Original paper

National dosimetric audit network finds discrepancies in AAA lung inhomogeneity corrections

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ABSTRACT

This work presents the Australian Clinical Dosimetry Service's (ACDS) findings of an investigation of systematic discrepancies between treatment planning system (TPS) calculated and measured audit doses. Specifically, a comparison between the Anisotropic Analytical Algorithm (AAA) and other common dose-calculation algorithms in regions downstream (≥ 2 cm) from low-density material in anthropomorphic and slab phantom geometries is presented. Two measurement setups involving rectilinear slab-phantoms (ACDS Level II audit) and anthropomorphic geometries (ACDS Level III audit) were used in conjunction with ion chamber (planar 2D array and Farmer-type) measurements. Measured doses were compared to calculated doses for a variety of cases, with and without the presence of inhomogeneities and beam-modifiers in 71 audits. Results demonstrate a systematic AAA underdose with an average discrepancy of $2.9 \pm 1.2\%$ when the AAA algorithm is implemented in regions distal from lung-tissue interfaces, when lateral beams are used with anthropomorphic phantoms. This systemic discrepancy was found for all Level III audits of facilities using the AAA algorithm. This discrepancy is *not* seen when identical measurements are compared for other common dose-calculation algorithms (average discrepancy $-0.4 \pm 1.7\%$), including the Acuros XB algorithm also available with the Eclipse TPS. For slab phantom geometries (Level II audits), with similar measurement points downstream from inhomogeneities this discrepancy is also not seen.

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Introduction

In radiation therapy treatment planning, the dose calculation algorithm of the treatment planning system (TPS) is relied upon to accurately calculate the dose and determine the Monitor Units (MU) to be delivered by the treatment linear accelerator (linac) to treat a particular tumour. Commercial treatment planning systems each use a particular 'brand' of algorithm [1]. The major (non-full Monte Carlo) dose calculation algorithms used in TPS are:

- Superposition [2]
- Collapsed Cone Convolution [3] (CCC)
- Anisotropic Analytical Algorithm [4] (AAA)
- Pencil Beam [5,6] (PB)
- Collapsed Cone [7] (CC)

Generally, dose calculation algorithms fall into correction-based equivalent path-length algorithms and model based algorithms [8] with electron transport either explicitly accounted for, or neglected. There is a large body of literature evaluating the performance of each algorithm both compared to other algorithms/Monte Carlo [8–12] in clinical scenarios and measurement [13–15]. It is known that each algorithm has its associated advantages and disadvantages in terms of speed of calculation, accuracy and in dealing with

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inhomogeneities in both tissue structure and density. Improvements in the accuracy of calculated doses have been shown when algorithms explicitly consider volume scatter and changes in electron transport in low/high density regions, such as lung or bone.

In Australia, the Australian Clinical Dosimetry Service (ACDS) [16] has been performing Level II [17] and Level III audits [18] across Australian radiotherapy facilities for the past two years. In both audits, measurements are compared to doses calculated with the algorithms listed above for both anthropomorphic (Level III) and slab geometries (Level II). Measurements for both audits are done onsite by an ACDS audit team using Primary Standards Laboratory (PSL) calibrated Farmer type ionization chambers and an array of ionization chambers. To date (2014), 36 Level II and 35 Level III audits have been performed evaluating various algorithms. Gathering such a large amount of data has allowed the ACDS to begin identifying systematic, consistent calculation discrepancies between algorithms for particular phantom measurements. Such a discrepancy is the topic of this paper.

The AAA dose calculation model is a 3D pencil beam convolution superposition algorithm that has separate modelling for primary photons, scattered extra-focal photons, and electrons scattered from the beam limiting devices [19,20]. The AAA algorithm is convolution based with the dose from each pencil beam, or beamlet, being calculated through a convolution. Each beamlets' energy fluence is separated into components for primary and extra-focal photons and electron contamination. The dose distribution $D_\beta(x,y,z)$ for beamlet β is calculated using Equation (1) [21,22].

$$D_\beta(x,y,z) = \phi_\beta \times I_\beta(z, \rho) \times \iint_\beta K_\beta(x' - x, y' - y, z, \rho) dx' dy' \quad (1)$$

Here, the dose is calculated by a convolution of ϕ_β , the beamlet's fluence, I_β , an energy deposition function and a scatter kernel $K_\beta(x,y,z,\rho)$ which defines the lateral scatter component of the dose. The scatter kernels are density dependent and calculated in multiple directions laterally around the beamlet. The total dose calculated in a patient is a result of a superposition of each beamlet's contribution.

