Original Article

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Comparison of Anisotropic Analytic Algorithm Plan and Acuros XB Plan for Lung Stereotactic Ablative Radiotherapy Using Flattening Filter-Free Beams

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This study investigated the dosimetric effects of different dose calculation algorithm for lung stereotactic ablative radiotherapy (SABR) using flattening filter-free (FFF) beams. A total of 10 patients with lung cancer who were treated with SABR were evaluated. All treatment plans were created using an Acuros XB (AXB) of an Eclipse treatment planning system. An additional plans for comparison of different alagorithm recalcuated with anisotropic analytic algorithm (AAA) algorithm. To address both algorithms, the cumulative dose-volume histogram (DVH) was analyzed for the planning target volume (PTV) and organs at risk (OARs). Technical parameters, such as the computation times and total monitor units (MUs), were also evaluated. A comparison analysis of DVHs from these plans revealed the PTV for AXB estimated a higher maximum dose (5.2%) and lower minimum dose (4.2%) than that of the AAA. The highest dose difference observed 7.06% for the PTV $V_{105\%}$. The maximum dose to the lung was also slightly larger in the AXB plans. The percentate volumes of the ipsilateral lung (V_5, V_{10}, V_{20}) receiving 5, 10, and 20 Gy were also larger in AXB plans than for AAA plans. However, these parameters were comparable between both AAA and AXB plans for the contralateral lung. The differences of the maximum dose for the spinal cord and heart were also small. The computation time of AXB plans was 13.7% shorter than that of AAA plans. The average MUs were 3.47% larger for AXB plans than for AAA plans. The results of this study suggest that AXB algorithm can provide advantages such as accurate dose calculations and reduced computation time in lung SABR plan using FFF beams, especially for volumetric modulated arc therapy technique.

Key Words: Anisotropic analytical algorithm, Acuros XB, Stereotactic ablative radiotherapy, Lung cancer

Introduction

The accuracy of dose calculations directly affects radiation treatment efficacy when an MV X-ray beam travels though media of different densities. Evidence exists that a 1% accuracy improvement results in a 2% increase in cure rates for patients with early-stage tumors.[1] The heterogeneous components of the body and the complexity of human anatomy require the sophisticated dose calculation algorithms of treatment planning systems (TPSs) to precisely calculate the dose prescribed to targets and organs at risk (OARs), for which the electron density may vary from low, such as that in the lungs, to high, such as that in dense bones. Various dose calculation algorithms have been developed to incorporate heterogeneity correction. Currently, most clinical TPSs use convolution-based methods, such as collapsed cone convolution and anisotropic analytic algorithm (AAA), for pa-

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tient treatment planning. Inhomogeneity correction has greatly improved the accuracy of dose calculations, especially when low-density tissues such as lung tissue are involved in the treatment.[2] A good dose calculation algorithm should be able to calculate the dose accurately at the prescription point and tumor volume, as well as at the OARs. Therefore, dose calculation algorithms should be highly accurate throughout the entire treatment area. An inhomogeneity correction study on the AAA in the Eclipse TPS by Robinson[3] revealed that the discrepancy between his measurements and the AAA calculation exceeded 2% in low-density tissues, and the discrepancy was greater for 6-MV photon beams than for 15-MV photon beams. The widely used AAA is known to overestimate the dose at the air-tumor interface and underestimate the dose at the bone-tumor interface.[4,5]

A recently, a new dose calculation algorithm called Acuros XB (AXB) became commercially available for external photon beam dose calculations. The AXB fundamental radiation transport theory is based on the grid-based Boltzmann solver, commonly known as discrete ordinates. The linear Boltzmann transport equation (LBTE) is the governing equation that describes the distribution of radiation particles resulting from their interactions with matter.[6-8]

The dosimetric accuracy of AXB has been investigated in several studies. A previous study by Han et al.[9] revealed that the differences of doses calculated using AXB and AAA plans in the lung region were as large as 15% in a single open filed. In several other studies, validation results of AXB for inhomogeneous media indicated that the dose calculations from AXB were better than those from AAA when compared against the Monte Carlo (MC) results.[7,10-12] However, the use of the two algorithms in stereotactic ablative radiotherapy (SABR) using a flattening filter-free (FFF) beam has not been investigated for lung cancer.

The purpose of this study was to evaluate the difference in the dose distribution of AXB and AAA plans implemented in a commercial TPS for lung SABR with an FFF beam. We compared the dosimetric parameters for the target and OARs according to the AAA and AXB plans.

