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Original Research Article

Results of a remote audit program of reference and non-reference dosimetry of photon beams using alanine detectors

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ABSTRACT

Background and purpose: Remote beam output audits (BOAs) are important for verifying the calibration of the audited beam. However, BOAs (Level I audit) provide limited independent validation of the commissioned beam model in the treatment planning system (TPS). With Level II audits, the beam commissioning data is checked more thoroughly. This study presents the results of a remote audit program of reference and non-reference dosimetry, utilising alanine dosimetry. A particularity was to use the calculations of the TPS as reference values corrected by the daily output. The goal was to verify the beam commissioning data in the TPS, including the calibration.

Materials and methods: The audit consisted of five irradiations with a 10×10 cm^2 field and a small field test with field sizes up to 2×2 cm^2. Watertight sealed alanine detectors, along with a 3D-printed holder featuring three slots at depths of 8 cm, 10 cm, and 20 cm, were used. The results of 224 beams audited were included in this study.

Results: The difference between the measured and predicted doses was within ±5 % for all beams except one. No clear trend was observed in the results for uniform and FFF beams. The uncertainty in the alanine readout was 1 % ($k = 1$). The results maintained their accuracy, while a slight improvement was observed in the small field test.

Conclusions: All audit results were satisfactory. There is a slightly positive trend in the audit results over the years, suggesting that the accuracy of radiotherapy calculations is consistently maintained.

1. Introduction

Past incidents in radiotherapy centres have demonstrated the need for extensive quality control audit programs in radiotherapy (RT) [1–3]. The development of such independent quality assurance (QA) programs is a crucial component in ensuring the correct irradiation of patients. To this end, external dosimetry audits can be used to detect potential systematic measurement errors [4,5]. It has become common practice to use remote audits, at least for beam output audits (BOAs), where the beam output is checked under reference conditions. This is the reason why several institutions now provide BOAs [6–13] and dosimetry audits in non-reference conditions [14–18] using different types of detectors, such as thermoluminescent dosimeters (TLDs), radiophotoluminescent dosimeters (RPLDs), optically stimulated luminescent dosimeters (OSLDs), and alanine dosimeters. A BOA performed is classified as a Level I audit. This type of audit is one of the standard components of QA in clinical trials and is also mandated by law in certain countries [19].

Even if those simple BOAs with a single-point dose measurement provide the output of the beams, they are a necessary minimal requirement, but they offer limited information about the suitability of the audited beams for treatments. To this end, Level II audits have been introduced, where the beam commissioning data is checked more thoroughly [20]. This usually involves point dose measurements in non-reference conditions. Level III audits, on the other hand, check the entire treatment chain, such as end-to-end (E2E) audits.

To ensure the quality of radiotherapy treatment, it is crucial that not only the calibration of the linear accelerator (linac) is correctly performed but also that the beam model in the treatment planning system (TPS) is correctly built. Indeed, if the calibration of the beam or the commissioning of the beam model is incorrect, this will be transferred as a systematic error in the treatment of all patients.

The goal was to verify the linac calibration and check the beam commissioning data in the TPS. This was done by comparing audit measurements with calculated values from the TPS, rather than with measurements made by the local physicists, even when the measured output of the day was taken into account.

