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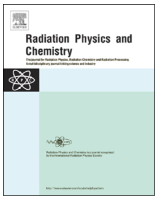

# Determination of transmission factors in tissue using a standard extrapolation chamber

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## HIGHLIGHTS

- Böhm extrapolation chamber was tested to be used as a primary standard system.
- The chamber was exposed to the three $^{90}$Sr+$^{90}$Y secondary standard sources.
- Transmission factors were obtained.
- Absorbed dose rates were determined using the sources at certificate conditions.
- The results showed the good performance of the extrapolation chamber.

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## ABSTRACT

A commercial ionization chamber, Böhm extrapolation chamber, PTW, model 23392, recommended for measurements in low energy X-rays and beta radiation fields, was tested in three different $^{90}$Sr+$^{90}$Y beams to verify its performance as a primary standard system for the calibration and dosimetry of beta radiation sources and detectors. Characterization tests were performed, as determination of the chamber null depth using two methods (the results presented a difference of only 0.9%), transmission factors in tissue, in comparison with those of the certificate (the maximum difference was 2.1%), and absorbed dose rates of the $^{90}$Sr+$^{90}$Y sources, in comparison with the values provided by the calibration certificates (the maximum difference was 4.90%). The results obtained confirmed that this extrapolation chamber presents a very good behavior in beta radiation fields as a primary standard system.

## 1. Introduction

Beta radiation is usually specified in terms of absorbed dose rates, and the adequate and designed instrument for this purpose is the extrapolation chamber (Böhm, 1986; ISO, 2004).

Böhm (1986) tested an extrapolation chamber, and established it as the German primary standard at the Physikalisch-Technische Bundesanstalt (PTB), Germany, for the determination of the absorbed dose rate in tissue. Afterward, this chamber was manufactured and commercialized by Physikalish-Technische Werkstätten (PTW), and named Böhm extrapolation chamber. It was manufactured to be used as a primary or secondary standard system for calibration of beta radiation detectors and sources (PTW, 2002).

In beta radiation dosimetry, and in the calibration of beta radiation sources and detectors, two of the characteristics to be determined are the transmission factors in tissue, and absorbed dose rates in air (Caldas, 1986), or in tissue (water) (ISO, 2004).

The Calibration Laboratory (LCI) at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) received a Böhm extrapolation chamber to establish as a primary standard system for calibration of beta radiation sources and detectors.

This work has the purpose to determine transmission factors in tissue using a Böhm extrapolation chamber, in $^{90}$Sr+$^{90}$Y beams. Furthermore, absorbed dose rates in air were also determined using three $^{90}$Sr+$^{90}$Y sources, in comparison with those provided in the calibration certificates. With the obtaining of the transmission factors and the absorbed dose rates, it was possible to verify the possibility of application of the Böhm extrapolation chamber as a primary standard system to the dosimetry and calibration of beta radiation detectors and sources. As there is no primary standard laboratory for beta radiation in Brazil yet, these results present a great importance to the LCI (IPEN), since a primary standardization using this extrapolation chamber was established in this work.

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**Table 1**
Main characteristics of the Böhm extrapolation chamber used in this work (PTW, 2002).

| Extrapolation chamber | Characteristics | |
|---|---|---|
| Chamber body | Aluminum | |
| Entrance window | Material | Mylar |
| | Density superficial (mg/cm$^2$) | 0.71 |
| | Diameter (mm) | 60.5 |
| Collecting electrode | Material | Polymethyl methacrylate (PMMA) graphited |
| | Diameter (mm) | 30 |
| | Area (cm$^2$) | 7.16 |
| Insulation ring | Thickness (mm) | 0.2 |
| | Width (mm) | 0.2 |
| Micrometer screw* | Chamber depth interval (mm) | 0.5–10.5 |

* Distance variation between the entrance window and the collecting electrode (from 0.5 mm to 10.5 mm, corresponding to a variation in the air volume from 0.353 cm$^3$ to 7.422 cm$^3$).

## 2. Experimental

The Böhm extrapolation chamber, PTW, model 23392, was the instrument of study in this work. The main physical characteristics of this chamber are presented in Table 1.

