MEDWIN PUBLISHERS
Committed to Create Value for Researchers

Clinical Radiology & Imaging Journal
ISSN: 2640-2343

Dosimetric Comparison between Two Dose Calculation Algorithms in SBRT Treatment of Lung Cancer in Ring-based and C-arm Radiation Therapy Equipment

Ng SY[1], Chau MC[1,2]*, Chow TH[1], Chui TY[1], Lei MY[2], Mak KL[2] and Qiu XB[2]

[1]Medical Science and Health (Radiation Therapy), Tung Wah College, Hong Kong
[2]Oncology Department, Kiang Wu Hospital, Macao

***Corresponding author:** Chau Ming Chun, Department of Radiation Therapy, Tung Wah College, Hong Kong, Email: rickychau@twc.edu.hk

Research Article
Volume 9 Issue 1
Received Date: January 27, 2025
Published Date: February 10, 2025
DOI: 10.23880/crij-16000230

Abstract

Aim: The purpose of this study is to compare the dosimetric differences between two dose calculation algorithms-Anisotropic Analytical Algorithm (AAA) and Acuros XB (AXB) - in Stereotactic Body Radiation Therapy (SBRT) for lung cancer using Halcyon and TrueBeam radiation therapy (RT) equipment, and to identify the optimal combination for treatment.

Materials and Methods: A Retrospective study which recruited 20 patients with peripherally located primary lung cancer or lung metastasis in the upper or middle lobes treated with SBRT at Kiang Wu Hospital, Macau (KWH) was conducted. CT images were imported into the Varian Eclipse Treatment Planning System (TPS) version 17.01 for re-planning using AAA and AXB in RT equipment. The plan quality and organs at risk (OARs) criteria were assessed based on Radiation Therapy Oncology Group (RTOG)-0813 and RTOG-0915 protocols. Also, Monitor Unit (MU), Beam on Time (BOT), and dose calculation time were recorded for evaluating treatment planning and delivery efficiency. Statistical significance was determined with p-values < 0.05.

Results: AAA provided better conformity, heterogeneity, and R50% than AXB (0.91 vs 0.89, 0.075 vs 0.096, 1.05 vs1.07, respectively, $p < 0.05$). Both calculation algorithms and RT equipment provided comparable dose to OARs. Notably, compared to Halcyon, TrueBeam required fewer MUs (65.1 vs 58.7, respectively, $p < 0.05$) to deliver the same dose, and TrueBeam with GPU-based AXB demonstrated advantages in reducing the dose calculation time ($p < 0.001$).

Conclusion: Both dose calculation algorithms and RT equipment are effective in SBRT lung cancer treatment, offering high precision in target coverage while comparable dose to OARs. TrueBeam with GPU-based AXB is notably efficient in RT treatment planning and delivery.

Keywords: VMAT; SBRT; Analytical Anisotropic Algorithm; Acuros XB; ring-based linac (Halcyon); C-arm linac (TrueBeam)

Abbreviations

AAA: Anisotropic Analytical Algorithm; AXB: Acuros XB; RT: Radiation Therapy; SBRT: Stereotactic Body Radiation Therapy; TPS: Treatment Planning System; OARs: Organs at Risk; RTOG: Radiation Therapy Oncology Group; MU: Monitor Unit; BOT: Beam on Time; NSCLC: Non-Small Cell Lung Cancer; MLC: Multi-Leaf Collimator; MC: Monte Carlo;

LBTE: Linear Boltzmann Transport Equation; PO: Photon Optimizer; NTO: Normal Tissue Objective; ACROP: Advisory Committee on Radiation Oncology Practice; ESTRO: European Society for Radiotherapy and Oncology; DVHs: Dose-Volume Histograms; CI: Conformity index; HI: Homogeneity index.

Introduction

According to the World Cancer Research Fund International, lung cancer has high incidence and mortality rates worldwide [1]. Lung metastasis is a type of cancer that tumour cells spread to the lungs from primary tumour sites. According to the American Cancer Society, lung is one of the common sites that has cancer metastasis [2].

