# Dose Calculation And Reporting With A Linear Boltzman Transport Equation Solver In Vertebral SABR

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# Abstract

Introduction

Vertebral Stereotactic ablative body radiotherapy (SABR) involves substantial tumour density heterogeneities. We evaluated the impact of a linear Boltzmann transport equation (LBTE) solver dose calculation on vertebral SABR dose distributions.

Methods

A sequential cohort of 20 patients with vertebral metastases treated with SABR were selected. Treatment plans were initially planned with a convolution style dose calculation algorithm. The plan was copied and recalculated with a LBTE algorithm reporting both dose to water ($D_w$) or dose to medium ($D_m$). Target dose as a function of CT number, and spinal cord dose was compared between algorithms.

Results

Compared with a convolution algorithm, there was minimal change in PTV D90% with LBTE. LBTE reporting Dm resulted in reduced GTV D50% by (mean, 95% CI) 2.2% (1.9-2.6%) and reduced Spinal Cord PRV near-maximum dose by 3.0% (2.0-4.1%). LBTE reporting Dw resulted in increased GTV D50% by 2.4% (1.8-3.0%). GTV D50% decreased or increased with increasing CT number with $D_m$ or $D_w$ respectively. LBTE, reporting either Dm or Dw resulted in decreased central spinal cord dose by 8.7% (7.1-10.2%) and 7.2% (5.7-8.8%) respectively.

Conclusion

Reported vertebral SABR tumour dose when calculating with an LBTE algorithm depends on tumour density. Spinal cord near-maximum dose was lower when using LBTE algorithm reporting $D_m$, which may result in higher spinal cord doses being delivered than with a convolution style algorithm. Spinal cord central dose was significantly lower with LBTE, potentially reflecting LBTE transport approximations.


# Introduction

Stereotactic ablative body radiotherapy is becoming standard of care for local treatment of amenable metastases in the oligometastatic paradigm [1–4]. Vertebral metastases are commonly observed in patients with breast and prostate cancer, and can result in significant morbidity if untreated. SABR for vertebral metastases has shown improvement in local control and pain control compared with conventional radiation therapy [2].

Recent improvements in dose calculation algorithms available in commercial treatment planning software such as Monte Carlo methods or linear Boltzmann transport equation (LBTE) solvers, have resulted in improvements in dose calculation accuracy, in particular in regions of heterogeneities that impact on lateral electron spread [5–7]. These algorithms however compute energy deposition in and report

dose to the medium of interest [8–10]. This departure from convolution/superposition style algorithms, which report dose to varying densities of water, results in different doses for the same incident fluence due to differences in the electron stopping power between medium and water [10–12]. This is most dramatically seen in bone, where the electron stopping power difference is up to 10% compared with water [9,13].

For bone metastases, advanced dose calculation algorithms such as Monte Carlo and LBTE solvers may result in variations in reported dose compared with convolution/superposition algorithms. This may be further impacted by the choice of prescription – coverage of a target that may or may not be in bone, or prescribing such that target dose coverage is maximised while sitting at organ at risk constraints such as in vertebral SABR. In this technical note, the difference between a convolution/superposition style algorithm and a linear Boltzmann equation solver is determined for vertebral SABR.

# Methods

Approval to conduct this study was given by local Ethical Review Board. A retrospective sequential cohort of 20 vertebral SABR cases were selected. The Gross Tumour Volume (GTV) was contoured using a combination of positron emission tomography, magnetic resonance imaging and computed tomography, and the Clinical Target Volume (CTV) was delineated according to the International Spinal Radiosurgery Consensus guidelines [14]. A 2 mm Planning Target Volume (PTV) margin was applied to the CTV. The spinal cord was delineated using MRI, with a 2 mm planning organ-at-risk volume (PRV) margin used for spinal cord dose constraints. The plans delivered either 20 Gy in 1 fraction or 24 Gy in 2 fractions. Vertebral SABR plans were prescribed to maximise the dose to 90% of the PTV whilst meeting the spinal cord PRV and oesophagus near maximum dose constraints. The maximum dose to the GTV was typically boosted to 125% of the prescription dose. These cases were originally planned with either intensity modulated radiation therapy (IMRT) or volumetric modulated arc therapy (VMAT) in the Eclipse treatment planning system (V11.0-13.5) using the Anisotropic Analytic Algorithm (AAA). The plans were all recomputed with AAA v15.5 and a linear Boltzman equation solver AcurosXB algorithm (v15.5). Previous work has shown agreement between AAA v15.5 and previous versions of AAA (v11.0 and v13.5) [15]. Plans were recomputed retaining the same MLC sequences and monitor units, with the physical material table set to AcurosXB v13.5. Dose calculation was computed at an isotropic resolution of 1.25 mm.