During the data collection, the measurements were always taken in terms of electric charge, using an electrometer from Keithley Instruments Inc., model 6517B. Correction factors were applied to the final ionization current values in order to correct them for the standard environmental conditions of temperature and pressure. In all measurements, the electric field applied to the chamber was always kept constant at 10 V/mm (Caldas, 1986; ISO, 2004).

The LCI has two beta secondary standard systems: BSS1, Buchler GmbH, & Co., Germany, and BSS2, Isotrak, Germany. During the determination of the chamber null depth, the transmission factors and absorbed dose rates, all three $^{90}$Sr+$^{90}$Y sources of these systems were used. In Table 2 the characteristics of the $^{90}$Sr+$^{90}$Y sources can be observed (PTW, 1981a, 1981b, 2005), emphasizing that the absorbed dose rates of the calibration certificates of the BSS1 sources are given at null tissue depth ($\dot{D}_t$ ($d=0$)), and the BSS2 sources are provided in 0.07 mm of tissue depth ($\dot{D}_t$ ($d=0.07$)).

### 2.1. Chamber null depth

The chamber null depth, $d_0$, is an important factor to be determined, because it represents the minimum distance between the electrodes. Furthermore, this value is necessary for correction of the chamber depth.

The determination of the chamber null depth was obtained using a method described by Caldas (1986), exposing the chamber to the $^{90}$Sr+$^{90}$Y source (1850 MBq), at the calibration distance of 11 cm (source-detector). The chamber depth varied in the interval of 0.5–3.0 mm, in steps of 0.5 mm; therefore, the voltage applied to the extrapolation chamber varied from 5 V to 30 V, in both polarities.

### 2.2. Transmission factors

In relation to the determination of the transmission factors, the measurements were taken using the $^{90}$Sr+$^{90}$Y source (1850 MBq), and with the chamber at the calibration source-detector distance of 30 cm, and chamber depth fixed at 1.0 mm (voltage applied of ± 10 V). Eight absorbers of Hostaphan were used, RN 8–RN 300 (corresponding of 8–300 μm), and two absorbers of Plexiglas of 1.0 mm and 2.0 mm. The measurements were also taken without any absorber. The absorbers were positioned as near as possible of the chamber entrance window.

**Table 2**
Characteristics of the $^{90}$Sr+$^{90}$Y beta radiation sources used in this work, according to their calibration certificates.

| Beta system | Nominal activity (MBq) | Filter presence | Absorbed dose rate (μGy/s) | Calibration date |
|---|---|---|---|---|
| BSS1 | 74 | Yes | 1.70 ± 0.02 | Jan 12, 1981 |
| | 1850 | No | 7.60 ± 0.71 | Feb 4, 1981 |
| BSS2 | 460 | Yes | 10.6 ± 0.14 | Dec 8, 2004 |
| | 460 | No | 16.5 ± 0.22 | Jan 12, 2005 |

To determine the transmission factor in tissue, it is necessary to use an equivalence relating the absorber materials with tissue. The equivalence between Hostaphan and tissue is 10.8 mg/cm$^2$ Hostaphan to10.0 mg/cm$^2$ tissue (Owen, 1973); the relation to Plexiglas and tissue is 10.4 mg/cm$^2$ Plexiglas to 10.0 mg/cm$^2$ tissue (Caldas, 1980). Using these relations, the superficial density to Hostaphan in tissue varied between 0.660 mg/cm$^2$ (without absorber) and 39.55 mg/cm$^2$ (RN 300). In the case of the Plexiglas material, the superficial density in tissue was 114.12 mg/cm$^2$ for only 1.0 mm absorber, and 227.58 mg/cm$^2$ for 2.0 mm. It is also necessary to convert the superficial density of the entrance window material, Mylar, in tissue; the following relation was used: 10.8 mg/cm$^2$ Hostaphan to 10.0 mg/cm$^2$ tissue (Pinto, 2010).

