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Implementation of Acuros XB in Treatment Planning of SBRT of Lung Cancer

Emma Hedin[1,2], Roumiana Chakarova[1,2] and Anna Bäck[1,2]*

[1]Department of Radiation Physics, Institute of Clinical Sciences, Sahlgrenska Academy, University of Gothenburg, Sweden

[2]Department of Medical Physics and Biomedical Engineering, Sahlgrenska University Hospital, Sweden

Abstract

Goal: The overall goal of this study is to present data assisting the implementation of the principle based dose calculation algorithm Acuros XB for Stereotactic Body Radiation Treatments (SBRT) of lung tumors. In particular, the goal is to investigate differences in target dose distributions calculated by the clinical algorithms AAA and Acuros XB as well as by the Monte Carlo method.

Materials and Methods: Twenty conventional 3D conformal plans for SBRT of lung cancer were investigated. The prescribed dose was 3 Gy × 22 Gy at the center and 3 Gy × 15 Gy at the periphery of PTV. The plans were originally designed with AAA based on the requirement PTV-$V_{100\%}$ (percentage of PTV receiving a dose larger than 100%=45 Gy), to be 100%. Recalculations were performed by utilizing Acuros XB as well as by full Monte Carlo method. Dose variations were evaluated in terms of DVH parameters $D_{5\%}$, $D_{50\%}$, $D_{98\%}$ for GTV and PTV as well as PTV-$V_{100\%}$. Five plans showing large algorithm sensitivity in terms of PTV-$V_{100\%}$ were re-planned by Acuros XB using the same treatment planning criteria.

Results: AAA systematically overestimated the PTV dose compared to Acuros XB and Monte Carlo. Differences between AAA and Acuros XB of up to 8%, 10% and 5% were observed for PTV-$D_{50\%}$, PTV-$D_{98\%}$ and PTV-$V_{100\%}$, correspondingly. The values obtained by the Monte Carlo method were up to 7% lower than these for Acuros XB. The variations in the PTV dose estimation could not be related to patient/plan characteristics like target volume, lung tissue volume included in the target or tumor proximity to the lung wall. The variations in the GTV parameters were smaller and the agreement between AAA and AXB as well as between Acuros XB and Monte Carlo was within 3%. Planning with Acuros XB increased the volume of the lung tissue close to the tumor receiving full dose by more than 20%.

Conclusion: PTV dose coverage was overestimated in plans calculated by AAA. Transition to Acuros XB without changing the treatment planning criteria increased the dose to the lung tissue close to the tumor. The GTV dose coverage was more robust with respect to the algorithm changes.

Keywords: SBRT lung cancer; AAA; Acuros XB; Monte carlo

Introduction

Prior to radiotherapy delivery, the treatment is simulated in a Treatment Planning System (TPS) and optimized based on a calculated dose distribution. Dose Calculation Algorithms (DCAs) used in the clinical praxis are continuously evolving. The newest generation of dose calculation algorithms includes principle based algorithms such as Acuros XB (AXB) in Eclipse TPS, described in [1,2]. AXB has been fundamentally investigated [1,3-11] and found to perform superiorly to other available DCAs and to provide a valid and accurate alternative to Monte Carlo calculations. The prevailing algorithm in the Eclipse TPS was until recently the pencil beam based Analytical Anisotropic Algorithm (AAA). Therefore, the transition from AAA to AXB is currently of interest. Dose distributions obtained by the two algorithms were found to deviate in or near tissues with electron densities different from water (i.e., lung or bone). Whether AAA over or underestimated dose compared to AXB depended on field size, beam energy and electron density [5]. Dose differences were larger for smaller fields and low-density lung tissue [3,5,12].

