

Validation of an alanine-based postal dosimetry audit system for radiotherapy quality assurance

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ABSTRACT

In radiotherapy practice, external dosimetry audits represent a valuable tool for identifying systematic errors, improving the quality and safety of treatments, and ensuring consistency in clinical dosimetry procedures. Despite their proven importance, many radiotherapy centers are still unable to access these audits, especially in resource-constrained settings. With this in mind, the present study aimed to validate an independent postal dosimetry audit service for photon radiotherapy, currently being developed at the Department of Nuclear Energy of Federal University of Pernambuco (DEN/UFPE), using alanine-EPR dosimeters. The proposed system features a structure designed to support six dosimeter holders simultaneously, allowing the evaluation of central-axis and off-axis dose, as well as quality index, flatness and symmetry of photon beams generated by linear accelerators. The system's performance was assessed by comparing measurements from the DEN/UFPE QA setup with results from the TLD-based dosimetry audit program of the Brazilian National Cancer Institute (PQRT/INCA) and with reference data obtained using a PTW 30013 ionization chamber under identical irradiation conditions. The interlaboratory comparison results demonstrated agreement among the systems, with dose deviations relative to the ionization chamber not exceeding 2.0% for the DEN/UFPE system and 1.9% for the PQRT/INCA system. Therefore, these findings provide robust evidence supporting the reliability, accuracy, and overall effectiveness of the proposed alanine-based postal dosimetry audit system, confirming its suitability for clinical implementation.

1. Introduction

Radiation oncology treatments demand high levels of accuracy, particularly regarding the absorbed dose in tumor tissues and the geometric precision of radiation delivery. Dosimetry audits constitute a fundamental component of radiotherapy quality assurance programmes and are routinely implemented worldwide. Such audits have currently been conducted by several international and national providers, including the International Atomic Energy Agency (IAEA) (Izewska, 2002; Dimitriadis et al., 2017; Izewska et al., 2020), the Imaging and Radiation Oncology Core – Houston (IROC-H) (Alvarez et al., 2017), the

Australian Clinical Dosimetry Service/Australian Radiation Protection and Nuclear Safety Agency (ACDS/ARPANSA) (Williams et al., 2012), the National Physical Laboratory (NPL) in the United Kingdom (Clark et al., 2015; Thomas et al., 2017), and the European Society for Radiotherapy and Oncology (ESTRO) in Europe (Ferreira et al., 2000). Beyond supporting the detection and correction of errors, external dosimetry audits contribute to minimizing uncertainties and standardizing dosimetry protocols across participating institutions (Dimitriadis et al., 2023; Grochowska and Izewska, 2013). Over the years, many radiotherapy centers have benefited from this type of service, improving their dosimetry accuracy while also establishing and maintaining proper

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medical physics practices (Lye et al., 2019; Misson et al., 2024).

The International Atomic Energy Agency (IAEA), in partnership with the World Health Organization (WHO), pioneered the implementation of postal dosimetry systems for quality assurance in radiotherapy (Izewska, 2002). During fifty years of operation, this audit program has carried out more than 13,000 audits across 136 countries in six regions (Izewska et al., 2020). In each audit, doses measured with mailed dosimeters are compared to the values reported by the centers. Deviations within $\pm 5\%$ are considered acceptable, while larger discrepancies imply the adoption of follow-up actions. Izewska et al. (2020) reported that, over its 50-year history, the quality of reference dosimetry in radiotherapy centers participating in the IAEA/WHO program has improved substantially, with the proportion of acceptable results increasing from about 50% in the early years to 99% nowadays, despite some variability among countries.

Concerning the type of dosimeters traditionally used in postal audit systems, passive detectors are predominant, including thermoluminescent (TLD) and optically stimulated (OSLD) dosimeters, as well as alanine, radiophotoluminescence dosimeters (RPLD), and radiochromic films. For evaluations performed under non-reference conditions, most audit networks adopt ionization chambers and films, followed by other dosimeters types such as TLD, alanine, diodes, diamond, and dosimeter arrays. Typical measurement uncertainties for passive dosimeters generally range between 1% and 3% ($k = 1$) (Izewska et al., 2018).

Although several national dosimetry audit networks have been established, global access to these services by radiotherapy centers remains insufficient to fulfill current needs. According to Izewska et al. (2018), based on the IAEA audit network database, the number of radiotherapy facilities continues to grow each year, and the demand for quality control assessments exceeds the capacity of existing audit networks. Thus, expanding the availability of external audits is crucial to ensure the highest level of protection for patients receiving radiotherapy treatments and to strengthen clinical dosimetry practices in aforementioned facilities.

Given this background, the aim of this study was to develop and validate an alanine/EPR based postal dosimetry audit system for radiotherapy. This system enables the evaluation of important parameters of photon beams — including central-axis dose, off-axis dose, depth dose, as well as photon beam quality index, flatness, and symmetry — through a single irradiation. Alanine dosimeters were selected due to their significant dosimetric advantages, such as excellent post-irradiation stability, a wide linear dose-response range, high reproducibility and accuracy, a response independent of radiation energy above 100 keV, and minimal dose-rate dependence (Regulla and Deffner, 1982; Borgonove et al., 2007; Waldeland and Malinen, 2011; Baffa and Kinoshita, 2014) — features that are particularly relevant for audits spanning diverse clinical settings. As validation, the proposed dosimetry audit system was compared to a dosimetry system used by the postal audit service in the Quality Program in Radiotherapy (PQRT) of the Brazilian National Cancer Institute (INCA). The PQRT/INCA is recognized as a national reference in radiotherapy quality assurance. This program has been operating for over 25 years, systematically assessing the physical parameters of photon beams under both reference and non-reference conditions. According to reported data, between 2003 and 2018 the PQRT/INCA evaluated 708 linear accelerator beams, conducting more than 5000 tests (Araújo et al., 2019).

