doi.org/10.15392/2319-0612.2026.2992
Braz. J. Radiat. Sci., Rio de Janeiro
2026, 14(1) | 01-15 | e2992
Editor: Prof. Dr. Bernardo Maranhão Dantas
Editor: Prof. Dr. Alfredo Lopes Ferreira Filho
Editora: Dra. Ana Cristina Murta Dovales
Submitted: 2025-08-02
Accepted: 2025-11-20

Original Article

Electronic Brachytherapy: A Calibration Protocol in Terms of Absorbed Dose to Water"

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Abstract: New radiotherapy techniques have been innovative in recent decades with the aim of maximizing the dose to tumor tissue and reducing the dose to healthy tissue. One of the modalities that has gained prominence, using low-energy beams, is intraoperative radiotherapy (IORT), as it is a method based on high radiation doses (10–20 Gy) administered to the tumor bed immediately after surgical excision. IORT can be achieved through treatment with low-energy X-ray beams with some devices available on the market. However, such devices provide little dosimetric information and lack a calibration protocol. According to the recently updated recommendations of the TRS 398 standard (2024), for the use of low-energy beams, the ideal is to use a parallel plate ionization chamber calibrated in terms of absorbed dose in water. Based on TRS 398, this work established a calibration protocol for parallel plate dosimeters in terms of absorbed dose in water at the Center for Ionizing Radiation Metrology (CEMRI) of the Institute for Energy and Nuclear Research (IPEN).

Keywords: intraoperative radiotherapy, radiation metrology, dosimeter calibration, absorbed dose in water.

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Braquiterapia eletronica: protocolo de calibração em termos da dose absorvida na água

Resumo: Novas técnicas de radioterapia têm sido inovadoras nas últimas décadas com o objetivo de maximizar a dose no tecido tumoral e reduzir a dose no tecido sádio. Uma das modalidades que tem ganhado destaque, utilizando de feixes de baixa energia, é a radioterapia intraoperatória (IORT), por ser um método baseado em alta dose de radiação (10–20 Gy) administrada no leito tumoral imediatamente após a excisão cirúrgica. A IORT pode ser obtida por meio de tratamento com feixes de raios X de baixa energia com alguns aparelhos disponíveis no mercado. No entanto, tais aparelhos fornecem pouca informação dosimétrica e carecem de um protocolo de calibração. De acordo com as recomendações recentemente atualizadas da norma TRS 398 (2024), para o uso de feixes de baixa energia, o ideal é utilizar uma câmara de ionização de placas paralelas calibrada em termos de dose absorvida em água. Com base na TRS 398, este trabalho estabeleceu um protocolo de calibração para dosímetros de placas paralelas em termos de dose absorvida em água no Centro de Metrologia de Radiações Ionizantes (CEMRI) do Instituto de Pesquisas Energéticas e Nucleares (IPEN).

Palavras-chave: radioterapia intraoperatória, metrologia das radiações, calibração de dosímetros, dose absorvida na água.

1. INTRODUCTION

The global incidence of cancer, according to data from the International Agency for Research on Cancer, reached approximately 19.3 million new cases and 10 million deaths in 2020, with estimates indicating that one in five people in the world will develop neoplasia. In this context, radiotherapy emerges as a low-cost and highly effective therapeutic modality, provided that appropriate diagnostic and therapeutic equipment is available and operated by qualified multidisciplinary teams [1].

The last decades have witnessed the implementation of new radiotherapy techniques that aim to optimize the dose to tumor tissue while simultaneously minimizing exposure to healthy tissue. Among the most promising approaches, Intraoperative Radiotherapy (IORT) stands out. This technique is based on the administration of a high dose of radiation directly to the tumor bed, immediately after surgical excision, which can significantly reduce the total treatment time and can be classified as electronic brachytherapy [2, 3, 4]. IORT is often performed with miniature accelerators, such as the ZEISS INTRABEAM system (Carl Zeiss Meditec AG, Jena, Germany), which uses low energy X-rays of approximately 35 keV (from 30 to 50 kV) [2, 3, 4].

However, the use of these systems, as well as others used in radiotherapy, requires rigorous calibration and dosimetry, aspects that are critical to ensuring patient safety and therapeutic efficacy. Recent guidelines from the INTERNATIONAL ATOMIC ENERGY AGENCY, specified in Technical Reports Series no. 398 (TRS 398), recommend, for low-energy X-rays, the use of parallel plate ionization chambers calibrated in terms of absorbed dose in water in reference radiation beams. [5]. However, TRS 492, which specifically deals with brachytherapy dosimetry methods, highlights in its Appendix II that Absorbed dose to water primary standards for electronic brachytherapy sources are still being developed in many european countries and at the moment NIST at the USA is the only national metrology institute that developed a primary calibration standard and that is offering a calibration service for at least one single source type of the Xoft Axxent System [4].