In Stereotactic Body Radiation Treatment (SBRT) of lung tumors, small fields are applied to a heterogeneous patient geometry including lung tissue and the dose determination is expected

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Correspondence:
Roumiana Chakarova, Department of Radiation Physics, Gula straket 2B, Sahlgrenska University Hospital, SE-413 45 Gothenburg, Sweden, Tel: 46-70-3064884; E-mail: roumiana.chakarova@vgregion.se

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to be sensitive to the calculation algorithm. SBRT plans utilizing Volumetric Arc Therapy (VMAT) [12,13] as well as non-VMAT SBRT technique [14-17] have been studied and Dose Volume Histograms (DVH) for the Planned Target Volume (PTV) analyzed. In general, AAA overestimated the dose in the exterior region of PTV, i.e., in the lung tissue part of PTV, as compared to AXB [12-17]. The magnitude of the deviations in the dose distributions determined by the two algorithms varied between the plans [12-14]. Small volume targets were largely affected by the algorithm change.

Investigation of larger number of clinical plans incorporating a variety of tumor locations is needed in order to confirm or to introduce corrections in the treatment planning criteria before implementation of AXB in clinical praxis. Furthermore, it is important to compare the AXB dose distributions to independent Monte Carlo (MC) calculations because of beam model approximations in the TPS and AXB approximations due to energy, angle and spatial discretization [1]. In this study, the differences between target dose coverage calculated by the clinical algorithms AAA, AXB and the MC method were quantified for 20 SBRT plans of lung tumors designed according to a published study protocol [18]. Patient/plan characteristics were studied in detail to find eventual relation to the differences observed between AAA and AXB estimate target dose.

Materials and Methods

Clinical material

Twenty consecutive conventional 3D conformal treatment plans for SBRT of lung cancer were included in the study. A variety of tumor locations is there by considered, however, to be eligible for the treatment; the tumors were not adjacent to trachea, main bronchus or esophagus [18]. The prescribed dose was 3 Gy × 22 Gy at isocenter and 3 Gy × 15 Gy at the periphery of PTV [18]. The dose was normalized to 15 Gy per fraction. Thus, the PTV-$V_{100\%}$ (percentage of PTV receiving a dose larger than 100%=45 Gy), should be 100% for a treatment plan to be approved. All treatments were planned for a Varian Clinac iX linear accelerator delivery (6 MV photons) with static Multileaf Collimator (MLC) (Varian Millenium 120-leaf) and Enhanced Dynamic Wedges (EDW) when necessary.

For each patient, 3D and a 4D CT scan were performed. The CT scans were acquired on a Toshiba Aquilion LB CT-scanner (Toshiba Medical Systems) with 2 mm slice separation. The tumor was delineated by physicians using the following window settings for viewing of the CT scan: a lower window level of -800 HU and an upper level of 200 HU. A four dimensional gross tumor volume (4D-GTV) was defined as the volume encompassing all the positions of GTV during a breathing cycle. An Internal Target Volume (ITV) was determined and PTV was defined as ITV with 5 mm margin. The lung tissue was automatically delineated by the clinical segmentation wizard in Eclipse TPS utilizing HU range of -1000 to -195 (density range of 0 g/cm^3 to 0.84 g/cm^3) within the body contour. Dose calculation was performed on the 3D CT scans.

The treatment planning was following the study protocol [18] and plans were created with 5-7 coplanar or non-coplanar 6 MV fields defined by jaw and MLC. The tolerance doses for the organs at risk were taken from the National Comprehensive Cancer Network (NCCN) Guidelines Version 2.2013 for non-small cell lung cancer.

Dose calculations

The original treatment plans were designed by AAA in Eclipse (version 11.0.31, Varian Medical Systems). All plans were recalculated with AXB (version 11.0.31) as well as with the MC method, based on the EGSnrc code package [19], using the same number of monitor units, MLC/collimator positions, EDWs and beam arrangement. A clinically realistic dose grid of 2 mm was implemented for all dose calculations. The MC calculations included particle transport through the accelerator head and the patient geometry (denoted as a full MC in the literature). The accelerator model was previously validated against measured data in water phantom (profiles, depth dose curves and output factors) for an extensive variety of field sizes (2 cm^2 × 2 cm^2 to 40 cm^2 × 40 cm^2) [20] and applied to different clinical situations [21,22].

Table 1: Density intervals used for tissue segmentation in Acuros XB and Monte Carlo calculations.

