Original Article

PROGRESS in MEDICAL PHYSICS 27(4), Dec. 2016
https://doi.org/10.14316/pmp.2016.27.4.180
pISSN 2508-4445, eISSN 2508-4453

Dosimetric Validation of the Acuros XB Advanced Dose Calculation Algorithm for Volumetric Modulated Arc Therapy Plans

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Acuros XB advanced dose calculation algorithm (AXB, Varian Medical Systems, Palo Alto, CA) has been released recently and provided the advantages of speed and accuracy for dose calculation. For clinical use, it is important to investigate the dosimetric performance of AXB compared to the calculation algorithm of the previous version, Anisotropic Analytical Algorithm (AAA, Varian Medical Systems, Palo Alto, CA). Ten volumetric modulated arc therapy (VMAT) plans for each of the following cases were included: head and neck (H&N), prostate, spine, and lung. The spine and lung cases were treated with stereotactic body radiation therapy (SBRT) technique. For all cases, the dose distributions were calculated using AAA and two dose reporting modes in AXB (dose-to-water, AXB_w, and dose-to-medium, AXB_m) with same plan parameters. For dosimetric evaluation, the dose-volumetric parameters were calculated for each planning target volume (PTV) and interested normal organs. The differences between AAA and AXB were statistically calculated with paired t-test. As a general trend, AXB_w and AXB_m showed dose underestimation as compared with AAA, which did not exceed within −3.5% and −4.5%, respectively. The maximum dose of PTV calculated by AXB_w and AXB_m was tended to be overestimated with the relative dose difference ranged from 1.6% to 4.6% for all cases. The absolute mean values of the relative dose differences were 1.1±1.2% and 2.0±1.2% when comparing between AAA and AXB_w, and AAA and AXB_m, respectively. For almost dose-volumetric parameters of PTV, the relative dose differences are statistically significant while there are no statistical significance for normal tissues. Both AXB_w and AXB_m was tended to underestimate dose for PTV and normal tissues compared to AAA. For analyzing two dose reporting modes in AXB, the dose distribution calculated by AXB_w was similar to those of AAA when comparing the dose distributions between AAA and AXB_m.

Key Words: Acuros XB advanced dose calculation algorithm, Anisotropic Analytical Algorithm, Volumetric modulated arc therapy, Dose-volumetric parameter

Introduction

Volumetric modulated arc therapy (VMAT) modulating the multi-leaf collimator (MLC) positions, gantry rotation speed, and dose rates has been broadly adopted in the clinic, having benefits of delivering prescription dose to target volume while sparing normal tissue.[1-3] It has shown that VMAT can achieve a similar plan quality and monitor unit (MU) effectiveness as compared to intensity modulated radiation therapy (IMRT) resulting in shortening the treatment time in the clinic.[4-6] As the portion of complicated radiotherapy technique such as VMAT increases in the clinic, demands on the accuracy and speed of dose calculation increases.

In 2010, Acuros XB advanced dose calculation algorithm

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2015R1C1A1A02036331).
Received 22 November 2016, Revised 6 December 2016, Accepted 7 December 2016
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(AXB, Varian Medical Systems, Palo Alto, CA) has been released as a clinical deterministic dose algorithm in the Eclipse treatment planning system (TPS) to meet accuracy and speed requirements for dose calculation. AXB uses the grid-based Boltzmann solver (GBBS) to solve the Linear Boltzmann transport equation (LBTE) which describes the macroscopic behavior of radiation particles as they travel through and interact with matter.[7-9] Using the AXB, the radiation transport problem within small volumes could be solved to calculate dose distribution with accuracy and speed for dose calculation. Several studies have demonstrated that the dose calculation from the AXB were very close to those from Monte carlo (MC) simulation compared to the widely used Anisotropic Analytical Algorithm (AAA, Varian Medical Systems, Palo Alto, CA) and Collapsed-con Convolution algorithm (CCC) in heterogeneous slab phantom.[10-12] It has been shown that there were similar findings from other groups in dose calculation involving high density volumes,[13] small field segments defined by MLC,[14] and RPC phantoms of head and neck (H&N)[15] and thorax.[16] For clinical cases, several studies have performed dosimetric comparison of VMAT and IMRT plans between AXB and AAA indicating that AXB underestimated the doses to targets or normal tissues in the cases of prostate, lung, H&N, and pelvis compared to AAA.[17-20] In contrast to these results, other study has shown that AAA underestimated the dose in the cases of spine.[21] The difference between AXB and AAA depends on the treatment site and beam energy, which the results are patient-specific.

