}^3$ Volume) for $^{60}$Co Beams: Experimental and Monte Carlo Results

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***Abstract*—Ionization chambers are the most utilized dosimeters for precise measurements of absorbed dose, as required e.g., in radiotherapy. The most common type, for this application, is the Farmer type with a wall made of PMMA and/or graphite. With the aim to test new materials and configurations of ionization chambers, using low-cost and easily-available components, this work presents the study of a device developed at the Calibration Laboratory of IPEN (São Paulo). This dosimeter is a pencil-type cylindrical ionization chamber, with a wall of PVC coated with graphite, for routine use in $^{60}$Co beams. Following international recommendations, several characterization tests were conducted, and all achieved results were found to fulfill those recommendations. The influence of the chamber components on its response was also studied using the PENELOPE Monte Carlo code. According to the obtained results, this prototype presents potential usefulness for routine dosimetric procedures in radiotherapy.**

***Index Terms*—$^{60}$Co beams dosimetry, ionization chamber, Monte Carlo simulation, radiotherapy.**

## I. INTRODUCTION

THE application of $^{60}$Co in radiation therapy has a long history; however, in the past few decades most research and development efforts have led into the enhancement of linacs. Although they have been more utilized for radiotherapeutic treatments, there are studies that point out the advantages of the utilization of $^{60}$Co units in modern treatments, such as tomotherapy and intensity-modulated radiation therapy (IMRT). Furthermore, due to the simplicity and robustness of $^{60}$Co sources, in a large number of countries they continue to play a significant role for radiotherapy. In the last years, there has been a renewed interest in the utilization of $^{60}$Co in the development of new equipments for radiotherapy treatments. Joshi *et al.* [1] pointed out that $^{60}$Co-based tomotherapy units may offer a clinically competitive, low-cost, low-maintenance and relatively simple alternative to linac-based tomotherapy. Adams and Warrington [2] have also shown that $^{60}$Co units present a comparable quality in IMRT dose distributions when compared with linac units. In turn, Schreiner *et al.* [3] indicated that the results obtained in their work support that there is an ample potential for administering modern radiation therapy with $^{60}$Co sources, and they encourage further investigations and development.

Considering the fact that new technologies still use $^{60}$Co sources, there is a continuous interest in the development and characterization of radiation detectors for this energy range. One of the objectives of the research group of the Calibration Laboratory (LCI) of IPEN is to develop new ionization chambers as working metrological standards, both for clinical and scientific purposes. Some ionization chambers were constructed to be used mainly in diagnostic radiology and radiotherapy energy ranges [4]–[6]. With the aim to test new materials and designs of radiation dosimeters for $^{60}$Co beams, following international recommendations, this work presents the evaluation of a new pencil-type cylindrical ionization chamber for routine use in $^{60}$Co beams. Due to its small sensitive volume this ionization chamber has already been tested for radiation-field mapping in diagnostic radiology qualities [6], but not for $^{60}$Co beams yet.

The main differences between this ionization chamber prototype and the commercially available chambers used for dosimetry in radiotherapy are the geometry and constituent materials. This chamber is of pencil type, with a sensitive volume of $0.34\ \mathrm{cm}^3$ delimited by a thin layer of PVC located at the middle of the dosimeter, while the commercial chambers are Farmer type with their sensitive volumes located at the tip and with a wall material of PMMA and/or graphite.

In order to characterize this dosimeter for radiotherapy dosimetry, some important tests were undertaken: short- and medium-term stability, stabilization time, saturation, ion collection efficiency, polarity effect, leakage current and angular dependence. Furthermore, owing to the geometrical differences of this ionization chamber as compared to the commercial ones, the influence of some components on its response was studied by means of Monte Carlo simulations.

## II. MATERIALS AND METHODS

The ionization chamber characterized in this work is presented in Fig. 1. This chamber is made of PMMA, with $(155.00 \pm 0.02)$ mm length; the wall material of the chamber

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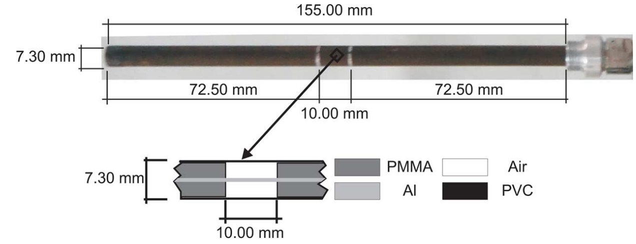

Fig. 1. Pencil ionization chamber developed at the IPEN with a schematic representation of its sensitive volume.