Stereotactic Body Radiation Therapy (SBRT) has revolutionized lung cancer treatment, particularly for patients who are ineligible for surgery. SBRT is an advanced RT technique that provides high precision and conformity radiation dose to small targets while minimizing the exposure to the OARs or healthy tissue nearby and only a few fractions are required. The local control rate and survival rate of non-small cell lung cancer (NSCLC) patients were enhanced by using SBRT treatment. Accurate RT equipment delivery and dose calculation are crucial for SBRT. With the launch of various RT equipment such as TrueBeam and Halcyon, it is necessary to understand the influence of different dose calculation algorithms on SBRT treatment in various RT equipment for lung cancer.

TrueBeam and Halcyon are two different types of linear accelerators (linacs), and both are manufactured by Varian. TrueBeam is a C-arm linac, and Halcyon is a ring gantry linac. Apart from the gantry design, the multi-leaf collimator (MLC) design is another major difference between TrueBeam and Halcyon. TrueBeam utilizes a single layer Millennium 120 MLC while Halcyon utilizes a unique stacked-and-staggered dual-layer MLC. It minimizes interleaf leakage and allows 100% over-travel and interdigitation capabilities [3]. The interleaf leakage in 6MV-FFF mode is only 0.01% of dual-layer MLC in Halcyon compared to 1.36% of single-layer MLC in TrueBeam [4]. This design enables Halcyon to achieve a jawless configuration, effectively modulating the field shape with sufficient attenuation. For Millennium 120 MLC, there is a limitation in field shaping for the maximum leaf travel for each leave is 15cm which is the maximum distance between the most extended and retracted leaves on the same side [5]. Moreover, TrueBeam supports various energy options including photon and electron while Halcyon provides 6MV photon only. Also, TrueBeam offers a higher dose rate of 1400 MU/min compared with 800 MU/min in Halcyon [6].

A dose calculation algorithm is a computational method used in RT for calculating the dose distribution in the patient's body. Analytical Anisotropic Algorithm (AAA) and Monte Carlo (MC) are different types of calculation algorithms. AAA is a model-based convolution-superposition algorithm while MC is a principle-based algorithm which considers nearly all recognized physical features related to microscopic interactions between radiation and tissues [7]. AXB is a non-analytical model-based dose calculation algorithm that can achieve accuracy comparable to MC in heterogeneous media by solving Linear Boltzmann Transport Equation (LBTE) [8]. Both AAA and AXB were implemented in Varian Eclipse TPS and were used in our project.

In the past, AAA has been commonly used in RT planning as it provides a balance between efficiency and accuracy. With the rapid revolution of technology, AXB was released which promised a high level of accuracy in modeling the microscopic interaction. The difference between both calculation algorithms is consequential in SBRT treatment of lung cancer especially because of the heterogeneous media.

Previous studies typically explored the dosimetric differences between AAA and AXB for various cancers. There are many studies supporting that AXB was more accurate than AAA and AXB provided benefits for lung cancer treatment planning using SBRT technique [9-13]. Nevertheless, most of these studies focused on a single treatment equipment especially in TrueBeam, leaving the research gap regarding how different calculation algorithms, AAA and AXB, perform across different RT equipment, C-armed Linac (TrueBeam) and ring-based Linac (Halcyon).

Also, many studies reported that Halcyon provided comparable plan quality to TrueBeam for various treatment sites that has been supported by some researchers. However, in clinical practice, both calculation algorithms and RT equipment are interdependent variables that influence treatment outcomes.

With the rapid advancement in radiation therapy equipment and dose calculation algorithms, it is necessary to have a deeper understanding on how these factors influence treatment accuracy. Especially, the improved in dose modeling precision with AXB, which accounts for tissue heterogeneities more effectively, combined with the advanced RT equipment, ensures dose distribution accuracy, minimizes the uncertainties in treatment, and contributes ultimately better local control. This study aims to address this influence by evaluating the dosimetric differences between AAA and AXB in SBRT for lung cancer, specifically when using different RT equipment such as TrueBeam and Halcyon. The study also provides insights into the optimal selection of dose calculation algorithms and RT equipment for SBRT lung cancer treatment, potentially improving local control and aiding clinical decision-making.