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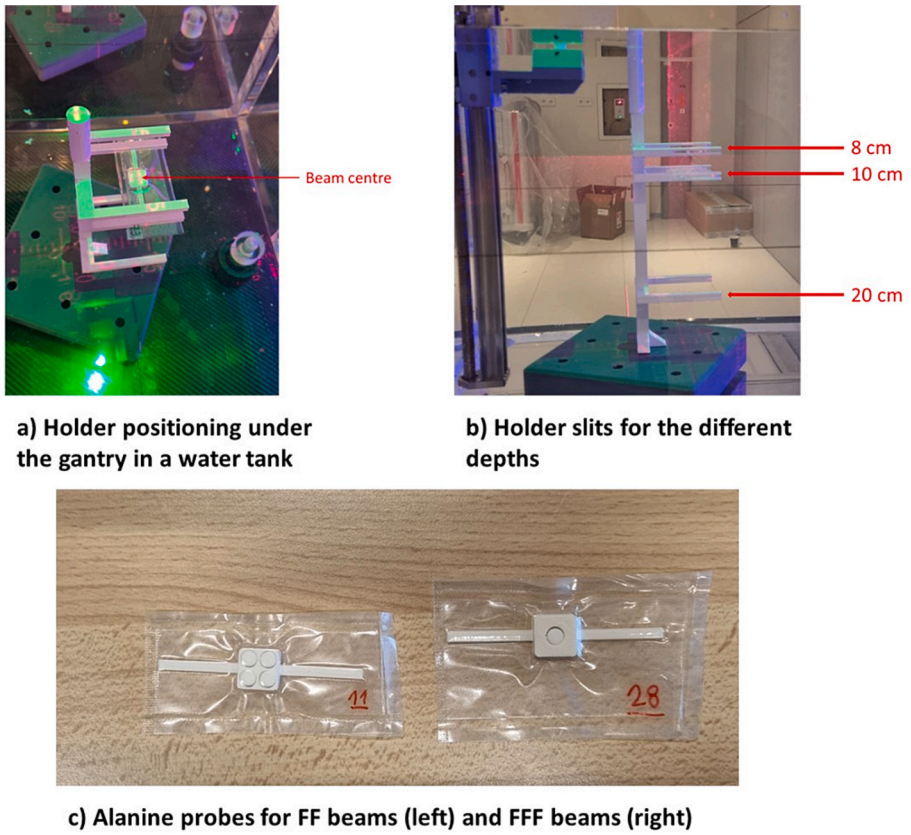


Fig. 1. 3D-printed alanine holder with the alanine probe, which consists of alanine pellets placed in a 3D-printed template. b) The alanine holder with the different slits at different depths, allowing the placement of the alanine probe at the correct depth. c) 3D printed alanine probes, which are sealed watertight.

2. Materials and methods

2.1. Audit methodology

The centres received the audit procedure and material beforehand. The audit consisted of measurements in a water tank. A custom 3D-printed holder was supplied to the centres performing the audit (Fig. 1). The centre performing the audit was requested to place this holder in a water tank and add water to the level of the top of the holder. The holder had three slots for placing detectors, corresponding to depths of 8 cm, 10 cm, and 20 cm. Only 1 alanine probe was placed in the holder during irradiation. The alanine pellets themselves were placed in 3D-printed moulds, sealed watertight, and emptied of air. The packages contained four pellets for Flattening Filter (FF) beams and one pellet for Flattening Filter Free (FFF) beams. The centres were requested to deliver 8 Gy to the detectors for each test. We choose to request that the number of monitor units should be calculated with the TPS. The centres were also requested to provide the daily output of the audited beams measured with their local detectors, which was taken into account when comparing the doses measured with the alanine with the intended dose. The centres were also requested to monitor the water temperature.

The beam output was checked under reference conditions, and additional measurements were performed in non-reference conditions. For the reference beam output, the centre was requested to irradiate at 10 cm depth using either SSD or SAD setup with a 10x10 cm^2 field. Next, measurements were also performed at depths of 8 cm and 20 cm to verify the PDD of the beam as entered in the TPS. The dose was also verified at 8 cm depth with an SSD of 85 cm as part of the validation of the beam model in the TPS. Optionally, the centre could also make measurements in a wedged field at 8 cm depth. For this test, the delivery was split into two halves with the collimator rotated 180° to remove the influence of incorrect positioning. Finally, the output of small fields was checked at 8 cm depth using a minimum field size of 2x2 cm^2. For this irradiation, a small piece of radiochromic film was used to verify that the detector was correctly positioned during the irradiation.

2.2. Detectors and analysis

Cylindrical alanine pellets from Harwell Dosimeters (Oxfordshire, UK) with a thickness of 2.8 ± 0.1 mm and a diameter of 4.8 ± 0.1 mm were used. The average mass in a batch ($\overline{m}$) was 60 ± 2 mg. The alanine pellets consisted of 90.1 % of L-α-alanine and 9.9 % of paraffin as a binder, with 1.2 g/cm^3 as the bulk density. The alanine readout and analysis were based on [21–25].