For the determination of the transmission factors, $T'$, it is necessary to relate the ionization currents, $I(d_0)$, and the superficial densities in tissue; from this relation, the ionization current extrapolated to a null superficial density, $I(0)$, can be determined, and the transmission factors can be obtained by means of Eq. (1) (Caldas, 1980)

$$T' = I(d_0)/I(0) \quad (1)$$

However, to these transmission factors a correction factor, $k_d$, has to be incorporated, relating the source-detector distance (30 cm) $a$, and the absorber thickness $a_1$, due to the use of different absorbers. This correction factor can be calculated by Eq. (2) (Caldas, 1980)

$$k_d = (a - a_1)^2/a^2 \quad (2)$$

Thus, the final transmission factors, $T$, can be obtained by Eq. (3) (Caldas, 1980)

$$T = T' k_d \quad (3)$$

### 2.3. Absorbed dose rates

The absorbed dose rates of the three $^{90}$Sr+$^{90}$Y were determined, taking into account the angular coefficient, $B$, from the extrapolation curves, for the three $^{90}$Sr+$^{90}$Y sources of the BSS1 and BSS2 systems, at a source-detector distance of 30 cm; the chamber depth was varied from 0.5 mm to 2.5 mm (in steps of 0.5 mm), and using the polarization voltage from ±5 V to ±25 V. Using the $B$ values, the absorbed dose rates, $\dot{D}_a$, (in air of the chamber volume), were determined by (Caldas, 1980)

$$\dot{D}_a = \frac{\overline{W}}{e}\frac{k}{a_{ef}\rho}B \tag{4}$$

where $\overline{W}/e$ is the quotient of the average energy required to produce an ion pair in air in reference conditions and the elementary charge [(33.75 ± 0.15) J/C] (Böhm, 1986) for the BSS1 sources, and [(33.83 ± 0.06) J/C] (ISO, 2004) to BSS2 sources; $k$ is the product of correction factors to Bremsstrahlung, source decay, humidity, insulating material thickness (between collecting electrode and guard ring), scattering by material between source and detector and chamber wall, lack of saturation due to initial and general recombination, density of air, and inhomogeneity of the primary standard radiation field in the collecting volume; $a_{ef}$ is the effective area of the collecting electrode, obtained from the extrapolation chamber manually, taking into account the diameter of the collecting electrode and the thickness of the guard ring (7.16 cm$^2$) (PTW, 2002); $\rho$ is the density of air in reference conditions of pressure, temperature and humidity [(1.1995 ± 0.04) kg/m$^3$] (Böhm, 1986) for the BSS1 sources, and [(1.197 ± 0.000) kg/m$^3$] (ISO, 2004) for the BSS2 sources; and $B$ is the angular coefficient.

Due to the fact that this work presents preliminary results of essential studies with an extrapolation chamber, it was not possible to calculate all correction factors to be applied to the determination of the absorbed dose rates. The only correction factors used in this work were $k_{inh}$=inhomogeneity of the primary standard radiation field in the collecting volume = 1.0014 (calculated for the BSS1 and BSS2 sources); $k_R$=correction factor for the backscattering between the tissue and chamber material = 1.000 to the BSS1 sources (Böhm, 1986), and 1.010 to the BSS2 sources (Caldas, 1980); $k_F$=correction factor due to the thickness and material of the entrance window foil = 1.000 to the BSS1 and BSS2 sources (Caldas, 1980). The following correction factors were considered unitary: $k_{gap}$=insulating material thickness (between collection electrode and guard ring) = 1.000 (Caldas, 1980); and $k_{esp}$=scattering by the material between source and detector and chamber wall = 1.000 (Caldas, 1980). The other correction factors that are demonstrated in the literature were not calculated yet and, for this reason, were not taken into account in the calculations of this work.

After obtaining $\dot{D}_a$, the absorbed dose rates in tissue ($\dot{D}_t$) were determined by

$$\dot{D}_t = \dot{D}_a s_{t,a} k_R k_F \tag{5}$$

where $s_{t,a}$ is the ratio of the average mass stopping power of tissue to air [(1.111 ± 0.011) for the BSS1 sources, and (1.110 ± 0.005) for the BSS2 source (PTB, 1981a, 1981b, 2005); $k_R$ is the correction factor for the backscattering between the tissue and chamber material (1.010); and $k_F$ is the correction factor due to the thickness and material of the entrance window foil (1.000) (Caldas, 1980).