Methodology

Patient Selection

The study recruited 20 patients aged 18 or above with stage I-II primary lung tumours or metastases located peripherally or centrally in the middle or upper lobe treated with SBRT at KWH. Data, including planning CT images and contouring of targets and OARs, were imported to the Varian Eclipse TPS version 17.01. Patients were categorized according to tumour location, with treatment plans optimized based on RTOG-0813 and RTOG-0915 protocols. Table 1 summarized the collected patient and tumour characteristics, and the treatment plan conditions for 20 patients included in the study.

Data Collection

Twenty patients recruited in this study retrospectively, all received SBRT treatment for lung tumours in KWH between December 2020 and November 2023. The anonymized data, including the planning CT images and the associated contouring of the targets and OARs were imported to the TPS. After importing the data, the samples were categorized according to the tumour location. There were 12 cases with peripherally located tumours that were eligible to apply the dose prescription and dose constraints specified in RTOG-0915 protocol. For the remaining 8 cases with centrally located tumours, RTOG-0813 protocol was applied. The dose prescription for an individual patient was based on the respective RTOG protocol according to the tumour location.

Structures and Target Contouring

Target and OARs structures delineation were done by oncologists in KWH. An extra 0.5 cm in the axial plane and 1 cm in the craniocaudal plane will be added to the GTV to form the PTV, aligning with the RTOG-0813 and 0915 protocols. All OARs contours including spinal cord, esophagus, brachial plexus, heart, trachea and proximal bronchial tree, proximal trachea, whole lung, great vessels, and skin were checked for any discrepancy and were revised according to the contouring guidelines in RTOG-0915 and RTOG-0813 protocols if necessary.

RT Equipment and Dose Calculation Algorithms

Two types of RT equipment (TrueBeam and Halcyon) and two different dose calculation algorithms (AAA and AXB) were included in this study. Varian Eclipse TPS version 17.01 at was used for treatment planning. The photon optimizer (PO) algorithm version 17.01 was used for dose optimization in all cases. Acuros XB-13.5 physical material table was chosen for AXB dose calculation. Four VMAT plans were computed for each patient, namely, TrueBeam-AAA (TB-AAA), TrueBeam-AXB (TB-AXB), Halcyon-AAA (Hal-AAA), and Halcyon-AXB (Hal-AXB).

Truebeam VMAT Planning Technique

For TB-AAA and TB-AXB plans, 6MV FFF mode was implemented with Millennium 120 MLC and a maximum dose rate of 1400 MU/min. After careful evaluation of treatment delivery efficiency and the achievement of desired target coverage, a 2-half arc coplanar field arrangement was implemented in all SBRT plans. The arc angles were fixed at 350° to 179° clockwise (CW) and 179° to 350° counterclockwise (CCW) for left lung cases, and at 181° to 10° CW and 10° to 181°CCW for right lung cases to optimize target coverage while sparing normal lung tissues, particularly the contralateral lung. Collimator angles of 30° and 330° were chosen to minimize overlapping interleaf leakage caused by the tongue-and-groove effect. Isocenters for each field were initially positioned at the PTV mass center, then the X and Y coordinates were rounded off to the nearest 1 decimal place and the Z coordinate was rounded off to the nearest multiple of 0.25 based on the CT scan slice thickness (2.5mm). The field sizes were set with approximately 5mm margins around the PTV.

In plan optimization, two standard templates were constructed for all treatment plans. With reference to RTOG-0813 and RTOG-0915 protocols, all the treatment plans were optimized using the dose-volume constraints of the target volume and OARs set in the standard templates. The normal tissue objective (NTO) priority was set to 100. During optimization, fine adjustments of the planning objective priorities and construction of additional pseudo-structures were used on a case-by-case basis. After the generation of treatment plans with TB-AAA, plans were re-optimized using TB-AXB. The optimization criteria were identical for both TB and HAL plans, ensuring consistency in treatment planning and enabling a direct comparison between the two equipment and dose calculation algorithms.

Halcyon VMAT planning technique

For comparison, TB-AAA treatment plans were re-optimized in Eclipse TPS using Hal-AAA followed by Hal-AXB. 6MV FFF mode was implemented with dual-layered stacked-and-staggered MLC and a maximum dose rate of 800 MU/min. Identical arc geometry, collimator rotation and isocenter placement were used as in TrueBeam VMAT plans. In addition, the procedures of plan optimization and the settings were all identical to TrueBeam plans as described above.