Depending on the energy dependent fluence-to-dose response function, AXB provides two dose reporting modes: dose-to-water (AXB_w) and dose-to-medium (AXB_m). For the AXB_w, energy dependent fluence-to-dose response functions are based on the water whereas for the AXB_m those are based on each material. Until now, selecting between AXB_w and AXB_m is debate in the clinic.[22] Walters et al. have determined that dose-to-medium from MC provided a better estimation of the dose to the radiosensitive red bone marrow (RBM) and bone surface cells (BSC) in spongiosa, or cancellous bone as compared with dose-to-water from MC.[23] It is essential to investigate if the selection of either AXB_m or AXB_w will affect the dosimetric parameters of VMAT plans in the clinical. The purpose of this study is to evaluate the AXB using two dose reporting modes (AXB_w and AXB_m) compared as AAA in the cases of prostate, H&N, spine, and lung treated with VMAT plans.

Materials and Methods

1. Patient selection

Among patients previously treated with VMAT technique in our institution, 10 patients for each prostate cancer, H&N cancer, spine cancer, and lung cancer were selected retrospectively for this study. The spine and lung cancers were treated with stereotactic body radiation therapy (SBRT) technique.

2. Planning and dose calculation

VMAT plans of all four cases of patients were generated in the Eclipse TPS using a TrueBeam™ equipped with a high-definition 120 Millennium™ MLC (Varian Medical Systems, Palo Alto, CA). For prostate cases, the total dose prescribed to the planning target volume (PTV) was 70 Gy with a daily dose of 2.5 Gy in 28 fractions. The prostate VMAT plans were generated using a two-full-arcs with 10 MV photon beam. In the case of H&N, the total prescription dose to PTV was 67.5 Gy (2.25 Gy/fraction) and the H&N VMAT plans were generated by using a two-full-arcs with 6 MV photon beam. The total dose prescription dose to the PTV regarding spine SBRT was 8 Gy in 1 fraction. The VMAT plans for spine SBRT were made using a two-full-arcs with 10 MV flattening-filter-free (FFF) photon beam. For lung SBRT cases, prescription dose to PTV was 60 Gy with a daily dose of 15 Gy in 4 fractions. The VMAT plans for lung SBRT were made using a two-partial-arcs with 6 MV FFF photon beam. Optimizations for all VMAT plans were performed by the progressive resolution optimizer 3 (PRO4, ver. 10, Varian Medical Systems, Palo Alto, CA). To improve the dosimetric quality in VMAT plans, all VMAT plans were re-optimized using the current dose distribution as a reference for re-optimization. The dose distributions were calculated by using AAA. The calculation grid used in this study was 2.5 mm except for 1.0 mm for lung SBRT cases. Then, dose distributions were calculated by using AXB_w and AXB_m with same plan parameters following dose calculation using AAA.

3. Analysis and evaluation of VMAT plans

For assessing the dosimetric quality with respect to PTV and normal organs, dose-volumetric histograms (DVHs) of AAA, AXB_w, and AXB_m were calculated in the Eclipse TPS. The dose-volumetric parameters for PTV for all 4 clinical cases were the mean dose, maximum dose, minimum dose, $D_{95\%}$ (dose received by at least 95% volume), and $D_{5\%}$. For the normal organs, mean dose and $D_{70\%}$ of rectum and bladder, maximum dose and $D_{50\%}$ of left and right femur heads and kidneys, maximum dose of brain stem and optic chiasm, mean dose and $V_{20\ Gy}$ (percent volume of the normal organ irradiated by at least 20 Gy) of left and right parotid glands, maximum dose and $V_{13.5\ Gy}$ of spinal cord, maximum dose and $V_{27.5\ Gy}$ of heart, and maximum dose and $V_{20\ Gy}$ of left and right lungs were calculated. For a comparative purpose, the relative dose differences in the corresponding dose-volumetric parameters the AAA and AXB of the same case were calculated as follows[21)]

$$\text{Relative dose difference (\%)} = \frac{(values\ of AXB_x - values\ of AAA)}{values\ of AAA} \times 100 \quad (1)$$

where, AXB_x is selected between AXB_w and AXB_m depending on what dose reporting mode should be compared. To investigate the statistical significance of the differences between AAA and AXB, p values were calculated using the paired t-test, indicating that p values less than 0.05 means statistically significance.

Results

The dose-volumetric parameters of AAA, AXB_w, and AXB_m with respect to H&N, prostate, spine, and lung cases are shown in Tables 1, 2, 3, and 4, respectively. The p-values providing the comparisons of mean values of dose-volumetric parameters between 2 calculation algorithms among AAA, AXB_w, and AXB_m are listed in all tables. For almost dose-volumetric parameters of PTV for 4 cases, the differences of dose-volumetric parameters are statistically significant while there are no

Table 1. The mean dose-volumetric parameters of PTV and normal tissues for head and neck cases.