Material name AXB	AXB (v. 11 and 13) Density interval (g/cm^3)	Material name MC	MC Density interval (g/cm^3)
Air	0.0000-0.0204	Air	0.001-0.0157
Lung	0.0110-0.6242	Lung	0.0157-0.5891
Adipose	0.5539-1.0010	Adipose	0.5891-0.9852
Muscle	0.9693-1.0931	Muscle	0.9852-1.100
Cartilage	1.0556-1.6000	Bone 1	1.100-1.270
Bone	1.1000-3.000	Bone 2	1.270-1.440
		Bone 3	1.440-1.600
		Bone 4	1.600-1.770
		Bone 5	1.770-3.000

The implementation of AAA in Eclipse involved an electron-density CT calibration curve. For AXB, tissue segmentation was required which utilized a mass-density CT calibration curve and a clinical tissue type table with pre-defined six tissue types, i.e., air, lung, adipose tissue, skeletal muscle, cartilage and bone. It should be noted that air was not taken into account in AXB version 10. The patient in the MC calculations was represented by nine tissues defined on the basis of the mass-density CT calibration curve, namely, air, lung, adipose, muscle skeletal and five bone tissues obtained by interpolation of bone mass density and composition between spongiosa skeletal and cortical bone. Elemental compositions of the materials were obtained applying the formalism [23,24]. Tissue segmentation data used in AXB and MC calculations are summarized in Table 1.

Calculations by AXB allowed the dose to be expressed in terms of dose to water or dose to media. The 'dose to water' reporting mode was used for comparison with AAA data and the 'dose to media' reporting mode was used for comparison with the MC calculations. The Monte Carlo method calculates the energy deposition in different media and expresses dose to a medium. Performing a retrospective conversion of the MC data from dose-to-tissue to dose-to-water [25] may increase the uncertainty of the calculated dose distribution, may introduce hot/cold spots and systematic errors [26,27]. Therefore MC results obtained in this work are not converted in dose to water and are not compared to AAA distributions since AAA reports dose to water.

Evaluation of the dose distributions

The dose calculation methods were evaluated by visual comparison of the corresponding DVHs as well as by quantifying the differences between the DVH parameters $D_{5\%}$, $D_{50\%}$ and $D_{98\%}$ for GTV

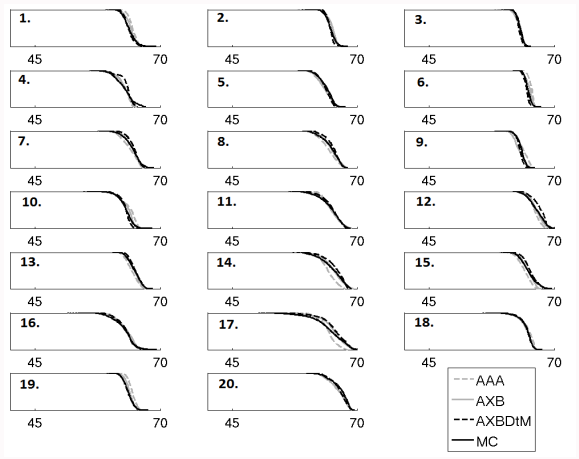

Figure 1: DVHs for GTV based on AAA, Acuros XB (dose to water), Acuros XB DtM (dose to medium) and Monte Carlo calculations.

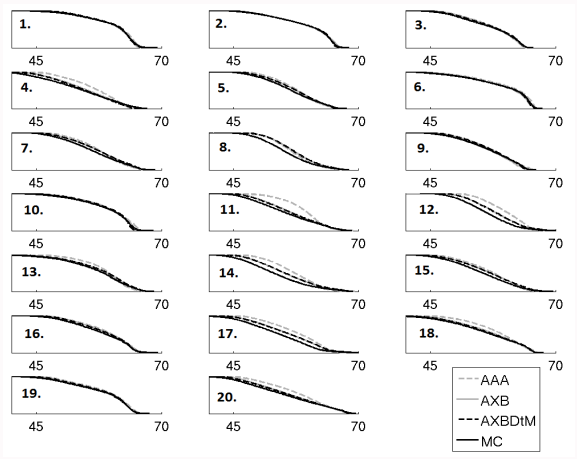

Figure 2: DVHs for PTV based on AAA, Acuros XB (dose to water), Acuros XB DtM (dose to medium) and Monte Carlo calculations.