Dose Prescription and Dose constraints of OARs

All the treatment plans fulfilled the prescription dose constraints as per RTOG-0915 and RTOG-0813 requirements.

The prescription dose for RTOG 0813 was 50 Gy delivered in 5 fractions, while for RTOG 0915, it was 48 Gy delivered in 4 fractions as listed in Table 1. The plans in all samples were normalized to achieve 98% PTV volume receiving 100% of the prescription dose (PTV $V_{98\%}$ = 100%) and maximum PTV dose within 125% of the prescription dose. The rationale for limiting the maximum dose to 125% in this study was to ensure the prescribed dose was delivered effectively to the PTV, maintain dose homogeneity, and help achieve the D_{2cm} dose constraint of RTOG-0813 and 0915. The planning objectives were used with reference to the Advisory Committee on Radiation Oncology Practice (ACROP) Guideline established by faculty members of the European Society for Radiotherapy and Oncology (ESTRO) and previous literature [14]. In addition, 99% of PTV volume received at least 90% of the prescription dose (PTV $V_{99\%}$ > 90%) in all plans [13,15].

Median PTV in cm^3 (Range)				21.2 (5.97 – 87.65)	
Case	**PTV(cm^3)**	**Tumour location**	**Prescribed Dose (Gy)**	**Number of Fractions**	**RTOG protocol**
1	87.65	RUL	50	5	813
2	11.9	LML	48	4	915
3	12.78	RUL	50	5	813
4	29.1	RML	50	5	813
5	76.9	LUL	50	5	813
6	48	LUL	50	5	813
7	19.65	RUL	48	4	915
8	22.5	RUL	48	4	915
9	52.29	LUL	50	5	813
10	82.61	LML	48	4	915
11	18.08	RUL	48	4	915
12	68.9	LUL	48	4	915
13	23.4	RML	48	4	915
14	11.8	LUL	50	5	813
15	19.9	RML	50	5	813
16	8.1	LML	48	4	915
17	18.6	RML	48	4	915
18	5.97	LUL	48	4	915
19	27.4	LML	48	4	915
20	16.3	LML	48	4	915

Note: RUL – right upper lobe; RML – right middle lobe; LUL – left upper lobe; LML – left middle lobe.
Table 1: List of tumour size, locations, prescription dose and protocol of the selected 20 patients.

All plans either met RTOG-0813 or RTOG-0915 protocol criteria normal tissue dose constraints based on the tumour locations. OARs included spinal cord, skin, lung, esophagus, heart, great vessels, ribs, and trachea and ipsilateral bronchus. The details of RTOG-0813 and RTOG-0915 protocol criteria were listed in Table 2.

Structure	Dose constraints and planning objectives			
RTOG	813		915	
PTV	V50Gy=100%	Dmax exists within the PTV	V50Gy=100%	Dmax exists within the PTV

Spinal Cord	V22.5Gy < 0.25cc V13.5Gy < 0.5cc	Dmax < 30Gy	V20.8Gy < 0.35cc V13.6Gy < 1.2cc	Dmax < 26Gy
Skin	V30Gy < 10cc	Dmax < 32Gy	V33.2Gy < 10cc	Dmax < 36Gy
Lung	V13.5Gy < 1000cc V12.5Gy < 1500cc	-	V12.4Gy < 1000cc	-
Esophagus	V27.5Gy < 5cc	Dmax < 50.4Gy	V18.8Gy < 5cc	Dmax < 30Gy
Heart	V32Gy < 15cc	Dmax < 50.4Gy	V28Gy < 15cc	Dmax < 34Gy
Great Vessels	V47Gy < 10cc	Dmax < 50.4Gy	V43Gy < 10cc	Dmax < 49Gy
Trachea and Ipsilateral bronchus	V18Gy < 4cc	Dmax < 50.4Gy	V15.6Gy < 4cc	Dmax < 34.8Gy
Ribs	N/A		V32Gy < 1cc	Dmax < 40Gy

Note: No dose constraints and planning objectives for Ribs in RTOG-0813; Sourced from RTOG-0813 & RTOG-0915 [13,15].
Table 2: Dose constraints and planning objectives of RTOG-0813 & 0915.