Other types of ionization chambers, for instance thin-window parallel-plate ionization chambers with suitable holders which can be traceably calibrated against primary standards, might be more appropriate for performing measurements close to these devices, except that the use of a parallel-plate chamber does not account for the 360-degree aspect of the source [4].

In this scenario, radiation metrology plays a fundamental role, ensuring the traceability and metrological consistency of X-ray beams. Regulatory and standardization bodies require specialized laboratories to maintain the standardization of reference beams, allowing dosimeters to be calibrated and compared under identical irradiation conditions in different institutions.

In view of the above, the present work aimed to establish a specific procedure for the calibration of parallel plate ionization chambers in terms of absorbed dose in water at the Center for Ionizing Radiation Metrology (CEMRI) of the Institute for Energy and Nuclear Research (IPEN). To validate the procedure, three parallel plate ionization chambers were calibrated. As part of the work, a verification of the stability of the qualities of low-energy radiotherapy X-rays, in the range of 10 to 50 kV, established by CEMRI, was carried out, in accordance with the recommendations of the Bureau International des Poids et Mesures (BIPM) [6].

2. MATERIALS AND METHODS

According to the recommendations of TRS 398, for the use of low energy beams, the ideal is to use a parallel plate ionization chamber that contains an entrance window composed of a thin membrane with a thickness in the range of 2 to 3 mg/cm^2 [5].

Following these recommendations, three Physikalisch-Technische Werkstätten (PTW) flat parallel plate ionization chambers, model 23344, serial numbers 0708 and 0709, volume of

$0.2\ \text{cm}^3$, and one model 23342, serial number 0706, volume of $0.02\ \text{cm}^3$, were used. In order to facilitate reading, they will be referred to in the text as D1, D2 and D3, respectively.

Figure 1: PTW brand parallel plate ionization chambers, model 23344.

The X-ray beams were produced by a Pantak Seifert industrial equipment, model ISOVOLT HS 160 with constant potential, consisting of a Comet X-ray tube, model MRX 160/22, installed at CEMRI. The equipment operates in the voltage range of 5 to 160 kV, with current ranging from 0.1 to 45 mA.

The measurements were corrected for the reference environmental conditions (20 °C and 101.3 kPa) using Equation 1. Measurements were made within the relative humidity range of 40% to 75% and, for possible corrections, barometers, thermometers and chronometers calibrated by the Rede Brasileira de Calibração (RBC) were used.

$$\mathrm{f}_{T,P} = \left(\frac{T + 273{,}15}{293{,}15}\right) \times \left(\frac{101{,}325}{P}\right) \qquad \text{Eq. 1}$$

Where: T is the temperature, in °C, at the time of measurement and P is the atmospheric pressure, in kPa, at the time of measurement.

2.1. Evaluation of the Stability of Reference Qualities for Low-Energy X-ray Beams in Radiotherapy

To evaluate the stability of the X-ray qualities of low-energy radiotherapy, range of 10 to 50 kV, in addition to the BIPM recommendations, the procedures carried out by Bessa, 2007, were followed, measuring the 1st Half Value Layer (HVL) [6, 7]. According to TRS 398, traditionally the 1st HVL is used as the primary beam quality specifier to describe the change in ionization chamber response with beam energy and to select beam quality correction factors. [5].

Aluminum absorbing filters with purity greater than 99.99% from the manufacturer Goodfellow were used to determine the HVLs. The collimator used was 25.5 mm in diameter, a size sufficient to cover the sensitive volume of the ionization chamber used, which is 0.20 cm^3, and was positioned at a distance of 38 cm from the focal point.

The reference distance for calibration in low-energy X-ray beams for radiotherapy is 50 cm, since at shorter distances the scattering of additional filters can interfere with the measurement results. This was the distance used to perform the measurements. [8, 9].

2.2. Calibration Procedure for Parallel Plate Ionization Chambers

The TRS 398 code of practice establishes the methodology for determining the absorbed dose in water, D_{WQ0}, and subsequently the calibration coefficient, N_{DWQ0}. In this study, the parallel plate ionization chamber D1 was chosen as reference, since it is calibrated in absorbed dose in water by the Physikalisch-Technische Werkstätten (PTW) laboratory.