2. Material and methods

2.1. Alanine EPR-dosimetry

The alanine dosimeters used in the present study are based on the Electron Paramagnetic Resonance (EPR) dosimetry technique, which quantifies the concentration of free radicals generated in crystalline α -alanine by ionizing radiation. The amplitude of the central line of the EPR spectrum of irradiated alanine is proportional to the free radical

concentration and, consequently, to the absorbed dose (ISO/ASTM, 2013; Baffa and Kinoshita, 2014; Goodman et al., 2016).

The alanine dosimeters utilized in this study were produced by Aéréal (Illkirch, France) with a diameter of 4 mm and a thickness of 2.5 mm. Each dosimeter weighed 37.40 ± 0.21 mg and consisted of 93% alanine and 7% binder. Unlike TLDs, which generally require pre-irradiation or pre-readout procedures, these dosimeters do not need any such preparation. Measurements were conducted using a Magnetech ESR 5000 EPR spectrometer (Bruker, Bremen, Germany) operating in the X-band. The microwave power and modulation amplitude were set to 10 mW and 0.7 mT, respectively, with a modulation frequency of 100 kHz.

To compensate for potential variations in spectrometer stability, the alanine EPR signal intensity was normalized to the signal intensity of a reference sample permanently fixed within the resonant cavity: synthetic ruby. The ruby crystal contains approximately $10^{-2}\%$ Cr^{3+} , which yields an exceptionally stable EPR signal under standard laboratory conditions (Sleptchouk et al., 2000). This reference sample was measured simultaneously with each alanine dosimeter.

The alanine-EPR response was evaluated by measuring the peak-to-peak amplitude of the central line in each dosimeter's spectrum. The ruby EPR response was determined in a similar way, by measuring the amplitude between the maximum and minimum points of its spectrum. In addition to normalization using the ruby EPR response, the alanine response was also normalized by the dosimeter mass.

It should be noted that the alanine-EPR response has previously been characterized for radiotherapy photon beams, by assessing its reproducibility, linearity, and dependence on both dose rate and beam energy, in order to ensure its reliability under typical clinical conditions (Albino et al., 2024).

2.1.1. Calibration curve

To establish the calibration curve, alanine-EPR dosimeters were irradiated with a True Beam STx linear accelerator (Varian, California, USA) with doses ranging from 2 Gy to 30 Gy. Irradiations were conducted using a 6 MV photon beam with a nominal dose rate of 600 MU/min and a square radiation field of $10 \times 10 \text{ cm}^2$. The experimental setup employed a source-to-surface distance (SSD) of 100 cm, with the dosimeters positioned at a depth of 10 cm.

The resulting curve represents the dosimeter response, normalized to both its mass and the ruby-EPR signal amplitude, as a function of absorbed dose. The calibration factor was determined from the slope of the linear fit.

2.2. DEN/UFPE postal audit system

The quality control system (Fig. 1), currently under development at the Department of Nuclear Energy of the Federal University of Pernambuco (DEN/UFPE), essentially consists of a support containing two acrylic (polymethyl methacrylate, PMMA) rods, both with a diameter of 25 mm and spaced 100 mm apart at their centers. These rods hold a total of six dosimeter holders, which were fabricated via 3D printing on a Form2 Desktop 3D printer (Formlabs, Somerville, Massachusetts) employing two types of resins: Black V4 and Flexible (Formlabs, Somerville, Massachusetts), both with a manufacturer-specified relative density of 1.09 g/cm^3 . Each holder houses two alanine pellets.

Fig. 2 illustrates the typical irradiation setup of the DEN/UFPE system, which must be positioned inside a water phantom to allow the simultaneous irradiation of the six dosimeter holders. This arrangement allows for the assessment of central axis doses at 10 cm and 20 cm depths, off-axis doses at 2 cm and 4 cm, as well as quality index (in terms of Tissue-Phantom Ratio in water at depths of 20 g/cm^2 and 10 g/cm^2 , that is, $\text{TPR}_{20,10}$), flatness, and symmetry of the photon beam. All evaluations are conducted in accordance with TRS-398 (IAEA, 2024), TEC DOC-1151 (INCA, 2000), and TG-142 (Klein et al., 2009). It is noteworthy that beam flatness and symmetry parameters, which are traditionally assessed in on-site audits or using radiochromic films and

