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Original Research Article

Dosimetric end-to-end tests in a national audit of 3D conformal radiotherapy

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ABSTRACT

Background and purpose: Independent dosimetry audits improve quality and safety of radiation therapy. This work reports on design and findings of a comprehensive 3D conformal radiotherapy (3D-CRT) Level III audit.
Materials and methods: The audit was conducted as onsite audit using an anthropomorphic thorax phantom in an end-to-end test by the Australian Clinical Dosimetry Service (ACDS). Absolute dose point measurements were performed with Farmer-type ionization chambers. The audited treatment plans included open and half blocked fields, wedges and lung inhomogeneities. Audit results were determined as Pass Optimal Level (deviations within 3.3%), Pass Action Level (greater than 3.3% but within 5%) and Out of Tolerance (beyond 5%), as well as Reported Not Scored (RNS). The audit has been performed between July 2012 and January 2018 on 94 occasions, covering approximately 90% of all Australian facilities.
Results: The audit pass rate was 87% (53% optimal). Fifty recommendations were given, mainly related to planning system commissioning. Dose overestimation behind low density inhomogeneities by the analytical anisotropic algorithm (AAA) was identified across facilities and found to extend to beam setups which resemble a typical breast cancer treatment beam placement. RNS measurements inside lung showed a variation in the opposite direction: AAA under-dosed a target beyond lung and over-dosed the lung upstream and downstream of the target. Results also highlighted shortcomings of some superposition and convolution algorithms in modelling large angle wedges.
Conclusions: This audit showed that 3D-CRT dosimetry audits remain relevant and can identify fundamental global and local problems that also affect advanced treatments.

1. Introduction

Quality of Radiation Therapy delivery directly impacts the outcome of the treatments delivered to patients. This includes avoiding catastrophic failures but also adherence to the details of dosimetric procedures, which can have a measurable impact on clinical outcomes [1]. The role of dosimetry audits in the context of clinical trials has been established [2–5] and dosimetry audits for clinical trials are being performed worldwide [6]. The role of dosimetry audits as a quality assurance tool outside clinical trials is expanding [7,8]. They are part of government efforts to improve and maintain quality in radiation therapy. Participation in dosimetry audits has become a component of licensing processes in some jurisdictions.

Level III audits commonly use a phantom which is put through the

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entire chain of procedures that a patient would go through during radiation treatment simulation, planning and delivery [2]. Substantial experience in Level III and other comprehensive dosimetry audits has been reported on from the northern hemisphere; including audits in the United Kingdom (UK) [7,9–11] and those offered by Imaging and Radiation Oncology Core (IROC) [12–18]. Audits use different dosimeters, including thermoluminescence detectors (TLD) [19], optically stimulated luminescence detectors (OSLD) [18,20,21], Alanine [7], radiochromic film [22], ionization chambers [10,23,24] and electronic portal imaging devices [25,26] the choice of which impacts accuracy and timeframe of result availability. High level audits often rely on volunteer efforts [7], and some comprehensive audits have been cut back due to financial constraints [18]. Many high level audits nowadays focus on the use of advanced treatment modalities [27–29].

The presented Level III (end-to-end test) dosimetry audit for 3D conformal radiotherapy (3D-CRT) differed from similar audits in several aspects: Using primary standard calibrated dosimeters and an onsite audit approach with a team exclusively dedicated to radiotherapy audits the audit was able to have lower uncertainties and tighter action levels. Combined with covering almost an entire country and continent, including private and public providers alike and irrespective of clinical trials participation, this meant that the audit did not only give an overview of the status of the dosimetry therein, but it was also able to identify even small problems and trends with certain equipment combinations.

2. Material and methods

2.1. Australian Clinical Dosimetry Service

Starting in 2011 Australia has implemented a national dosimetry audit program with the Australian Clinical Dosimetry Service (ACDS). The program had initially been trialled as a government funded pilot project [30] and is now self-funded (as of January 2017). The ACDS has built their audit system utilizing the work of others [7,31,32] while further improving the methods [20,30,33] and adapting to the dimensions, population densities and technological diversity of Australia and to the rules of the pilot funding [30,34]. The latter included deliverables for a three year time line, a focus on general clinical needs rather than on clinical trials, and inclusion of 3D conformal therapy audits. Details of ACDS Level I and Level II audits have been reported [23,35]. So have selected findings of the Level II and III audits [36]. This work reports comprehensively on the Level III 3D-CRT audit. Following four field trials, February-April 2012, the audit has been performed on 94 occasions between July 2012 and January 2018, covering approximately 90% of all Australian facilities.