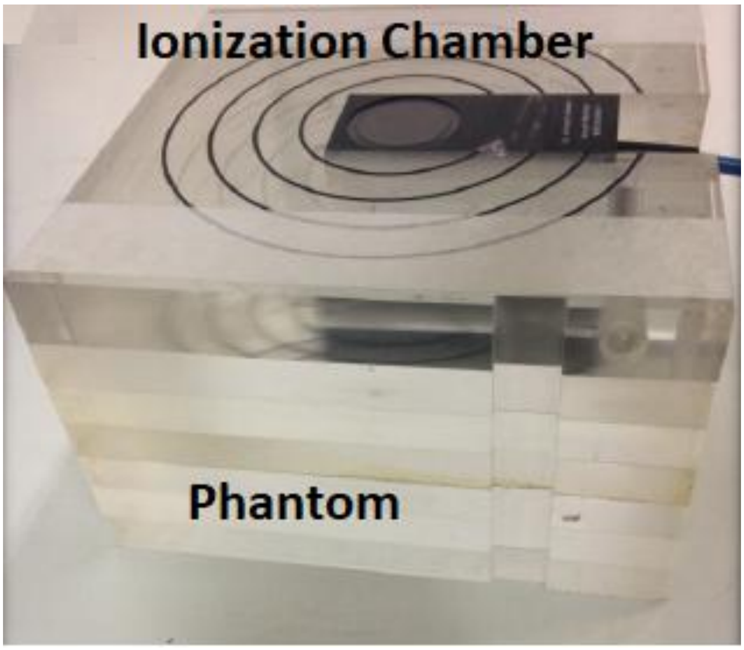
According to TRS 398, the absorbed dose in water $D_{W,Q0}$ at a reference depth Z_{ref} in water or equivalent material, for a radiation quality of Q_0, is shown in Equation 2:

$$D_{WQ0} = M_{Q0} \times f_{T,P} \times N_{DWQ0} \times k_Q \qquad \text{Eq. 2}$$

Where M_{Q0} is the dosimeter reading, in Coulomb, under the reference conditions used in the calibration laboratory, N_{DWQ0} is the calibration coefficient in terms of absorbed dose in water, given in Gy/C, obtained in a standard laboratory and k_Q is the correction factor for each reference quality.

To obtain the absorbed dose in water, an acrylic PTW phantom, type 2962, suitable for depth dose measurements and calibrations using X-ray beams from 7.5 kV to 100 kV was used, as shown in Figure 2.

Figure 2: Side view of the ionization chamber inserted in the acrylic phantom.



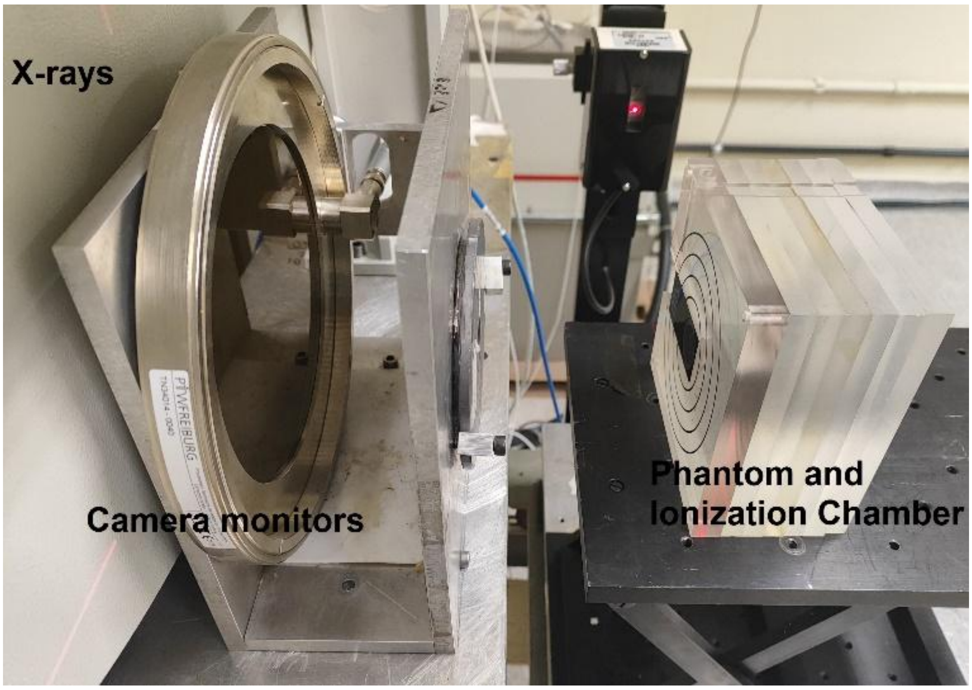
After the accurate determination of the absorbed dose in water, $D_{W,Q0}$, calibration of other ionization chambers can be performed using the substitution method, an internationally recognized procedure. This standardized method, as described in the TRS 398 code of practice and in the Technical Reports Series no. 469 (TRS 469), consists of two main steps: first, measurements are performed with the reference dosimeter; then, measurements are repeated with the dosimeter to be calibrated, strictly maintaining the same experimental conditions in both steps. This procedure ensures the traceability of the measurements, which is essential for quality assurance. [5, 8].