The dose to the targets and adjacent organs at risk were evaluated for both algorithms. The median (D50%) and near maximum (D02%) to the GTV and dose to 90% (D90%) of the PTV were evaluated. The dose to 0.03 $cm^3$ of the spinal cord PRV was compared between algorithms. The dose to a 3 mm diameter circle in the middle of the spinal cord was also evaluated, as a surrogate for the out of field doses and that which may represent a measurement point in quality assurance measurements.

# Results

Figure 1 shows the dose distribution for the three calculation modes for a lytic and a blastic lesion. The profiles through the anterior-posterior direction indicated by the white line on Fig. 1 are shown in Fig. 2. In regions of tissue or low density bone, there are minimal differences between algorithms. The exception to this is in the region in the middle of the spinal cord, where both AXB $D_m$ and AXB $D_w$ are lower than AAA. In regions of increased HUs, such as increased density bone, AXB Dm is decreased relative to AAA, and AXB $D_w$ is increased relative to AAA. Figure 1a shows a lytic GTV, with the main differences observed in higher density components of the lytic GTV with AXB $D_w$. Figure 1b shows a blastic GTV, with AXB $D_m$ lower than AAA by approximately 5%, and AXB D $D_w$ w approximately 6% higher than AAA in the GTV.

The change in GTV dose as a function of HU is shown in Fig. 3. As the mean CT number of the GTV increases, the median GTV dose calculated with AXB $D_m$ increasingly lower than that calculated with AAA, by up to 3.5%. Conversely, as the mean CT number of the GTV increases, the median GTV dose calculated with AXB $D_w$ increases compared with AAA by up to 6%.

Figure 4 shows the differences between AAA and AXB reporting dose to medium or water. This data is summarised in Table 1. When calculating with AXB $D_m$, there was minimal impact on PTV D90%, GTV D50% and D02%. Larger reductions were observed for the SpinalCord PRV D0.03cc and SpinalCord central dose. Conversely, calculating with AXB $D_w$ resulted in increased target doses, no difference in SpinalCord PRV D0.03cc, and reduced SpinalCord central dose of a similar magnitude to that observed with AXB $D_m$.

Table 1
Relative difference between AAA and AXB $D_m$ and AXB $D_w$ for target and OAR dose metrics

| Metric | Relative difference (%, (95% CI)) | |
|---|---|---|
| | AAA – AXB $D_m$ | AAA – AXB $D_w$ |
| PTV D90% | 1.5 (1.1, 1.9) | -1.3 (-1.7, -0.8) |
| GTV D50% | 2.2 (1.9, 2.6) | -2.4 (-3.0, -1.8) |
| GTV D02% | 2.0 (1.6, 2.4) | -3.5 (-4.5, -2.6) |
| SpinalCord PRV D0.03cc | 3.0 (2.0, 4.1) | 0.3 (-1.2, 1.7) |
| SpinalCord centre | 8.7 (7.1, 10.2) | 7.2 (5.7, 8.8) |

# Discussion

Vertebral SABR presents a challenging dose calculation scenario due to heterogeneities in material, high dose gradients and small fields. As a result, dose calculation with Monte Carlo or linear boltzman transport equation (LBTE) algorithms is an attractive option due to its improved dose calculation

accuracy. Compared with Type B algorithms however, LBTE algorithm presents a number of key differences which may impact reporting of dose distributions in vertebral SABR.

Reporting dose to medium or water results in substantial differences in reported GTV dose, which depends on the density of the bone in the target. Lytic lesions exhibit minimal difference between AAA and either reporting mode for AXB; however increased HU in blastic lesions results in differences of up to 3.5% with dose to medium and 6% with dose to water in median GTV dose. This is a result of the increased difference in stopping power between bone and water, which is increasing with density of the bone. These differences translate into small reporting differences in PTV coverage metric. Zhen et. al. compared AAA and AXB $D_m$ (v10.0.28), and showed increased dose in the vertebral body GTV and PTV with AXB $D_m$ compared with AAA by 1–2%, in opposition to our finding [5]. The cause of this discrepancy is unknown, but may be related to the different versions. Usmani et. al. compared Monte Carlo $D_m$ with $D_w$ for IMRT vertebral plans in iPlan [16]. Increases in dose in high density bone were observed with $D_w$ compared with Dm. The CTV mean dose was increased by approximately 5% with $D_w$ compared with $D_m$ a similar magnitude to that observed in our study.