2.2. Onsite audit

This audit was designed as an onsite audit. Prescribed planning, quality assurance (QA) and delivery were performed by clinical staff from the audited facility while an audit team measured the dose delivered to the phantom. Outreach to radiation therapists through presentations at their national meetings and a publication in their journal helped to closer involve them in the audit process [37].

The onsite approach was chosen over a postal audit as it allowed the program to start quickly with a single phantom and to use ionization chambers. Being onsite during the audit provided the opportunity for the audit team to observe any problems with the audit procedures. Additionally, an onsite audit team could help with troubleshooting in case of suboptimal audit results, bringing the facility back to high quality patient treatment more quickly.

2.3. Dosimetry equipment

Ionisation chambers offer the highest accuracy for field measurements and immediate readout and therefore quick availability of (preliminary) audit result. Farmer type PTW 30013 chambers (Physikalisch Technische Werkstätten, Freiburg, Germany) were selected for this audit, as they were for the ACDS Level Ib audit [30]. This overlap and the chamber's known quality and robustness were accepted as a trade-off for their larger volume compared to available smaller chambers.

The "PC electrometer" (Sun Nuclear, Melbourne, FL, USA) was selected for its small size, enabling the audit team to also bring a backup device. The lightweight two channel electrometer was thoroughly tested before deployment. The presence of a second channel allowed for concurrent measurement at two locations in the phantom. Some of the secondary measurement locations were considered interesting but not critical for evaluation and potentially subject to larger uncertainties. For those points the "Reported Not Scored", RNS category was introduced, which is also used in the ACDS Level II audit [23]. The electrometer's log function provided a record of all measurements.

Facility independent equipment including backup was brought onsite. Ionization chambers and electrometers had been directly calibrated by the Australian Primary Standards Laboratory. See Supplemental Material for details regarding logistics.

2.4. Audit phantom

The commercial anthropomorphic "IMRT Thorax Phantom Model 002LFC" (CIRS, Norfolk, VA, USA) had been initially chosen over a custom phantom to reduce the risk of downtime if the phantom was lost or damaged in transport. This choice also allowed facilities to replicate audit conditions when troubleshooting.

To reduce its weight and size for easier transport, the phantom (Supplementary Fig. 1) was shortened by seven slices. In mid-2016 the commercial phantom was replaced with a custom phantom designed to accommodate both, the here discussed 3D-CRT fields, some of which are continued to be used, and new, intensity modulated and volumetric arc therapy fields for additional checks, which are beyond the scope of this work. The risk of downtime due to loss or damage remains and will be mitigated by maintaining two phantoms.

2.5. Audit cases and measurement locations

At the time of the audit set-up (2012) the majority of patients in Australia were treated with 3D-CRT. Conformal treatment plans were chosen to test performance with wedges, asymmetric fields and low density inhomogeneities.

Measurements were performed as absolute dose measurements using an adapted TRS 398 [38] approach. This included corrections for temperature and pressure. The correction factor k_Q was calculated based on the facility provided beam quality information, while standard correction factors k_s and k_{pol} were used based on experience with each ionization chamber.

For efficiency reasons all cases were initially only delivered with standard (flattened) 6 MV beams. Higher energy 3D-CRT beams were introduced in mid-2016 and are not discussed here.

Case 1 investigated system performance close to reference conditions in a surface distance based setup at 3 cm depth (Point 1). Illustrations of all cases are in Supplementary Figs. 2–5. Table 1 in [36] lists plan details. Point 10 was used to assess depth dose accuracy. A measured correction factor of ~1% was applied to compensate for the increased dose at Point 10 due to the presence of a chamber at Point 1.

Case 2 tested performance with a wedge on an oblique body surface using a single field plan adapted from [32]. Point 1 was the isocenter and prescription point. Point 4 was located upstream and posteriorly, moving it towards the thinner end of the wedge. Point 7 was measured as RNS to gain understanding about the performance of the planning system for points far outside the field.