Therefore, to determine the calibration coefficients, $N_{DW,Q0}$ for the ionization chambers as a function of the standard reference dosimeter, the ratio between the absorbed dose in water and the ionization chamber measurements was calculated as shown in Equation 3.

$$N_{DWQ0} = \frac{D_{WQ0}}{M_{QD2} \times f_{T,P}} \quad \text{Eq. 3}$$

Then, using positioning lasers, the entrance window of the parallel plate ionization chamber D1 was positioned 50 cm from the focus of the X-ray tube. Ten measurements were performed with an exposure time of 60 s. Then, the other parallel plate ionization chambers, D2 and D3, were positioned under the same conditions to perform the measurements. The arrangement used is shown in Figure 3.

Figure 3: PTW parallel plate ionization chambers, model 23344.



3. RESULTS AND DISCUSSIONS

The measurements showed the stability of the established radiotherapy qualities T-10 to T-50, with traceability to the Bureau International des Poids et Mesures, aiming to improve the reproducibility and accuracy of the calibrations. The experimental set up was optimized by reducing the size of the collimator, minimizing the contribution of secondary radiation in the parallel plate ionization chamber (DAVIS, 2014), resulting in a more accurate representation of the radiation incident on the collected charge. Table 1 presents the results obtained at CEMRI when the qualities were initially established (data from Bessa, 2007) and the results of the stability verification performed in this work. The T-50 (a) and T-50 (b) qualities refer to configurations with different thicknesses of additional aluminum filtration, allowing for different HVL values for the same tube voltage.

Table 1: Radiation qualities of low-energy X-ray beams for radiotherapy established at LCI and stability verification results.

Reference quality	Voltage (kV)	Additional filtration (mmAl)	1ª HVL (mmAl) [7]	1ª HVL - This Work (mmAl)	Difference (%)
T-10	10	-	0.043	0.041	4.7
T-25	25	0.372	0.279	0.265	5.0
T-30	30	0.208	0.185	0.178	3.8
T-50 (a)*	50	3.989	2.411	2.319	3.8
T-50 (b)	50	1.008	1.079	1.055	2.2

* T-50 (a) is the most filtered radiation quality.

Building upon the methodology established by Bessa (2007), this study implemented a modified experimental setup. A significant alteration involved the reduction of the collimator diameter from 70.5 mm to 25.5 mm; a strategic modification aimed at minimizing the contribution of secondary radiation to the measurements within the parallel plate ionization chamber (D1). The obtained HVL values exhibited a high degree of agreement with those reported by Bessa (2007), demonstrating a maximum percentage variation of 5%, which falls within the established uncertainty range. This consistency underscores the longterm reproducibility of the reference beam qualities. The minor observed variations can be primarily attributed to the refined experimental geometry, particularly the reduced collimation and the specific characteristics of the smaller-volume ionization chamber employed. These factors collectively contribute to a more precise assessment by mitigating the influence of secondary radiation effects.

The calibration of the parallel plate ionization chambers was performed according to the substitution method, using the D1 dosimeter, traceable to the PTW for the absorbed dose in water, as reference. Table 2 presents the comparison between the absorbed dose to water values, $D_{W,Q}$, obtained in this study and the results from Oliveira (2015), who used the methodology based on the DIN standard (DEUTSCHES INSTITUT FÜR NORMUNG) [10,11], which employed air kerma to obtain the absorbed dose to water. In contrast, the present work established a calibration protocol based on the updated recommendations of the TRS 398 cod of practice (2024), which recommends the calibration of parallel plate ionization chambers directly in terms of absorbed dose to water.

Table 2: Comparative analysis of absorbed dose to water: validation of the CEMRI protocol based on historical data [10,11].

