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Original Research Article

Remote beam output audits: A global assessment of results out of tolerance

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ABSTRACT

Background and purpose: Remote beam output audits, which independently measure an institution's machine calibration, are a common component of independent radiotherapy peer review. This work reviews the results and trends of these audit results across several organisations and geographical regions.

Materials and methods: Beam output audit results from the Australian Clinical Dosimetry Services, International Atomic Energy Agency, Imaging and Radiation Oncology Core, and Radiation Dosimetry Services were evaluated from 2010 to the present. The rate of audit results outside a ± 5% tolerance was evaluated for photon and electron beams as a function of the year of irradiation and nominal beam energy. Additionally, examples of confirmed calibration errors were examined to provide guidance to clinical physicists and auditing bodies.

Results: Of the 210,167 audit results, 1323 (0.63%) were outside of tolerance. There was a clear trend of improved audit performance for more recent dates, and while all photon energies generally showed uniform rates of results out of tolerance, low (6 MeV) and high (≥ 18 MeV) energy electron beams showed significantly elevated rates. Twenty nine confirmed calibration errors were explored and attributed to a range of issues, such as equipment failures, errors in setup, and errors in performing the clinical reference calibration. Forty-two percent of these confirmed errors were detected during ongoing periodic monitoring, and not at the time of the first audit of the machine.

Conclusions: Remote beam output audits have identified, and continue to identify, numerous and often substantial beam calibration errors.

1. Introduction

High quality radiotherapy is critically important for patient outcomes; it also improves the power of clinical trials and thereby improves their effectiveness [1–3]. High quality radiotherapy requires the accurate calibration of external beam radiotherapy equipment; any error in the clinical reference calibration of a beam is a systematic error that impacts all patients treated with that beam. As such, independent verification of machine output (i.e., a beam output audit) is a standard component of clinical trial quality assurance (QA), and is often conducted as part of good-practice quality assurance. A common approach to such output verification is through a remote audit – i.e., where the dosimeters are mailed to the institution for irradiation.

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Numerous QA groups across the world provide independent, remote, beam output audits, and the nature of these programs has been well documented [6–12]. However, a focused evaluation of audit results outside of tolerance, particularly from a large-scale global perspective, has not previously been performed. The current study therefore presents such an evaluation from remote audits conducted by four QA groups, including identified causes of calibration errors. Such information can provide guidance to the medical physics community about where problems originate, as well as highlighting the value of such remote output verification programmes.

2. Materials and methods

2.1. Remote beam output audits

Audit results in this study were conducted by four QA groups that are part of the Global Quality Assurance of Radiation Therapy Clinical Trials Harmonisation Group (Global Harmonisation Group [GHG]: https://rtqaharmonization.com/). The GHG works to ensure consistency and coordination of QA efforts. This group is currently comprised of six member groups (who provide quality assurance for clinical trials) and three observer QA groups (who provide radiotherapy quality assurance services not focused on clinical trials) [13]. Remote beam output audits are typically conducted using passive luminescent dosimeters that are mailed to an institution [14]. The institution irradiates them to give a known dose under reference/calibration conditions. These dosimeters are returned and analyzed, and the measured dose is compared to that intended by the institution.

Of the nine groups involved in the GHG, six conduct remote beam output audits. Details about these programmes are shown in Table 1. Although similar, the tolerance for agreement between the measured and stated dose was not identical between groups. Notably, even for a nominal 5% tolerance, some groups round the audit result to 2 decimal places before evaluating (acceptability therefore being ≥0.945 and < 1.055) while other groups do not round (acceptability being defined as ≥0.950 and ≤1.050). For consistency and inter-comparability, a ± 5%-rounded tolerance (the loosest tolerance) was used in all evaluations in this study (i.e., results outside of tolerance were < 0.945 or ≥1.055), even though that did not exactly match the criteria used by some auditing bodies. Results of remote beam output audits were available only for 4 QA groups because not all results were accessible. Therefore only these four groups were evaluated further.