The alanine detectors were read out in a continuous-wave Bruker EMX^{micro} with a 9″ magnet and ER4119HS-W1 high-sensitivity resonator operating in the X-band. The EPR spectra were acquired as the first derivative of the absorption spectrum using the following spectrometer settings. Microwave frequency 9.7 GHz; Microwave power = 0.25 mW; Field modulation = 0.5 mT; Modulation frequency = 100 kHz; Centre of magnetic field = 348 mT; Sweep width = 30 mT; 2048 channels sampled per sweep with conversion time = 46 ms and time constant = 46 ms. Five spectra per sample, acquired at equal rotation steps, were used to rule out angular dependency. The spectrometer and pellets were in a constantly monitored air-conditioned room with a temperature (T = 18 °C) and relative humidity (≤40 %). Each pellet was weighed individually, and its response was corrected for the actual mass. Variations in the spectrometer sensitivity were corrected by simultaneously measuring the signal of a reference chromium substance placed in the cavity with the alanine pellet.

Table 1
Uncertainty budget on the readout of four irradiated pellets with 8 Gy.

	Uncertainty (%)
Primary standard	0.30
Test probes	**0.93**
Reproducibility	0.50
Irradiation temperature	0.10
Intrabatch homogeneity	0.15
Average mass of 4 alanine probes	0.05
EPR amplitude	0.34
Fading correction	0.10
Environment of irradiation different from calibration irradiation	0.50
Radiation quality different from ^{60}Co	0.45
Base function	**0.25**
Reproducibility	0.05
Irradiation temperature	0.05
Intrabatch homogeneity	0.15
Average mass of 4 alanine probes	0.05
EPR amplitude	0.11
Systematic uncertainty	0.15
Relative combined standard uncertainty (k = 1)	**1.01**

The alanine/EPR system was calibrated by using pellets irradiated in a ^{60}Co reference beam by the Physikalisch-Technische Bundesanstalt (PTB) (0–25 Gy), which NuTeC received annually. The measured alanine spectra contained the signal from the irradiated alanine pellet and from the reference substance. The amplitudes of each alanine pellet and the reference substance were determined using a linear least-squares method. Two base functions were fitted, one containing the pure alanine signal and one containing the signal of the reference substance and background. The base functions for this fit were constructed from (baseline-subtracted) experimental signals from four unirradiated pellets and four pellets irradiated with 25 Gy from the calibration set delivered by the PTB. These pellets must be read on the same day as the test pellets. The spectrum of each test pellet can then be fitted using a linear combination of the two base functions. As part of the internal QA of the alanine/EPR system, four pellets irradiated with 5 Gy (or 7.5 Gy) and four pellets with 15 Gy from the calibration set supplied by PTB were always read alongside the test pellets on each day of alanine readout.

The dose-normalised amplitude $\overline{A_D}$, which can be identified with the absorbed dose (D), can be described as:

$$D = \overline{A_D} = \frac{\overline{A_m}}{\overline{m}} \bullet \overline{m^b} \bullet D^b \bullet \prod_l k_l \tag{1}$$

and $\prod_l k_l$ was defined as:

$$\prod_l k_l = k_Q \bullet \frac{k_t \bullet k_f \bullet k_{pos} \bullet k_{sleeve}}{k_t^b \bullet k_f^b \bullet k_{pos}^b \bullet k_{sleeve}^b} \tag{2}$$

The superscript "b" accounted for the base function derivation. $\overline{A_m}$ was the mass-normalised amplitude with $\overline{m}$ and $\overline{m^b}$ the average masses of the test and base function detectors, respectively. D^b was the dose that the alanine samples received to construct the base function (25 Gy). k_Q was the energy correction factor for the used beam quality during irradiation. $k_T = 1 - c_T(T - T_0)$ was the temperature correction factor with $c_T = 1.8 \bullet 10^{-3} K^{-1}$, T was the temperature of the alanine pellet during irradiation and

$T_0 = 292.15$ K. $k_f = e^{(-C_t(t_{reading} - t_{irradiation}))}$ with t in days and $C_t = \frac{7.10^{-5}}{d}$, with d in days is the fading correction.

k_{sleeve}^b was a correction for the beam attenuation in the sleeve, which is assumed to be unity. k_{pos} was the correction factor for positioning, which was also assumed to be unity because we assumed the alanine detector was positioned correctly in the radiation beam for the depth. The uncertainty of the alanine/EPR dosimetry system was calculated according to [22]. The major contribution of the uncertainty budget for the readout originated from the amplitude determination (±45 mGy per pellet) and also the uncertainty of the amplitudes of the base functions. Other prominent contributors included the homogeneity and weights of the detector material (±0.3 % per pellet), the dose values of the irradiations D and D^b, and the correction for the irradiation temperature. An estimate of the uncertainty in the readout of 4 pellets irradiated with 8 Gy is given in Table 1 [22,26].