	AAA	AXB_m	AXB_w	p_A*	p_B†	p_C‡
PTV						
$D_{95\%}$ (Gy)	70.7±0.2	69.6±0.4	70.7±0.3	<0.001	0.992	<0.001
$D_{5\%}$ (Gy)	67.5±0.0	66.0±0.2	67.2±0.2	<0.001	<0.001	<0.001
Min (Gy)	51.6±4.8	50.4±4.6	51.4±5.4	0.552	0.916	0.652
Max (Gy)	73.1±0.6	73.0±0.9	75.4±1.0	0.879	<0.001	<0.001
Mean (Gy)	69.3±0.1	67.9±0.2	69.1±0.2	<0.001	0.075	<0.001
Spinal cord						
Max (Gy)	42.9±1.0	41.6±0.9	42.3±0.9	0.005	0.159	0.079
Brain stem						
Max (Gy)	52.9±1.0	52.0±1.2	52.9±1.1	0.072	0.885	0.103
Optic chiasm						
Max (Gy)	27.7±16.7	27.1±16.9	27.6±17.1	0.931	0.987	0.945
Left parotid gland						
$V_{20\ Gy}$ (%)	48.2±14.9	47.0±14.6	47.8±14.6	0.857	0.950	0.905
Mean (Gy)	25.0±4.3	24.3±4.2	24.7±4.2	0.749	0.898	0.848
Right parotid gland						
$V_{20\ Gy}$ (%)	51.5±5.7	50.3±5.9	51.2±5.9	0.648	0.911	0.736
Mean (Gy)	26.3±2.2	25.6±2.2	26.0±2.2	0.530	0.799	0.711

*p_A: p-value for the comparison of dose-volumetric parameters between AAA and AXB_m.
†p_B: p-value for the comparison of dose-volumetric parameters between AAA and AXB_w.
‡p_C: p-value for the comparison of dose-volumetric parameters between AXB_m and AXB_w.

Table 2. The mean dose-volumetric parameters of PTV and normal tissues for prostate cases.

	AAA	AXB_m	AXB_w	p_A*	p_B†	p_C‡
PTV						
$D_{95\%}$ (Gy)	73.7±0.4	73.4±0.3	73.6±0.5	0.077	0.476	0.383
$D_{5\%}$ (Gy)	70.1±0.2	68.9±0.2	69.2±0.3	<0.001	<0.001	0.017
Min (Gy)	61.5±3.6	59.6±3.0	59.8±3.3	0.225	0.301	0.880
Max (Gy)	76.7±0.8	77.3±0.9	77.6±0.9	0.103	0.023	0.533
Mean (Gy)	72.2±0.3	71.3±0.3	71.9±0.4	<0.001	0.079	0.003
Rectum						
$D_{70\%}$ (Gy)	17.6±2.9	16.8±2.9	17.0±3.0	0.555	0.657	0.886
Mean (Gy)	31.6±2.7	30.9±2.8	31.1±2.7	0.564	0.725	0.821
Bladder						
$D_{70\%}$ (Gy)	15.8±10.3	15.3±10.2	15.5±10.3	0.921	0.955	0.966
Mean (Gy)	33.1±8.8	32.4±8.7	32.8±8.8	0.863	0.953	0.910
Left femur head						
$D_{50\%}$ (Gy)	14.0±4.4	13.7±4.3	14.0±4.4	0.850	0.981	0.868
Max (Gy)	25.9±5.3	25.2±5.1	25.8±5.2	0.775	0.979	0.793
Right femur head						
$D_{50\%}$ (Gy)	14.5±4.7	14.1±4.6	14.5±4.7	0.864	0.992	0.871
Max (Gy)	25.2±5.5	24.6±5.3	25.2±5.4	0.799	0.985	0.782

*p_A: p-value for the comparison of dose-volumetric parameters between AAA and AXB_m.
†p_B: p-value for the comparison of dose-volumetric parameters between AAA and AXB_w.
‡p_C: p-value for the comparison of dose-volumetric parameters between AXB_m and AXB_w.

Table 3. The mean dose-volumetric parameters of PTV and normal tissues for spine cases.