Remote beam output audit results were reviewed from 2010 to the present to examine contemporary machine calibration issues. Minor variations in this time period were allowed to limit the analysis to a single dosimeter: in mid-2010 IROC transitioned from TLD to OSLD; only OSLD results are included. In 2017 the IAEA transitioned from TLD to radiophotoluminescent (RPL) glass dosimeters; only TLD results are included. Additionally, the ACDS has only conducted these audits since 2012.

Individual audit results were excluded from consideration when there were known human errors in the irradiation of the audit dosimeters, e.g., if the institution reported (before any result was issued) that the wrong field size, SSD, or similar had been accidentally used, or when the result had double the expected dose or approximately zero dose (indicating the dosimeters were accidentally irradiated twice and/or not irradiated).

2.2. Data analysis

The rate of audit results outside of the ± 5% tolerance was compared between the QA groups for each beam type (all, photon, electron). These rates were compared using ANOVA with follow up using pairwise, two-sided, tests including Benjamini-Hochberg corrections for multiple comparisons. These incorporated the binomial nature of the response and a logit link function. The 95% binomial confidence intervals for the rate of results outside of tolerance in each group were computed using the Agresti-Coull method.

The ACDS reported no beams outside a ± 5% tolerance, and the IAEA does not audit electron beams, so no further analysis was performed on these data sets. For all other data sets (each QA group and beam type), the out-of-tolerance rates were evaluated both as a function of year of irradiation, and as a function of beam energy.

To assess the rate of results outside tolerance versus the year of irradiation, a generalized linear model was fit for each dataset with a logit link function and a binomial distribution for the rate. This regression model was chosen because it forces the predicted probability of result outside tolerance in future years to remain greater than zero.

To assess the rate of audit results outside tolerance versus beam energy, photon beams were subdivided to include SRS and FFF beams (which did not include Cyberknife or Tomotherapy beams). Cobalt sources included both historical c-arm external beam units as well as modern ViewRay units. All analysis was conducted using ANOVA, assuming a binomial distribution for the rate and a logit link function, and results were evaluated relative to the most common beam energy audited (6 MV for photons and 12 MeV for electrons). Significant ANOVA results were followed up with pairwise tests using the Benjamini-Hochberg correction for multiple comparisons.

Table 1
Methods for conducting remote beam output audits. Details of the dosimeter and dosimetry programme are shown for each QA group in the GHG that performs remote beam output audits.

QA Group	Dosimeter	Frequency	Mandatory audit?	Primary recipients	Uncertainty (%) (k = 1)	Tolerance (± %)	Beams per year (ave)	Key ref(s)
ACDS*	nanoDot OSLD	Every other year	Yes	Australian facilities	Electrons:1.7 Photons: 1.3	Electrons: 5.1 Photons: 3.9	392	4,5
EORTC	Various	When joining a trial if last audit > 2 years prior	Yes	European clinical trial participants	Varies-not always known by EORTC	5	356	6
IAEA*	TLD-100	By request	No	Facilities in low/middle income countries	^{60}Co: 1.5 X-rays: 1.7	5	623	7–9
IROC*	nanoDot OSLD	Annual	Yes	North American clinical trial participants	1.7	5	16,680	10,11
JCOG**/ ANTM	Glass RPLD	Every 3 years	Yes	Japanese facilities	1.1	5	~500	12
RDS*	TLD-100	By request	No	North American facilities	1.3	5	11,775	11

Abbreviations: ACDS: Australian Clinical Dosimetry Services; EORTC: European Organisation for Research and Treatment of Cancer; IAEA: International Atomic Energy Agency; IROC: Imaging and Radiation Oncology Core; JCOG: Japan Clinical Oncology Group; ANTM: Association for Nuclear Technology in Medicine; RDS: Radiation Dosimetry Services; OSLD: optically stimulated luminescence dosimeter; TLD: thermoluminescent dosimeter; RPLD: radiophotoluminescent dosimeter.

* Beam output audit results evaluated in this study.

** Measurements of the reference output dose for JCOG trials are performed by ANTM for designated cancer centers.