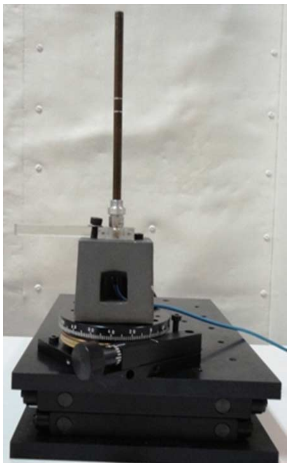

Fig. 2. Positioning system utilized in the angular dependence test.

sensitive volume is PVC with graphite coating, and its collecting electrode material is made of aluminum, with a diameter of $(1.20 \pm 0.02)$ mm. The chamber internal diameter is $(6.70 \pm 0.02)$ mm, and its wall thickness and the sensitive length are $(0.26 \pm 0.02)$ mm and $(10.00 \pm 0.02)$ mm, respectively, and the ionization chamber has a sensitive volume of $(0.34 \pm 0.05)$ cm$^3$. A special build-up cap for $^{60}$Co beams was made of PMMA, with a thickness of $(4.05 \pm 0.02)$ mm.

All experimental tests were undertaken according to international recommendations [7], using a Gammatron II S80 irradiation system ($^{60}$Co source), and an electrometer, model UNIDOS E, Physikalisch-Technische Werkstätten (PTW) Freiburg, Germany. For the angular dependence test, a commercial goniometer, OPTRON, model GN1 200, and a special positioning system (Fig. 2) were employed. The irradiation conditions for all measurements were fixed at a reference field of $10 \times 10$ cm$^2$ using the $^{60}$Co unit for 15 s. The air kerma rate was $(0.76 \pm 0.01)$ mGy/s, measured with a secondary standard ionization chamber PTW, model TN30012, with traceability to the Bureau International des Poids et Mesures (BIPM). All readings were corrected for standard environmental conditions of temperature and pressure.

In this study, the Monte Carlo simulations of the ionization chamber were carried out with PENELOPE/penEasy [8], [9], a general-purpose subroutine package and main program for the coupled simulation of electron/photon transport.

The ionization chamber was modeled according to its dimensions and composition, including a very detailed description of the BNC connector. This procedure was undertaken because normally commercial ionization chambers have the connector on the extremity of a cable, and not directly connected to the chamber, as in this case. This description of the connector will allow a more confident analysis of its influence on the energy deposited in the sensitive volume. The simulated ionization chamber and its constituent materials are shown in Fig. 3.

Other geometrical parameters such as the distances and field sizes utilized during the experiments were also modeled in the simulation. The ionization chamber was positioned 100 cm from the gamma source, and there was a 5-cm-thick air layer in front and behind of the ionization chamber. The selected simulation parameters are listed in Table I. In Table I, parameters other than cutoff energies control the electron transport mechanics: $C_1$ is the average angular deflection; $C_2$ is the maximum average fractional energy loss between consecutive hard elastic events; $W_{\rm CC}$ is the cutoff energy loss for hard inelastic collisions and $W_{\rm CR}$ is the cutoff energy loss for hard Bremsstrahlung. The maximum allowed step length was set to $10^{30}$ cm, to switch off the external step-length control.

The photon spectrum of the Gammatron II S 80 $^{60}$Co unit used in the experiments was not found in the literature, and the blueprints of this unit were not available either. Therefore, three photon spectra were adopted and compared, namely that of a bare source of $^{60}$Co and the spectra calculated by Mora *et al.* [10] and by Tedgren *et al.* [11]. In the work of Mora *et al.* [10] an Eldorado 6 $^{60}$Co unit was simulated with the BEAM-EGS4 code [12], while Tedgren *et al.* [11] simulated a Siemens Gammatron 1 $^{60}$Co unit employing BEAMnrc [13]. Both spectra were determined free in air for a $10 \times 10$ cm$^2$ field size, with a source-detector distance of 100 cm.