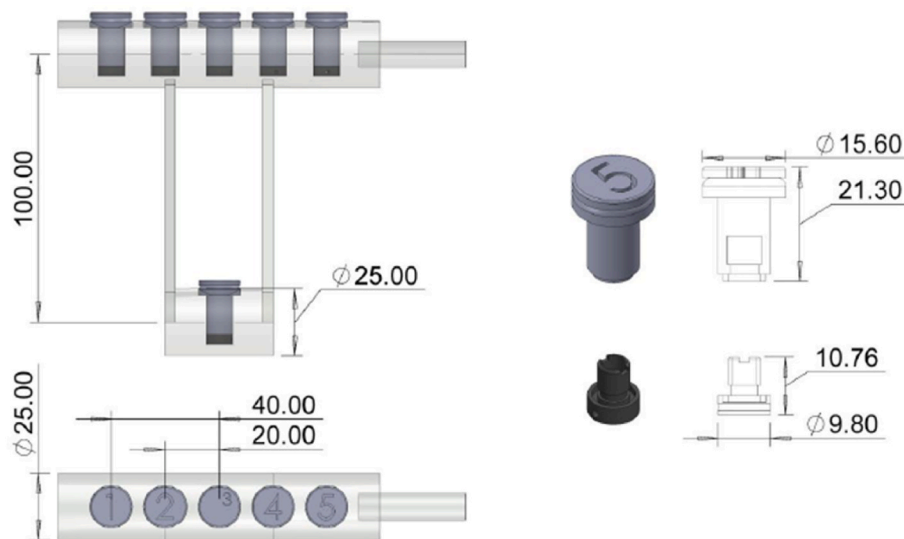


Fig. 1. Schematic and 3D illustration of the DEN/UFPE postal audit system. The left figure depicts the support structure composed of acrylic rods, while the right figure illustrates the dosimeter holder, including the cover (top) and the dosimetric support (bottom). All dimensions are in millimeters.

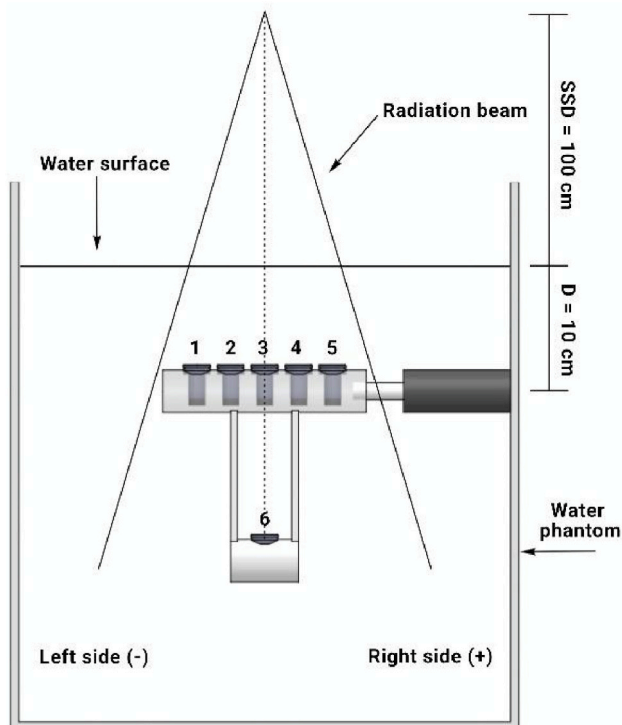


Fig. 2. Irradiation setup of the DEN/UFPE system. For standardization, the left and right sides are defined from the perspective of an observer facing the linear accelerator gantry. SSD: source-to-surface distance; D: depth in water.

two-dimensional detector arrays, were determined in the present study through a postal audit system, based on dose values obtained from dosimeters positioned at a depth of 10 cm, thereby providing greater practicality and improved operational suitability for clinical routine.

2.3. Uncertainty budget

The uncertainties related to alanine-EPR dosimetry were evaluated following the Guide to the Expression of Uncertainty in Measurement (GUM) provided by the International Organization for Standardization

(ISO/IEC Guide 98-3, 2008), at a 95.45% confidence level.

2.4. Interlaboratory comparison with the TLD postal audit service of PQRT/INCA

To validate the DEN/UFPE system, two interlaboratory comparisons were performed with the postal audit service of Quality Program in Radiotherapy (PQRT) of the Brazilian National Cancer Institute (INCA), which uses TLD-100 (LiF:Mg,Ti) powder dosimeters as the element detector (Araújo et al., 2019).

The DEN/UFPE and the PQRT/INCA systems were assessed in terms of central-axis dose, off-axis dose, depth dose, quality, flatness, and symmetry of the radiation beam. Reference measurements obtained with the PTW 30013 ionization chamber were used to calculate the percentage deviations, as both systems were irradiated with different doses.

For the first interlaboratory comparison, the two systems were individually positioned in a 1D Scanner water phantom (Sun Nuclear, Florida, USA) and irradiated with a True Beam STx linear accelerator (Varian, California, USA) with 6 MV energy and dose rate of 600 MU/min.

In the second interlaboratory comparison, both systems were irradiated with a Trilogy linear accelerator (Varian, California, USA) at 6 MV and 400 MU/min. The differences in the dose rate values were attributable solely to limitations associated with equipment availability.

In both comparative evaluation tests, radiation doses were 10 Gy for the DEN/UFPE system and 2 Gy for the PQRT/INCA system. These dose values were selected to align with the operational range of each dosimeter type. In addition, the dosimetry measurements obtained with these systems were compared with those of a Farmer 30013 ionization chamber (PTW, Freiburg, Germany), irradiated under the same conditions and doses. The parameters used for irradiation were: SSD of 100 cm, $10 \times 10 \text{ cm}^2$ radiation field, and depth of 10 cm.

Fig. 3 shows the experimental setup of the DEN/UFPE (Fig. 3a) and the PQRT/INCA (Fig. 3b) systems within the water phantom for the first comparison test.