With the absorbed dose rates $\dot{D}_t$ determined, it was possible to obtain the absorbed dose rates at the external surface of the chamber, $\dot{D}_t(0)$. It was necessary to calculate the transmission factor of the radiation in the entrance window material, Mylar. This factor was calculated for each source, using the respective calibration certificates. After the determination of the transmission factors, $\dot{D}_t(0)$ was obtained. The ratio between $\dot{D}_t(0)$ and $s_{t,a}$ provides the absorbed dose rates in air, $\dot{D}_c$, for each source, which can be compared with the values provided in the calibration certificates.

In the case of the two $^{90}$Sr+$^{90}$Y sources of the BSS1 system, the experimental results and those given in the certificates are for a null depth; then they were converted to 0.07 mm depth. They were calculated correcting them to the transmission factors presented in the calibration certificates for both sources. This procedure was adopted to the absorbed dose rates in air and in tissue.

For the $^{90}$Sr+$^{90}$Y source of the BSS2 system (in two conditions: with and without filter), only the experimental results were corrected to the transmission factors of their calibration certificates, because only these results were obtained at null depth. In relation to the values of absorbed dose rates presented in their calibration certificates, they were already provided at a 0.07 mm depth.

## 3. Results

The determination of the transmission factors and absorbed dose rates in air and in tissue are the main characteristics of a primary standard for calibration of beta radiation sources, and they were studied in this work. Initially, the chamber null depth was obtained for correction of the measurements in relation to the real chamber depth.

### 3.1. Chamber null depth

The result for the chamber null depth obtained can be observed in Fig. 1. The $d_0$ value obtained was (0.1250 ± 0.0002) mm, and in all these measurements, the variation coefficient was lower than 0.6%.

Although the extrapolation curves were obtained at a source-detector distance of 30 cm (as described at the item 2.3), the chamber null depth was determined at 11 cm distance. Due to the fact that for the chamber null depth study measurements are needed at various chamber depths, and of small chamber depths (generating low collected charges), these measurements were taken at the source-detector distance of 11 cm. At this distance, the collected charge was higher, presenting enough good values for the ionization currents and associated uncertainties. The extrapolation curves were obtained at a distance of 30 cm to

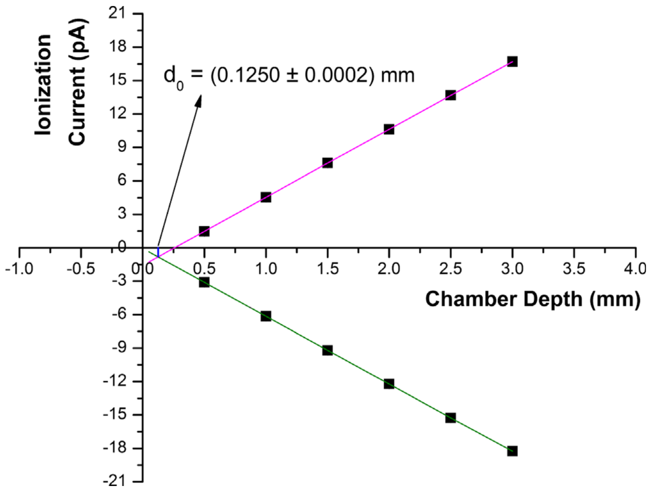

**Fig. 1.** Determination of the chamber null depth taking measurements in both polarities.

standardize the determination of these curves at a calibration distance that is request for all three $^{90}$Sr+$^{90}$Y sources, in the four conditions studied in this work. As the source-detector distance of 11 cm is not common for the three sources, the distance of 30 cm was used. Then, as the absorbed dose rates depend on the transmission factors, as will be explained at the item 3.3, the transmission factors were also determined at this distance (30 cm).

### 3.2. Transmission factors

The transmission factors are necessary to determine the absorbed dose rate in a thickness of tissue. In the case of extrapolation chamber, this is possible when the ionization current is obtained for different thickness absorbers, and it is extrapolated to the null thickness absorber (that represents the skin surface).

The transmission factors, $T,'$ were obtained by means of Eq. (1) after the determination of the ionization current, $I(0)$, which is shown in Fig. 2a. From the results of $T'$, the final transmission factors, $T$ could be obtained applying the first values and the $k_d$ values in Eq. (3). The final curve obtained in this study can be seen in Fig. 2b.