This paper presents an investigation into systematic discrepancies between TPS calculated and measured audit doses seen when comparing the AAA algorithm's prediction to other algorithms, in regions adjacent to and downstream from low-density material in anthropomorphic and slab phantom geometries.

Materials and methods

Level III (WAIL) audit

The ACDS Level III Audit [18] determines absorbed dose to water delivered to selected points in an anthropomorphic phantom (CIRS IMRT Phantom Model 002LFC (thorax), Computerized Imaging Reference Systems, Inc., Norfolk, VA, United States). An axial CT slice of the phantom is shown in Fig. 1. The Level III audit is an “end-to-end” test of the complete radiotherapy treatment chain. The Level III audit includes Wedged and Asymmetric fields with Inhomogeneities in Lung (WAIL). For this audit, five ACDS prescribed treatment cases are planned and the dose to selected points, indicated by numbers in Fig. 1, is calculated. Treatment fields are fully prescribed by the ACDS using 3D conformal planning for 6 MV photons only with static gantry and collimation. The details of the five cases are shown in Table 1. Cases 2 and 3 are based on cases 2 and 7 from IAEA TECDOC 1583 [23], while the others have been developed by the ACDS as reference (Case 1) and to further investigate the impact of the wedge (Cases 4 and 5, added later).

Figure 1. A sample CT of the central slice of the Level III phantom including the measurement points used in the ACDS Level III audit.

Dosimetry measurements are made by an onsite audit team with PSL calibrated Farmer type ionisation chambers and electrometers. Measurement locations correspond to the selected calculated points, which are listed for each case in Table 1 Fig. 1.

To investigate the findings of this study with the intent of finding a practical solution for facilities using the Eclipse AAA dose calculation algorithm, additional dose calculations were performed using the Acuros XB algorithm, which is also available with the Eclipse TPS, (Varian Medical Systems, Palo Alto, CA). Acuros XB is a modern algorithm which calculates dose to water by directly solving the Linear Boltzmann Transport Equation (LBTE). The algorithm can also calculate dose-to-medium, however for comparison to the current generation of algorithms evaluated in this study, only dose to water calculations are presented. Using a CT scan of the Level III phantom from one facility, absorbed doses per MU were calculated with AAA and Acuros for all measured points discussed.

Level II audit

The ACDS Level II Audit [17] evaluates accuracy of absorbed dose to water delivered to selected arrays of points at specific planes within a “slab” geometry phantom. This is an audit of the beam model within a treatment planning system, where the simulated (computer generated) CT of the measurement phantom is supplied by the ACDS to the Facility for treatment planning. The Level II audit includes Wedged and Asymmetric fields with Inhomogeneities for Lung (WAIL) treatments with sixteen separate single field cases planned. Fields are fully prescribed by the ACDS and underpin the ACDS Level III (WAIL) Audit. The audit is for 3D planning with 6 MV photons only with static (zero degree) gantry and collimator angles. Centres audited planned using their own treatment planning systems with an ACDS supplied CT to ED (electron density) table.

Dosimetry measurements are made in custom phantoms of CIRS Solid Water and CIRS Lung materials (Computerized Imaging Reference Systems, Inc., Norfolk, VA, United States). The detector used in the Level II audit is a PTW Octavius 729 2D ionisation chamber array (PTW GmbH, Freiburg Germany). Measurements are performed at two different depths for each field from Case 4–16. Details of the 16 cases are included in Table 2. Case 1 is not listed in this table since it is not measured. Case 1 is planned only and constitutes a $10 \times 10 \text{ cm}^2$ field with 10 Gy prescribed to the dose output specification point of the facility. This is used to verify that the treatment planning system calculates $1000 \pm 5 \text{ MU}$ to be delivered, as by definition the dose to the dose output specification point is 1 cGy/MU.