3. Results and discussion

3.1. Calibration curve

Fig. 4 presents the calibration curve of alanine dosimeters for 6 MV

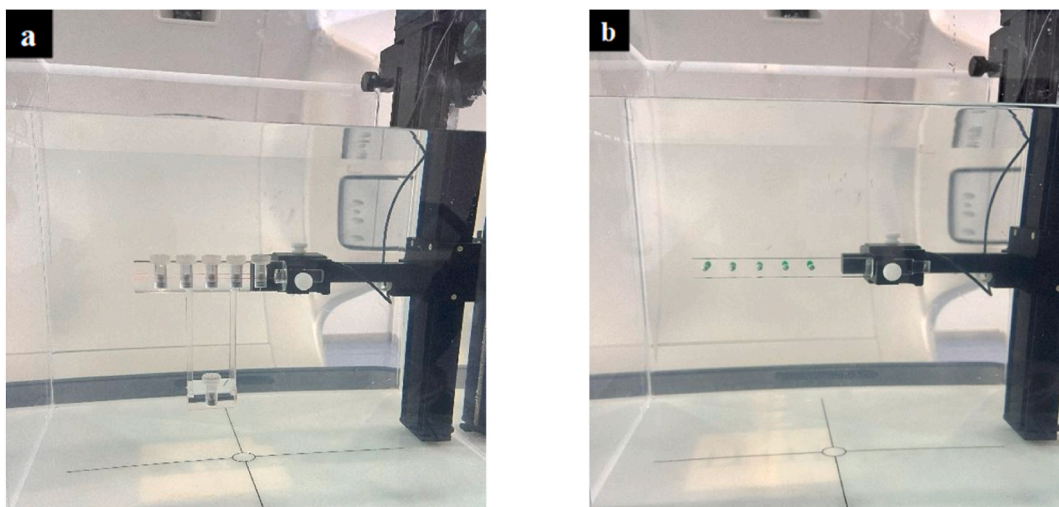


Fig. 3. Positioning of (a) DEN/UFPE system and (b) PQRT/INCA system within the water phantom.

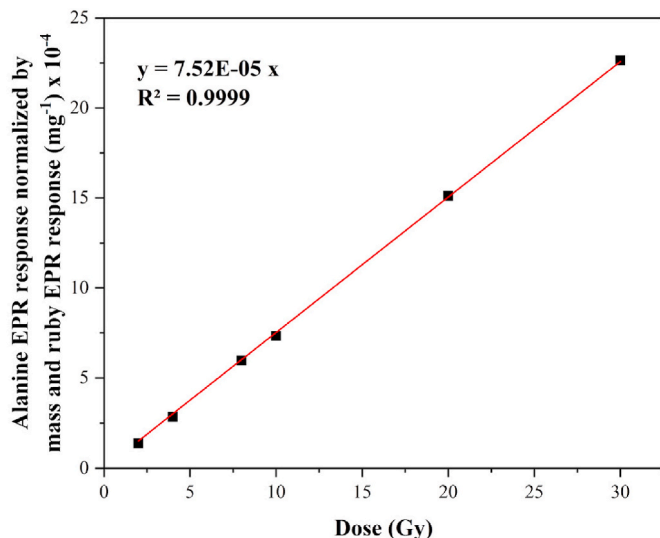


Fig. 4. Alanine calibration curve for 6 MV radiation energy.

radiation beam. A linear regression was applied to the experimental data, demonstrating that the alanine-EPR response is linear across the evaluated dose range, with a determination coefficient (R^2) of 0.99994.

Table 1

Sources of uncertainty and percentage contribution to the combined uncertainty for a 10 Gy absorbed dose to water measurement with two alanine dosimeters, at the reference depth, for an irradiation with a 6 MV beam quality.

Symbol	Description	Standard Uncertainty $u(x_i)$	Unit	Type/Distribution	Standard Uncertainty Coef. x Sensibility (Gy) $ c_i \cdot u(x_i)$	Percentage contribution to the combined uncertainty
u_1	Reproducibility ¹ [Alanine/Ruby] _m	0.86%	%	A/N	0.0086	28%
u_2	Alanine mass	0.28%	%	B/N	0.0028	2.9%
u_3	Calibration Curve Linearity ²	0.80%	%	A/N	0.0080	24%
u_4	Calibration Reference Dose Estimation	1.1%	%	A/N	0.011	44%
u_5	Signal Fading ³	0.058%	%	B/R	0.00058	0.13%
u_6	Humidity dependence ⁴	0.058%	%	B/R	0.00058	0.13%
u_7	EPR spectrometer stability ⁵	0.050%	%	A/R	0.00050	0.10%
u_8	Temperature difference alanine and ruby ⁶	0.058%	%	B/R	0.00058	0.13%
Expanded Uncertainty, $U = 3.3\%$ ($k=2$, $\nu_{\text{eff}} = 42$)						

A: Type A uncertainty evaluation; B: Type B uncertainty evaluation; N: normal distribution; R: rectangular distribution.

This finding aligns with previous studies reported in the literature (Helt-Hansen et al., 2009; Baffa and Kinoshita, 2014). As noted by Regulla and Deffner (1982), the dose-response curve of alanine dosimeters generally remains linear from a few grays up to approximately 100 kGy.