In each run, $10^{10}$ histories were simulated, and the energy deposited in the air contained in the sensitive volume was scored. This value was then compared to the experimental results, in order to validate the simulation, and also to evaluate the influence of some components of the ionization chamber: the PMMA body, collecting electrode and BNC connector.

The results obtained with these spectra and the experimental data were compared, analyzing the energy deposited in the sensitive volume of the ionization chamber for several different build-up caps with thicknesses of 2.63, 3.49, 4.05, 4.85, 9.66 and 14.9 mm, as well as with no build-up cap. This comparison had the objective to determine whether the ionization chamber was correctly simulated, and to ascertain which spectrum presented a better agreement with the experiments. The analysis of the influence of the chamber components on the energy deposited in the sensitive volume was made with the spectrum of Tedgren *et al.* [11].

The uncertainties associated to all experimental results in this work are expanded uncertainties, obtained by the combination in quadrature of type A and B uncertainties, using 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

The characterization of the homemade ionization chamber was carried out in accordance to the IEC 60731 standard [7], exposing the ionization chamber to the $^{60}$Co beam, with the

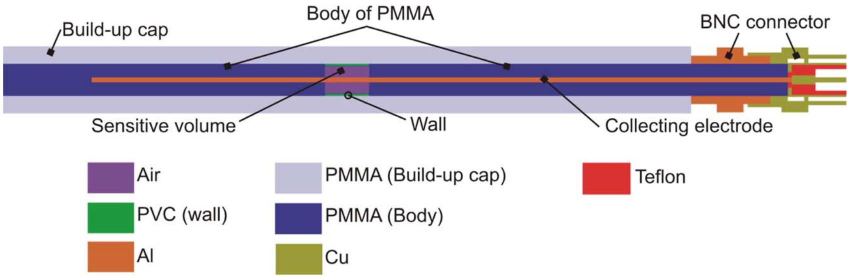

Fig. 3. Geometry and materials of the ionization chamber used during the simulations. (Color figure available only in the electronic version of this paper.)

TABLE I
PARAMETERS [8] ADOPTED IN THE SIMULATIONS

| Simulation parameter | Value |
|---|---|
| Cutoff energy for photons | 1 keV |
| Cutoff energy for $e^+$ and $e^-$ | 1 keV |
| $C_1$ | 0.05 |
| $C_2$ | 0.05 |
| $W_{CC}$ | 0.1 keV |
| $W_{CR}$ | 1 keV |
| Maximum step length | $10^{30}$ cm |

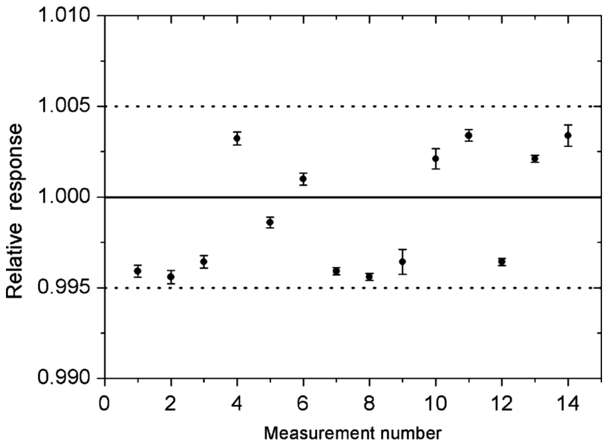

Fig. 4. Medium-term stability of the homemade ionization chamber.

following tests: short- and medium-term stability, stabilization time, saturation, ion collection efficiency, polarity effect, leakage current and angular dependence. Moreover, the ionization chamber was also studied using Monte Carlo simulations.

### *A. Short- and Medium-Term Stability*

In the short-term stability test ten consecutive measurements were taken under reproducible conditions. The maximum variation of the ionization chamber response was 0.1%, which satisfies the IEC 60731 standard requirements [7]. The medium-term stability of the ionization chamber response was assessed by taking the mean value of ten measurements of the short-term stability test during a period of 60 days (Fig. 4). The maximum variation observed was also found to be within the international recommendations of ±0.5% [7].