	AAA	AXB_m	AXB_w	p_A*	p_B†	p_C‡
PTV						
$D_{95\%}$ (Gy)	8.3±0.1	8.2±0.1	8.4±0.1	0.001	0.055	<0.001
$D_{5\%}$ (Gy)	8.0±0.0	7.8±0.0	8.0±0.0	<0.001	0.015	<0.001
Min (Gy)	6.8±1.1	6.6±1.0	6.7±1.0	0.619	0.771	0.831
Max (Gy)	8.7±0.1	8.6±0.1	9.2±0.1	0.657	<0.001	<0.001
Mean (Gy)	8.2±0.0	8.0±0.0	8.2±0.0	<0.001	0.673	<0.001
Left kidney						
$D_{50\%}$ (Gy)	0.8±0.9	0.8±0.9	0.8±0.9	0.958	0.980	0.979
Max (Gy)	3.7±3.2	3.6±3.1	3.6±3.1	0.936	0.953	0.983
Right kidney						
$D_{50\%}$ (Gy)	0.7±0.8	0.7±0.8	0.7±0.8	0.950	0.971	0.979
Max (Gy)	3.6±3.3	3.5±3.3	3.6±3.3	0.947	0.965	0.982

*p_A: p-value for the comparison of dose-volumetric parameters between AAA and AXB_m.
†p_B: p-value for the comparison of dose-volumetric parameters between AAA and AXB_w.
‡p_C: p-value for the comparison of dose-volumetric parameters between AXB_m and AXB_w.

statistical significances for all dose-volumetric parameters of normal tissues for 4 cases. Almost dose-volumetric parameters calculated using AXB_m and AXB_w tended to be underestimated compared to those calculated using AAA.

Figs. 1, 2, 3, and 4 show that the averaged DVHs and the relative dose difference between AXB and AAA for PTV and normal tissues for H&N, prostate, spine, and lung, respectively. For H&N cases, AAA overestimated the dose compared with AXB_w and AXB_m, with maximum value of the relative dose difference of −3.4% while maximum doses of PTV from

Table 4. The mean dose-volumetric parameters of PTV and normal tissues for lung cases.

	AAA	AXB_m	AXB_w	p_A*	p_B†	p_C‡
PTV						
$D_{95\%}$ (Gy)	63.1±0.7	63.5±1.0	63.4±1.0	0.319	0.424	0.851
$D_{5\%}$ (Gy)	60.5±0.7	59.9±1.0	60.1±1.0	0.136	0.303	0.671
Min (Gy)	56.8±0.7	55.9±1.1	56.3±1.0	0.032	0.189	0.373
Max (Gy)	64.5±0.9	65.7±1.1	65.3±1.4	0.017	0.166	0.480
Mean (Gy)	62.0±0.7	61.9±1.0	62.0±0.9	0.792	0.862	0.930
Spinal cord						
$V_{13.5\ Gy}$ (%)	1.9±2.6	1.4±2.2	1.6±2.4	0.645	0.748	0.892
Max (Gy)	13.5±5.1	13.0±4.8	13.2±4.8	0.812	0.883	0.926
Heart						
$V_{27.5\ Gy}$ (%)	0.0±0.0	0.0±0.0	0.0±0.0	0.702	0.900	0.785
Max (Gy)	13.0±9.9	12.9±9.8	12.9±9.8	0.984	0.982	0.999
Left lung						
$V_{20\ Gy}$ (%)	3.0±4.9	3.0±4.9	3.0±4.9	0.998	0.996	0.999
Mean (Gy)	2.5±2.5	2.5±2.5	2.5±2.5	0.989	0.992	0.997
Right lung						
$V_{20\ Gy}$ (%)	4.6±4.8	4.6±4.9	4.6±4.9	0.983	0.980	0.997
Mean (Gy)	3.1±2.4	3.1±2.4	3.1±2.4	0.996	0.999	0.996

*p_A: p-value for the comparison of dose-volumetric parameters between AAA and AXB_m.
†p_B: p-value for the comparison of dose-volumetric parameters between AAA and AXB_w.
‡p_C: p-value for the comparison of dose-volumetric parameters between AXB_m and AXB_w.