Materials and Methods

Ten lung cancer patients who had treated with SBAR at our institution between May 2013 and January 2014 were enrolled in the current planning study, which was approved by our institutional review board (No. B-1406-254-109).

1. Dose calculation algorithms for heterogeneity correction

All calculations were performed using a new version of the Eclipse 11.0 TPS with AAA 11.0.34 and AXB 11.0.34 (Varian Medical Systems, Palo Alto, CA). Two dose-reporting modes are available in AXB: dose-to-water and dose-to-medium. The latter mode was selected for AXB. AAA and AXB share the same beam model, which was configured through the TPS beam configuration feature. Compared with the previous version 10, version 11 includes several updates as follows: (1) improved efficiency of the algorithm by optimising parallelisation, cache usage, and other variables; (2) reduced electron energy cutoff from 500 keV to 200 keV; (3) improved photon ray tracing and electron contaminant source efficiency for cases with many fields; (4) implementation of “transport correction” to accelerate iterative convergence and improve accuracy; and (5) improved handling of structure boundary when Hounsfield units or material is assigned.

The AAA is an analytical photon dose calculation algorithm based on a pencil beam convolution/superposition technique. The tissue heterogeneity in the AAA is handled by radiologic scaling of primary photons and photon scatter kernel scaling in lateral directions according to the local electron density.[13,14] AXB is considered similar to classic MC methods for accurate modelling of the dose deposition in heterogeneous media. AXB utilizes the LBTE and solves numerically that describes the macroscopic behavior of radiation particles as they travel through and interact with the matter. A description of the original AXB algorithm for external beam was provide by Vassiliev et al.,[7] whereas a description of its implementation in Eclipse was reported by Fogliata et al.,.[15] The detailed mathematical formulas and implementations for AXB, including beam modelling, material assignments, and calculation options, were described in previously reported publications.[9,16]

2. Treatment setup and planning

All patients were treated in the supine position with their arms crossed above their heads. The SABR immobilization platform (Body Pro-Lok, CIVCO, Orange City, IA, USA) was used to fix the thoracic and abdominal regions and reduce residual body motion. The computed tomography (CT) data of these patients with lung tumors who underwent SABR were used, and the scans were acquired with 2-mm slice spacing on the flat table top of a Philips Big-bore CT scanner. The treatment plans were created using different dose calculation algorithms in this study. The Digital Imaging and Communications in Medicine (DICOM) CT data were electronically transferred to the Eclipse TPS for contouring and planning. Planning treatment volumes (PTVs) were created by adding 5-mm margins to the clinical treatment volume (CTV) in all directions. The OARs considered were the lungs, heart, and spinal cord. The lung volume was divided into ipsilateral and contralateral lung volumes. The contralateral lung volume was defined as the bilateral lung outside the PTV.

The beam parameters of the clinical treatment plans in this study were set up in the Eclipse TPS, and the treatment plans were calculated using a volumetric modulated arc therapy (VMAT) technique with two partial arcs allowing the optimizer to use a maximum dose rate of 1400 monitor units (MUs)/min for a 6-MV FFF beam. The dose calculations were performed with inhomogeneity correction and 2.5-mm grid resolution in all plans. In all plans, 48 Gy of radiation were delivered in four equal fractions to deliver a biological equivalent dose exceeding 100 Gy.

The optimization goals were to ensure that the entire CTV received 95% of the prescribed dose and for the PTV to cover 95% of the volume that received 95% of the prescribed dose, with no PTV hot spot receiving 107% or more of the prescribed dose. Doses exceeding 107% were permitted only inside the target. The constraints for the OARs were a maximum dose (D_{max})$<$30 Gy for the heart and $D_{max}<$20 Gy for the spinal cord. For the contralateral lung, the percentage volume receiving 20 Gy (V_{20}) or more was restricted to 10%. For the ipsilateral lung, the dose constraint was $V_{20}<$30%

3. Plan evaluation and analyses

The dose-volume histogram (DVH) of the calculated SABR plans for lung cancer was generated in the Eclipse TPS. The average DVH of the PTV was generated for the AAA and AXB plans by averaging the data for the 10 analyzed patients. For the PTV and CTV, the mean dose, minimum dose, maximum dose (high point dose), and homogeneity were compared. Homogeneity was evaluated using the sigma index (SI). This index has a linear correlation with the equivalent normalized dose, and it represents the standard deviation of the differential DVH. Our previous study and other literature indicated that the SI was superior to the conventional homogeneity index because it provides complete information for the entire DVH curve in treatment plans.[17,18)]