Case 3 was a three field plan with an anterior field and two half-

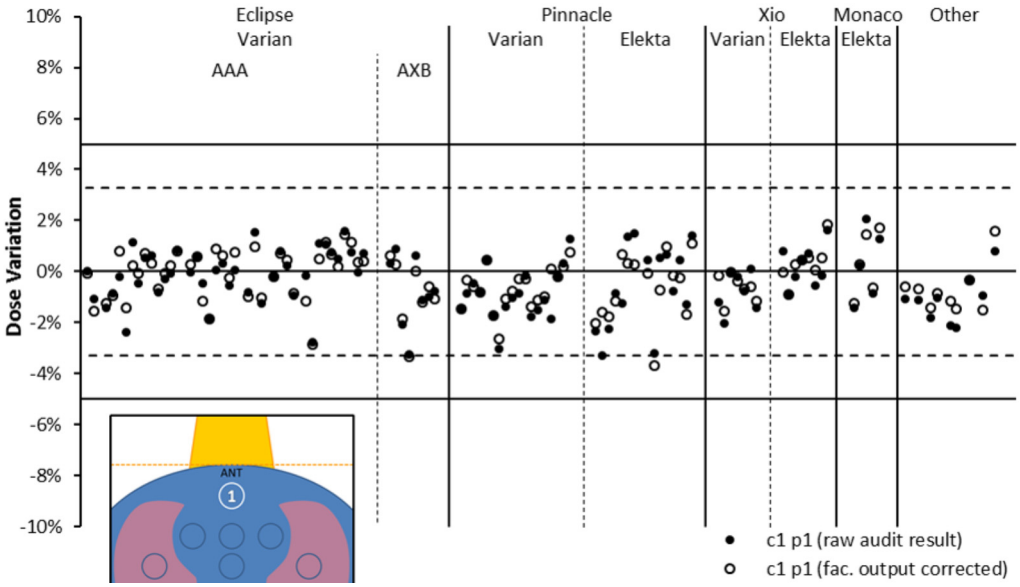

Fig. 1. Dose variation at near reference condition (Case 1 Point 1): raw variation as per equation (1) (closed circles, Mean −0.4%, SD 1.2%) and variation corrected by facility reported output (open symbols, Mean −0.5%, SD 1.0%). Here and in all following figures results are broken down by planning and delivery system combination. Eclipse results are further broken down into dose calculation algorithms, as some results differ between them. Results for Pinnacle, Xio and Monaco are not further broken into the encountered respective dose calculation algorithms, as no significant differences have been observed here.

beam blocked lateral fields with 30° wedges passing though lung material [32]. The main measurement location was Point 5. Additional measurements were taken at Point 8, inside the lung material, and at Point 10, at greater depth for the anterior beam. Each beam was analysed separately.

Cases 4 and 5 were added to test the modelling of a 60° wedge. The phantom position was not changed between the two cases allowing for assessing the impact of the wedge at a series of points at different depths and at one off-axis point. Case 4 by itself also served in the assessment of the handling of dose behind lung inhomogeneities.

2.6. Audit scoring

The variation from the ACDS measured dose was calculated with local reference for each point:

$$\text{Dose Variation from ACDS}_{\text{Local Reference}} = \frac{\text{Facility Stated Dose} - \text{ACDS Measured Dose}}{\text{ACDS Measured Dose}} \quad (1)$$

Audit point results were determined as Pass Optimal Level (deviations within 3.3%), Pass Action Level (greater than 3.3% but within 5%) and Out of Tolerance (beyond 5%), in addition to the above mentioned RNS. The result of the overall audit was equal to that of the worst measurement point.

Facilities provided their assessment of the current linac output. However, for audit scoring no corrections were made for deviations from 1 cGy/MU. For comparisons across facilities, and as noted with the corresponding figures, the results have often been displayed relative to those of Case 1, Point 1 focussing them on the specific test and eliminating the impact of daily output fluctuations and reference condition accuracy.

$$\text{Dose Variation}_{\text{corrected}} = \frac{\text{Dose Variation}_{\text{uncorrected}} + 1}{\text{Dose Variation}_{\text{c1p1}} + 1} - 1 \quad (2)$$

3. Results

3.1. Linac output/Reference

The facility reported dose variation from the nominal 1 cGy/MU ranged from −2.0% to 1.3% (Mean ± 1 SD: 0.1 ± 0.6%).

Planning system accuracy close to reference conditions, measured with Case 1 Point 1, was within “Pass Optimal” for all audits, as shown in Fig. 1.