Table 2: Differences (mean value and minimum-maximum range) in % for the DVH parameters of PTV and GTV calculated by AAA, Acuros XB and Monte Carlo method.

	Mean difference (range)	
	AAA-AXB*	**AXB-MC****
PTV-D 5% (%)	-0.1 (-2.6; 2)	0 (-2.1; 2.6)
PTV-D 50% (%)	2 (-1; 7.7)	2 (-0.4; 5)
PTV-D 98% (%)	3.5 (-0.5; 10)	3.4 (-0.8; 6)
GTV-D 5% (%)	-0.4 (-3.7; 1.4)	-0.7 (-2.3, 0)
GTV-D 50% (%)	-0.3 (-2.6; 2)	0.3 (-1; 2)
GTV-D 98% (%)	0.7 (-2.3; 6.6)	1.6 (-0.5, 5)

*DtW: Dose to water; **DtM: Dose to medium

and PTV. The parameters were chosen to cover the low- ($D_{98\%}$) and high ($D_{5\%}$) dose regions and to detect eventual shift of DVHs ($D_{50\%}$). The parameter PTV-$V_{100\%}$ was also retrieved to discuss the feasibility of a 100%-isodose prescription to PTV. The statistical significance of the difference between parameters calculated with different dose calculation algorithms were calculated using the student's t-test for paired distributions and were considered as significant for a p-value <0.05. Furthermore, the following plan/patient characteristics were recorded: GTV volume, PTV volume, the ratio between ITV and GTV (i.e., ITV/GTV), the volume of lung tissue part of PTV, the smallest distance between the GTV- and lung-contours and the average of the lung density at three points within 1 cm to 2 cm from the PTV. These plan/patient characteristics were chosen to investigate eventual relation to the sensitivity of the target coverage on the calculation algorithm. The target volume was assumed to be of relevance since it implicitly impacts the field sizes; ITV/GTV was assumed to be a measure of the amount of lung tissue in PTV. The distance to the lung contour impacted the angle that the fields are spread in and how much lung tissue the fields are passing through before entering PTV. The lung density was of interest since lower density was more challenging for the dose calculation algorithms.

Five plans were identified with the largest difference in PTV-$V_{100\%}$ after recalculation with AXB. These were re-planned by AXB so that PTV-$V_{100\%}$ within 0.5% of the value for the original AAA plan was obtained. For the re-planned cases, the treatment planning criteria defined in the study protocol were recorded as well as the mean doses to GTV.

Results

The DVHs for GTV and PTV for the 20 patients plans designed by AAA and recalculated by the AXB and MC method are shown in Figure 1 and 2. In general, the DVHs for GTV obtained by the different calculation methods were more similar to each other than the PTV DVHs. The variations in the estimation of the PTV and GTV DVH parameters $D_{5\%}$, $D_{50\%}$, $D_{98\%}$ by the different calculation methods for all plans analyzed are given in Table 2. It was found that the PTV-$V_{100\%}$ values, obtained by AAA, are up to 5% larger than these obtained by AXB. Furthermore, the AXB values were up to 7% larger than the corresponding MC data. The difference in the high dose part of the PTV-DVH (i.e., $D_{5\%}$), was unsignificant (p-value >0.05) regardless of algorithm choice whereas the differences in the lower dose part of the DVH (PTV-$D_{50\%}$, PTV-$D_{98\%}$ and PTV-$V_{100\%}$) were significant (p-value <0.05). AAA was consistently calculating higher value for PTV-$D_{50\%}$, PTV-$D_{98\%}$ and PTV-$V_{100\%}$ than AXB. Also AXB was consistently calculating higher value than MC for these parameters. The variations in the GTV parameter values between AAA and AXB were not significant and the agreement between AXB and MC was within 3%.