A value of conformity have been suggested, including the lesion coverage factor (LCF), healthy tissue conformity index (HTCI), and conformity number (CN). The LCF is the ratio of the PTV receiving 95% of the prescribed dose ($V_{95\%}$) to the PTV. The HTCI is the ratio between the PTV covered by the 95% of isodose and the volume of the 95% isodose. The CN is the product of the LCF and HTCI, integrating information regarding both the size of the 95% isodose and the degree of overlap with the PTV and was therefore used as the primary measure of conformity.[19-22)]

For the lungs, the mean dose, maximum dose, and percentage volumes receiving 5 and 10 Gy (V_5 and V_{10}, respectively), as well as V_{20}, were compared. The maximum dose was evaluated for the heart and spinal cord. Additionally, the technical parameters such as the computation times and total MUs for SABR plans using the AAA and AXB were compared. The difference in MUs between the AAA and AXB plans was evaluated. The percent difference (D_{MU} (%)) of the corresponding computed value between the AXB and AAA plans of the same patient was calculated using Eq. (1).

$$D_{MU}(\%) = \left[\frac{MU_{(AXB)} - MU_{(AAA)}}{MU_{(AAA)}} \right] \times 100 \qquad (1)$$

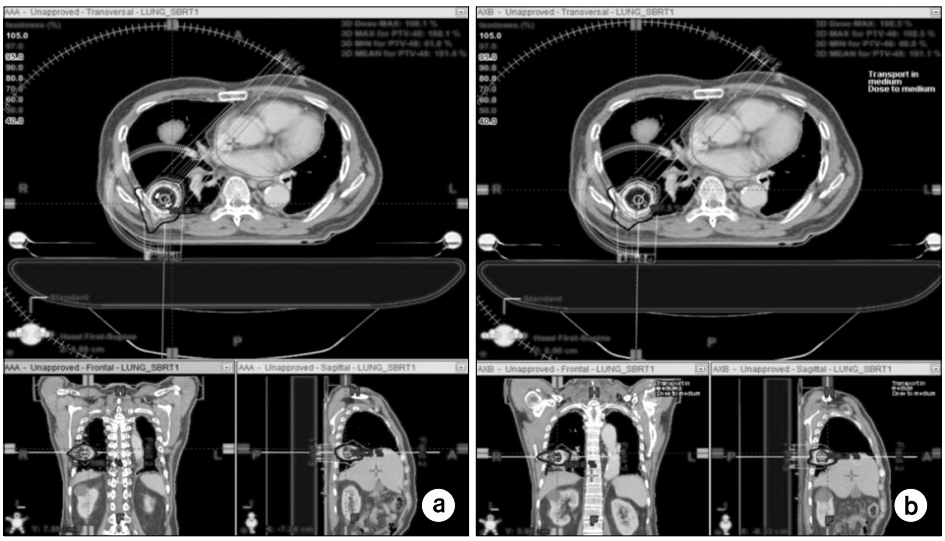

Fig. 1. An example of dose distribution between AAA (a) and AXB (b) plan for PTV when 48 Gy was prescribed at the isoceneter.

Results

Between April 2013 and January 2014, 10 patients with lung tumours were treated using SABR with an FFF beam of 6 MV. The mean CTV and PTV in the patients were 5.54 (range 0.42～12.55 cm^3) and 24.23 cm^3 (range 6.11～38.97 cm^3), respectively. Fig. 1 presents the dose distribution of the AAA and AXB plans in the Eclipse TPS for lung SABR using a two-partial-arc technique. Fig. 2 shows the average DVH of the PTV for the AAA and AXB plans. The coverage, homogeneity, and conformity of the PTV and CTV for the AAA and AXB in the lung SABR plans are listed in Table 1.

The mean values of the minimum, mean, and maximum doses for the PTV were 39.36, 47.98, and 53.63 Gy, respectively, when 48 Gy were delivered to the isocenter using the AXB. When the doses were recalculated using the AAA, these values were 41.52, 48.16, and 51.37 Gy, respectively. Regarding the different calculation algorithms, the mean $V_{95\%}$, $V_{100\%}$, and $V_{105\%}$ for the PTV displayed large differences, with the largest difference (7.06%) observed for the PTV $V_{105\%}$. However, $V_{95\%}$ and $V_{100\%}$ differed by no more than 0.4% between the two plans for the CTV. The mean PTV and CTV SI was 3.89 and 1.28 Gy for the AXB, and 2.52 and 1.05 Gy for the AAA. The mean SI using the AXB was higher than that of the AAA. These results mean that 95% (2 standard deviations) and 99% (3 standard devations) of PTV using the AXB is encompassed 44.11～51.89 to 42.83～53.17 Gy, and