The spinal cord PRV near maximum dose is a hard constraint in vertebral SABR planning. During optimisation, the spinal cord PRV is typically taken to the constraint, and the PTV coverage is maximised while meeting this constraint. When using AXB $D_m$, the spinal cord PRV near maximum dose was on average 3% lower than that with AAA. This may result in a systematic increase of spinal cord PRV dose when planning with AXB $D_m$. There was no systematic difference however when using AXB $D_w$. In Zhen et. al., the spinal cord maximum dose and D0.5 cc was lower with AXB $D_m$ compared with AAA [5]. Miura et. al. the near maximum spinal cord dose was on average 1% higher with $D_w$ compared with $D_m$ [16]. Head and neck cancer radiotherapy presents a similar geometry, with the target volume wrapping around the spinal cord. Munoz-Montplet et. al. [17] compared AXB (v13.0.26) with AAA for 140 H&N plans. The near maximum dose was on average 1.07 Gy lower with AXB $D_m$ compared with AAA, but 0.17 Gy higher with AXB $D_w$ compared with AAA. Zifodya et. al. [18] compared AXB (v11.0.3.1) with AAA for head and neck plans; AXB $D_m$ resulted in systematically lower mean spinal cord dose and near maximum spinal cord dose compared with AAA, however AXB $D_w$ did not show the same trend, and was much closer to AAA.

The dose at the centre of the spinal cord was significantly lower than AAA when calculated with AXB, reporting either $D_m$ or $D_w$. It is hypothesised this is a result of energy cut-off used in dose calculation. The AXB algorithm uses 200 keV for electrons and 1 keV for photons. The spinal cord is predominantly in the gradient region of the apertures, therefore selection of the electron cut off energy will have a large impact on the dose in this region. As demonstrated by Hughes et. al., electron energy is deposited proximal to the field edge, and as a result the dose calculated further from the field edge, in the centre of the cord, is reduced [19]. The selection of energy cut-off may also be the cause of lower near maximum cord doses, due to a resultant sharper dose gradient with AXB. Given the serial nature of the spinal cord with respect to toxicity, the dose at the centre of the spinal cord may be of limited clinical importance. In treatment

plan verification measurements however, the dose in the spinal cord is often measured. Further work is required to determine the accuracy of AXB compared to measurement; due to electron energy cut-off, substantial underestimates of the spinal cord dose may be observed.

# Conclusion

Given high dose gradients, and planning process in which organs at risk are taken to tolerance in each plan, dose calculation accuracy in vertebral SABR doses is of critical importance. Use of a linear boltzman equation solver algorithm has the potential to improve dose calculation accuracy, however there are fundamental differences between this and convolution/superposition algorithms which can result in reporting differences and organ at risk dose differences. Median GTV doses depend on whether the lesion is lytic or blastic, with up to 3.5% lower than AAA when reporting dose to medium, and 6% higher when reporting dose to water. PTV coverage metrics are not impacted. Near maximum spinal cord PRV doses are systematically 3% lower when calculating with AXB Dm, however with AXB Dw there is no systematic difference. When calculating with AXB and reporting dose to medium or water, the dose to the centre of the spinal cord is on average 7.1–8.7% lower than with AAA.

# Declarations

Funding:

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Conflicts of Interest:

Nicholas Hardcastle, Tomas Kron and Shankar Siva receive funding for an unrelated project from Varian Medical Systems.

Availability of data and material:

Will be available upon reasonable request to the authors.

Ethics approval:

This study received ethics approval from the Peter MacCallum Cancer Centre.