Dosimetric Evaluation and Statistical Analysis

Several dosimetric parameters were generated for evaluation and comparison between 4 plans. RTOG-0915 and RTOG-0813 protocols were employed to conduct a comparative analysis of the TrueBeam and Halcyon VMAT plans with the utilization of AAA and AXB dose calculation algorithms for lung SBRT treatment planning. The primary objectives of this study evaluated several key parameters derived from the dose-volume histograms (DVHs) of the treatment plans generated.

For evaluating the high and intermediate dose spillage parameters of the PTV, Conformity index (CI), Homogeneity index (HI), Maximum dose (D_{max}), $R_{50\%}$, and D_{2cm}, the parameters were generated and defined as:

$$CI = \frac{TV_{PIV}^{\ 2}}{TV \times PIV}$$

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}}$$

Where TV_{PIV}, TV and PIV represent the volume of the target covered by the prescription isodose the target volume and the prescription isodose volume respectively. The ideal value for CI is 1 and the clinical desirability. The ideal value of HI is 0. $D_{2\%}$ and $D_{50\%}$ were evaluated separately. $R_{50\%}$ which quantifies the ratio of the 50% prescription isodose volume to the PTV volume. The acceptable range of $R_{50\%}$ depends on the variations in PTV size, and the acceptable range of $R_{50\%}$ based on the RTOG-0813 and 0915 protocols. D_{2cm} refers to the maximum dose at any point 2 cm away from the PTV margin in any direction. Compliance with the criterion of D_{2cm} depends on the specific dimensions of the PTV and based on the RTOG-0813 and 0915 protocols. For evaluating the treatment planning and delivery efficiency, total number of monitor units (MU) per fraction and dose calculation time were recorded. Also, estimated BOT is simply defined as:

$$\text{BOT} = \frac{Total\ MU}{Dose\ Rate}$$

While the dose rate is modulated throughout the treatment to meet the requirements of the treatment plan, each machine typically operates at the highest achievable dose rate within the limits of its technical specifications and clinical constraints. Therefore, maximum dose rates of TrueBeam (1400 MU/min) and Halcyon (800 MU/min) will be used for analysis. As two protocols were used in our project, all dosimetric parameters were expressed as ratios relative to the prescription dose to normalize for variation in the prescription dose across individual plans. All plans either met RTOG-0815 or 0915 criteria normal tissue dose constraints. Also, due to variations in prescription dose between two RTOG protocols, individual plan values for any parameter were expressed as a ratio relative to the prescription dose and * was used to indicate the ratio of the dose, where

$$\text{Ratio}^* = \frac{Dosimtric\ parameter}{Prescription\ dose}$$

Statistical Analysis

All the collected data were subjected to statistical analysis using the Statistical Package for the Social Sciences (SPSS) version 26.0 software (IBM, Armonk, NY). In terms of the aforementioned dosimetric parameters, a two-way ANOVA Test was performed to assess and compare the significance of differences between the various independent variables: AAA vs AXB, Halcyon vs TrueBeam, and the combination of both calculation algorithms and both

treatment equipment, namely, Hal-AAA, Hal-AXB, TB-AAA, and TB-AXB as mentioned above. A p-value less than 0.05 was considered statistically significant among the dosimetric outcomes.The primary endpoints were to gauge and compare key dosimetric parameters such as the CI, HI, D_{max}, $R_{50\%}$, and D_{2cm} between both calculation algorithm (AAA and AXB) in TrueBeam and Halcyon by using dose-volume histograms (DVHs) derived from treatment plans. Secondary endpoints included evaluation of treatment planning and delivery efficiency by comparing the MUs, estimated BOT, and dose calculation time between AAA and AXB in both TrueBeam and Halcyon for SBRT lung cancer treatment.

Results

All dosimetric comparison details with p-value between both calculation algorithms, RT equipment, and the combination between both calculation algorithms in both RT equipment (Hal-AAA, Hal-AXB, TB-AAA, and TB-AXB) are summarized in Table 3 and Table 4. The analysis includes the classification of high and intermediate dose spillage based on $R_{50\%}$ and D_{2cm} in accordance with both RTOG protocols, dose to OARs, treatment delivery, and dose calculation time.