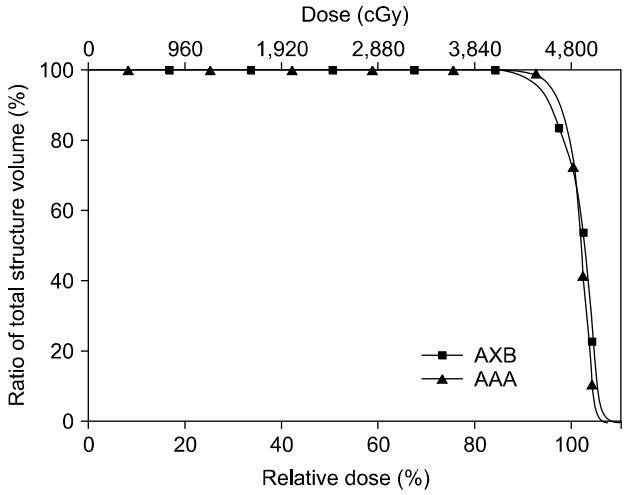

Fig. 2. Cumulative dose-volume histogram of the PTV using AAA and AXB in all plans.

that using the AAA is encompassed 45.48～50.52 to 44.43～51.57 Gy, respectively.

The mean V_5, V_{10}, and V_{20} for the ipsilateral lung were 24.60, 12.37, and 3.86%, respectively, when 48 Gy were delivered to the isocenter using the AXB. After recalculation with AAA, these values were 23.11, 11.41, and 3.63%, respectively. The percentage volume to the ipsilateral lung was statistically reduced in the AAA calculation compared with the AXB calculation. However, the corresponding values for the contralateral lung were comparable (within 2%) between the AAA and AXB plans as shown in Table 2. No significant difference

was observed for the maximum dose to the spinal cord and heart between the plans.

The computation times for lung SABR between the AAA and AXB plans are listed in Table 3. The AXB computation times by automatic optimization were faster than those of the AAA. The relative difference between these algorithms was 13.7%. Table 4 shows the percentage difference in MUs between the AAA and AXB plans for 10 patients, and the difference varied from −0.66 to 7.12%. The average percentage difference in MUs for the 10 patients was 3.47%.

Discussion

Two benefits can be expected from the use of FFF beams

Table 1. Target coverage, homogeneity, and conformity in lung SABR plans between the AAA and AXB.

Coverage indices	Algorithm		
	AXB (Mean±SD)	AAA (Mean±SD)	Relative difference (%) (AXB−AAA)/AAA×100
PTV $V_{95\%}$ (%)	92.35±5.53	95.01±0.35	−2.89
PTV $V_{100\%}$ (%)	82.25±6.81	86.50±1.33	−4.91
PTV $V_{105\%}$ (%)	3.08±2.58	2.87±1.05	7.06
CTV $V_{95\%}$ (%)	99.90±0.83	100.01±0.36	−0.11
CTV $V_{100\%}$ (%)	98.58±1.23	98.93±0.63	−0.35
PTV			
Maximum dose (Gy)	53.63±2.98	51.37±2.13	4.40
Mean dose (Gy)	47.98±1.51	48.16±1.49	−0.37
Minimum dose (Gy)	39.36±3.79	41.52±3.25	−5.20
CTV			
Maximum dose (Gy)	52.53±2.11	51.07±1.79	2.86
Mean dose (Gy)	48.99±1.53	48.63±1.55	0.74
Minimum dose (Gy)	45.59±3.04	46.32±2.71	−1.58
HI			
PTV sigma index (Gy)	3.89±0.52	2.52±0.31	54.37
CTV sigma index (Gy)	1.28±0.33	1.05±0.13	21.90
CI			
LCF	0.89±0.12	0.92±0.10	−3.26
HTCI	0.87±0.19	0.88±0.21	−0.68
CN	0.77±0.15	0.81±0.09	−4.94

HI: homogeneity indices, CI: conformity indices, LCF: lesion coverage factor, HTCI: health tissue conformity index, CN: conformity number $V_{95\%}$, $V_{100\%}$, $V_{105\%}$: the volumes receiving 95%, 100%, and 105% of the prescribed dose, respectively.