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# Figures

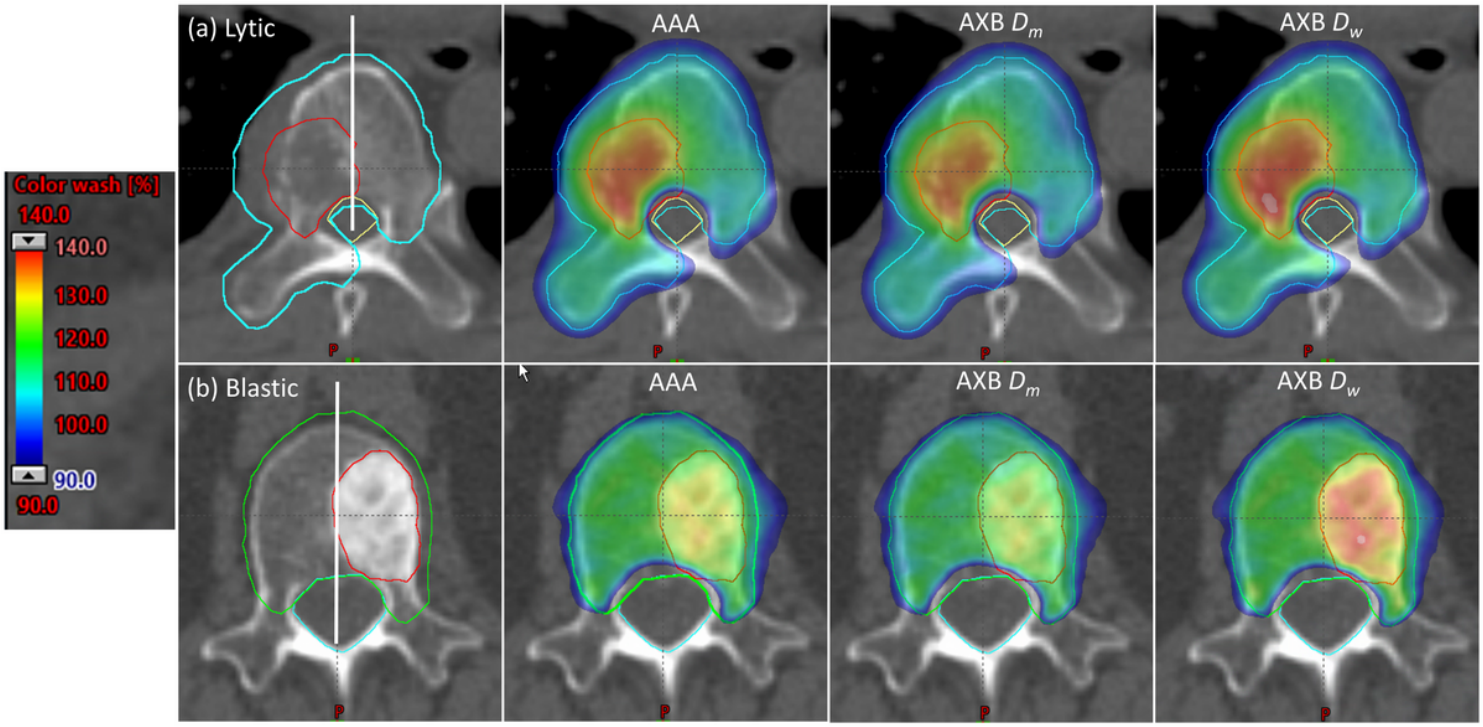



**Figure 1**

Dose distributions for a lytic lesion (top) and blastic lesion for AAA, AXB Dm and AXB Dm algorithms. The white vertical line on the CT image shows the location of the dose profile in Figure 2.

