Radiation Physics and Chemistry 104 (2014) 310–315

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Bohm extrapolation chamber: Study of its behavior in beta radiation fields at the Calibration Laboratory of IPEN

Patrícia L. Antonio*, Marcos Xavier, Linda V.E. Caldas

Instituto de Pesquisas Energéticas e Nucleares, Comissão Nacional de Energia Nuclear, IPEN/CNEN-SP – Av. Prof. Lineu Prestes 2242, CEP 05508-000, São Paulo, Brazil

HIGHLIGHTS

- The Bohm extrapolation chamber response was studied in two different conditions.
- The extrapolation chamber was studied with two different entrance windows.
- The instrument was exposed to $^{90}Sr+^{90}Y$ beams.
- Different characterization tests of the chamber were performed.
- All results confirmed the adequate behavior of the chamber in both situations.

ARTICLE INFO

Article history:
Received 11 June 2013
Accepted 28 April 2014
Available online 9 May 2014

Keywords:
Bohm extrapolation chamber
$^{90}Sr+^{90}Y$ sources
Characterization tests
Aluminized Mylar
Hostaphan

ABSTRACT

The Calibration Laboratory (LCI) at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) is going to establish a Bohm extrapolation chamber as a primary standard system for the dosimetry and calibration of beta radiation sources and detectors. This chamber was already tested in beta radiation beams with an aluminized Mylar entrance window, and now, it was characterized with an original Hostaphan entrance window. A comparison between the results of the extrapolation chamber with the two entrance windows was performed. The results showed that this extrapolation chamber presents the same effectiveness in beta radiation fields as a primary standard system with both entrance windows, showing that any one of them may be utilized.

1. Introduction

The absorbed dose rate in tissue is the quantity associated to beta particles, and more specifically, it shall be determined at the depth of 0.07 mm in tissue, recommended internationally (ISO, 2004; NIST, 2010; Behrens et al., 2011). The primary standard instrument established for this function, for excellence, is the extrapolation chamber which allows the absorbed dose rate determination at different depths in tissue, when measurements are taken using different thickness absorbers in front of its entrance window. This chamber differs from a traditional parallel plate ionization chamber due to the possibility of variation of its sensible volume (Bohm, 1986a, 1986b; ISO, 2004; NIST, 2010).

At the Calibration Laboratory (LCI) of the Instituto de Pesquisas Energéticas e Nucleares (IPEN), one of the metrology laboratories of Brazil, there is a Bohm extrapolation chamber, manufactured by PTW, model 23392 (Bohm, 1986b; PTW, 2002). The LCI offers several calibration services of different instruments and using standard ionizing radiation beams. The possibility to establish this instrument as a primary standard system for calibration and dosimetry of beta radiation sources and detectors is the final purpose of this work.

Therefore, some tests recommended by the International Electrotechnical Commission (IEC, 2011), in the case of equipments used in radiotherapy, were realized to verify the chamber response. Although the objective of the use of this chamber is in radioprotection area (calibration of detectors), the IEC recommendation was choosen, because it provides more restrictive limits for tests in ionization chambers when they are used in radiotherapy beams (this chamber is also used in this area because it allows the determination of absorbed dose rates in tissue).

The objective of this work was to perform definitive characterization tests (leakage current, stability of response, real null depth, polarity effect, ion collection efficiency, extrapolation curves and absorbed dose rates, and variation of the chamber response in function of the source–detector distance) of the extrapolation chamber with an original entrance window (acquired from the

* Corresponding author. Tel.: +55 11 3133 9652; fax: +55 11 3133 9671.
E-mail addresses: patrilan@ipen.br (P.L. Antonio), mxavier@ipen.br (M. Xavier), lcaldas@ipen.br (L.V.E. Caldas).

http://dx.doi.org/10.1016/j.radphyschem.2014.04.035

manufacturer) of Hostaphan (superficial density of 0.72 mg/cm^2), in beta radiation fields, to be used as a primary standard system at LCI. Furthermore, some of these results were compared with other ones presented by Antonio et al. (2013), in which this chamber was submitted to some preliminary tests, but with an aluminized Mylar entrance window (superficial density of 0.71 mg/cm^2), before the LCI received the original graphite Hostaphan entrance window. Both Hostaphan and Mylar are composed by the same material: polyethylene terephthalate, but the layers on them are different (aluminum and graphite), and both are very good conducting materials.