More detailed analysis of the sensitivity of the dose determination on the clinical geometry is presented in Figure 3 where deviations between AAA and AXB estimate of PTV-$V_{100\%}$ are plotted against different plan/patient characteristics. The risk for larger deviation was seen to increase for PTV volumes smaller than 80 cm^3 and for distances from the lung wall below 1 cm. However, a large number of the plans were below these thresholds (80% of the plans) while large differences between AAA and AXB were manifested only for a few of them. Combined analysis, for example, the PTV volume and the distance from the lung wall, did not characterize the difference between AAA and AXB in PTV-$V_{100\%}$ as shown in Figure 4.

The five plans with largest differences in PTV-$V_{100\%}$ between AAA and AXB that were replanned had the following plan numbers: 4, 13, 17, 18, 20. In order to keep the PTV-$V_{100\%}$ value the same as in the AAA-plan, the fields had to be extended 1 mm to 2 mm in the cranial/caudal directions unless the field boundary was in soft tissue (then no extension was necessary). Furthermore, the MLC-leaves generally had to be retracted somewhat so that they were not overlapping with PTV in beams eye view. The ratio $V_{100\%}/V_{PTV}$ was increased but could be kept within the allowed interval 1.0-1.4. No large changes in the mean

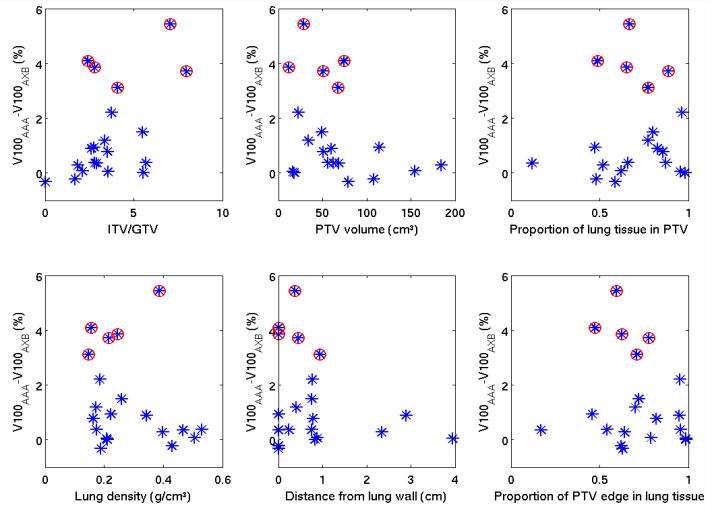

Figure 3: Difference in PTV-$V_{100\%}$, between AAA and Acuros XB calculations. Data plotted against different patient/plan characteristics. The encircled symbols mark the five plans with largest differences in PTV-$V_{100\%}$ between AAA and AXB that were replanned.

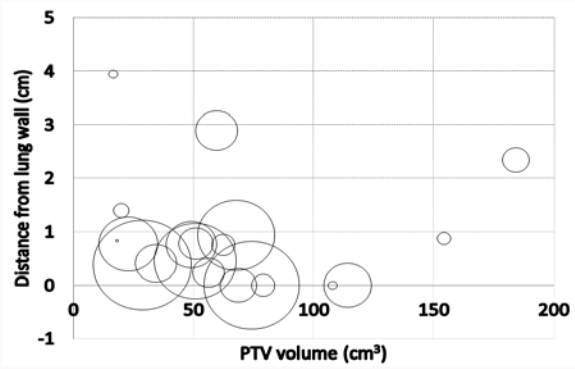

Figure 4: Circles with radius representing the difference (absolute values) between PTV-$V_{100\%}$ as calculated by AAA and Acuros XB. PTV volume on the x-axis versus distance from lung wall on the y-axis.

dose to GTV and the dose to organs at risk were seen after this re-planning strategy. The volume encompassed by the 100% isodose and the 100% isodose volume ratios (AXB-replanned/AXB-recalculated) are presented in Table 3. The 100% isodose volume is increased by 7% to 23% for the five re-planned cases as shown in Table 3.