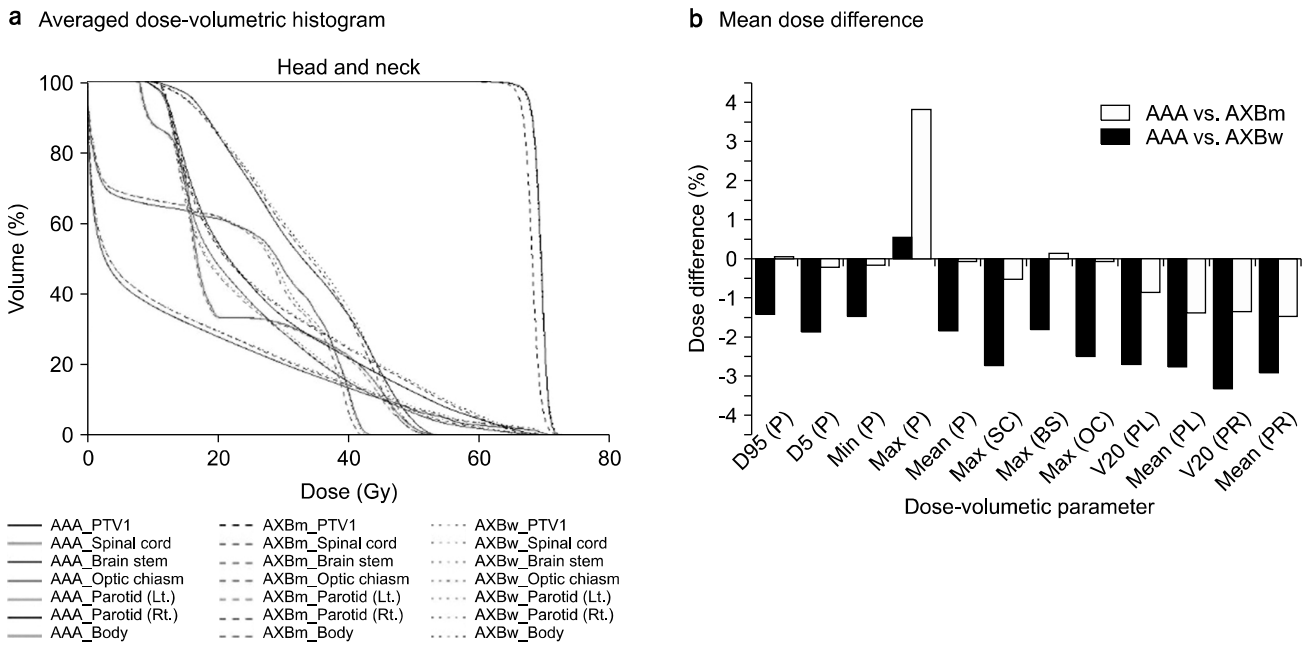

Fig. 1. The averaged dose-volume histograms (DVHs) (a) and the mean values of the relative dose differences (b) for PTV and normal tissue in the case of head and neck. Solid lines, dotted lines, and dashed lines are for DVHs calculated by AAA, AXB_w and AXB_m, respectively. The $D_{n\%}$ (structure) means dose received n% volume of certain structure. $V_{n\ Gy}$ (structure) means the percent volume of certain structure irradiated by at least n Gy. The minimum dose, maximum dose, and mean dose were abbreviated to min, max, and mean, respectively. The PTV, spinal cord, brain stem, optical chiasm, left parotid grand and right parotid grand were abbreviated to P, SC, BS, OC, PL and PR, respectively.