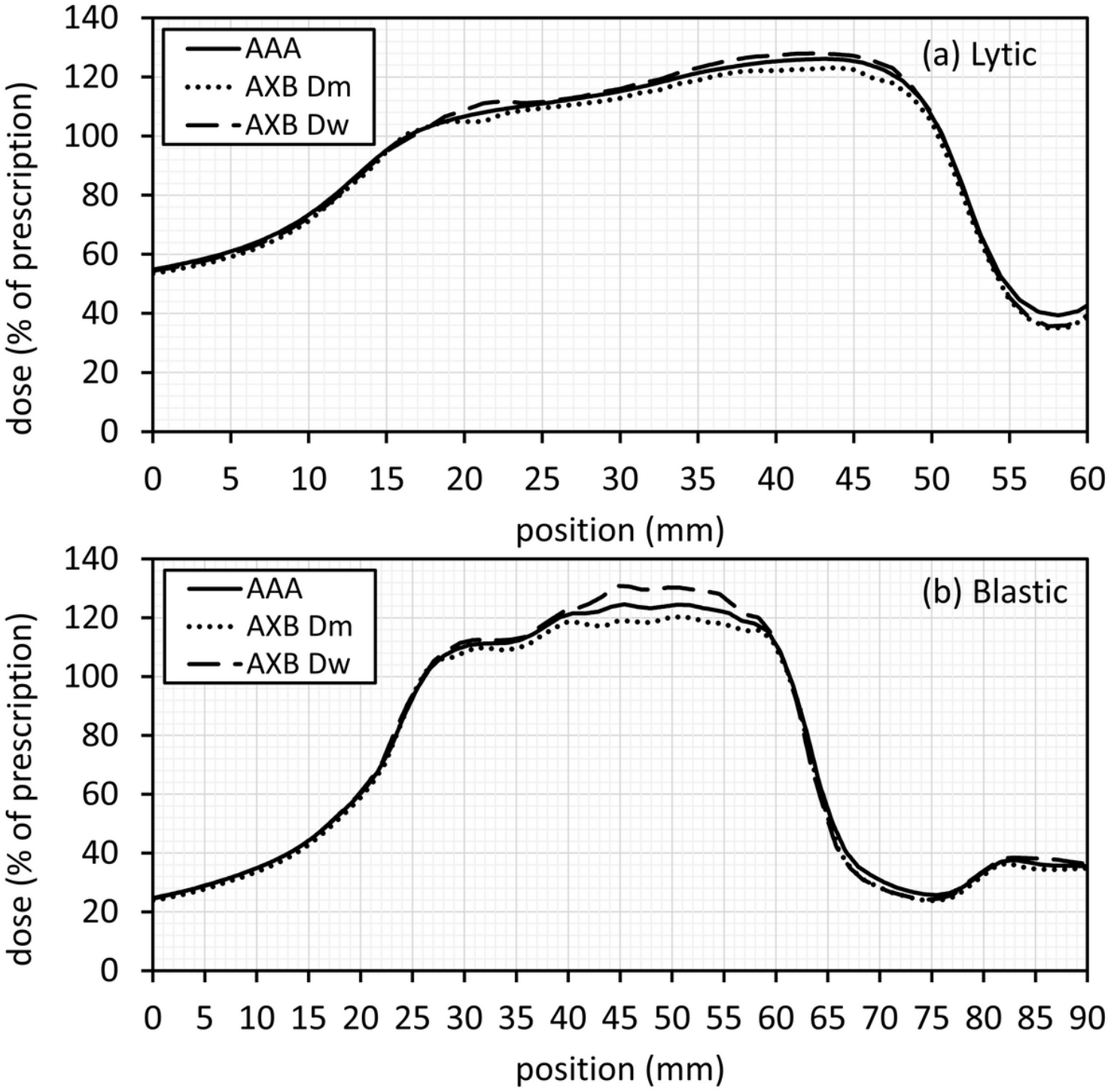
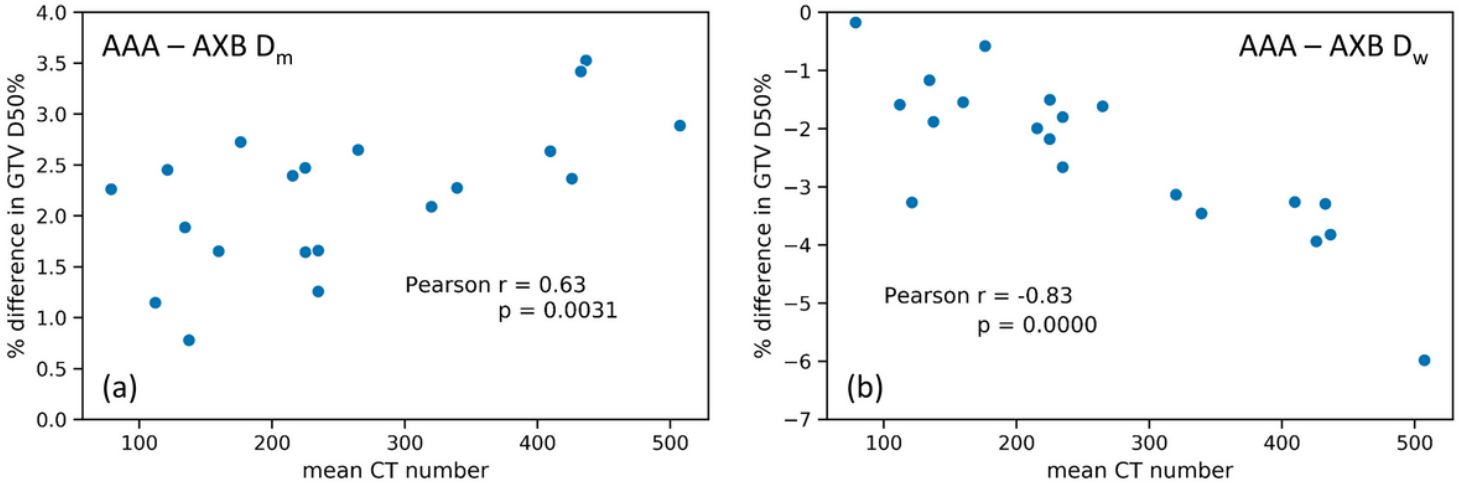