Reference quality	Absorbed Dose in Water, Oliveira, 2015 (Gy)	Absorbed Dose in Water - This Work (Gy)	Difference (%)
T-10	0.171	0.173	1.38
T-25	0.168	0.165	2.25
T-30	0.572	0.548	4.23
T-50 (a)	0.056	0.053	4.48
T-50 (b)	0.261	0.252	3.49

* T-50 (a) is the most filtered radiation quality.

The comparison in Table 2 between the results of this study and Oliveira (2015) showed relative differences ranging from 1.38% to 4.48%, indicating good agreement between the methods. These observed variations can be primarily attributed to the methodological differences, particularly how the absorbed dose in water was determined (air kerma in Oliveira (2015) versus direct absorbed dose in water in the current study). Other contributing factors include equipment calibration, measurement conditions, and X-ray tube wear. This comparative analysis is crucial for validating the calibration protocol established at CEMRI, and highlights the importance of standardizing radiation dosimetry protocols to improve accuracy and reproducibility.

After determining the absorbed dose in water using the reference chamber, D1, presented in Table 2, it was possible to determine the calibration coefficients, $N_{DW,Q0}$ for chambers D2 and D3 by applying Equation 3. The results obtained for the calibration coefficients $N_{DW,Q0}$ of chambers D2 and D3 for radiation qualities from T-10 to T-50 are shown in Table 3.

Table 3: Calibration coefficients, $N_{DW,Q0,}$ for parallel plate ionization chambers D2 and D3.

Reference quality	**Absorbed Dose in Water (Gy)**	**$N_{DW,Q,D2,3}$ (Gy/C)**		**Uncertainties (%)**
		D2	**D3**	
T-10	0.173	8.662×10^7	$1,309 \times 10^9$	2.11
T-25	0.165	8.612×10^7	1.206×10^9	2.10
T-30	0.548	8.639×10^7	1.226×10^9	2.11
T-50 (a)	0.053	8.786×10^7	1.205×10^9	2.11
T-50 (b)	0.252	8.754×10^7	1.227×10^9	2.10

* The expanded uncertainty (U) of the reported measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2.00.

The difference in the calibration coefficients between chambers D2 and D3 is attributed to their different sensitive volumes. Specifically, Chamber D3 has a sensitive volume of 0.02 cm^3, which is ten times smaller than the 0.2 cm^3 sensitive volume of chamber D2. Despite this volumetric disparity, the absorbed dose rates measured by both chambers were practically identical under reference conditions. This result demonstrates excellent metrological consistency of the obtained values, as it indicates that the chambers provide very close absorbed dose values in water.

To practically validate the consistency of the calibration protocol, Table 4 presents the absorbed dose to water recalculated from the readings of each chamber (D1, D2, D3) and their respective calibration coefficients, $N_{DW,Q0}$, under the same reference conditions. The minimal dispersion observed in the dose values for each beam quality validates that the protocol produces clinically consistent results, regardless of the calibrated chamber used.

Table 4: Calibration coefficients, $N_{DW,Q0,}$ for parallel plate ionization chambers D2 and D3.

Reference quality	Absorbed Dose in Water D1 (Gy)	Absorbed Dose in Water D2 (Gy)	Absorbed Dose in Water D3 (Gy)	Maean (Gy)	Standard Deviation (Gy)	Uncertainties (%)
T-10	0,173	0,173	0,174	0.173	0,173	2.11
T-25	0,165	0,164	0,162	0.165	0,165	2.10
T-30	0,548	0,548	0,547	0.548	0,548	2.11
T-50 (a)	0,053	0,052	0,054	0.053	0,053	2.11
T-50 (b)	0,252	0,252	0,251	0,252	0,252	2.10

* The expanded uncertainty (U) of the reported measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2.00.

The calculated uncertainties demonstrated a dominance of one source of uncertainty, related to the calibration of the primary standard, a Type B uncertainty assessed from the calibration certificate, responsible for approximately 98% of the combined uncertainty.

Among the other sources of uncertainty, which together contribute about 2%, the calibration uncertainty of the thermometer (0.71%, Type B) and the statistical uncertainty associated with the variation in electrometer readings (0.33%, Type A, assessed as the standard deviation of the mean) stand out. The uncertainties related to the limited resolution of the instruments (electrometer, thermometer and barometer), all of Type B with a rectangular distribution, as well as the environmental variations in temperature and pressure (Type A), proved to be low.