	AAA	AXB	p-value	TrueBeam	Halcyon	p-value	TrueBeam		Halcyon		p-value
							AAA	AXB	AAA	AXB	
CI	0.909 ± 0.003	0.888 ± 0.004	<0.001	0.905 ± 0.003	0.892 ± 0.004	0.004	0.914 ± 0.004	0.896 ± 0.005	0.903 ± 0.005	0.880 ± 0.005	0.539
HI	0.075 ± 0.003	0.096 ± 0.003	<0.001	0.084 ± 0.004	0.087 ± 0.004	0.509	0.073 ± 0.005	0.094 ± 0.005	0.076 ± 0.004	0.098 ± 0.005	0.892
D2%*	1.079 ± 0.004	1.103 ± 0.004	<0.001	1.089 ± 0.004	1.093 ± 0.004	0.525	1.078 ± 0.005	1.101 ± 0.006	1.080 ± 0.005	1.105 ± 0.006	0.893
D50%*	1.052 ± 0.003	1.070 ± 0.003	<0.001	1.060 ± 0.003	1.062 ± 0.003	0.562	1.051 ± 0.004	1.069 ± 0.004	1.053 ± 0.004	1.071 ± 0.004	0.998
Dmax*	1.109 ± 0.004	1.134 ± 0.004	<0.001	1.122 ± 0.005	1.121 ± 0.004	0.928	1.110 ± 0.006	1.133 ± 0.006	1.108 ± 0.005	1.134 ± 0.006	0.84
R50%	4.599 ± 0.075	4.824 ± 0.081	0.047	4.726 ± 0.077	4.697 ± 0.083	0.797	4.603 ± 0.099	4.849 ± 0.115	4.595 ± 0.115	4.799 ± 0.118	0.853
D2cm*	0.591 ± 0.013	0.599 ± 0.014	0.68	0.597 ± 0.014	0.593 ± 0.013	0.82	0.596 ± 0.019	0.599 ± 0.020	0.587 ± 0.017	0.599 ± 0.019	0.792
Total MU*	62.235 ± 1.084	61.574 ± 1.222	0.653	58.741 ± 0.977	65.068 ± 1.098	<0.001	60.140 ± 1.377	57.342 ± 1.349	64.331 ± 1.571	65.806 ± 1.556	0.149
Beam-on time (mins)	3.001 ± 0.154	2.997 ± 0.168	0.954	2.041 ± 0.031	3.957 ± 0.062	<0.001	2.090 ± 0.043	1.992 ± 0.042	3.912 ± 0.089	4.002 ± 0.087	0.181
Dose cal. Time (s)	45.675 ± 2.623	18.350 ± 0.376	<0.001	22.900 ± 1.119	41.125 ± 3.329	<0.001	29.550 ± 0.659	16.250 ± 0.228	61.800 ± 0.659	20.450 ± 0.256	<0.001

Note: *Due to variations in prescription dose between 2 protocols, individual plan values for any parameter are expressed as a ratio relative to the prescription dose.

Table 3: Dosimetric comparison between dose calculations of AAA and AXB and RT equipment of TrueBeam and Halcyon in target coverage, CI, HI, $D_{2\%}$*, $D_{50\%}$*, D_{max}*, $R_{50\%}$, and D_{2cm}*.

		AAA	AXB	p-value	Halcyon	True Beam	p-value	Halcyon		TrueBeam		p-value
								AAA	AXB	AAA	AXB	
Trachea and ipsilateral bronchus	Dmax*	0.410 ± 0.030	0.421 ± 0.031	0.797	0.413 ± 0.030	0.419 ± 0.031	0.893	0.407 ± 0.043	0.418 ± 0.043	0.413 ± 0.044	0.425 ± 0.045	0.985
Esophagus	Dmax*	0.201 ± 0.010	0.206 ± 0.011	0.75	0.200 ± 0.010	0.207 ± 0.011	0.664	0.198 ± 0.015	0.202 ± 0.015	0.203 ± 0.015	0.210 ± 0.016	0.912