2.3. Audit data

The results of the BOA in reference and of the measurements in non-reference conditions between September 2016 and December 2024 are presented in the next section. For audits requiring follow-up, only the results after the follow-up audits are included. The uncertainty on the alanine readout was approximately 1 % (k = 1) [18], as documented in the local audit reports. An example of a local report is available in Supplementary material: Example audit report. Results were excluded in cases where known human error had been identified (e.g., incorrect field size, SSD). Both FF and FFF beams were audited. The majority of the audits were conducted on Varian (58 %) and Elekta machines (39 %). The dataset included one MR-linac.

The results of 224 beams audited were included in this study. For 160 beams, all mandatory tests were performed, and for 64 beams, only the beam output in reference conditions was audited. 49 beams also included irradiations with a wedged field. 156 FF beams and 68 FFF beams were audited (see Fig. 2). For one case, the result at 8 cm was excluded due to human error, and for another case, the small field irradiation could not be performed due to problems with the linac.

3. Results

Across all audits performed between September 2016 and December 2024, the mean absolute deviation between measured and calculated doses was approximately 1 %. For small-field tests, the mean deviation decreased from 1.4 % in 2017 to 1.0 % in 2024. For 10 × 10 cm^2 fields, the mean deviation remained approximately 1 % over the entire period. For all beams, the difference between measured and calculated doses was within ±5 %, except for two small-field beams. For 10 × 10 cm^2 fields, all results were within 2 % of the planned dose. For small-field irradiations, 76 % of beams were within 2 % of the planned dose (see Fig. 3). Comparable results were obtained for FF and FFF beams. Across linear accelerator vendors, overall agreement was similar. For beam output measurements, 70 % of Varian machines were within 1 % of the planned dose, compared with 50 % for Elekta machines (see Fig. 4).

Most audited beams were FF beams while the number of audited FFF beams increased over time.

As part of our internal QA described in 2.2, alanine pellets at certain dose levels were measured from the calibration set sent by PTB on each day of reading. For most measurement days, deviations from the expected dose were within 0.5 %. In February and March 2018, deviations exceeded 1 % and worsened over time. Alanine readout operations were suspended due to a technical issue with the spectrometer and resumed in April 2018 (see Fig. 5).

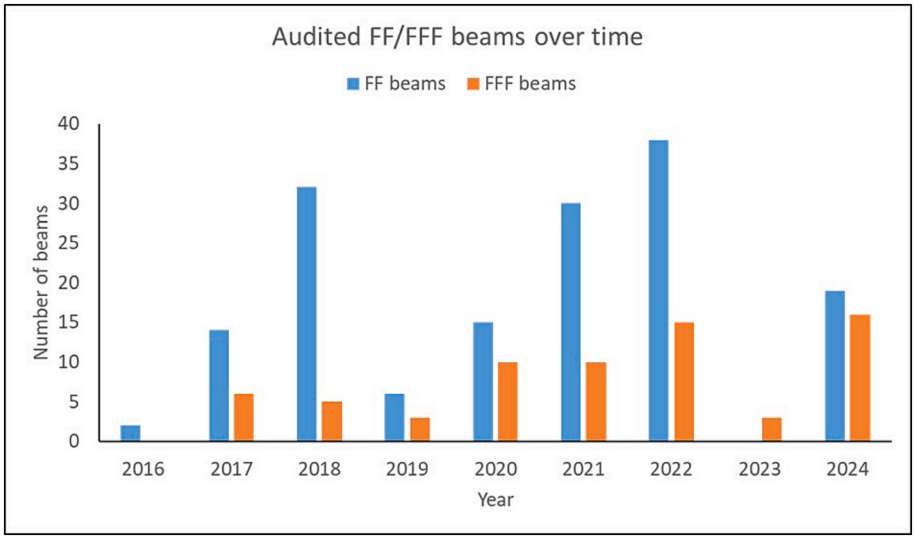


Fig. 2. Evolution in time of audited FF/FFF beams.