3.2. PDD modelling

Fig. 2 shows the variations found for doses measured at larger depths in the phantom, corrected for those found for Point 1 Case 1, which describes the ability of the planning system to correctly model depth dose.

For the larger depth (Case 1 Point 10) the average variation was −0.4 ± 1.3%, indicating that there is no general bias towards either overestimating or underestimating the depth-dose curve. This is supported by the results for the shallower Point 5 of Case 3 (−0.2 ± 0.8%) and as well Case 3 Point 10 (−0.1 ± 2.8%, not shown).

3.3. Lung inhomogeneity

The analytical anisotropic algorithm (AAA) overestimated the dose in water equivalent material behind lung (Case 4 Fig. 3), leading to an underdose in the measurement. When investigating multiple points at different depths behind the lung material (Points 2, 3 and 4) there was no depth dependence of the magnitude of the overestimation from the AAA algorithm (1.9 ± 1.0%, 2.2 ± 0.8% and 1.9 ± 0.8%, respectively). However, deviations were larger for the off axis point 5 (3.2 ± 1.2%) which included a longer path through the lung material.

Fig. 4 shows exploratory investigations (RNS) into the performance of treatment planning system (TPS) algorithms to accurately predict the dose in lung using a chamber directly inserted into the lung material (Case 3 Point 8). AAA underestimated the dose in this case. For the right lateral (RLAT) field the underestimation was markedly larger than for the left lateral (LLAT) field. Assessment of a point located centrally in

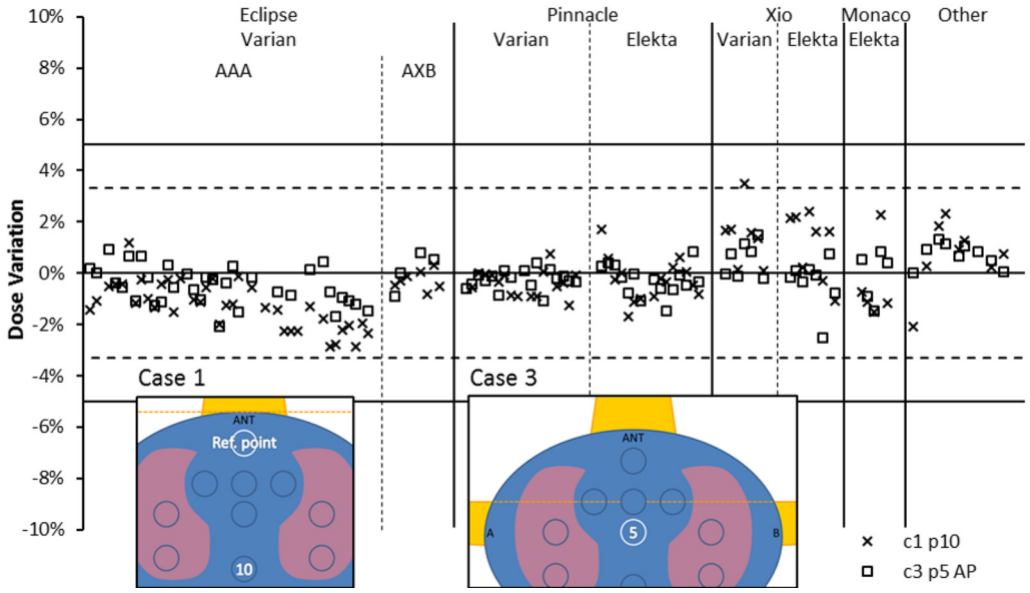

Fig. 2. PDD investigations: dose variations for points at different depths in the phantom corrected by the dose variation measured in Case 1 Point 1 per Eq. (2).

the phantom in water equivalent material (Point 5 – Supplemental Fig. 8) showed the overestimation of dose behind the lung for the AAA algorithm as in Case 4 (Fig. 3). The Monaco system also underestimated the dose in lung but equally for both beams, while Xio overestimated the dose in lung for Varian machines for both beams. In both systems dose calculation for the central Point 5 was in agreement with measurement. Small variations seen for Pinnacle/Elekta inside lung material are similar to those in the central point in water equivalent material.