Great Vessels	Dmax*	0.367 ± 0.040	0.373 ± 0.040	0.92	0.367 ± 0.040	0.374 ± 0.040	0.905	0.364 ± 0.057	0.370 ± 0.058	0.371 ± 0.058	0.376 ± 0.058	0.993
Heart	Dmax*	0.299 ± 0.044	0.312 ± 0.045	0.83	0.298 ± 0.044	0.312 ± 0.045	0.825	0.295 ± 0.062	0.302 ± 0.064	0.302 ± 0.064	0.323 ± 0.065	0.915
	Dmean*	1.131 ± 0.210	1.145 ± 0.212	0.962	1.110 ± 0.212	1.167 ± 0.210	0.851	1.110 ± 0.308	1.110 ± 0.300	1.153 ± 0.294	1.181 ± 0.306	0.963
Lung	V20Gy (%)	3.730 ± 0.293	3.903 ± 0.303	0.688	3.818 ± 0.301	3.815 ± 0.296	0.995	3.725 ± 0.424	3.910 ± 0.438	3.735 ± 0.417	3.895 ± 0.431	0.977
	V10Gy (%)	8.815 ± 0.569	9.083 ± 0.575	0.745	8.940 ± 0.571	8.958 ± 0.573	0.983	8.810 ± 0.817	9.070 ± 0.818	8.820 ± 0.813	9.095 ± 0.829	0.993
	V5Gy (%)	14.793 ± 0.751	15.105 ± 0.689	0.762	14.730 ± 0.690	15.168 ± 0.749	0.672	14.435 ± 0.973	15.025 ± 0.999	15.150 ± 1.163	15.185 ± 0.973	0.788
Ribs	Dmax*	0.927 ± 0.037	0.939 ± 0.038	0.83	0.932 ± 0.038	0.934 ± 0.037	0.983	0.925 ± 0.054	0.940 ± 0.055	0.929 ± 0.052	0.938 ± 0.053	0.954
Skin	Dmax*	0.386 ± 0.015	0.385 ± 0.018	0.977	0.381 ± 0.016	0.391 ± 0.018	0.67	0.385 ± 0.022	0.377 ± 0.025	0.388 ± 0.022	0.394 ± 0.028	0.759
Spinal Cord	Dmax*	0.167 ± 0.012	0.167 ± 0.011	0.995	0.172 ± 0.012	0.162 ± 0.011	0.548	0.172 ± 0.017	0.171 ± 0.017	0.161 ± 0.016	0.162 ± 0.016	0.939

Note: *Due to variations in prescription dose between 2 protocols, individual plan values for any parameter are expressed as a ratio relative to the prescription dose.

Table 4: Dosimetric comparison between dose calculations of AAA and AXB and RT equipment of TrueBeam and Halcyon in various OARs

Dosimetric Comparison of CI, HI, $D_{50\%}$, and D_{max}

AAA vs AXB

CI was found to be higher for AAA (0.909 ± 0.003) compared to AXB (0.888 ± 0.004) and HI was lower in AAA (0.075 ± 0.003) than in AXB (0.096 ± 0.003), with both differences being statistically significant ($p < 0.001$), indicating better conformity and homogeneity with AAA.

The dose to 50% of the volume ($D_{50\%}$*), and maximum dose (D_{max}*) of the PTV were slightly higher for AXB (1.070 ± 0.003 and 1.134 ± 0.004, respectively) when compared with AAA (1.052 ± 0.003 and 1.109 ± 0.004, respectively) and the differences were statistically significant ($p < 0.001$).

Halcyon vs TrueBeam

When comparing both RT equipment, TrueBeam (0.905 ± 0.003) had better CI than Halcyon (0.892 ± 0.004) with $p = 0.004$. No significant differences were observed in HI, $D_{50\%}$*, and D_{max}* (p-values > 0.05).

Calculation Algorithms vs RT Equipment (Hal-AAA, Hal-AXB, TB-AAA and TB-AXB)

When comparing the dosimetric outcomes of the AAA and AXB in Halcyon and TrueBeam, all p-values were greater than 0.539 and no significant differences were observed.