3.2. Uncertainty budget

The overall uncertainty in the alanine dosimetry results was determined by combining Type A and Type B components in accordance with the ISO GUM (ISO/IEC Guide 98-3, 2008). The primary sources of uncertainty considered in this study, summarized in Table 1, included the reproducibility of the EPR response, uncertainties associated with the calibration curve fitting parameters, variations in environmental humidity, dosimeter mass and fading.

The model equation uses a linear fit between 2 and 30 Gy in terms of absorbed dose to water at the reference depth (6 MV beam). The calibration curve is given by:

$$\left(\frac{M_{\text{ala}}/m}{M_{\text{ruby}}} \right)_{\text{cali}} = D_{w,\text{ref},i} \cdot B_1 + B_0 \quad (1)$$

where $\left(\frac{M_{\text{ala}}/m}{M_{\text{ruby}}} \right)_{\text{cali}}$ is the i th measurement for the calibration dosimeters of the ratio of the alanine to ruby per unit mass; $D_{w,\text{ref},i}$ is the reference value of the i th measurement of absorbed dose to water determined with

the standard ion chamber; B_1 is the slope, B_0 is the intercept. The result for the estimation of the absorbed dose to water measured with alanine dosimeters can therefore be modeled using:

$$R(\text{Gy}) = \frac{\left[\left(\frac{M_{\text{ala}}/m}{M_{\text{ruby}}/m} \right)_m - B_0 \right]}{B_1} \cdot f_{\text{fad}} \cdot f_{\text{hum}} \cdot f_{\text{EPRstab}} \cdot f_{\text{temp}} \quad (2)$$

where $\left(\frac{M_{\text{ala}}/m}{M_{\text{ruby}}/m} \right)_m$ is the average measurement of the ratio of the alanine to ruby per unit mass; and $f_{\text{fad}} \cdot f_{\text{hum}} \cdot f_{\text{EPRstab}} \cdot f_{\text{temp}}$ are factors to account for fading, humidity, stability of the EPR reader and temperature differences within the measurement cavity between the alanine sample and the reference ruby.

The uncertainty components presented in Table 1 were evaluated under the following assumptions:

- the reproducibility (Type A, normal distribution) was determined for the ratio of the simultaneous measurement of the alanine dosimeters divided by the internal ruby reference;
- the linearity of the alanine system was assessed over absorbed doses to water ranging from 2 to 30 Gy (Fig. 4). The uncertainty component resulting from the use of a calibration curve derived from a linear fit was evaluated following the methodology described by Ellison and Williams (2012);
- for the signal fading component, an upper limit value of $0.1\%/\sqrt[3]{3}$ was assumed (Type B, rectangular distribution). Fading of alanine dosimeters is around $1.5\% \text{ yr}^{-1}$ and may be considered negligible for an interval between irradiation and readout of a few days (Anton, 2008);
- the effect of humidity on alanine dosimeters has been previously investigated by Khoury et al. (2016). Based on these results, an uncertainty of $0.1\%/\sqrt[3]{3}$ was assigned (Type B, rectangular distribution);
- the uncertainty associated with EPR spectrometer stability was estimated from intermediate verification data ($n = 153$) collected between May 2002 and March 2025 (Type A, rectangular distribution);
- the in-cavity temperature correction was measured as $-1.0\% \text{ } ^\circ\text{C}^{-1}$; however, this effect influences both the alanine dosimeters and the ruby reference. An additional uncertainty of 0.1% was therefore assigned to account for possible temperature differences between the alanine samples and the ruby reference.

The combined standard uncertainty was subsequently expressed as an expanded uncertainty at a specified confidence level, defined by the coverage factor (k). For an irradiation dose of 10 Gy at the reference point, the expanded uncertainty (U) for a dose estimation using the alanine system corresponds to $U = 3.3\%$ ($k = 2$).

3.3. Validation of DEN/UFPE postal audit system

The results of the two interlaboratory comparisons tests are summarized in Tables 2 and 3. In the off-axis dose analysis, the “+” symbol denotes measurement points located to the right of the central axis, whereas the “−” symbol indicates those positioned to the left, considering a front view of the gantry.

Table 2 presents the results of the first interlaboratory comparison between the DEN/UFPE and PQRT/INCA postal audit systems, utilizing a True Beam STx linear accelerator. The data demonstrates that for the central axis dose at a 10 cm depth, the PQRT/INCA system exhibited a difference of 0.43% relative to the ionization chamber, while the DEN/UFPE system showed a difference of 0.22%. For off-axis doses, the percentage differences ranged from -0.77% to 0.90% for PQRT/INCA and from -1.15% to 1.08% for DEN/UFPE, indicating that both systems display agreement with the values measured by the ionization chamber. Fig. 5a presents the off-axis ratio measurements at -4 , -2 , 0 , $+2$, and $+4$ cm. Overall agreement among the three measurement systems is observed, with differences remaining within experimental uncertainties.

At a 20 cm depth, which was only available for the DEN/UFPE system, the percentage difference relative to the ionization chamber was 0.58% . This data could not be included for the PQRT/INCA system due to an inconsistency identified in the dose value estimated for this parameter. Regarding beam uniformity, for flatness and symmetry parameters, the percentage differences for PQRT/INCA were -0.23% and 0.03% , respectively, while for DEN/UFPE they were -0.03% and -1.20% . In Fig. 5b, the off-axis ratio measurements at -4 , -2 , 0 , $+2$, and $+4$ cm are compared, with the three measurement systems exhibiting agreement within 2% .