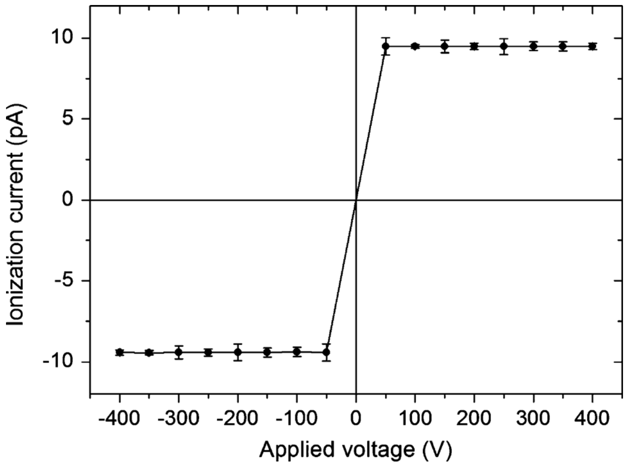

Fig. 5. Saturation curve of the pencil ionization chamber.

### *B. Stabilization Time*

In this test, the ionization chamber was continuously irradiated, using the operational voltage of +100 V. The ionization current was measured after 0.5, 1, 5, 10, 15, 60 and 120 min. The ionization current obtained 15 and 120 min after switching on the measuring system was 99.9% of the 1 h stabilization current. This result is within the limit of ±0.5% of response variation [7].

### *C. Saturation, Ion Collection Efficiency and Polarity Effect*

The saturation curve was obtained by measuring the collected charge for several applied voltages ranging from ±50 V to ±400 V (Fig. 5).

Two parameters were analyzed using the saturation curve: ion collection efficiency and polarity effect. The ion collection efficiency $(K_s)$ in a continuous radiation beam can be calculated by the two voltage method [14] according to

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

where $M_i$ is the collected charge at a voltage $V_i$ $(i = 1, 2)$. For $V_1 = 100$ V and $V_2 = 200$ V, the ion collection efficiency was better than 99%. In turn, the polarity effect was evaluated comparing the collected charges at similar voltages of opposite

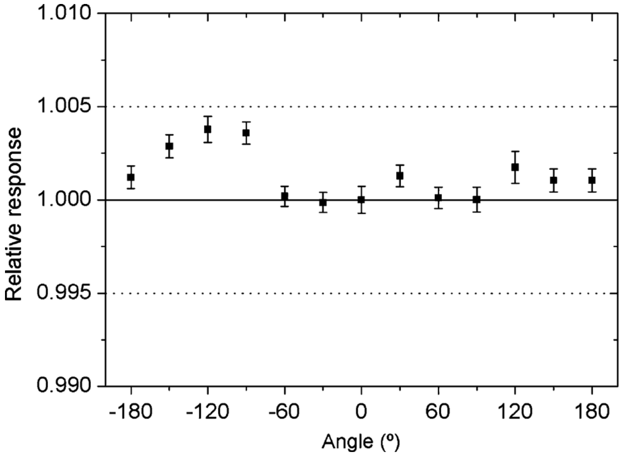

Fig. 6. Angular dependence test of the ionization chamber, normalization to the response at 0°.

signs. For all pairs of voltages tested, the polarity effect was less than 0.5% [7].

### *D. Leakage Current*

The leakage current was measured during 20 min before and after irradiation. The maximum value observed was 0.3% of the ionization current. This value satisfies the limit of 0.5% recommended by the IEC 60731 standard [7].

### *E. Angular Dependence*

In the angular dependence test, the chamber was completely rotated around its central axis in steps of 30° while being exposed to the $^{60}$Co beam. According to IEC 60731 [7], the value obtained at each angle must not differ from 0° by more than 0.5%. Observing the results in Fig. 6, the maximum variation was 0.4%.