Table 2. Comparison of OARs dosimetric data in lung SABR plans between the AAA and AXB.

Coverage indices	Algorithm		
	AXB (Mean±SD)	AAA (Mean±SD)	Relative difference (%) (AXB−AAA)/AAA×100
Ipsilateral lung			
V_5 (%)	24.60±6.13	23.11±5.61	6.45
V_{10} (%)	12.37±4.31	11.41±3.69	8.41
V_{20} (%)	3.86±1.53	3.63±1.36	6.34
MLD (Gy)	4.26±1.14	4.14±1.20	2.90
Contralateral lung			
V_5 (%)	12.28±3.73	12.07±3.70	1.74
V_{10} (%)	5.86±2.44	5.76±2.43	1.74
V_{20} (%)	2.97±2.02	2.92±2.01	1.71
MLD (Gy)	2.40±0.66	2.39±0.65	0.42
Spinal cord			
Maximum dose (Gy)	8.40±2.19	8.24±1.73	1.94
Heart			
Maximum dose (Gy)	12.32±9.58	12.45±9.47	−1.04

MLD: mean lung dose. V_5, V_{10}, V_{20}: the percentage volumes receiving 5, 10, and 20 Gy dose, respectively.

Table 3. The average computation time of AAA and AXB for 10 lung SABR plans using VMAT technique.

	AXB (Mean±SD)	AAA (Mean±SD)	Relative difference (%) (AXB−AAA)/AAA×100
Time (Sec)	529.5±49.4	613.9±76.5	−13.7

Table 4. The percentage difference of total MUs in the two different calculation algorithms.

Algorithm	Patients [MUs]										
	1	2	3	4	5	6	7	8	9	10	Mean
AXB	2857	2894	2396	3340	3005	2698	2652	2525	2811	2951	2812.9
AAA	2698	2760	2412	3118	2936	2658	2555	2458	2739	2825	2715.9
D_{MU} (%)	5.89	4.86	−0.66	7.12	2.35	1.50	3.80	2.73	2.63	4.46	3.47

MUs: monitor units, D_{MU} (%): percentage difference in MUs

for radiation therapy; 1) The first benefit is a reduction in the out-of-field dose due to reduced head scatter and residual electron contamination. This leads to reduced exposure of normal tissue to scattered doses outside the field. 2) The second benefit is a fast delivery time with larger dose rates due to removal of the flattening filter. This implies the possibility of delivering treatment up to a factor of four at 10 MV.[23] The stereotactic VMAT technique with FFF beams has been confirmed as a powerful technique for irradiating many treatment sites, and the strategy is associated with higher dose conformity to the tumor and decreased intra-fraction movements because of the shorter treatment time.[24-27] In our institution, lung SABR treatments possessing these advantages were administered using stereotactic VMAT with 6-MV FFF beams.

The dosimetric accuracy of AXB for intensity-modulated radiation therapy and VMAT plans with FFF beams has been investigated in several studies.[9,12,28] In the current study, we investigated the dosimetric differences between AXB and AAA plans for lung SABR with FFF beams.

A comparison of DVHs from these plans revealed that the AXB plans produced a high maximum dose and lower minimum dose for PTV. The relative difference of maximum dose and minimum dose was 4.40% and 5.20%. The mean dose was found to be smaller for the AXB plans when the target was located in soft tissue; however, the value was larger for the AXB plans when the target was located in lung tissue. We used the SI to evaluate the detailed dose homogeneity for the PTV and CTV. It qualitatively provided significant information regarding the dosimetric spread across the PTV and CTV. The PTV coverage using the AXB was reduced than that for the AAA, as shown in Fig. 2. These dosimetric differences may be due to the different beam modelling approaches within the AAA and AXB plans to account for electronic disequilibrium in different regions, such as the high-dose region near the target and in intermediate- or low-dose regions distant from the target.

The maximum dose delivered to the lungs was slightly larger in the AXB plans than in the AAA plans. The differences in lung doses calculated by the two algorithms were dependent on patient-related factors such as the field size of the target, location of the target inside the lungs, and density of the lungs. The previous study reported by Bush et al. indicated that the AAA can underestimate or overestimate the lung dose depending on the actual combination of field size, target location, and lung density.[10]

The values of V_5, V_{10}, and V_{20} for the ipsilateral lung were larger ($>6\%$) in the AXB plans than in the AAA plans. For the contralateral lung, these parameters were comparable between the plans. The low doses to the contralateral lung were mainly contributed from the exit doses because beam entrance though the contralateral lung was avoided.