All values estimated for the parameters evaluated in this comparison are consistent, within their respective associated uncertainties, with the reference values obtained using the ionization chamber. The combined uncertainties considered were 1.6% for the DEN/UFPE system ($k = 1$) and 1.7% for the PQRT/INCA system ($k = 1$), and no statistically significant discrepancies were observed between the evaluated systems. With respect to the second interlaboratory comparison test, whose results are presented in Tables 3 and it can be observed that the absolute differences between the values measured with the DEN/UFPE system and those obtained with the ionization chamber did not exceed 2.00% . For the PQRT/INCA system, the maximum percentage deviation was -1.90% . All deviations for every dose and beam profile parameter for both systems are within their respective expanded uncertainty limits. These results not only validate the accuracy of the DEN/UFPE system but also confirm that its dosimetry performance meets the stringent criteria established by quality assurance programs in radiotherapy.

Another point to be highlighted is the performance of the linear accelerators themselves. Reference documents such as Task Group (TG) reports 40 (Kutcher et al., 1994), 142 (Klein et al., 2009), and 198 (Hanley et al., 2021), as well as TEC DOC 1151 (INCA, 2000), establish a tolerance limit of $\pm 2\%$ for verifying the constancy of reference dose, off-axis dose, and flatness parameters, while a $\pm 3\%$ limit applies to

Table 2

Results of the first interlaboratory comparison between PQRT/INCA and DEN/UFPE postal audit systems with a True Beam STx linear accelerator.

Parameter	Value measured		Deviation (%)	Value measured		Deviation (%)
	PQRT/INCA	Ionization chamber		DEN/UFPE	Ionization chamber	
Dose in the central axis at a depth of 10 cm	2.03 Gy	2.02 Gy	0.43	9.99 Gy	9.97 Gy	0.22
Off-axis dose at -2 cm	2.01 Gy	2.05 Gy	-0.77	9.95 Gy	9.98 Gy	-0.39
Off-axis dose at $+2$ cm	2.03 Gy	2.02 Gy	0.66	9.84 Gy	9.96 Gy	-1.15
Off-axis dose at -4 cm	1.98 Gy	1.97 Gy	0.90	9.68 Gy	9.70 Gy	-0.17
Off-axis dose at $+4$ cm	1.98 Gy	1.96 Gy	0.87	9.77 Gy	9.67 Gy	1.08
Dose in the central axis at a depth of 20 cm	-	-	-	5.74 Gy	5.71 Gy	0.58
Beam flatness	1.37%	1.60%	-0.23	1.57%	1.60%	-0.03
Beam symmetry	0.31%	0.28%	0.03	-0.92%	0.28%	-1.20

The deviation values correspond to the percentage differences between the measurements obtained with alanine or TLD dosimeters and those obtained with the ionization chamber, except for the flatness and symmetry parameters, for which the values represent absolute percentage deviations.

Table 3

Results of the second interlaboratory comparison between PQRT/INCA and DEN/UFPE postal audit systems using a Trilogy linear accelerator.

Parameter	Value measured		Deviation (%)	Value measured		Deviation (%)
	PQRT/INCA	Ionization chamber		DEN/UFPE	Ionization chamber	
Dose in the central axis at a depth of 10 cm	2.03 Gy	2.00 Gy	1.56	10.01 Gy	10.00 Gy	0.11
Off-axis dose at -2 cm	2.01 Gy	2.00 Gy	0.70	9.80 Gy	10.00 Gy	-1.94
Off-axis dose at +2 cm	2.02 Gy	2.00 Gy	1.32	9.79 Gy	9.99 Gy	-2.00
Off-axis dose at -4 cm	1.96 Gy	1.94 Gy	1.02	9.57 Gy	9.72 Gy	-1.53
Off-axis dose at +4 cm	1.94 Gy	1.93 Gy	0.57	9.51 Gy	9.66 Gy	-1.53
Dose in the central axis at a depth of 20 cm	1.13 Gy	1.15 Gy	-1.90	5.86 Gy	5.77 Gy	1.66
Beam flatness	2.20%	1.70%	0.49	2.54%	1.70%	0.84
Beam symmetry	1.00%	0.60%	0.42	0.57%	0.60%	-0.03

The deviation values correspond to the percentage differences between the measurements obtained with alanine or TLD dosimeters and those obtained with the ionization chamber, except for the flatness and symmetry parameters, for which the values represent absolute percentage deviations.