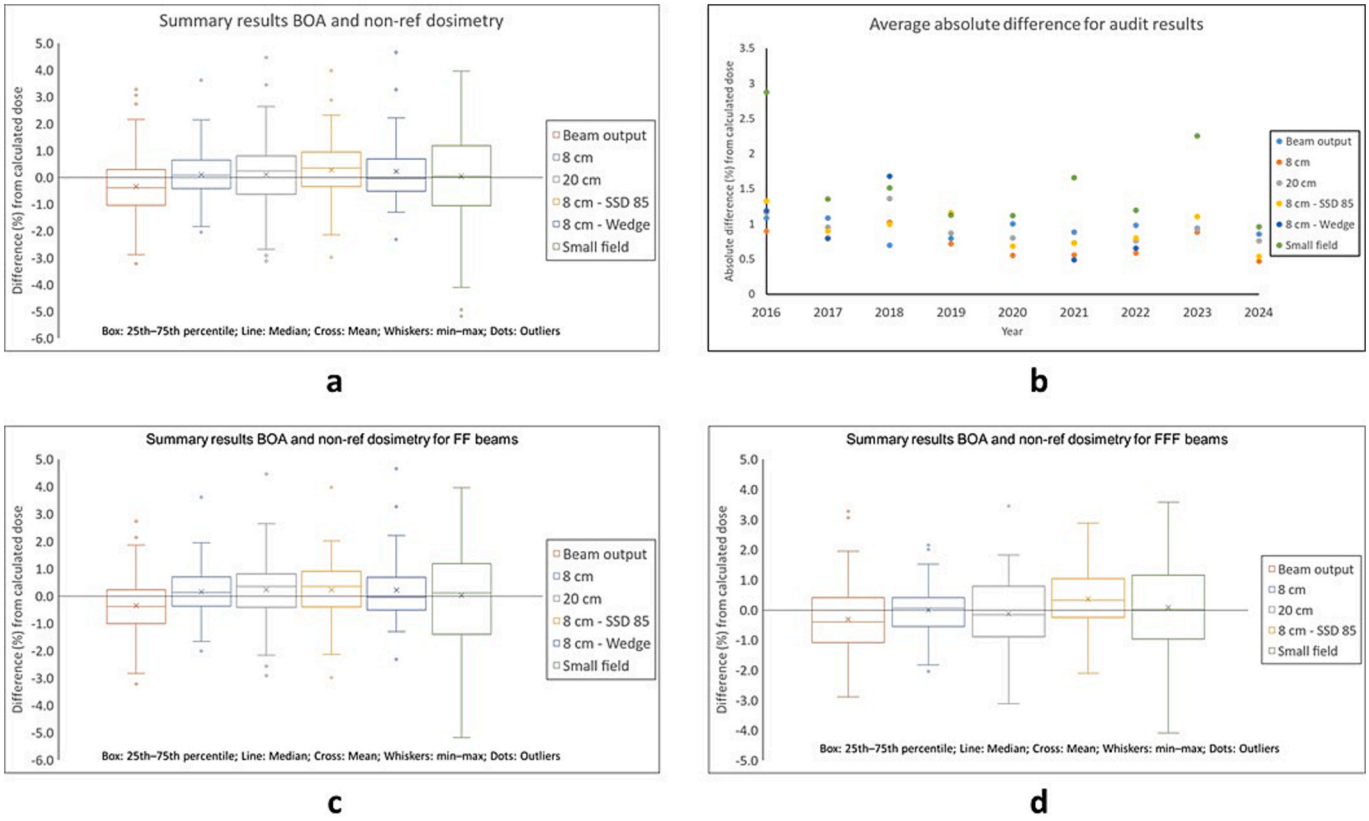
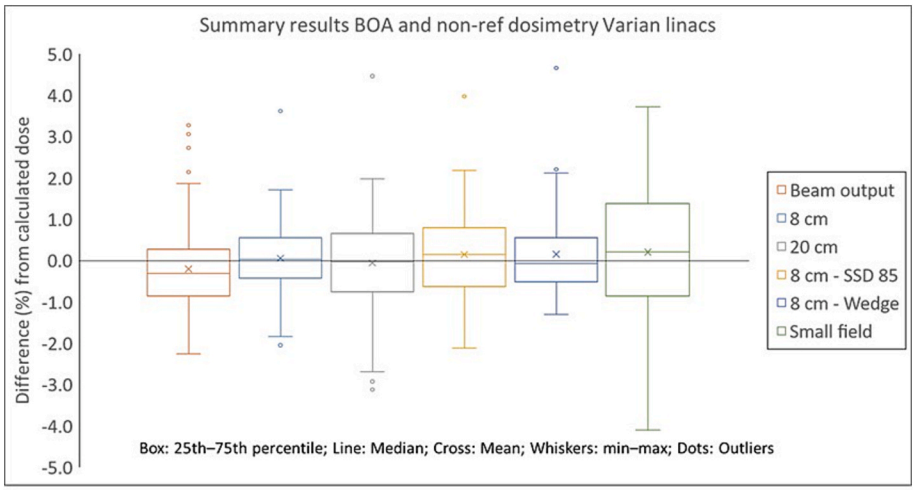