2. Methodology and results

The parallel plate ionization chamber used in this work was the Bohm extrapolation chamber, from Physikalisch-Technische Werkstätten (PTW), Freiburg, model 23392, which was manufactured to be used as a primary or secondary standard system for calibration of beta radiation detectors and sources. This chamber presents aluminum body, Hostaphan entrance window, graphited collecting electrode of Polymethylmethacrylate (PMMA) and diameter of 30 mm, and a sensible volume which may be varied from 0.5 mm to 10.5 mm, and consequently, with a possibility of variation in the air volume of 0.353-7.422 cm^3 (PTW, 2002).

In all measurements, the electric charge values were taken (then they were converted to ionization currents and corrected to the standard environmental conditions) using an electrometer Keithley Instruments Inc., model 6517B. A constant electric field of 10 V/mm was applied to the extrapolation chamber (Caldas, 1986; ISO, 2004).

During the irradiation procedures, the chamber was exposed to the two $^{90}Sr+^{90}Y$ radiation sources, from the beta secondary standard system of the LCI, BSS1, Buchler GmbH & Co., Germany. Their main information are presented in Table 1.

Different characterization tests were performed with the Bohm extrapolation chamber, and the results obtained are presented after the methodology used in each experiment.

2.1. Saturation curve, polarity effect and ion collection efficiency

The saturation curves were obtained exposing the chamber to the BSS1 $^{90}Sr+^{90}Y$ source of 1850 MBq, and for three different chamber depths (0.7, 1.5 and 2.5 mm), in order to analyze the performance of the chamber response in each air volume, the polarity effect, the ion collection efficiency and ion recombination.

During the data collection of the saturation curves, the voltage applied to the electrode of the chamber was varied from ± 5 V to ± 300 V, the charge collection time was 60 s, and the chamber was positioned at the distance of 11 cm from the radiation source.

From the saturation curves, the saturation current, I_S, was obtained for each chamber depth. This current I_S (necessary for the determination of the ion collection efficiency) was obtained from the ionization current measured in function of the inverse square-root of the voltage values applied to the chamber electrode during the experiments, and adjusting the values extrapolating them to an infinite chamber voltage.

Table 1
Characteristics of the $^{90}Sr+^{90}Y$ beta radiation sources from the BSS1 system.

Nominal activity (MBq)	Filter presence	Absorbed dose rate (μGy/s)	Calibration date
74	Yes	1.707 ± 0.017	Jan 12, 1981
1850	No	70.60 ± 0.71	Feb 4, 1981

Table 2
Mean ionization current in the saturation region obtained for the positive and negative voltage polarities with the Bohm extrapolation chamber, and for different chamber depths.

Chamber depth, *d* (mm)	Mean ionization current, *I* (pA)		Maximum variation coefficient (%)
	Positive polarity	Negative polarity	
0.700	$+3.385 \pm 0.015$	-4.995 ± 0.017	-1.08
1.500	$+8.169 \pm 0.019$	-9.601 ± 0.012	-2.19
2.500	$+14.12 \pm 0.018$	-15.61 ± 0.026	-0.83

The polarity effect factor, k_{pol}, which provides the variation between the responses of the chamber obtained in positive and negative voltage polarities, was determined for the Bohm extrapolation chamber by means of Eq. (1) (Bohm, 1986b)

$$k_{pol} = \frac{(I_- + I_+)}{(I_- - I_+)} \tag{1}$$

where k_{pol} is the polarity effect factor, I_+ is the ionization current measured at the positive polarity, and I_- is the ionization current measured at the negative polarity.

The ion collection efficiency of the chamber, f, was calculated by Eq. (2) (Caldas, 1980; Dias and Caldas, 1999; Silva and Caldas, 2012), relating the measured and saturation ionization currents

$$f = \frac{I}{I_s} \tag{2}$$

where f is the ion collection efficiency; I is the mean ionization current (pA) measured at both polarity voltages, and I_S is the ideal saturation current (pA), obtained from the saturation curves.