The computer generated CT series (ImSimQA, version 3.0.76a, Oncology Systems Ltd, Delmar, NY) used in the Level II WAIL Audit are based on a $30 \times 30 \times 30 \text{ cm}^3$ cube of water. Series 1 consists of

Table 1

The measurement cases with the points evaluated in the Level III (WAIL) audit. Additional measurement points (not listed here) are taken for exploratory purposes. Fields are designated as beam incident from anterior-posterior (AP), left-lateral (LLAT) and right-lateral (RLAT) directions respectively. For the isocentric setups (cases 2–5) the beam setup point is specified in parentheses. Further specific details on beam arrangements can be found in Ref. [18].

Case	Field	Measurement points	Setup	Field size	Wedge
1	AP	1, 10	SSD = 100 cm	10 cm (SI) × 10 cm (LR)	None
2	LLAT	1, 4	Isocentric (Point 1)	8 cm (SI) × 10 cm (AP)	45° wedge
3	AP	4, 5, 10	Isocentric (Point 3)	10 cm (SI) × 12 cm (LR)	None
3	LLAT	5	Isocentric (Point 3)	10 cm (SI) × 0.6 cm (AP)	30° wedge
3	RLAT	5	Isocentric (Point 3)	10 cm (SI) × 0.6 cm (AP)	30° wedge
4	LLAT	2, 3, 4, 5	Isocentric (Point 3)	10 cm (SI) × 12 cm (AP)	None
5	LLAT	2, 3, 4, 5	Isocentric (Point 3)	10 cm (SI) × 12 cm (AP)	60° wedge

Table 2

The cases used in the Level II (WAIL) audit.

CT series	Case	Measurement depths (cm)	SSD (cm)	Field size	Wedge
1	2	10	90	20 cm (SI) × 20 cm (LR)	None
1	3	10	90	10 cm (SI) × 10 cm (LR)	None
1	4	8,15	85	12 cm (SI) × 12 cm (LR)	None
1	5	8,15	85	12 cm (SI) × 12 cm (LR)	30° wedge
1	6	8,15	85	8 cm (SI) × 10 cm (LR)	None
1	7	8,15	85	8 cm (SI) × 10 cm (LR)	30° wedge
1	8	8,15	85	10 cm (SI) × 0, 6 cm (LR)	None
1	9	8,15	85	10 cm (SI) × 0, 6 cm (LR)	60° wedge
1	10	8,15	85	4 cm (SI) × 4 cm (LR)	None
2	11	8,15	85	12 cm (SI) × 12 cm (LR)	None
2	12	8,15	85	12 cm (SI) × 12 cm (LR)	30° wedge
2	13	8,15	85	8 cm (SI) × 10 cm (LR)	None
2	14	8,15	85	8 cm (SI) × 10 cm (LR)	30° wedge
3	15	8,15	85	10 cm (SI) × 0, 6 cm (LR)	None
3	16	8,15	85	10 cm (SI) × 0, 6 cm (LR)	60° wedge

only water. For Series 2 and 3 a 5 cm thick slab of inhale lung is placed within the cube at a depth of 1 cm (to boundary). The central transverse slices of the three CT series are shown in Fig. 2. Dose calculations are performed by the facilities on a 1 mm³ dose grid.

Results

Performance of the AAA algorithm in the level III audit

In Fig. 3 the results from the Level III audit are shown for all 12 points downstream from a low density (lung) inhomogeneity; referring to Table 1 and Fig. 1 these points are: Case 2 Points 1 and 4, Case 3 Point 5 for left and right lateral, Case 4 all points, and Case 5 all points. Each point shows the dose difference/deviation from ACDS [(planned dose – measured dose)/(measured dose)] relative to the dose difference of the reference Case 1 Point 1 to eliminate daily linac output and individual facility dosimetry deviations. Figure 3 (a) shows the results of audits of facilities using Eclipse AAA and (b) shows the results of audits using all facilities using

other algorithms. The average difference ($\pm 1\sigma$) for all the points calculated with the AAA algorithm is $2.9 \pm 1.2\%$ high (Fig. 3a). This means, following the above given ACDS definition of difference that the treatment linacs were underdosing. The average difference and standard deviation for the points calculated with the other algorithms is $-0.4\% \pm 1.7\%$ (Fig. 3b).