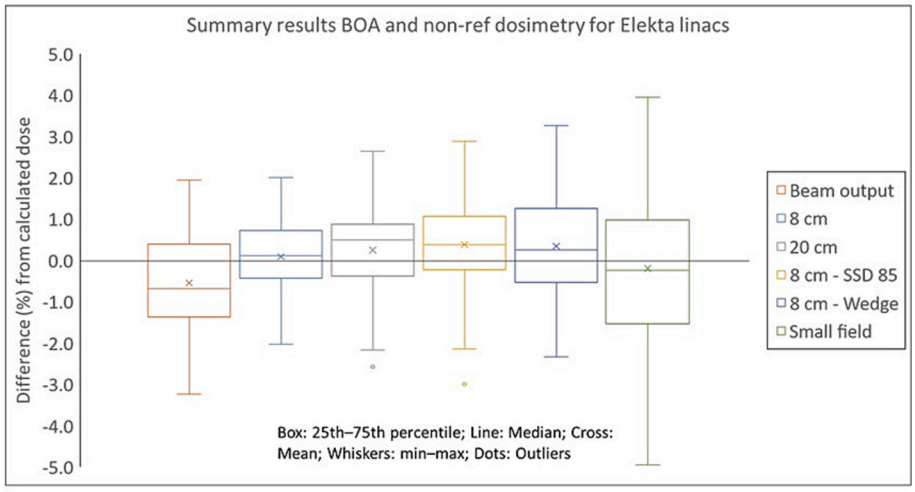