The dose differences between the models for the other OARs were small. However, there was a significant difference in the calculation time between the AAA and AXB plans, including a difference of approximately 21% for patient 4. We found that the use of AXB could reduce the total computation time for VMAT plans using FFF beams, which have a large number of orientations. This is mostly due to the fact that the primary source component needs to be calculated for each beam via ray tracing, whereas the scatter components are calculated only once regardless of the number of beam angles.

The average number of MU differences for all patients was larger for the AXB plans than for the AAA plans, excluding patient 3. These outcomes indicated that application of AXB plans results in a 3.47% increase of the delivered dose relative to the AAA plans (Table 5). The greatest difference (7.12%) of MUs was observed in patient 4 with the smallest PTV. For larger PTVs, these differences of MUs from the 2 algorithms were decreased. The PTV margin of this patient was included with air in the PTV distant from soft tissue. The dose at the periphery of the PTV is likely to decrease because the PTV margin is covered with air, while in the PTV adjacent chest wall, the dose at the PTV is less likely to decrease because the PTV margin is close to or overlaps with soft tissues. The MUs in the AXB plans had to be increased in order to obtain the suitable PTV coverage as in the AAA plans. We found that the percentage difference in MUs between the models is dependent on the individual patient anatomy, including the target size and its position. Our results are comparable to those of Narabayashi et al., who reported that the distance from the PTV margin to the chest wall was significantly correlated with the rate of increase in MUs.[29]

Conclusion

In SABR plans using FFF beams for lung cancer, we investigated the impact of two different dose calculation algorithms with heterogeneity correction on the dose distribution. On average, the AXB calculations produced smaller magnitudes of $V_{95\%}$ and $V_{100\%}$ for the CTV and PTV but a larger $V_{105\%}$. The AXB plans also predicted larger homogeneity index and smaller conformity index values than the AAA plans. For the ipsilateral lung, V_5, V_{10}, and V_{20} were larger in AXB plans than in AAA plans. However, these values were similar for the contralateral lung. The averaged maximum doses delivered to the spinal cord and heart also were similar between the AAA and AXB plans. The AXB algorithm provided advantages such as accurate dose calculations and reduced computation time in lung SABR plan using FFF beams, especially for VMAT planning.

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비편평화여과기 빔을 이용한 폐 정위절제방사선치료를 위한 AAA와 Acuros XB 계산 알고리즘의 치료계획 비교

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이 연구는 비편평화여과기(flattening filter-free, FFF) 빔을 이용한 폐 정위절제방사선치료(stereotactic ablative radiotherapy, SABR)에 대하여 서로 다른 선량계산 알고리즘의 선량적 효과를 조사하였다. SABR를 받은 10명의 폐암 환자를 대상으로 하여 평가하였다. 모든 치료계획은 Eclipse 치료계획시스템의 Acuros XB (AXB) 알고리즘을 이용하여 수립되었다. 다른 선량계산 알고리즘과 비교를 위하여, 추가적으로 anisotropic analytic algorithm (AAA) 알고리즘을 적용한 치료계획을 재 수립하였다. 두 알고리즘 평가를 위해서, 치료표적과 손상위험장기의 선량체적히스토그램(dose-volume histogrim, DVH)를 분석하였다. 그리고 기술적 인자로써 계산시간과 총 MU 값을 평가하였다. DVH 비교분석을 통해, PTV의 최대선량은 AXB이 AAA 보다 5.2% 높았으며 최소선량은 4.4% 낮게 나타났다. PTV의 $V_{105\%}$에서 7.06%까지 큰 차이를 나타났다. 폐의 최대선량은 AXB 치료계획에서 약간 크게 나타났다. 동측성 폐에 5, 10과 20 Gy 선량이 조사되는 체적은 AAA 보다 AXB에서 더 크게 나타났으나 대측성 폐에 대해서는 거의 비슷하게 나타났다. 척수와 심장에서 최대선량의 차이도 크지 않았다. 계산시간의 경우, AXB가 AAA보다 13.7% 정도 소요시간이 적었고 MU 값은 AXB에서 3.47% 더 많았다. 이 연구의 결과들은 회전조절치료 기법을 포함하여 FFF 빔이 적용된 폐 SABR 치료계획에서 AXB 알고리즘은 선량계산의 정확성과 계산시간의 감소의 장점을 제공할 수 있을 것이다.

중심단어: Anisotropic analytic algorithm, Acuros XB, 정위절제방사선치료, 폐암