In Fig. 4 the average audit results are shown for individual points downstream from the lung inhomogeneity. Again, all results have been normalized to the corresponding reference (Case 1, Point 1) to eliminate linac output and individual facility dosimetry deviations. As before, the results are divided into audits with the AAA algorithm and audits with all other algorithms. The 3.0% underdose is present consistently with all points behind lung when using the AAA algorithm, regardless of the presence of a wedge, depth behind lung, or distance to field edge.

A comparison of calculations with the AAA algorithm to calculations done with the Acuros algorithm (dose to water) in the same phantom and planning system are shown in Fig. 5. The diagram shows differences in dose per MU for the same points in the

Figure 2. Central transverse slices of (a) CT Series 1, (b) CT Series 2 and (c) CT Series 3. The basic phantom in each series is a 30 × 30 × 30 cm³ block of water. Series 2 and 3 include volumes of material equivalent to “inhale” lung tissue.

Figure 3. (a) Level III audit results for points downstream from the lung material for only the points calculated with the AAA algorithm, and (b) Level III audit results for points calculated with all other algorithms. Differences are defined as (planned dose – measured dose)/(measured dose) and have each been normalized to the difference of the reference Case 1 Point 1 to eliminate daily linac output and individual facility dosimetry deviations. Please note that the facility numbers are randomised in each of Figure 3 (a) and (b) and facilities 1 – 11 do not correspond to the same facilities for both audits.

phantom as analysed before. The difference on average was found to be -2.8% and thereby generally of the same magnitude and in the opposite direction as the deviation found for the AAA algorithm calculations in comparison to the measurements across the country. The exception is Case 2 Point 4, where the difference is smaller but still in the same direction with -0.85% . These results indicate that the Acuros XB algorithm largely corrects the erroneous calculation by the AAA algorithm.

Performance of the AAA algorithm in the level II audit

The Level II results have been analysed and are presented in the same manner as the Level III results (Figs. 3 and 4). Figure 5 (a) shows the Level II audit results for all facilities evaluated in the cases where the measurement point was downstream from the lung inhomogeneity using the AAA algorithm. Figure 6 (b) shows the Level II audit results for all facilities excluding those facilities

employing the AAA algorithm. Referring to Table 2 and Fig. 2, the cases that meet these conditions are Cases 11 to 15, points 1 and 3. The results from Case 16, the asymmetric field with 60° wedge are not included due to the inability of some treatment planning system and linac combinations to calculate this field accurately [18]. In Fig. 7, each point shows the average dose discrepancy between measured and planned doses, relative to the dose difference of the reference Case 2 Point 1 to eliminate daily linac output and individual facility dosimetry. The distinct 3.0% offset present in the Level III audit results (Figs. 3 and 4) is not seen for the Level II audit, with the average discrepancy for AAA and other algorithms with the mean and standard deviation of the average differences for AAA and all other algorithms found to be $0.2 \pm 0.7\%$ and $-0.7 \pm 0.9\%$ respectively.

Discussion

The data presented in this manuscript demonstrates a peculiarity of the AAA algorithm, as implemented in the Varian Eclipse TPS. For curved, ‘patient realistic’ inhomogeneities such as those

Figure 4. Measurement beam specific average Level III audit result for individual points downstream from the lung material. The closed circles show the results for only the AAA algorithm and the open circles shows the results for all other algorithms. Differences are calculated and normalized as before. Error bars represent the standard error of the mean.

Figure 5. Difference in dose per MU for the points of level III audits when calculated using the Acuros (dose to water) vs the AAA algorithm.

Figure 6. Level II audit results for (a) AAA algorithm and (b), audits excluding those facilities implementing the AAA algorithm. Measurement cases and points downstream from the lung interface are shown. All individual dose differences have been normalized to the dose difference of the reference Case 2 Point 1 to eliminate daily linac output and individual facility dosimetry deviations. The mean and standard deviation of the average differences for AAA and all other algorithms is $0.2 \pm 0.7\%$ and $-0.7 \pm 0.9\%$ respectively.

present in the CIRS thorax phantom, the AAA algorithm consistently calculates a higher dose than is measured. On average, this difference amounts to approximately 3.0% when the measurement point is downstream from the lung inhomogeneity in tissue equivalent material. Other algorithms, tested in the same manner do not show this behaviour. The systematic discrepancy of the AAA algorithm was not found when the phantom and the inhomogeneity were of a rectilinear slab geometry. Here, on average, the AAA algorithm calculated the dose actually more accurately, though not significantly higher than the average of the other algorithms ($0.2 \pm 0.7\%$ and $-0.7 \pm 0.9\%$ mean $\pm$ SD, respectively).