The mean ionization currents in the saturation region obtained during the measurements for the three saturation curves, and the maximum variation coefficient obtained in each case are shown in Table 2. These curves were plotted together in the same figure, in order to allow the comparison among them, as in previous papers (Bohm, 1986b; Silva and Caldas, 2012), and they can be observed in Fig. 1a. From the saturation curves, the saturation currents were obtained, shown in Fig. 1b.

From the saturation curves, it was possible to study the polarity effect caused inside each chamber sensible volume. Table 3 demonstrates the polarity effect of the Bohm extrapolation chamber in different chamber depths, obtained in this work. These results are compatible with those obtained for the same extrapolation chamber, and at same conditions, with the aluminized Mylar entrance window in a previous work (Antonio et al., 2012).

The results shown in Table 3 demonstrate that the polarity effect values decrease according to the increase of the chamber depth. The IEC 60731standard (IEC, 2011) recommends a limit of 1.0% for this test, but the results of this work can be considered, because they are related to a beta radiation beam. In the case of this radiation, the presence of an ionization current occurs at the moment in which the beta particles interact with the entrance window material. Bohm (1986b) and NIST (2010) obtained polarity effects higher than 10%. Bohm (1986b) obtained a polarity effect up to 10%, and at NIST (2010) a maximum value of 16% was obtained for a chamber depth of 0.7 mm. Therefore, the results of this work can be considered compatible with those obtained by NIST (2010).

Using the saturation currents (Fig. 1b), the collection efficiencies were determined by Eq. (2). The results obtained for each tested chamber depth (0.7, 1.5 and 2.5 mm) are within those established by IEC (2011), which recommends that the chamber response should achieve more than 99.0% ion collection efficiency. This limit was reached for higher voltages than 50 V for all three

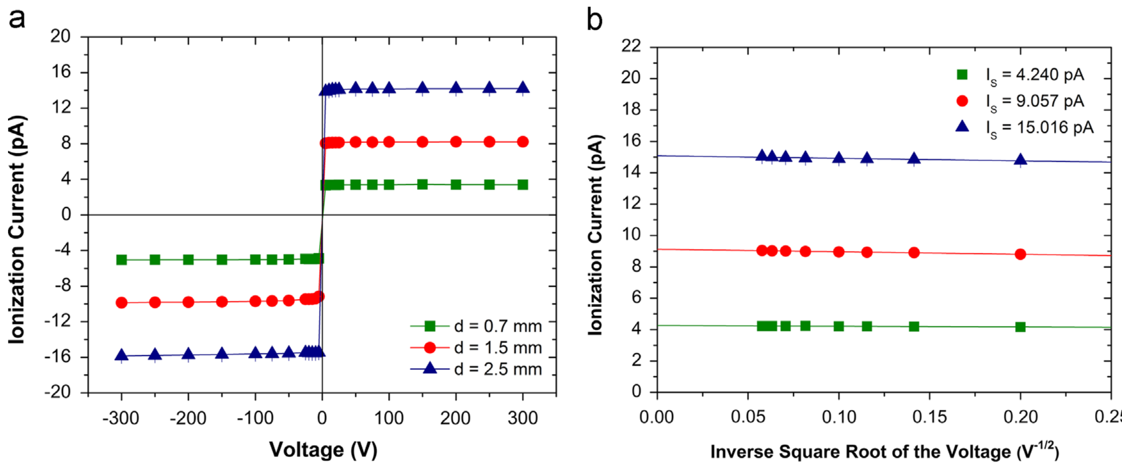

Fig. 1. Measurements for the saturation of the Bohm extrapolation chamber response: (a) saturation curves and (b) ionization currents.

Table 3
Polarity effects of the Bohm extrapolation chamber to different chamber depths, with Hostaphan entrance window, in comparison with the results of the previous work (NIST, 2010).