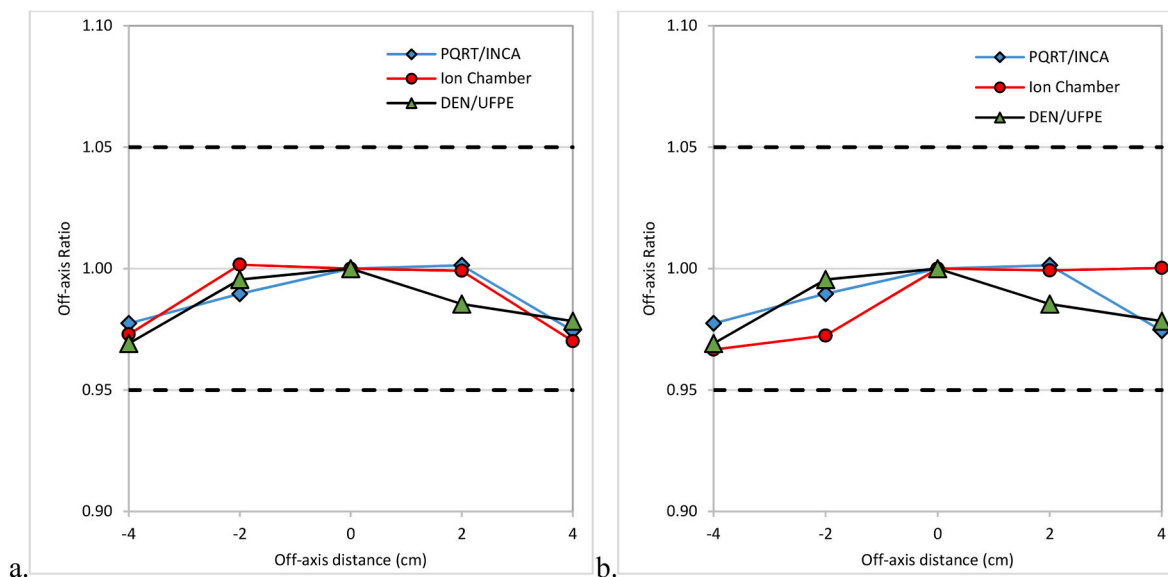


Fig. 5. Off-axis ratio for the comparison with the (a) True Beam STx linear accelerator and (b) Trilogy linear accelerator. The dashed lines correspond to the $\pm 5\%$ acceptance criteria.

beam symmetry. The measurements obtained for both the TrueBeam STx and Trilogy linear accelerators are within these acceptance criteria, demonstrating full compliance with internationally recognized standards.

Maintaining these parameters within the specified tolerances is essential for ensuring accurate dose delivery and patient safety in radiotherapy. Consistent quality control of linear accelerators not only guarantees the reliability and reproducibility of treatments but also reinforces confidence in the entire therapeutic process.

4. Conclusions

The system developed by DEN/UFPE exhibited consistent and reliable performance, confirming its technical adequacy for use in dosimetry audit programs. The agreement with the results from an established national service attests to the robustness and credibility of the proposed methodology. These findings support its implementation as an independent tool for verifying dosimetric accuracy in radiotherapy treatment units. Moving forward, the next phase involves the deployment of this system to radiotherapy centers nationwide, aiming to strengthen quality assurance practices and enhance the safety of patient treatments.

CRediT authorship contribution statement

Árcia Ravane Pereira da Cruz: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Lucas Delbem**

Albino: Investigation. **Ernesto Roesler:** Supervision. **Claudio Castelo Branco Viegas:** Validation, Methodology, Investigation. **Gabriel Henrique Rocha Barreto de França:** Methodology. **Josemary Angélica Corrêa Gonçalves:** Writing – review & editing, Supervision, Methodology, Investigation. **Carmen Cecília Bueno:** Writing – review & editing, Supervision. **Vinícius Saito Monteiro de Barros:** Writing – review & editing, Writing – original draft, Supervision. **Viviane Khoury Asfora:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