Results for Point 1 of Case 2, the direct beam path to which passes close by but does not traverse lung tissue, indicated a similar effect as that of lung for the AAA algorithm (Fig. 5). Point 4 of Case 2 caused many out of tolerance results for the audit. Its location close to the field edge required accurate setup and jaw position calibration in addition to correct inhomogeneity handling by the planning system.

3.4. Wedges

Wedged field calculations presented problems for few selected facilities only (Fig. 6). System related trends were seen for the Pinnacle/Elekta combination with a negative bias due to the wedge and for the Xio/Elekta combination with most points grouped around −3 to −4%. A single beam model had results in the opposite direction grouped, suggesting variation in the individual facility implementation of the algorithm.

3.5. Overall outcomes

Of the 94 audits 50 (53%) scored “Pass Optimal Level”, 32 (34%) “Pass Action Level” and 12 (13%) “Out Of Tolerance”.

Recommendations were given regarding the modelling of low-density inhomogeneities (16), photon calibration (6), the handling of wedges in general (5) and off axis (5), depth dose modelling (2), and temperature/pressure correction (2). Additionally, problems occurred

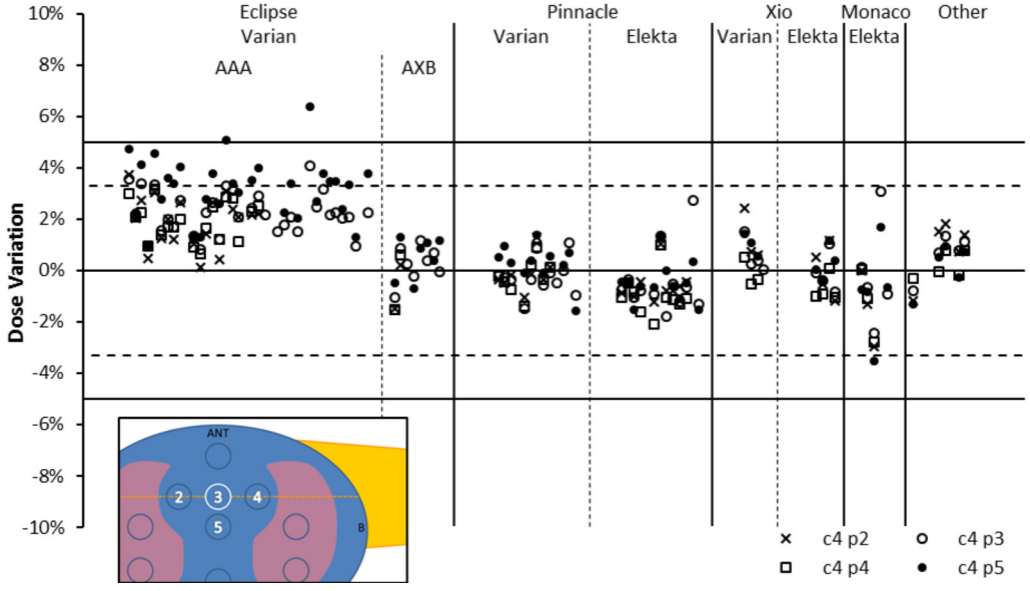

Fig. 3. Dose variation for points behind lung (Case 4 Points 2–5), corrected by the dose variation measured in Case 1 Point 1 per Eq. (2).