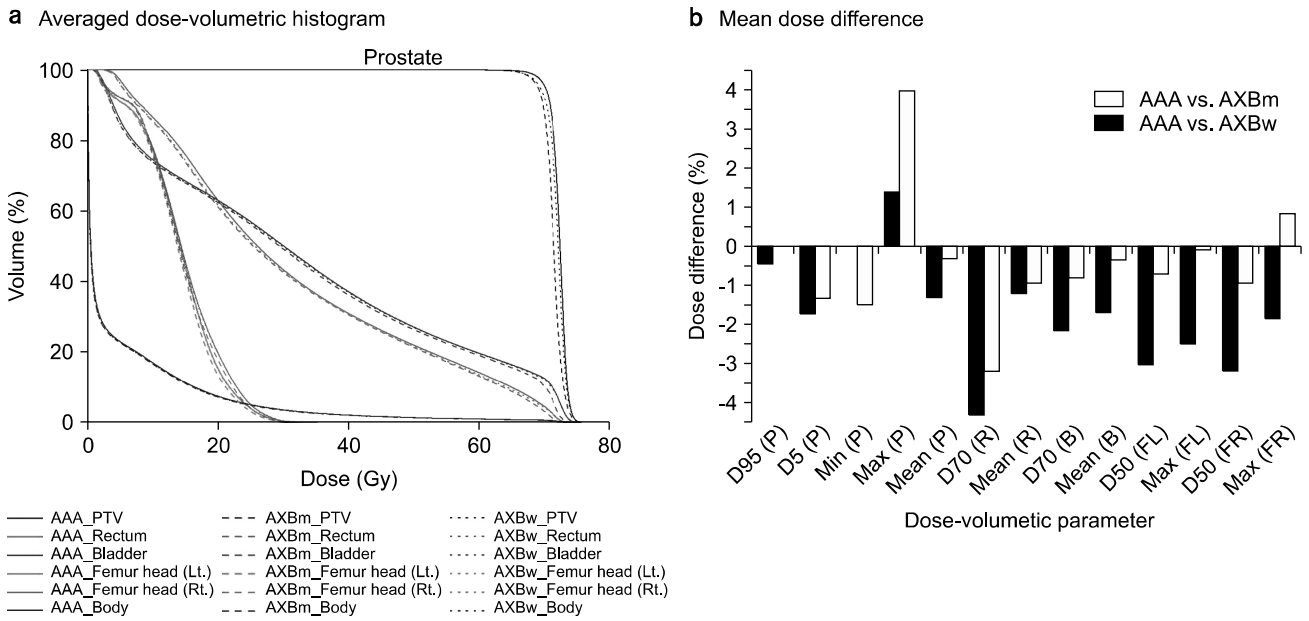

Fig. 2. The averaged dose-volume histograms (DVHs) (a) and the mean values of the relative dose differences (b) for PTV and normal tissue in the case of prostate. Solid lines, dotted lines, and dashed lines are for DVHs calculated by AAA, AXB_w and AXB_m, respectively. The $D_{n\%}$ (structure) means dose received n% volume of certain structure. $V_{n\ Gy}$ (structure) means the percent volume of certain structure irradiated by at least n Gy. The minimum dose, maximum dose, and mean dose were abbreviated to min, max, and mean, respectively. The PTV, rectum, bladder, left femur head and right femur head were abbreviated to P, R, B, FL and FR, respectively.

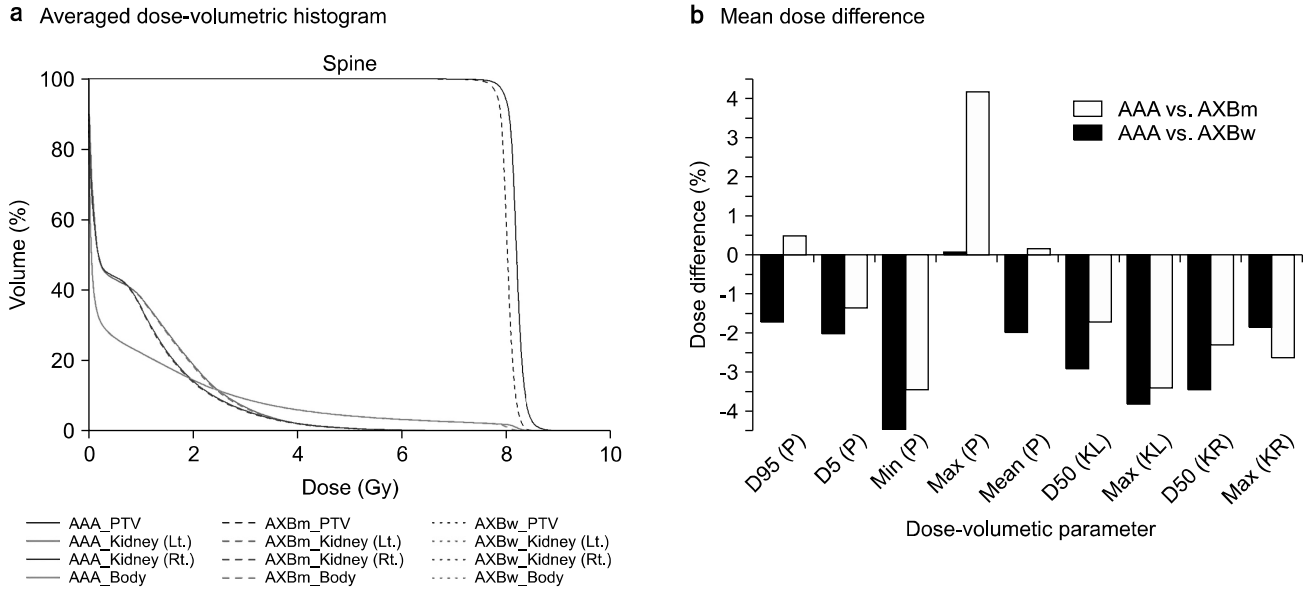

Fig. 3. The averaged dose-volume histograms (DVHs) (a) and the mean values of the relative dose differences (b) for PTV and normal tissue in the case of Spine. Solid lines, dotted lines, and dashed lines are for DVHs calculated by AAA, AXB_w and AXB_m, respectively. The $D_{n\%}$ (structure) means dose received n% volume of certain structure. $V_{n\ Gy}$ (structure) means the percent volume of certain structure irradiated by at least n Gy. The minimum dose, maximum dose, and mean dose were abbreviated to min, max, and mean, respectively. The PTV, left kidney and right kidney were abbreviated to P, KL and KR, respectively.