Discussion

The dosimetric parameters PTV-$D_{98\%}$, PTV-$D_{50\%}$ and PTV-$V_{100\%}$ were significantly affected (up to 10%, 8% and 7%) by the algorithm choice with the lowest coverage obtained by the MC method (Table 2). The agreement between MC and AXB was acceptable, considering the completely independent way of beam modeling and patient description as well as the stochastic *vs.* deterministic particle transport simulation. Larger differences between MC and AXB and between AAA and AXB (up to 20% for PTV-$D_{95\%}$) were previously reported [17]. The study cited referred to centrally located tumors. A previous AXB version was utilized before changes were introduced, for example, in the tissue segmentation, cutoff value for electron interactions. Also MC tissue segmentation with four materials was performed [17].

The treatment planning criteria involving PTV-$V_{100\%}$ were not fulfilled for the plans recalculated by AXB and MC. AAA was found to overestimate the dose and the level of the overestimation could not be

Table 3: The volume encompassed by the 100% isodose. Values for the recalculated and re-planned Acuros XB-cases are shown. Ratio between 100% isodose volumes is presented in the last column.

	100% isodose volume (cm³)		Ratio
Plan ID	AXB	AXB replan	AXB replan/AXB
04	30.61	36.51	1.19
13	87.01	96.8	1.11
17	54.48	66.75	1.23
18	85.71	94.06	1.10
20	13.37	14.36	1.07

related to the chosen plan/patient characteristics. This is in contrast to a previous study of the standard Pencil Beam algorithm compared to the MC algorithm [28], where linear regression fit enabled prediction of the magnitude of the difference using some of the investigated characteristics. This might be explained by the approximate modelling of lateral electron transport in the AAA algorithm that is improved compared to the standard pencil beam algorithms. This approximate modeling seems to cause the difference between AAA and AXB to be more random than the differences between a standard Pencil Beam algorithm and a principle based algorithm.

Visual examination of the DVHs (Figure 2) revealed large deviations between AAA and AXB for plan numbers 11, 12 and 14. This was seen as a shift of the DVH curve mainly reflected in the PTV-$D_{50\%}$ parameter. However, the parameter PTV-$V_{100\%}$, but not PTV-$D_{50\%}$ was included in the treatment planning criteria and the shape of the DVH was not taken into account. The plans showing the largest visual difference between AAA and AXB were not the same plans showing the largest difference between AAA and AXB in terms of PTV-$V_{100\%}$.

The prescription praxis on which this study was based addressed the PTV dose coverage. Transition from AAA to AXB algorithm when keeping the same treatment planning criteria resulted in an increase of the volume receiving the prescribed dose by up to 23% (Table 3). This volume with increased dose consisted of lung tissue but the effect on the whole DVH of the lung was small. Implementation of a different prescription volume has been discussed in the literature; GTV or CTV [29,30]. The GTV dose coverage was found to be less

sensitive to the algorithm change (Figure 1 and Table 2). Appropriate prescription volume would increase the quality in clinical multicenter studies because of an increased homogeneity for treatments at different hospitals using different DCAs.

Conclusion

Target dose distributions calculated by the clinical algorithms AAA and AXB as well as by the MC method were evaluated for 20 conventional plans for SBRT of lung cancer. The plan design was based on treatment planning criteria involving PTV-$V_{100\%}$ (percentage of PTV receiving a dose larger than 100%). The PTV dose coverage was found to be more sensitive to the algorithm choice than the GTV one.

AAA systematically and significantly overestimated the PTV dose compared to AXB and MC. Differences between AAA and AXB of up to 8%, 10% and 5% were observed for PTV-$D_{50\%}$, PTV-$D_{98\%}$ and PTV-$V_{100\%}$, correspondingly. The corresponding values obtained by the MC method were up to 7% lower and significantly different than those for AXB. The variations in the PTV dose estimation could not be related to patient/plan characteristics like target volume, lung tissue volume included in the target or tumor proximity to the lung wall. The difference in the GTV parameters between AAA and AXB were not significant and the agreement between AAA and AXB as well as between AXB and MC was within 3%. Transition from AAA to AXB algorithm for designing of clinical plans while keeping the same treatment planning criteria based on PTV-$V_{100\%}$ may increase the volume of the lung tissue close to the tumor receiving full dose by more than 20%.

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