Figure 7. The average Level II audit results (Figure 5) for the centre of field points for individual cases behind lung. The closed circles show the results for only the AAA algorithm and the open circles show the results for all other algorithms. All individual dose differences have been normalized to the dose difference of the reference Case 2 Point 1 to eliminate daily linac output and individual facility dosimetry deviations. Error bars represent the standard error of the mean.

This could potentially be a problem if commissioning measurements for a Varian Eclipse TPS are done with rectilinear phantoms. In end-to-end tests, which are generally also performed as part of the commissioning, any algorithm rooted deviations might be diminished by other small deviations or might be within the larger allowed tolerances for such tests [24].

There are a number of experimental studies for which the AAA algorithm has been shown to be accurate in both homogeneous and heterogeneous geometries [21,25–27]. Ronde et al. [28] investigated two-dimensional dose distributions for a variety of different field configurations in solid water with a 2D array of ion chambers, as well as patient specific treatment plans in a thorax lung phantom with Gafchromic films. Their study found that the AAA algorithm was superior to the PBC algorithm in heterogeneous media, especially for 15 MV. Furthermore, when measuring in a thorax phantom, the deviations between planned and measured doses in lung and mediastinum regions was found to be less than their specified criteria of 3% in dose and 3 mm in distance-to-agreement (DTA) respectively.

Van Esch et al. [4] tested the accuracy of AAA for different field sizes (symmetric and asymmetric) for open fields, wedged fields, and static and dynamic multi-leaf collimation fields. Measurements were performed on homogeneous (water equivalent), phantoms containing cork inhomogeneities, and on the thorax of an anthropomorphic phantom. Their measurements demonstrated that at the interface between solid water and cork, dose profiles showed a better agreement with AAA compared to Pencil Beam. Depth dose curves in the cork were also improved substantially with AAA when compared to Pencil Beam models. For the thorax phantom dose measurements, the agreement between planned and measured doses was found to be mostly within 5%. This result is not in disagreement with the results presented in Fig. 3, though the systematic offset of 3% was not reported, possibly due to the assessment criteria of 5%.

Bragg et al. [29] compared predicted and measured dose distributions with ion chamber and film measurements in homogeneous and inhomogeneous phantoms, with simple and complex fields. The effect of inhomogeneities was investigated using a range of phantoms constructed of water, bone and lung substitute materials. Simulated treatment plans were also

delivered to an anthropomorphic phantom and the delivered doses compared to the doses predicted by the Anisotropic Analytical Algorithm. For homogeneous phantoms, Bragg et al. found that the agreement was within 2% and 2 mm DTA in most instances. When heterogeneities were present, discrepancies between measured and planned doses were generally found to be within 2.5% for slab and anthropomorphic phantoms respectively.

In contrast to the above studies, Robinson [30] evaluated the ability of the AAA algorithm to accurately account for the presence of inhomogeneities in simple geometries by comparing calculated and measured doses. The study used a planar geometry phantom consisting of upper and lower layers of Solid Water separated by a heterogeneity region of variable thickness modelled in Eclipse. The goal of 2% accuracy in correcting for heterogeneities, as set out by the American Association of Physicists in Medicine Task Group 65 [31] was used as the criteria for evaluation. In general, over all non-unit density materials examined, the AAA was found to over-predict (number of MUs for actual treatment delivery would result in a dose deficiency) dose beyond low-density regions and in many cases, the deviation between the AAA and experimental results exceeds the Task Group 65 target of 2%. The source of these deviations was speculated to arise from an inability of the AAA algorithm to correctly account for altered attenuation along primary ray paths.