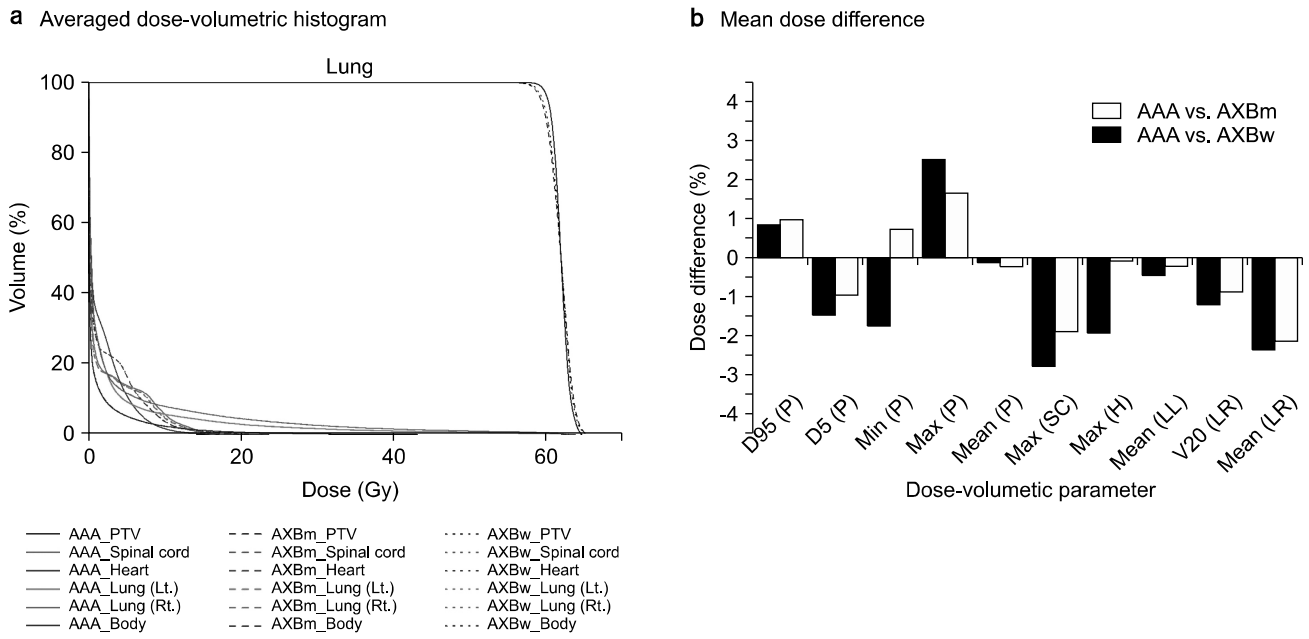

Fig. 4. The averaged dose-volume histograms (DVHs) (a) and the mean values of the relative dose differences (b) for PTV and normal tissue in the case of lung. Solid lines, dotted lines, and dashed lines are for DVHs calculated by AAA, AXB_w and AXB_m, respectively. The $D_{n\%}$ (structure) means dose received n% volume of certain structure. $V_{n\ Gy}$ (structure) means the percent volume of certain structure irradiated by at least n Gy. The minimum dose, maximum dose, and mean dose were abbreviated to min, max, and mean, respectively. The PTV, spinal cord, heart, left lung, and right lung were abbreviated to P, SC, H, LL, and LR, respectively.

AXB_w and AXB_m, and maximum dose of brain stem from AXB_w were overestimated with maximum value of the relative dose difference of 3.8%. For prostate cases which shows a similar tendency with H&N cases, the maximum value of the relative dose difference was −4.3% for $D_{70\%}$ of rectum comparing AAA with AXB_m while those was 4.0% for maximum dose of PTV comparing AAA with AXB_w. In the case of spine, overestimation for AAA did not exceed within −4.5% compared with AXB_m while maximum underestimation for AAA was 4.2% compared with AXB_w. For lung cases, the maximum value of the relative dose difference was −2.8% for maximum dose of spinal cord comparing AAA with AXB_m while those was 2.5% for maximum dose of PTV comparing AAA with AXB_m. As a general trend, the relative dose differences comparing AAA and AXB_w were tended to be smaller than those comparing AAA and AXB_m for all 4 cases demonstrating that the absolute mean values of the relative dose differences were 1.1±1.2% and 2.0±1.2% when comparing between AAA and AXB_w, and AAA and AXB_m, respectively. The averaged DVHs for AAA were shown to be very similar for normal tissue structures, but some notable differences in PTV compared against AXB_w and AXB_m.