References

- Albino, L.D., Cruz, A.R.P., Pieri, K., et al., 2024. Quality control of the stereotactic radiosurgery procedure with the alanine-EPR dosimetry. *Radiat. Phys. Chem.* 224, 112080. <https://doi.org/10.1016/j.radphyschem.2024.112080>.
- Alvarez, P., Kry, S.F., Stingo, F., et al., 2017. TLD and OSLD dosimetry systems for remote audits of radiotherapy external beam calibration. *Radiat. Meas.* 106, 412–415. <https://doi.org/10.1016/j.radmeas.2017.01.005>.
- Anton, M., 2008. Postirradiation effects in alanine dosimeter probes of two different suppliers. *Phys. Med. Biol.* 53 (5), 1241–1258.
- Araújo, A.M.C., Viegas, C.C.B., Souza, R.S., et al., 2019. TLD postal audits in radiotherapy in Brazil. In: *SSDL Newsletter*, vol. 70. IAEA, Vienna, pp. 26–27.
- Baffa, O., Kinoshita, A., 2014. Clinical applications of alanine/electron spin resonance dosimetry. *Radiat. Environ. Biophys.* 53, 233–240.
- Borgonove, A.F., Kinoshita, A., Chen, F., et al., 2007. Energy dependence of different materials in ESR dosimetry for clinical X-ray 10 MV beam. *Radiat. Meas.* 42 (6–7), 1227–1232.
- Clark, C.H., Aird, E.G., Bolton, S., et al., 2015. Radiotherapy dosimetry audit: three decades of improving standards and accuracy in UK clinical practice and trials. *Br. J. Radiol.* 88, 20150251.
- Dimitriadis, A., Kazantsev, P., Chelminski, K., et al., 2023. IAEA/WHO postal dosimetry audit methodology for electron beams using radiophotoluminescent dosimeters. *Med. Phys.* 50, 7214–7221.
- Dimitriadis, A., Palmer, A.L., Thomas, R.A.S., et al., 2017. Adaptation and validation of a commercial head phantom for cranial radiosurgery dosimetry end-to-end audit. *Br. J. Radiol.* 90 (1074), 20170053. <https://doi.org/10.1259/bjr.20170053>.
- Ellison, S.L.R., Williams, A. (Eds.), 2012. *Eurachem/CITAC Guide: Quantifying Uncertainty in Analytical Measurement*. Third edition. ISBN 978-0-948926-30-3. www.eurachem.org.
- Ferreira, I.H., Dutreix, A., Bridier, A., Chavaudra, J., Svensson, H., 2000. The ESTRO quality assurance network (EQUAL). *Radiother. Oncol.* 55, 273–284. [https://doi.org/10.1016/S0167-8140\(99\)00101-2](https://doi.org/10.1016/S0167-8140(99)00101-2).
- Goodman, B.A., Worasith, N., Ninlaphruk, S., et al., 2016. Radiation dosimetry using alanine and electron paramagnetic resonance (EPR) spectroscopy: a new look at an old topic. *Appl. Magn. Reson.* 48, 155–173. <https://doi.org/10.1007/s00723-016-0855-8>.
- Grochowska, P., Izewska, J., 2013. An IAEA survey of dosimetry audit networks for radiotherapy. In: *SSDL Newsletter*, vol. 61. IAEA, Vienna, pp. 23–27.
- Hanley, J., Dresser, S., Simon, W., et al., 2021. AAPM Task Group 198 report: an implementation guide for TG-142 quality assurance of medical accelerators. *Med. Phys.* 48, e830–e885. <https://doi.org/10.1002/mp.14992>.
- Helt-Hansen, J., Rosendal, F., Kofoed, I.M., et al., 2009. Medical reference dosimetry using EPR measurements of alanine: development of an improved method for clinical dose levels. *Acta Oncol.* 48 (2), 216–222.
- IAEA, 2024. Absorbed dose determination in external beam radiotherapy. Technical Reports Series No. 398 Rev. 1. IAEA, Vienna.
- INCA, 2000. TECDOC-1151: Aspectos físicos da garantia da qualidade em radioterapia. INCA, Rio de Janeiro.
- ISO/ASTM, 2013. ISO/ASTM Standard 51607: Standard Practice for Use of an Alanine-EPR Dosimetry System.
- ISO/IEC, 2008. Guide 98-3: Uncertainty of Measurement — Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995). International Organization for Standardization, Geneva.
- Izewska, J., 2002. Introductory remarks. In: *SSDL Newsletter*. IAEA, Vienna, 46, 5.
- Izewska, J., Lechner, W., Wesolowska, P., et al., 2018. Global availability of dosimetry audits in radiotherapy: the IAEA dosimetry audit networks database. *Phys. Imaging Radiat. Oncol.* 5, 1–4.
- Izewska, J., Bokulic, T., Kazantsev, P., et al., 2020. 50 years of the IAEA/WHO postal dose audit programme for radiotherapy: what can we learn from 13,756 results? *Acta Oncol.* 59 (5), 495–502.
- Khoury, H.J., Mehta, K., Barros, V.S., et al., 2016. Dose assurance service for low energy X ray irradiators using an alanine-EPR transfer dosimetry system. *Fla. Entomol.* 99 (S2), 14–17.
- Klein, E.E., Hanley, J., Bayouth, J., et al., 2009. Task Group 142 report: quality assurance of medical accelerators. *Med. Phys.* 36, 4197–4212. <https://doi.org/10.1118/1.3190392>.
- Kutcher, G.J., Coia, L., Gillin, M., et al., 1994. Comprehensive QA for radiation oncology: report of AAPM Radiation Therapy Committee Task Group 40. *Med. Phys.* 21, 581–618. <https://doi.org/10.1118/1.597316>.
- Lye, J., Kry, S., Shaw, M., et al., 2019. A comparison of IROC and ACDS on-site audits of reference and non-reference dosimetry. *Med. Phys.* 46 (12), 5878–5887. <https://doi.org/10.1002/mp.13800>.
- Misson, S., Palmer, A.L., Diez, P., et al., 2024. National radiotherapy dosimetry audit in the UK – a vision and roadmap. *Radiother. Oncol.* 12, 100032. <https://doi.org/10.1016/j.radonc.2024.100032>.
- Regulla, D.F., Deffner, U., 1982. Dosimetry by ESR spectroscopy of alanine. *Int. J. Appl. Radiat. Isot.* 33 (11), 1101–1114.
- Sleptchouk, O.F., Nagy, V., Desrosiers, M.F., 2000. Advancements in accuracy of the alanine dosimetry system. Part 1: the effects of environmental humidity. *Radiat. Phys. Chem.* 57, 115–133.
- Thomas, R.A.S., Bolt, M.A., Bass, G., et al., 2017. Radiotherapy reference dose audit in the United Kingdom by the National Physical Laboratory: 20 years of consistency and improvements. *Phys. Imaging Radiat. Oncol.* 3, 21–27. <https://doi.org/10.1016/j.phro.2017.07.005>.
- Waldeland, E., Malinen, E., 2011. Review of the dose-to-water energy dependence of alanine and lithium formate EPR dosimeters and LiF TL-dosimeters – comparison with Monte Carlo simulations. *Radiat. Meas.* 46 (9), 945–951.
- Williams, I., Kenny, J., Lye, J., et al., 2012. The Australian Clinical Dosimetry Service: a commentary on the first 18 months. *Australas. Phys. Eng. Sci. Med.* 35, 407–411. <https://doi.org/10.1007/s13246-012-0161-1>.