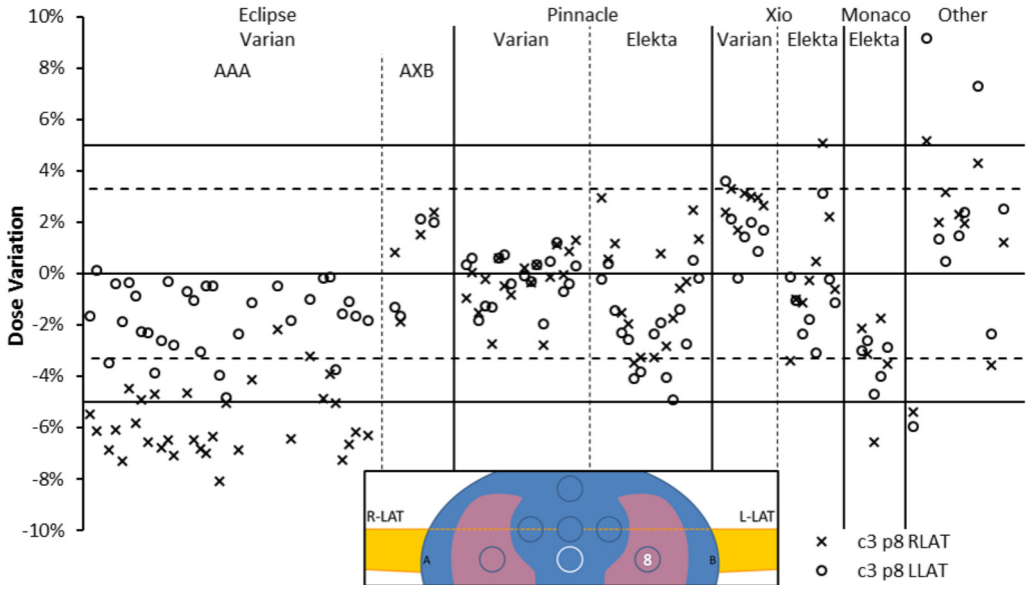

Fig. 4. Dose variation inside lung: Case 3 Point 8, right lateral (RLAT) and left lateral (LLAT) beams, corrected by the dose variation measured in Case 1 Point 1 per Eq. (2).

when facilities did not follow their internal procedures when preparing or delivering the audit cases (3), such as plan check and QA. Some of the action level results could be resolved to optimal by using MV based k_Q in the reference dosimetry as the audit team did.

4. Discussion

Results of this audit confirmed and further illustrated dosimetric problems with selected planning system – delivery system combinations. This applied to the modelling of the Elekta wedge in Xio [23,39] and to the overestimating of the dose behind low density inhomogeneities by Varian's AAA [36,40,41]. The latter also extended to beam setups, which resemble a typical breast cancer treatment beam placement (Fig. 5). While there is also a wedge in place, wedge calculation results for AAA have been shown to be accurate (Fig. 6) so the effect is likely due to AAA's handling of inhomogeneities. The resulting overestimation of the dose to the target was consistent with findings by Petillion et al. who reported a shrinking of the 95% and 100% isodoses in their breast treatment plans. Starting with pencil beam calculations (PBC) the isodoses shrunk when going to AAA, further when calculating with Acuros, dose to medium, and again further when Acuros, dose to water [42]. This in turn agreed with Yoo et al. who described that plans with AAA showed significant underdosage ($p = 0.002$) of the target volume compared to the original PBC plans. [43] Hence the target area in a breast cancer treatment with tangential beams likely receives a lower dose than calculated with AAA.

Measurements inside lung material of the phantom showed a variation in the opposite direction for AAA. Measured dose was found to be higher than calculated. This was more pronounced for the right lateral beam with the measurement point in the left lung. As this beam first traversed the right lung and then water equivalent material in the middle of the phantom before reaching the measurement point in the