From Fig. 2b, the transmission factors for the same equivalent tissue superficial densities for the $^{90}$Sr+$^{90}$Y source presented in its calibration certificate could be determined. Table 3 shows the transmission factors obtained, in comparison with those of the calibration certificate (PTB, 1981b).

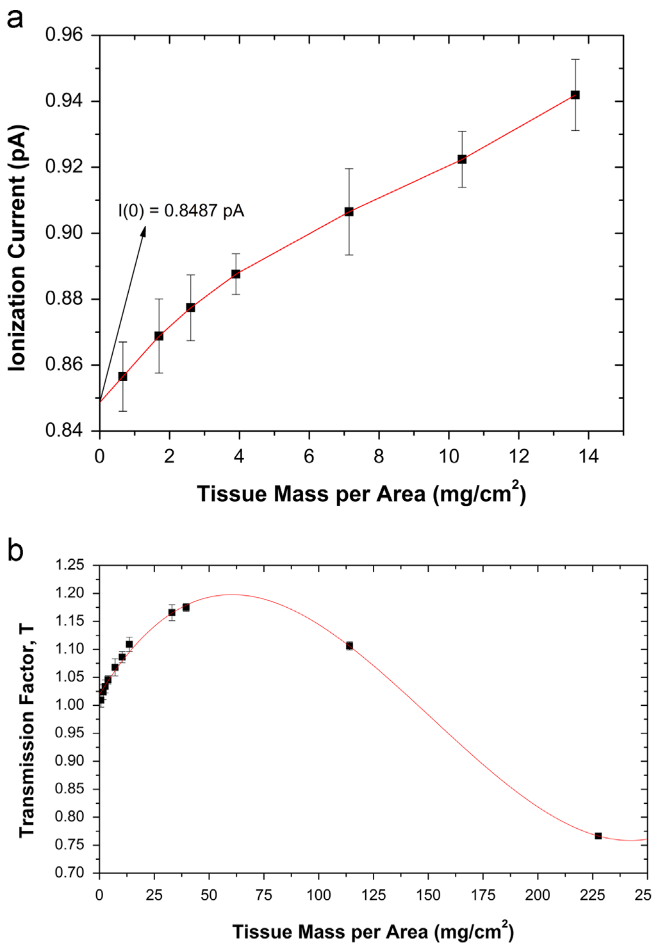

**Fig. 2.** Determination of transmission factors in tissue, with the Böhm extrapolation chamber and the $^{90}$Sr+$^{90}$Y source (1850 MBq): (a) obtaining the ionization current I(0), and (b) final curve of transmission factors.

**Table 3**
Transmission factors with the Böhm extrapolation chamber and the $^{90}$Sr+$^{90}$Y source (1850 MBq).

| Tissue | | Transmission factors, $T$ | | Difference (%) |
|---|---|---|---|---|
| Thickness (mm) | Superficial density (mg/cm$^2$) | Source certificate | This work | |
| 0 | 0 | 1.00 ± 0.010 | 1.00 ± 0.04 | 0.00 |
| 0.02 | 2 | 1.03 ± 0.011 | 1.03 ± 0.04 | 0.19 |
| 0.04 | 4 | 1.05 ± 0.011 | 1.04 ± 0.04 | 0.29 |
| 0.05 | 5 | 1.05 ± 0.011 | 1.05 ± 0.04 | 0.38 |
| 0.07 | 7 | 1.07 ± 0.011 | 1.06 ± 0.04 | 0.66 |
| 0.10 | 10 | 1.08 ± 0.011 | 1.08 ± 0.04 | 0.65 |
| 0.20 | 20 | 1.12 ± 0.012 | 1.12 ± 0.04 | 0.00 |
| 0.50 | 50 | 1.17 ± 0.012 | 1.19 ± 0.05 | 1.62 |
| 1.00 | 100 | 1.12 ± 0.012 | 1.14 ± 0.05 | 2.14 |

The maximum variation coefficient obtained in all measurements was 2.4%. The transmission factors in tissue obtained using the Böhm extrapolation chamber showed agreement with the values provided at the source certificate (maximum difference of 2.14% for 1.00 mm tissue).

### 3.3. Absorbed dose rates

The beta sources were calibrated in terms of absorbed dose rate, related in specified conditions in their PTB calibration certificates.