This distribution attests to the reliability of the method employed and the adequacy of the auxiliary measuring equipment, confirming that the laboratory offers stable environmental conditions and that the final uncertainty is effectively anchored in the quality of the reference standard.

4. CONCLUSIONS

The verification of the stability of T-10 to T-50 radiation qualities led to a reduction in scattered radiation contribution, which significantly increased the accuracy and precision of the obtained results. A comparative analysis between this research findings and the reference data from Bessa (2007) showed agreement, even with variations in radiation field size and dosimeter changes, thereby reinforcing the robustness and reliability of this study results.

This study established a critical calibration protocol for parallel-plate ionization chambers in low-energy X-ray beams, based on the updated recommendations of the TRS 398 standard (2024), which recommends calibration directly in terms of absorbed dose in water. This initiative directly addresses a significant dosimetric challenge in, particularly for a high-dose technique (10–20 Gy) using low-energy X-rays administered directly to the tumor bed after surgical excision. Existing IORT devices often provide limited dosimetric information and lack specific calibration protocols. Crucially, the implemented protocol validated using the reference chamber D1 and chambers D2 and D3, confirming its applicability for obtaining reliable absorbed doses in water under reference conditions.

Consequently, this established protocol provides a crucial standardized approach for ensuring accurate and reliable dosimetry for electronic brachytherapy methods like IORT, where primary standards are still under development in many countries, thereby enhancing patient safety and therapeutic efficacy.

ACKNOWLEDGMENT

F.S. Dias thanks CNPQ for the grant in project 140965/2021-1.

M.P.A. Potiens thanks FAPESP for the partnership in project 2018/05982-0

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study are available in the article. Derived data supporting the conclusions of this study are available upon request from the corresponding author.

REFERENCES

[1] IARC. The International Agency For Research On Cancer. News and events. Disponível em: https://www.iarc.who.int/news-events/latest-global-cancer-data-cancer-burden-rises-to-19-3-million-new-cases-and-10-0-million-cancer-deaths-in-2020/. Accessed on Jun. 2025.

[2] TEHRANI. Y. A; SETAYESHI. S. Intra-operative radiotherapy in breast cancer treatment: A literature review. **Iranian Red Crescent Medical Journal**. v. 21. n. 9. 2019.

[3] HENSLEY. F.W. Present state and issues in IORT Physics. **Radiation Oncology**. v. 12. n. 1. p. 1-30. 2017.

[4] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY. Dosimetry in brachytherapy. **An International code of practice for secondary standards dosimetry laboratories and hospitals.** Vienna. 2023. (Technical Report Series. 492).

[5] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY. Absorbed dose determination in external beam radiotherapy. **An International code of practice for dosimetry based on standards of absorbed dose to water.** Vienna. 2024. (Technical Report Series. 398).

[6] BIPM. Bureau International Des Poids Et Measures. **Measuring conditions used for the calibration of ionization chambers at the BIPM**. France. 1991 (Rapport BIPM – 91/5).

[7] BESSA. A. C. M. **Intercomparação de câmaras de ionização em feixes padrões de raios x. níveis radioterapia. radiodiagnóstico e radioproteção.** 2007. Dissertação (Mestrado em Tecnologia Nuclear - Instituto de Pesquisas Energéticas e Nucleares – IPEN-CNEN/SP). São Paulo – SP

[8] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY. **Calibration of reference dosimeters for external beam radiotherapy.** Vienna. 2009. (Technical Report Series. 469).

[9] DAVIS. A. T.; Safi. H. and Maddison. S. M. **The reduction of dose in paediatric panoramic radiography: the impact of collimator height and programme selection.** Department of Medical Physics. Portsmouth Hospitals NHS Trust. Queen Alexandra Hospital. Portsmouth. UK. A Journal of Head & Neck Imaging. November 20. 2014. DOI: http://dx.doi.org/10.1259/dmfr.20140223

[10] OLIVEIRA. C. T. **Desenvolvimento de uma metodologia para calibração de câmaras de ionização de placas paralelas em feixes de raios X de energia baixa em termos de dose absorvida em água**. 2015. Tese (Doutorado em Tecnologia Nuclear - Instituto de Pesquisas Energéticas e Nucleares – IPEN-CNEN/SP

[11] DIN. DEUTSCHES INSTITUT FÜR NORMUNG. ***Clinical dosimetry.*** Part 4: application of X-radiation with tube voltages of 10 to 100 kV in radiotherapy and soft tissue diagnostics**.** Germany. 1988. (DIN 6809 Part 4).

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