Chamber depth, *d* (mm)	Polarity effect (previous work), k_{pol} (%)	Polarity effect (this work), k_{pol} (%)
0.7	19.0	19.6
1.5	8.79	9.06
2.5	5.33	5.49

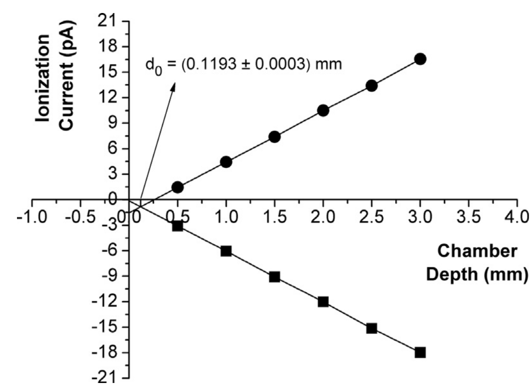

Fig. 2. Real null depth obtained for the Bohm extrapolation chamber.

chamber depths. The maximum ion collection efficiencies obtained were 99.56% (0.7 mm), 99.83% (1.5 mm) and 100.0% (2.5 mm), for a voltage of 300 V. Thus, the ion recombinations that occurred at each active volume of the extrapolation chamber were 0.44% (0.7 mm), 0.17% (1.5 mm) and null ion recombination for a chamber depth of 2.5 mm. As IEC (2011) establishes that this value should be lower than 1.0%, the results obtained were satisfactory.

2.2. Real null depth

All kinds of extrapolation chambers present a minimum distance between the electrodes, necessary to avoid that the electrodes touch each other when the collecting electrode is moved. This minimum distance, named real null depth, d_0, should be considered in all chamber depths.

The real null depth was determined using the $^{90}Sr+^{90}Y$ source (1850 MBq), according to the procedure performed by Caldas (1986). For the measurements, the extrapolation chamber was positioned at a distance of 11 cm from the source; the chamber depth was varied from 0.5 mm to 3.0 mm, and the voltage from $\pm$5 V to $\pm$30 V. These conditions were the same used for the extrapolation chamber with aluminized Mylar entrance window, in order to allow a comparison.

The real null depth obtained in this work, by the intersection of the linear fit between the measurements in the positive and negative polarity, was (119.3 ± 0.3) μm, and it is shown in Fig. 2. The maximum variation coefficient obtained in the measurements was 0.4%. Thus, in all other measurements, the chamber depth values were corrected for the null depth of 0.12 mm.

This result differs in 4.6% of the value obtained for the Bohm extrapolation chamber with aluminized Mylar entrance window of (125.0 ± 0.2) μm (Antonio et al., 2013).

2.3. Leakage current

The leakage current test, necessary to verify the ionization current inherent to the system electrometer, cables and chamber, was performed several times collecting electric charges using the extrapolation chamber without exposing it to the radiation source. The measurements were taken in a time interval of 20 min, applying a voltage of +10 V to the chamber electrodes, and using a chamber depth of 1.0 mm.

The maximum leakage current obtained in all measurements was (6.328 ± 0.008) fA, which represents 0.10% of the highest value measured during an irradiation procedure. As IEC (2011) recommends for the leakage current test a limit of 0.50%, in the case of ionization chambers for radiotherapy level, the result obtained in this work was satisfactory.

In the case of the Bohm extrapolation chamber with aluminized Mylar entrance window, the result obtained for the leakage current was (4.048 ± 0.002) fA, which means 0.06% (Antonio et al., 2012), also agreeing with the limit established by IEC (2011).

The results obtained for the chamber with both entrance windows confirm the good performance of the system composed by the electrometer, cables and extrapolation chamber, because there was no presence of any ionization current with influence on the measurements.

2.4. Stability of response

The stability of response of the Bohm extrapolation chamber was studied exposing it to the $^{90}Sr+^{90}Y$ source (1850 MBq), and performing the repeatability (short-term stability) and reproducibility (medium-term stability) tests.

The first test, repeatability, was performed taking ten electric charge measurements, during time intervals of 60 s, at the source–detector distance of 11 cm, using a chamber depth of 1.0 mm, and applying a voltage to the collecting electrode of ± 10 V. From the several repeatability tests, the reproducibility test results were obtained.