The extrapolation curves obtained for the $^{90}$Sr+$^{90}$Y sources in specific conditions (74 MBq, with filter and 1850 MBq, without filter (BSS1), and 460 MBq, with and without filter (BBS2)) can be observed in Fig. 3a–d.

For the calculation of the absorbed dose rates, the transmission factors of the radiation in the entrance window material (by interpolation using the factors provided in the calibration certificates) were obtained. Table 4 shows these values. The absorbed dose rates in air, $\dot{D}_c$, were obtained following the methodology described in the Experimental section. Table 5 shows the experimental results obtained in this work: absorbed dose rates in air at null depth.

The international recommendations (Böhm, 1986; ISO, 2004) establish the conditions to determine absorbed dose rates at 0.07 mm depth in tissue; calculations of the results obtained at 0.07 mm depth were done, in order to follow the established standards.

The absorbed dose rates values obtained during this work can be observed in Table 6, including those from the calibration certificates, and also a comparison among the values.

In Table 6 can be observed that the maximum difference (4.90%) among the absorbed dose rates at the calibration certificates and the ones obtained in this work occurred for the $^{90}$Sr+$^{90}$Y source of the BSS2 system, without filter.

In 1988, the National Bureal of Standards (Pruitt et al., 1988), nowadays called National Institute of Standards and Technology (NIST), presented a report describing their services and calibration procedures. In this guide, they demonstrate the use of an extrapolation chamber to calibrate beta radiation sources of the BSS1 system. Absorbed dose rates at surface are presented as results of calibrations performed at NBS and PTB (German primary standard laboratory that calibrated the sources of LCI, of the present work). The differences obtained between the calibrations by the two laboratories of the $^{90}$Sr+$^{90}$Y sources of 74 MBq and 1850 MBq, in the same conditions of this work, were −1.55% and −1.36%, respectively.

NIST (2010) reported calibration results of $^{90}$Sr+$^{90}$Y sources of the BSS1 and BSS2 systems. In the case of $^{90}$Sr+$^{90}$Y sources of the