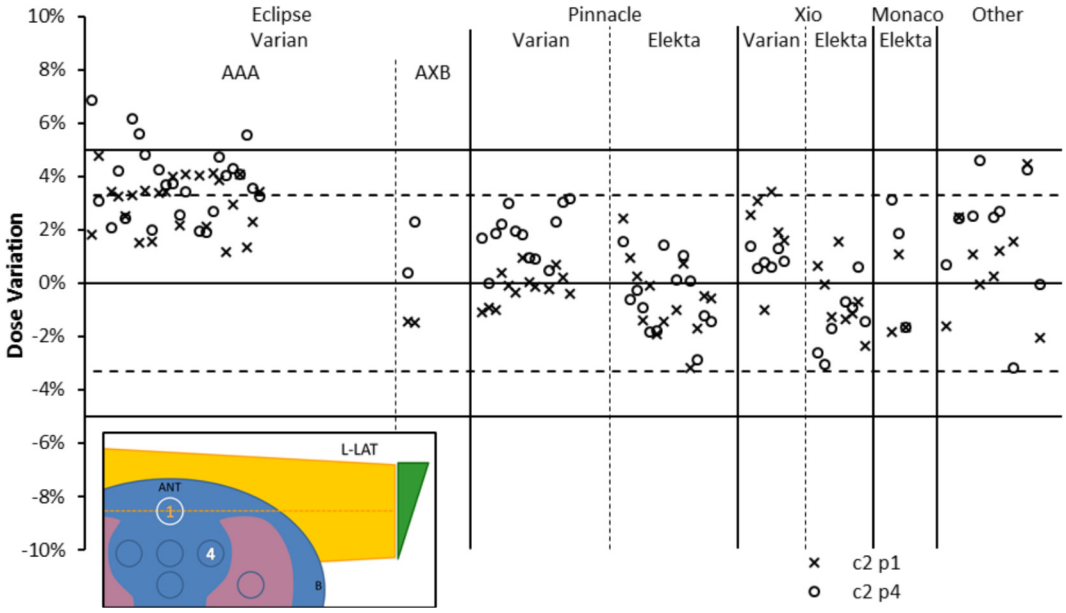

Fig. 5. Dose variations for Case 2. Dose variation at the measurement points has been corrected by the dose variation measured in Case 1 Point 1 per Eq. (2).

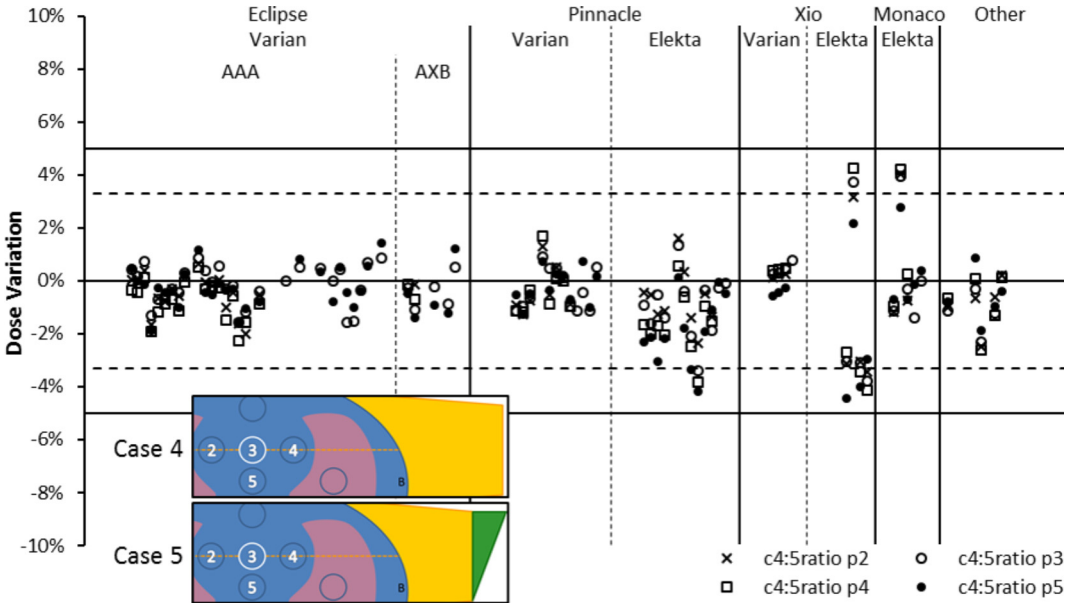

Fig. 6. Wedge impact. Difference in dose variations for Cases 4 (no wedge) and 5 (60° wedge).

left lung a combination of effects is assumed. Hence, using AAA for dose calculation risks under-dosing a target beyond lung and over-dosed the lung upstream and downstream of the target. For the Monaco algorithm, which calculated also low inside the lung, yet equally for both lateral beams, the cause is possibly the reported dose being dose to medium. Ion chamber measurements inside the lung carry a larger uncertainty. Therefore these results are RNS at this point.

Non-optimal results for audited facilities were often a combination of the inherent algorithm difficulties with inhomogeneities or wedges and local TPS implementation. This is in agreement with Kry et al., who wrote that dosimetric errors usually originated with the TPS beam model, and that more focus and attention should be given to beam model commissioning and QA [18].

The ACDS had a unique opportunity to implement high level onsite audits with sufficient resources while elsewhere site visits were no longer routinely offered because of budgetary constraints [18] or audits rely on volunteers [7].

Results from the presented comprehensive, high accuracy Level III 3D-CRT audit of Australian radiotherapy facilities illustrated dosimetric problems in clinically used dose calculation algorithms mainly related to low density inhomogeneities but also to wedges. Most facilities passed the audit. However, the number of action level and out of tolerance result showed that 3D-CRT dosimetry audits remain relevant and can identify fundamental global and local problems that will also affect advanced treatments.

Conflict of interest

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.phro.2018.03.006.

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