Discussion

The dosimetric performance of AAA, AXB_w, and AXB_m was investigated for the H&N, prostate, spine, and lung cases. The dosimetric evaluation was conducted regarding the results derived from the dose-volume parameters in the Eclipse TPS. The preliminary results from the clinical cases in this study showed that there was similar trend of underestimating the doses from AXB_w and AXB_m for almost dose-volumetric parameters of PTV and normal organs when comparing to those from AAA. This dosimetric characteristics of the AXB has been investigated in several studies. Suresh et al. have shown that the AAA predicted higher minimum, mean and maximum doses to the PTV but the dose difference was less than 0.50% and for normal organs the maximum doses in the AAA plans were higher by in average 0.58% when compared to the AXB plans.[24] For H&N patients who treated with IMRT, the mean

dose to the PTV was escalated naturally by 2.1%～3.7% by changing from AXB to AAA for 4 MV photon beam.[19] Dose underestimation by AXB has been showed in simple geometry including heterogeneous materials, compared to AAA.[25,26] This characteristics of AXB could affect the dose distributions in patient having complicated geometry. Another possibility of inconsistency between AAA and AXB was to use FFF photon beam. The difference in electron contamination parameter by removal of flattening filter was observed for modeling.[12] The dose differences by AAA and AXB were affected by many factors which were beam energy, field size, field number, and densities of normal tissue and then further investigation is necessary. In contrast to our results, Zhen et al. have demonstrated that AAA was shown to underestimate the dose for spine VMAT plans with no statistical significance compared to AXB_m.[21] However, numerical data for dose-volumetric parameter has shown that the dose differences between AAA and AXB_m were less than 0.2 Gy and our result was maximum dose difference of 0.4 Gy.

For statistically evaluation, the numbers of p values less than 0.05 were 10, 6, 9, and 2 for cases of H&N, prostate, spine, and lung, respectively. In order to assess the impact of calculation algorithms, the numbers of p values less than 0.05 for comparison of two algorithms which were AAA and AXB_m, AAA and AXB_w, and AXB_m and AXB_w were 11, 6, and 10, respectively. Although AAA and AXB_w had different calculation mechanism, these algorithms were based on “water”. It has demonstrated that the dose distribution calculated by AXB_w was similar to those of AAA when comparing the dose distributions between AAA and AXB_m. The tendency in the dosimetric impact of AXB depends on the tumor location, beam energy and near tissues.[26]

The mean values of the relative dose difference for lung cases were smaller than those for other cases as shown in Fig. 4. These findings are similar to what has been reported in the literature.[25,26,28] The reason for this small difference between AXB and AAA is attributed to the modeling of the heterogeneity of lung tissue in the AXB, compared to AAA as reported by other studies.[14,25] Robinson et al. have demonstrated that AAA overestimates the doses to interface of the heterogeneity supporting this findings.[29] Liu et al. have also reported that the effect of Hounsfield Unit (HU) values on the dose differences calculated AAA and AXB and lower HU values could make the dose differences between AAA and AXB larger.[30] In our study, 10 patients for lung cases had clear delineation of gross tumor volume in SBRT and then dosimetric impact of AXB was slightly significant to dose calculation in comparison with AAA.

As shown in Figures 1, 2, 3, and 4, the DVHs calculated by AXB_w was more matched with those of AAA for all cases in comparison with AXB_m and AAA. For calculation procedure of AAA, last step to convert the absorbed energy distribution to a dose is scaling water materials using electron density instead of mass density. The report mode in AAA could be generally considered as dose-to-water mode supporting our findings.[31,32] Selecting the appropriate dose reporting mode in the clinic is still debate. In 2003, Liu has asserted that dose-to-medium allows to provide a closer relationship between tissue response and dose while Keall has argued against this assertiveness and stated that all clinical experience and dosimetry protocols are based on the dose-to-water.[22] Further study is needed to determine the clinical impact depending on dose reporting modes in AXB.

Conclusion

In this study, the dose distributions calculated by AAA, AXB_w, and AXB_m were compared in all cases for H&N, prostate, spine, and lung for validating the performance of AXB. Both AXB_w and AXB_m were tended to underestimate dose for PTV and normal tissues compared to AAA. For analyzing two dose reporting modes in AXB, the dose distribution calculated by AXB_w was similar to those of AAA when comparing the dose distributions between AAA and AXB_m.

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