The repeatability test presented a maximum variation coefficient of 0.19%, while for the reproducibility test (successive repeatability tests), this result was 0.25%. Considering that IEC (2011) recommends a limit of 0.30% for the repeatability test, and of 0.50% for the reproducibility test, analyzing the results obtained in this work, it can be concluded that both tests agree with the recommended values, and that the Bohm extrapolation chamber presents the stability of response adequate for the experimental procedures.

This study was also performed for the chamber with aluminized Mylar entrance window, and the results were 0.20% for the repeatability test, and 0.40% for the reproducibility test, already showing the good behavior of the chamber response (Antonio et al., 2012).

2.5. *Variation of the chamber response in function of the source–detector distance*

In order to verify if the Bohm extrapolation chamber response follows the inverse square law in relation to the source–detector distance, measurements were taken with the chamber exposed to the $^{90}Sr+^{90}Y$ source (1850 MBq). In this test, the source–detector distance was varied in an interval from 10 cm to 55 cm, the measurements were taken in intervals of 60 s, the chamber depth was fixed in 1.0 mm, and the applied voltage was + 10 V.

This test was initially performed for the extrapolation chamber with aluminized Mylar entrance window (Fig. 3a). In this case, the ionization current varied from (0.2416 ± 0.0117) pA to (7.3412 ± 0.1521) pA, and a maximum variation coefficient of 3.9% (source–detector distance of 55 cm). This test was also obtained for the chamber with the Hostaphan entrance window, and it presented an interval of ionization current from (0.2451 ± 0.0074) pA to (7.2448 ± 0.1504) pA, and a maximum variation coefficient of 2.2% (source–detector distance of 55 cm). The result obtained can be observed in Fig. 3b.

The results obtained in this study show that the extrapolation chamber response do not follow the inverse square law in relation to the source–detector distance. The air density causes an influence in the measurements, because it acts as an absorber layer. So, with the increase of the source–detector distance, this effect becomes greater.

2.6. *Absorbed dose rates*

The two $^{90}Sr+^{90}Y$ sources of the BSS1 system, defined in Table 1, were calibrated in this work as if they were not standard sources. Thus, the absorbed dose rates, one of the main objectives to be determined in beta radiation dosimetry, were obtained for each source. Initially, an extrapolation curve was determined for each source, at a source–detector distance of 30 cm, varying the chamber depth from 0.5 mm to 2.5 mm, and applying a voltage from ± 5 V to ± 25 V (electric field constant at 10 V/mm). Using the limiting slope from each extrapolation curve, it was possible to obtain the absorbed dose rate using the methodology presented by ISO 6980-2 (ISO, 2004). Although the source calibration certificates present absorbed dose rates to null depth of air and tissue, in this work the results were converted to the 0.07 mm depth in tissue, established nowadays by international recommendations (Bohm, 1986b; ISO, 2004; NIST, 2010).

In this work, the absorbed dose rates, $\dot{D}_t$, were obtained using Eq. (3) (ISO, 2004)

$$\dot{D}_t = \frac{(\overline{W}_0/e)s_{t,a}}{\rho_0 a_{ef}}\left[\frac{d}{dl}\{kk'I(\ell)\}\right]_{l=0} \quad (3)$$

where $\overline{W}_0/e$ is the average air ionization energy [(33.83 ± 0.07) J/C] (ISO, 2004) for the BSS1 sources; ρ_0 is the air density in reference conditions of pressure, temperature and humidity [(1.1995 ± 0.0005) kg/m^3] (ISO, 2004) for the BSS1 sources; $s_{t,a}$ is the ratio of the average mass stopping power of tissue to air (1.110 ± 0.007) (ISO, 2004); a_{ef} is the effective area of the collecting electrode, obtained from the mechanical measurements [(7.354 ± 0.002) cm^2]; $[d/dl\{kk'I(\ell)\}]_{l=0}$ is the limiting slope of the corrected current I in function of the chamber depth ℓ; k is the product of different correction factors which vary with the chamber depth; and k' is the product of correction factors that do not vary with the chamber depth (are independent).