### *F. Monte Carlo Analysis of the Ionization Chamber Components*

The comparison between the experimental results and those from the simulations with the bare source of $^{60}$Co, the spectrum of Mora *et al.* [10] and the spectrum of Tedgren *et al.* [11] is shown in Fig. 7. In this study, PMMA build-up caps were utilized, with thicknesses of 2.63, 3.49, 4.05, 4.85, 9.66 and 14.9 mm, as well as no build-up cap (only for the simulated results). The results were normalized to that of the build-up cap thickness of 4.05 mm.

The maximum difference between the simulated and experimental data was 1.9% for the bare source of $^{60}$Co; 2.6% for the spectrum of Mora *et al.* [10]; and 0.8% for the spectrum of Tedgren *et al.* [11]. The latter were within the statistical uncertainties, whereas the simulation results for the bare source and the spectrum of Mora *et al.* [10] are significantly higher. This may be explained by the fact that the equipment simulated in [11] is very similar to the one at the LCI, as well as the geometrical arrangement of the $^{60}$Co source.

Since the ionization chamber was properly simulated, the same input parameters, geometry and spectrum of Tedgren *et al.* [11] were applied to determine the influence of the PMMA body, the collecting electrode and the BNC connector on the

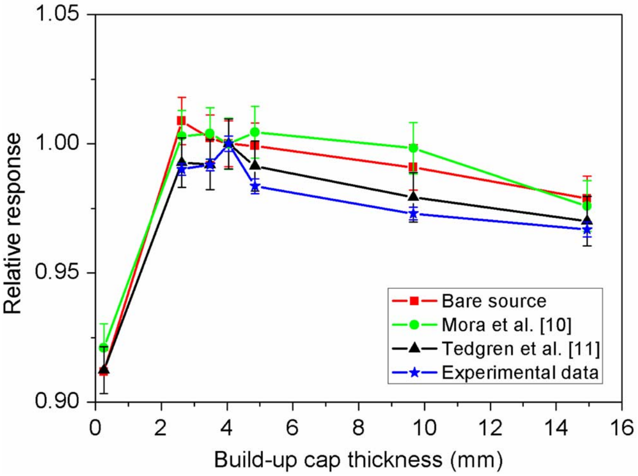

Fig. 7. Comparison between experimental results and Monte Carlo simulations for the ionization chamber response, utilizing several build-up caps. The results were normalized for those of a build-up cap of 4.05 mm. (Color figure available only in the electronic version of this paper.)

TABLE II
INFLUENCE OF THE IONIZATION CHAMBER COMPONENTS IN THE SENSITIVE VOLUME

| **Component studied** | **Variation in the energy deposition (%)** |
|---|---|
| BNC connector | 0.3 |
| Collecting electrode | 6.0 |
| PMMA body | 5.0 |

energy deposited on the sensitive volume of the ionization chamber. These components and materials were chosen because they represent the most significant differences between the ionization chamber characterized in this work and those commercially available.

This study was conducted by substituting each component by air, and comparing the results with the complete ionization chamber. To maintain electronic equilibrium, the build-up cap of 4.05 mm of PMMA was utilized during the simulation tests. The results are summarized in Table II.

The BNC connector presents the lowest influence, among the tested components, mainly because it is at the edge of the radiation field, not entirely irradiated by the direct beam (the same configuration used during the calibration procedures). Moreover, the PMMA body, which has approximately 7.3 cm in length, between the sensitive volume and the connector, may attenuate the radiation scattered by the connector towards the sensitive volume. On the other hand, the influence of the collecting electrode is mainly due to the Compton recoil electrons and photoelectrons generated by the interactions of photons with the aluminum atoms. These electrons will increase significantly, as seen, the energy deposited in the sensitive volume of the ionization chamber.

## IV. CONCLUSION

The ionization chamber studied in this work presented results within the recommended international limits, demonstrating that both the materials used for its composition, as well as the geometrical arrangement are suitable for dosimetry procedures in radiotherapy. Furthermore, the simulation results revealed a contribution, in the energy deposited on the sensitive volume, of 5.0% from the PMMA body, 0.3% from the BNC connector and 6.0% from the collecting electrode. Although the collecting electrode and the PMMA body have a larger influence on the energy deposited in the sensitive volume, it did not affect the performance of this dosimeter, for $^{60}$Co beams, as verified by the undertaken experimental characterization tests.

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