National/international audit programs to combine multi-centre data and can thus leverage a statistical power to identify correlations which are invisible within, or to, a single facility. The dosimetric discrepancy identified and quantified by the ACDS while mentioned in the published literature, has gone unnoticed or underestimated by individual facilities. These results reinforce the case that independent external dosimetric auditing is an invaluable tool for improving, and validating, the accuracy of radiation therapy. Kry et al. [32] and the Imaging and Radiation Oncology Core (IROC – Houston) group, further demonstrate the utility and value of such multi-centre auditing. Their study compared institution patient-specific IMRT QA plans to the results of their independent credentialing using a head phantom. The study found that in-house IMRT QA failed to detect unacceptable plan delivery as measured independently in an IROC head and neck phantom and concluded that IMRT QA was not a reasonable replacement for a credentialing (audit) phantom irradiation. In a similar study to the work presented here, Kry et al. [24] used a thorax phantom for a large ($n = 221$ different institutions, 304 irradiations) credentialing study that looked at the impact of dose calculation algorithm and their accuracy when accounting for heterogeneities. Measured doses were compared to calculated doses for a lung target and analysed as a function of calculation algorithm. Their results showed that the AAA algorithm as well as convolution-superposition algorithms overestimated the dose that was delivered to the target by 3.7% on average. Though direct comparisons cannot be made between the results presented here owing to the nature of the audits performed (in lesion surrounded by lung, versus in tissue downstream from lung), it is probable that such a systematic discrepancy may not have been uncovered were it not for the multi-centre audit.

A large European study by Gershkevitch et al. [33] conducted TPS audits in 60 radiotherapy centres using the TECDOC 1583 methodology also employed in the Level III audit presented here. In total, 190 data sets (combination of algorithm and beam quality) were collected and analysed. Their study found that dosimetry problems requiring interventions were discovered in about 10% of datasets and deficient beam modelling in TPSs was discovered in a number of cases. Like the RPC and ACDS audit programs, the IAEA European audit contributed to achieving a

better understanding of the performance of TPSs and helped to resolve issues related to imaging, dosimetry and treatment planning. Furthermore, their study also found similar discrepancies for the Varian AAA algorithm however the results were attributed to input beam data and beam modelling. Similar European and South American audits have also been reported and shown to be effective [34,35].

The results in this work have not been reported by previous studies, employing similar anthropomorphic phantoms. The possible reasons for this are the use of wider overall dose delivery tolerances of 5% [36], resulting in measurements with 3% discrepancy still passing the acceptance criteria. The Level III audits in this work are conducted on onsite audits using directly PSL calibrated Farmer type ionization chambers and electrometers resulting in low measurement uncertainties and allowing for tight action-level tolerances. The contribution of other factors, such as incorrect beam modelling and input data as reported in Gershkevitch et al. [33] may also have contributed to the oversight of the systematic nature of the discrepancy.

Conclusion

This work has demonstrated a systematic underdosing that occurs when the AAA algorithm is compared to measurements in the mediastinum region of an anthropomorphic thorax phantom, with lateral beams passing through lung. This systematic offset, which was absent for identical comparisons with other algorithms, results in an average discrepancy of 3% between planned and measured doses. This result, common amongst separate institutions using the same dose calculation algorithm and parameters, may have otherwise been overlooked by individual facilities, and was underestimated by others. An independent external auditing process was required to identify the dosimetric issue.

The ACDS Level III audit (as well as the Level II) has an out-of-tolerance level of 5% and discrepancies between measured and planned doses of 3% did not necessarily result in out-of-tolerance audit outcomes. However, the systematic discrepancy due to the AAA algorithm, when compounded with other errors in the treatment planning and delivery chain more often resulted in discrepancies outside the optimal level ($\leq 3.3\%$ difference between measured and planned dose) in comparison to other algorithms for the same measurements.

The potential implication of this finding in clinical scenarios is lower tumour control probability for lesions downstream from lung, for example, lung and mediastinal tumours when the AAA algorithm is used. Additionally, other sources of uncertainty in the radiotherapy treatment chain and dosimetry may compound together to result in a clinically relevant dose discrepancy between what was planned and actually delivered to the patient. Conversely, other sources may compensate for the calculation discrepancy, hiding the issue. We speculate that the reason for the results presented in this work is that AAA uses Gaussian functions to describe the mean heterogeneous effect in just four lateral directions, instead of over 4π as implemented in the Acuros XB algorithm. Therefore, a solution for facilities with the Eclipse TPS is to consider the use of the Acuros XB dose calculation algorithm, which appears to generally handle most of the situations investigated with the ACDS Level III audits more accurately.

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