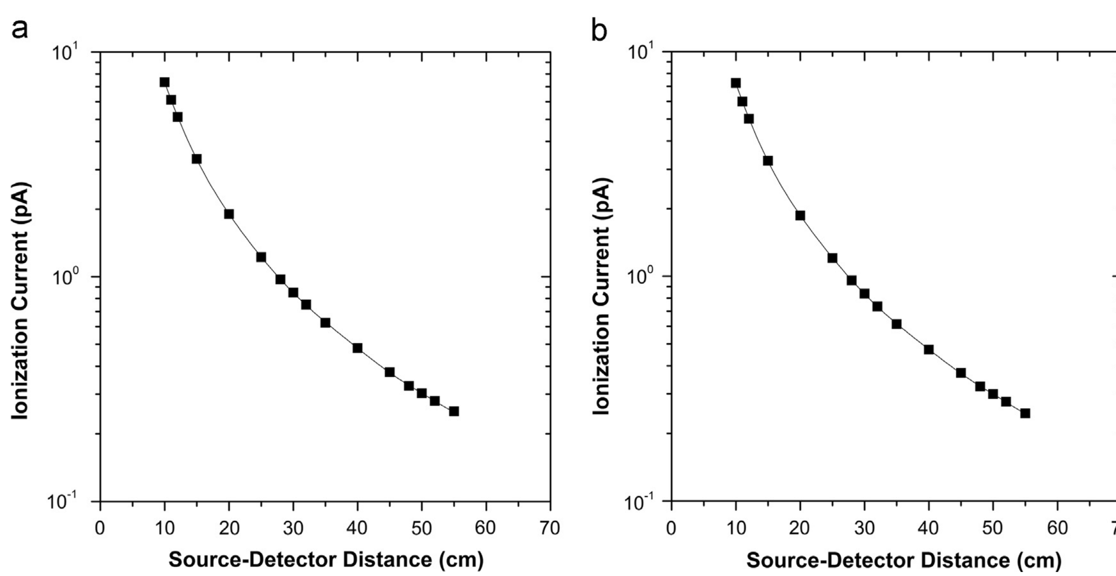

Fig. 3. Variation of the Bohm extrapolation chamber response in function of the source–detector distance, for the chamber with two entrance windows: (a) aluminized Mylar and (b) Hostaphan. The lines represents a polynomial fit of 8th order.

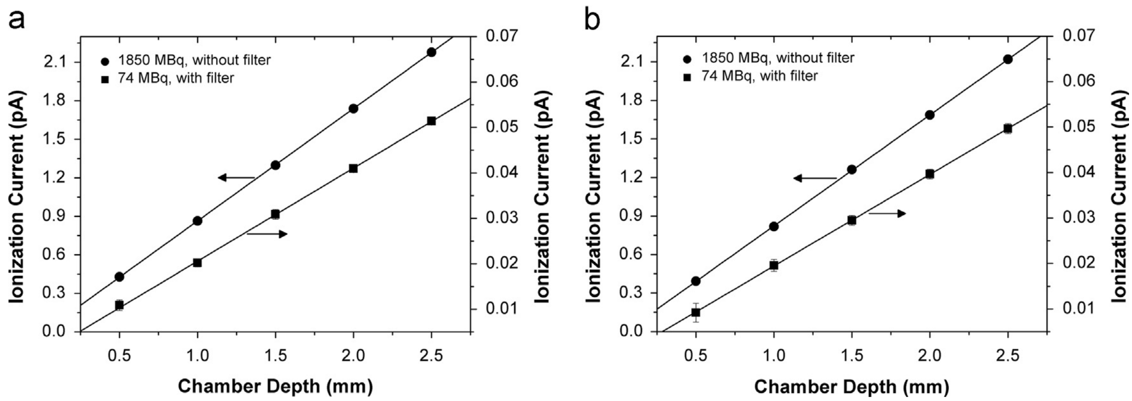

Fig. 4. Extrapolation curves obtained for the Bohm extrapolation chamber using the $^{90}Sr+^{90}Y$ sources of the BSS1 system, with two entrance windows: (a) aluminized Myla and (b) Hostaphan.