Fig. 3. a) Summary of all the audit results shown as box plots. b) Average absolute difference results for all audit results. c) Results for FF beams and d) FFF beams displayed as box plots. The results of the beam output using alanine dosimetry are used to correct the results for the other five tests.



a



b

Fig. 4. Summary of the audit results for a) Varian linacs and b) Elekta linacs. The results of the beam output using alanine dosimetry are used to correct the results for the other five tests.

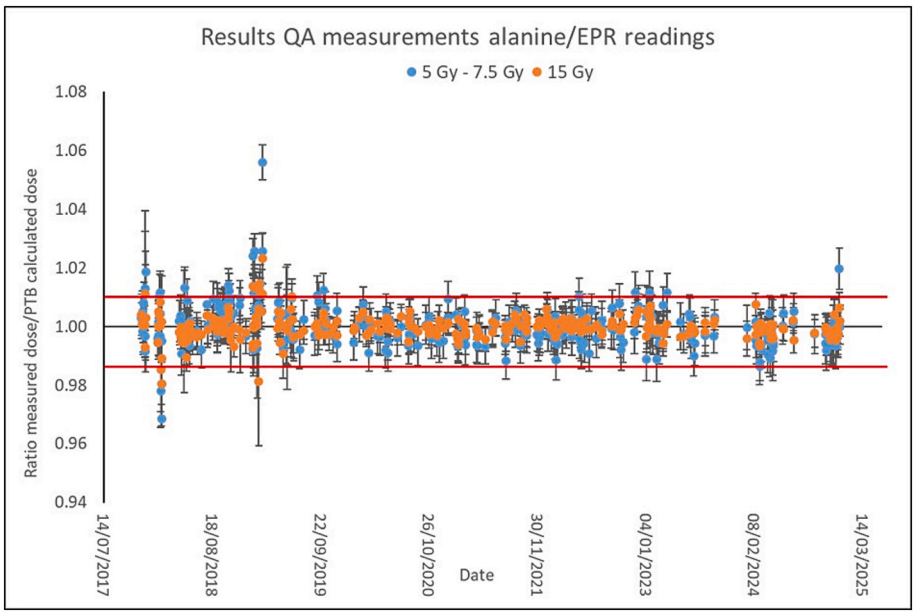


Fig. 5. Results of internal QA measurements on each day of the alanine readout. The error bars indicate the uncertainty on the readout for k = 1. The red horizontal lines indicate the tolerance level of 1 %. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

A remote audit procedure was developed for both reference dosimetry (Level I) and non-reference dosimetry (Level II) for photon beams using alanine pellets with electron paramagnetic resonance (EPR) dosimetry, utilising a custom 3D-printed holder for the detectors. For all the beams the differences between the measured and calculated doses were within ±5 %, except in one case for the small field. The small field results showed more variation compared to the results with a 10 × 10 cm^2 field size irradiation. Similar results were observed for all vendors except that the beam output results for Varian machines were slightly better than the others. A slight positive trend can be observed over the years, with the difference between measured and calculated doses decreasing over time.

The agreement observed in this audit over a long-term period is consistent with results reported for established postal and remote dosimetry programs using TLD and OSLD systems. Mean deviations of approximately 1 % and the high proportion of results within ±2 % indicate stable and accurate performance over time, with a slight improvement observed during the later years of the audit period. Alanine dosimetry is recognised for its high accuracy, dose linearity, and long-term stability, with lower intrinsic uncertainty compared with TLD and OSLD systems, particularly for reference-condition measurements [6,8,11]. The present results demonstrate that alanine-based audits achieve at least comparable, and in some aspects improved, agreement relative to widely used TLD- and OSLD-based audit programs [7,9–12,16,18]. For small-field and non-reference conditions, the broader spread remains consistent with previously reported challenges that are largely independent of detector type [14,15].

The reason we observe a positive trend could be explained by various factors: (1) many new linacs were being installed, (2) the users were getting used to the procedure and (3) we made our technique more robust over the years.

The measurement uncertainty only included the uncertainty in the readout of the alanine, which was around 1 % (k = 1). No uncertainty values were reported for the setup of the irradiation. Any errors during positioning that resulted in dosimetry errors were included in the audit results. This was considered a part of the dosimetry audit. It would be interesting to develop a procedure to separately quantify the part of the dose difference caused by a mistake in the irradiation setup and by actual problems in the linac calibration or TPS configuration in order to interpret the results more accurately.

A limitation inherent in remote auditing is the difficulty in identifying human errors. In cases of large discrepancies, identification is often easy; however, when the measured deviation falls within tolerance, this becomes very difficult or even impossible to assess. The audit procedure requested the centre to take pictures of the setup in an attempt to identify such mistakes, but it remained unclear. In the majority of the doubtful cases, the issues were resolved by performing a follow-up audit or by correctly identifying the human error. The follow-up remained a choice of the centre, however. This makes it very difficult to assess whether the poor results are caused by calibration errors, TPS errors, or simply obvious human errors. IROC also addressed this issue in [12]. If no follow-up audits are requested, the results are included in the statistics. In our case, the follow-up audit recurrence rate was approximately 5 % of the audited beams, which was similar to that reported in [12]. The decision to compare our measurements against calculations from the TPS allowed us to identify some rare minor issues in the modelling of the beam and to help some centres to make the transition towards newer models. It would not have been possible if we had simply compared measurements against measurements.

In conclusion, all audit results were satisfactory. There is a slight positive trend, or at least a status-quo, in the audit results over the years, which implies that the accuracy of the radiotherapy calculations is maintained.

CRediT authorship contribution statement

Burak Yalvac: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Nathalie Reulens:** Resources. **Brigitte Reniers:** Investigation, Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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Supplementary material: Example audit report.

See the Supplementary document. While the original reports are typically issued in Dutch or French, the version included in this paper has been translated into English.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.phro.2026.100914.

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