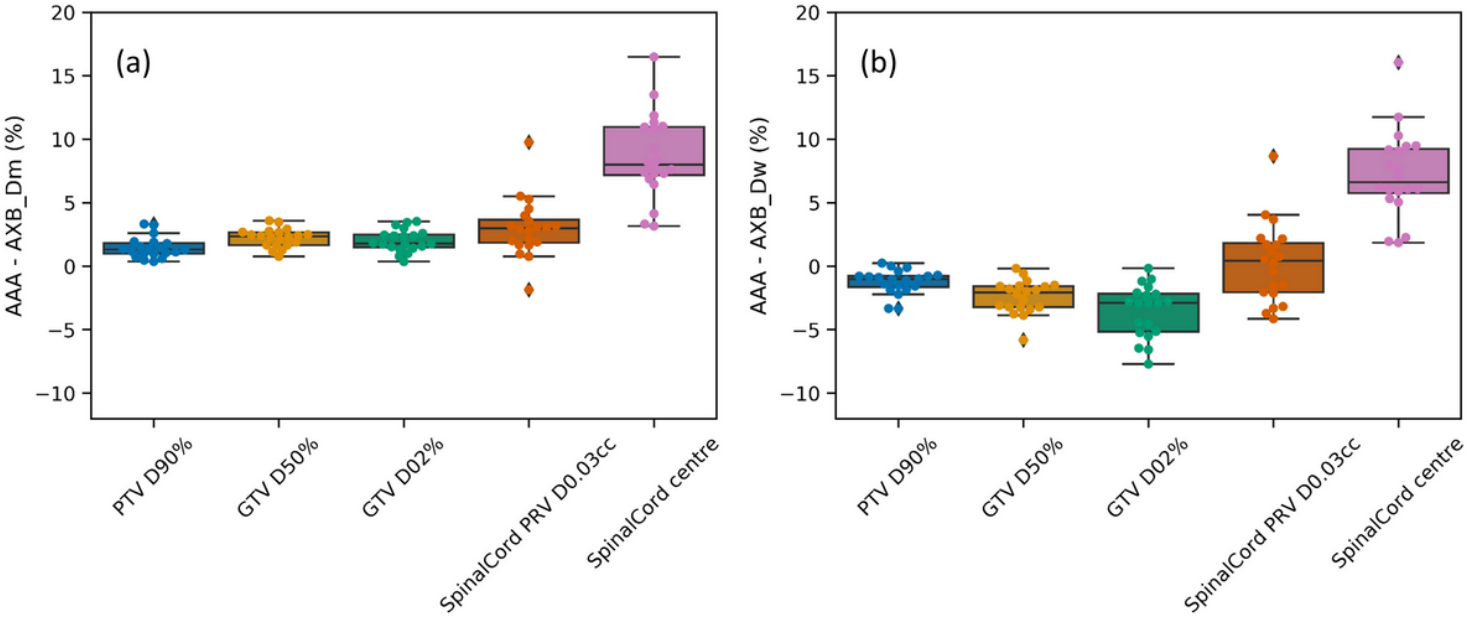

**Figure 2**

Dose profiles along the white line in Figure 1 for the lytic lesion (top) and blastic lesion. The divergence of the three algorithms from 17 mm in the lytic lesion corresponds to the high density bone around the edge of the vertebral body




## Figure 3

Difference in GTV median dose between (a) AAA and AXB Dm and (b) AAA and AXB Dw, as a function of the mean CT number of the GTV




## Figure 4

Swarm and box plots of relative differences between AAA and AXB Dm (a), AAA and AXB Dw (b)