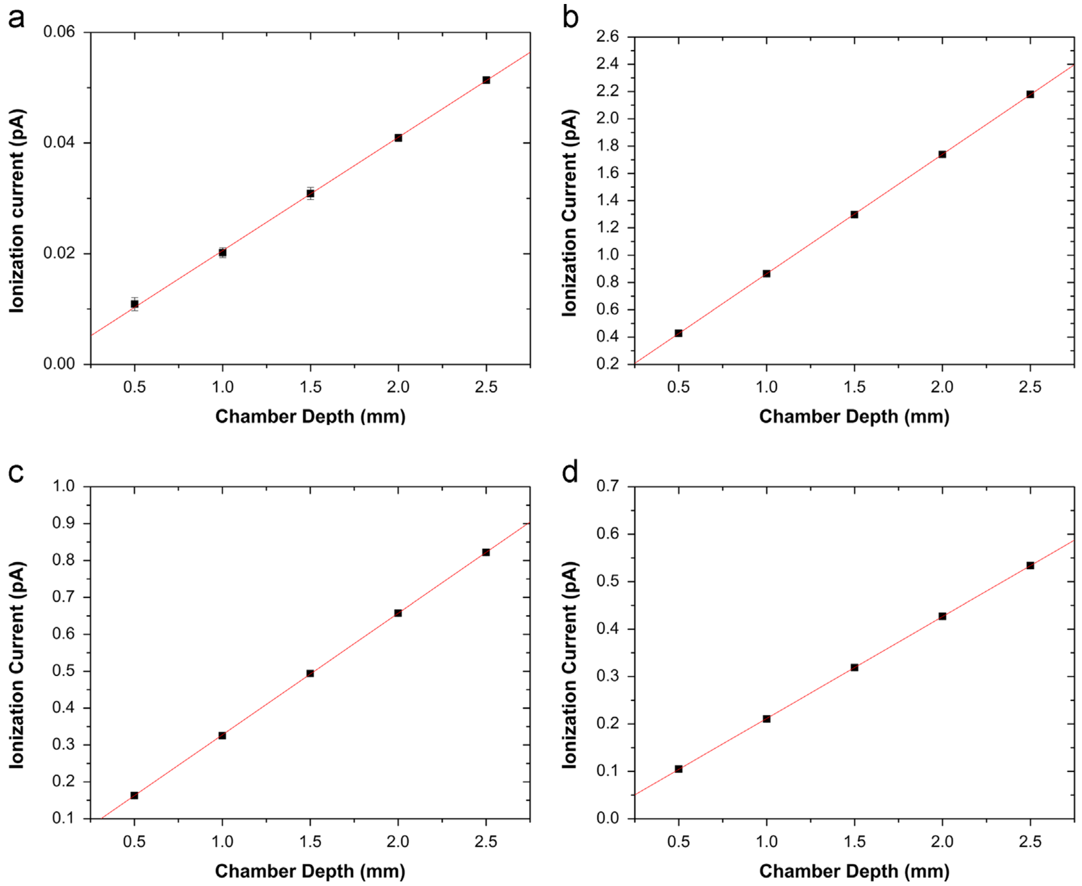

**Fig. 3.** Extrapolation curves for the Böhm extrapolation chamber using three $^{90}$Sr+$^{90}$Y sources but four irradiation conditions: (a) 74 MBq, with filter, (b) 1850 MBq, without filter, (c) 460 MBq, without filter, and (d) 460 MBq, with filter.

**Table 4**
Transmission factors obtained to the entrance window of the extrapolation chamber.

| Beta system | Nominal activity (MBq) | Filter presence | Transmission factor |
|---|---|---|---|
| BSS1 | 74 | Yes | 1.00 ± 0.02 |
| | 1850 | No | 1.01 ± 0.02 |
| BSS2 | 460 | Yes | 0.96 ± 0.01 |
| | 460 | No | 0.95 ± 0.01 |

**Table 5**
Absorbed dose rates in tissue, $\dot{D}_t(0)$, and in air, $\dot{D}_c$, at null depth, obtained for the $^{90}$Sr+$^{90}$Y sources, using the Böhm extrapolation chamber.

| Beta system | Field flattening filter | Nominal activity (MBq) | Absorbed dose rate in tissue ($10^{-6}$ Gy/s) | Absorbed dose rate in air ($10^{-6}$ Gy/s) |
|---|---|---|---|---|
| BSS1 | Yes | 74 | 0.90 ± 0.02 | 0.81 ± 0.02 |
| | No | 1850 | 38.3 ± 0.40 | 34.5 ± 0.50 |
| BSS2 | Yes | 460 | 9.87 ± 0.07 | 8.90 ± 0.08 |
| | No | 460 | 15.4 ± 0.09 | 13.9 ± 0.10 |

BSS1 system, the absorbed dose rates were determined at surface; in the case of the source of 74 MBq, the difference between NIST and PTB results was −1.55%, and for the source of 1850 MBq, the difference was −0.99%. For the $^{90}$Sr+$^{90}$Y sources of BSS2 system, the absorbed dose rates were obtained in water (0.07 mm depth) and the results of the calibration differences were −0.97% for the source with filter, and −1.84% for the source without filter.

Other results in terms of difference between calibrations of beta radiation sources can also be observed in a study performed by the laboratories of PTB and the D.I. Mendeleyev Institute for Metrology (VNIIM) (Behrens et al., 2011). For the $^{90}$Sr+$^{90}$Y source of BSS2 with filter, the difference between the absorbed dose rates obtained by the two laboratories (determined at the 0.07 mm depth in tissue) was 1.23%.

Considering that the differences of the absorbed dose rates at surface or in water are the same, it can be concluded that, taking into account the calibrations performed by NBS and NIST (Pruitt et al., 1988; NIST, 2010), the calibration of the $^{90}$Sr+$^{90}$Y source of 74 MBq in this work (difference of −1.60%) agrees completely with the calibration results of other two reports (difference of −1.55%). In relation to the $^{90}$Sr+$^{90}$Y source of 1850 MBq, the results obtained by LCI (−4.10%) are higher than those presented by Pruitt et al., 1988 and NIST (2010), of −1.36% and −0.99%, respectively.