Table 4
Absorbed dose rates for the $^{90}Sr+^{90}Y$ sources at a depth of 0.07 mm, in air and in tissue, in comparison with the values provided in their calibration certificates.

Nominal activity (MBq)	Filter presence	Absorbed dose rate in air (10^{-6} Gy/s)		Difference (%)	Absorbed dose rate in tissue (10^{-6} Gy/s)		Difference (%)
		Certificate	This work		Certificate	This work	
74	Yes	0.82 ± 0.02	0.80 ± 0.02	−2.00	0.91 ± 0.03	0.89 ± 0.07	−1.91
1850	No	34.7 ± 0.65	35.6 ± 0.97	−2.72	39.6 ± 2.92	38.5 ± 1.23	−2.72

According to the ISO 6980-2 (ISO, 2004), the product k is composed by the combination of the correction factors: (1) k_{abs} – variations in the attenuation of beta particles between the source and the collecting volume due to variations from reference conditions, (2) k_{ac} – attenuation of beta particles in the collecting volume, (3) k_{ad} – variations of the air density in the collecting volume from reference conditions, (4) k_{de} – radioactive decay of the beta-particle source, (5) k_{di} – axial non-uniformity of the beta-particle field, (6) k_{pe} – perturbation of the beta-particle flux density by the side walls of the extrapolation chamber, and (7) k_{sat} – ionization losses due to ionic recombination. The product k' represents the combination among the factors: (1) k_{ba} – difference in backscatter between tissue and the material of the collecting volume; (2) k_{ba} – effect of bremsstrahlung from the beta-particle source; (3) k_{el} – electrostatic attraction of the entrance window duw to the collecting volume; (4) k_{hu} – effect of the humidity of the air in the collecting volume on the average energy required to produce an ion pair; (5) k_{in} – interface effects between the air in the collecting volume and the adjacent entrance window and the collecting volume; and (6) k_{ra} – radial non-uniformity of the beam (ISO, 2004).

The correction factors k_{abs}, k_{ad}, k_{di}, k_{pe}, k_{sat}, k_{ba}, and k_{br}, and their uncertainties were calculated in this work, experimentally or using equations and values provided in the ISO 6980-2 (ISO, 2004). The correction factor k_{de} was considered unity, because there was no need to calculate a factor to correct the measurements; the initial absorbed dose rate was determined by the decay equation. The correction factors k_{el}, k_{hu}, and k_{in}, were considered as unity in this work, according to recommendations of ISO 6980-2 (ISO, 2004). For the correction factors k_{ac}, and k_{ra}, the values showed in the ISO 6980-2 (ISO, 2004) were adopted in this work.

The extrapolation curves for the two $^{90}Sr+^{90}Y$ sources were obtained following the conditions specified at the calibration certificates in relation to the use of beam flattening filter: sources of 74 MBq, with filter, and 1850 MBq, without filter. Fig. 4a shows the extrapolation curves obtained for the chamber with aluminized Mylar entrance window, already described and demonstrated in a previous work (Antonio et al., 2013).

In this work, new extrapolation curves were obtained (Fig. 4b) after the change of the entrance window for the Hostaphan material. For the 74 MBq source, the ionization current varied from (0.0092 ± 0.0021) pA to (0.0496 ± 0.0011) pA (maximum variation coefficient of 6.6% in the chamber depth of 0.5 mm); for the 1850 MBq source, the ionization current varied from (0.3938 ± 0.0055) pA to (2.1205 ± 0.0077) pA (maximum variation coefficient of 1.7% in the chamber depth of 0.5 mm). The extrapolation curves obtained with this new entrance window presented a correlation coefficient, R^2, higher than 0.9999. The measurements resulted with very low uncertainties, not visible in the graphics.

From the extrapolation curves, the absorbed dose rates in air and in tissue, at a depth of 0.07 mm, were obtained. Table 4 provides the values obtained.

The average difference (in air and in tissue) between the absorbed dose rates obtained for the Bohm extrapolation chamber with aluminized Mylar entrance window and those of the certificates were −1.57% for the 74 MBq source, and −4.11% for the 1850 MBq (Antonio et al., 2013). Comparing these results with those obtained in this study (Hostaphan entrance window), it can be concluded that the difference for the 74 MBq increased for the second entrance window, but the difference for the 1850 MBq decreased considerably. In the case of the first source (74 MBq), this increase presents no problem, because the activity of this source is already very low, difficulting the measurements (a very high interval time is necessary to collect the electric charges). In the case of the second source (1850 MBq), the difference decreased when the second entrance window (Hostaphan) was used, and this fact demonstrates the good performance and behavior of this chamber for the calibration of beta radiation sources.

3. Conclusions

The behavior of the Bohm extrapolation chamber response with an original entrance window of Hostaphan was studied through several characterization tests with the chamber exposed to the two $^{90}Sr+^{90}Y$ sources of the BSS1 system: saturation curve (polarity effect, ion collection efficiency, ion recombination), real null depth, leakage current, stability of response, variation of the chamber response in relation to the source–detector distance, and determination of absorbed dose rates.

All performed characterization tests presented results within the limits provided by the international recommendations or were compatible with results of other publications.

As the Bohm extrapolation chamber is being established at LCI as a primary standard system for calibration and dosimetry of beta radiation detectors and sources, the results obtained in this work are important and of great value for the laboratory.

Acknowledgments

The authors are very grateful to Mr. Graham Bass, from National Physical Laboratory (NPL), for all support about the extrapolation chamber and to the Brazilian agencies FAPESP (Process: 2009/52724-7), CNPq, CAPES and MCT (Project INCT for Radiation Metrology in Medicine), for partial financial support.

References

Antonio, P.L., Xavier, M., Caldas, L.V.E., 2012. Preliminary tests of a commercial extrapolation chamber for utilization as a beta radiation standard system. In: Proceedings of the Proteção 2012 – Third Congress on Radioprotection of the Countries and Communities of Portuguese Language, 20–23 November, Lisbon, Portugal.

Antonio, P.L., Xavier, M., Caldas, L.V.E., 2013. Determination of transmission factors in tissue using a standard extrapolation chamber. Radiat. Phys. Chem. 95, 38–43.

Behrens, R., Fedina, S., Oborin, A., 2011. Direct comparison of extrapolation chamber measurements of the absorbed dose rate for beta radiation between PTB (Germany) and VNIIM (Russia). Metrologia 48, 317–323.

Bohm, J., 1986a. Review of extrapolation chamber measurements of beta rays and low energy X rays. Radiat. Prot. Dosim. 14 (2), 193–198.

Bohm, J., 1986b. The National Primary Standard of the PTB for realizing the unit of the absorbed dose rate to tissue for beta radiation. Physikalisch-Technische Bundesanstalt, PTB-Dos-13: Braunschweig, Germany.

Caldas, L.V.E., 1980. Some Methods of Beta Radiation Dosimetry and Calibration (Ph.D. thesis). Instituto de Física, Universidade de São Paulo, São Paulo (in Portuguese).

Caldas, L.V.E., 1986. Performance characteristics of an extrapolation chamber for beta radiation detection. Appl. Radiat. Isot. 37 (9), 988–990.

Dias, S.K., Caldas, L.V.E., 1999. Characteristics of an extrapolation chamber for β-ray protection level measurements. J. Appl. Phys. 86 (1), 671–673.

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

ISO, International Organization for Standardization, 2004. Nuclear energy – Reference Beta-Particle Radiation – Part 2: Calibration Fundamentals Related to Basic Quantities Characterizing the Radiation Fields. Geneva, ISO 6980-2:2004.

NIST, National Institute of Standards and Technology, 2010. Ionizing Radiation Division: Protection-level Beta Particle Source & Instrument Calibrations. IRD-P-10: Washington, USA.

PTW, Physikalisch-Technische Werkstätten, 2002. Instruction Manual – Extrapolation Chamber according to Bohm, Type 23392.

Silva, E.A.B., Caldas, L.V.E., 2012. Application of extrapolation chambers in low-energy X-rays as reference systems. Appl. Radiat. Isot. 70, 1411–1416.