In relation to the calibration of the sources of BSS2 system, the results presented by NIST (2010), of −0.97% and −1.84% to the $^{90}$Sr+$^{90}$Y sources of 460 MBq with and without filter, respectively, are lower than the results obtained in this work, of 2.64% and 4.90% for the same source and in the same conditions. Behrens et al. (2011) also obtained a lower result for the calibration of the $^{90}$Sr+$^{90}$Y source of 460 MBq with filter (1.23%).

The reasons for the lack of agreement in the calibrations of the $^{90}$Sr+$^{90}$Y sources of 1850 MBq and 460 MBq, with and without filter respectively, with the results presented by primary laboratories are still in evaluation.

## 4. Conclusions

The Böhm extrapolation chamber was tested in $^{90}$Sr+$^{90}$Y secondary standard beta beams with the objective to verify the

**Table 6**
Absorbed dose rates to the $^{90}$Sr+$^{90}$Y sources obtained in this work, in a depth of 0.07 mm, in the air and in tissue, in comparison with the values provided in their calibration certificates.

| Beta system | 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 | |
| BSS1 | 74 | Yes | $0.83 \pm 0.01$ | $0.84 \pm 0.02$ | −1.54 | $0.92 \pm 0.02$ | $0.94 \pm 0.03$ | −1.60 |
| | 1850 | No | $35.3 \pm 0.51$ | $36.9 \pm 0.66$ | −4.12 | $39.3 \pm 0.82$ | $41.00 \pm 0.60$ | −4.10 |
| BSS2 | 460 | Yes | $8.76 \pm 0.12$ | $8.54 \pm 0.11$ | 2.62 | $9.73 \pm 0.13$ | $9.48 \pm 0.12$ | 2.64 |
| | 460 | No | $13.7 \pm 0.18$ | $13.1 \pm 0.17$ | 4.82 | $15.2 \pm 0.20$ | $14.5 \pm 0.18$ | 4.90 |

possibility of its application as a primary standard system in the calibration and dosimetry of beta radiation sources and detectors.

The results obtained in this study, as the determination of the chamber null depth (using two methods, with similar results), the transmission factors, which showed agreement with those provided in the calibration certificates, and the absorbed dose rates (with a maximum difference of 4.90% in relation to the certificates) demonstrate the good performance of the extrapolation chamber as a primary standard system. This conclusion is important to the LCI, taking into account that the results are considered preliminary, and new experiments are still in progress.

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## References

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.

Böhm, J., 1986. The National Primary Standard of the PTB for Realizing the Unit of the Absorbed Dose Rate to Tissue for Beta Radiation. PTB-Dos-13. Physikalisch-Technische Bundesanstalt, Braunschwieg, 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. J. Appl. Radiat. Isot. 37 (9), 988–990.

ISO, International Organization for Standardization, 2004. Nuclear energy—Reference beta-particle radiation—Part 2: Calibration fundamentals related to basic quantities characterizing the radiation fields. Geneve, ISO/FDIS 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.

Owen, B., 1973. Factors for converting beta-ray dose rates measured in air to dose rates in tissue. Phys. Med. Biol. 18, 355–368.

Pinto, T.N.C.O., 2010. Dosimetric Methodology for Extremities of Individuals Occupationally Exposed to Beta Radiation Using the Optically Stimulated Luminescence Technique (Ph.D. thesis). São Paulo, Instituto de Pesquisas Energéticas e Nucleares, Universidade de São Paulo (in Portuguese).

Pruitt, J.S., Soares, C.G., Ehrlich, M., 1988. NBS Measurement Services: Calibration of Beta-Particle Radiation Instrumentation and Sources. National Bureau of Standard (U.S.), Special Publication 250-21. U.S. Government Printing Office, Washington, USA.

PTB, Physikalisch-Technische Bundesanstalt, 1981a. Calibration certificate of $^{90}$Sr+$^{90}$ source. PTB-6.61/25, Braunschweig.

PTB, Physikalisch-Technische Bundesanstalt, 1981b. Calibration certificate of $^{90}$Sr+$^{90}$ source. PTB-6.61/37, Braunschweig.

PTB, Physikalisch-Technische Bundesanstalt, 2005. Calibration certificate of $^{90}$Sr+$^{90}$ source. PTB-6.34-BSS204, Braunschweig.

PTW, Physikalisch-Technische Werkstätten, 2002. Instruction Manual—Extrapolation chamber according to Böhm, Type 23392.