Dosimetric Comparison of $R_{50\%}$ and D_{2cm}

AAA vs AXB

The dose fall-off ($R_{50\%}$) was sharper in AAA (4.599 ± 0.075) than in AXB (4.824 ± 0.081), and the difference was significant ($p = 0.047$). No significant difference was found in D_{2cm}* ($p > 0.05$). Therefore, AAA provided better dose fall-off than AXB while maintaining similar levels of dose spillage compared to the AXB.

Halcyon vs TrueBeam

Similarly, no significant difference was observed between Halcyon and TrueBeam in $R_{50\%}$ and D_{2cm}* with both $p > 0.05$. This suggested that both RT equipment had comparable dosimetric precision for $R_{50\%}$ and D_{2cm}*.

Calculation Algorithms vs RT Equipment (Hal-AAA, Hal-AXB, TB-AAA and TB-AXB)

The analysis of the $R_{50\%}$ and D_{2cm}*, comparing the combinations of AAA and AXB in Halcyon and TrueBeam, indicated no significant differences with $p > 0.05$. The similar performance of different combination of calculation algorithms and RT equipment potentially allows for flexibility in clinical practice without compromising dosimetric accuracy.

Dosimetric Comparison of OARs

AAA vs AXB

There were no statistically significant differences in the maximum dose (D_{max}*) delivered to the trachea and ipsilateral

bronchus, esophagus, great vessels, heart, lungs, ribs, skin, and spinal cord in the comparison between AAA and AXB, which p-values were greater than 0.05 consistently. The V_{20Gy}(%), V_{10Gy}(%), and V_{5Gy}(%) of lung were also comparable between the two algorithms (p-values > 0.05).

Halcyon vs TrueBeam

Similarly, the dosimetric comparison between the Halcyon and TrueBeam revealed no significant differences in the OARs. All parameters of the evaluated OARs were comparable, with p-values > 0.05, indicating no significant variation between both RT equipment.

Calculation Algorithms vs RT Equipment (Hal-AAA, Hal-AXB, TB-AAA and TB-AXB)

The comparative analysis between Hal-AAA, Hal-AXB, TB-AAA, and TB-AXB indicates that there are no statistically significant differences in the dosimetric parameters including D_{max}, D_{mean}, V_{20Gy}(%), V_{10Gy}(%), and V_{5Gy}(%) evaluated for the OARs (p-values > 0.05).

This suggests that both AAA and AXB can be used interchangeably on either the Halcyon or TrueBeam systems without significant variations in dose delivery to the OARs. These findings could potentially support the flexibility of using either calculation algorithm in clinical practice, although treatment planning should always be carefully tailored to the individual patient's needs.

Dosimetric Comparison of Treatment Delivery and Dose Calculation Time

AAA vs AXB

Both total MU* and BOT in AAA and AXB had p-value > 0.05. There was no significant difference in dosimetric delivery efficiency between AAA and AXB based on total MU* and BOT. AAA and AXB demonstrated comparable dosimetric delivery efficiency. The dose calculation time for the AAA was significantly longer, averaging 45.675 ± 2.623 seconds, compared to the AXB with 18.350 ± 0.376 seconds. The difference in calculation times between the two algorithms was statistically significant ($p < 0.001$).

Halcyon vs TrueBeam

When comparing Halcyon and TrueBeam, a significant difference was found in both total MU* per fraction and BOT. Halcyon required more total MUs* per fraction (65.068 ± 1.098 MU*) compared to TrueBeam (58.741 ± 0.977 MU*), with p-value < 0.001. Additionally, the BOT of Halcyon was longer (3.957 ± 0.062 mins) than TrueBeam (2.041 ± 0.031 mins), with p-value < 0.001.

The dose calculation time for Halcyon was 41.125 ± 3.329 seconds, which was longer than the time of 22.900 ± 1.119 seconds calculated by TrueBeam. Significant differences were observed in dose calculation time between Halcyon and TrueBeam with $p < 0.001$.

Calculation Algorithms vs RT Equipment (Hal-AAA, Hal-AXB, TB-AAA and TB-AXB)

The combination of calculation algorithms in Halcyon and TrueBeam revealed no significant difference in total MU* and BOT ($p > 0.05$).

Significant differences were observed in the dose calculation time in the combination of both calculation algorithms in Halcyon and TrueBeam with $p < 0.001$. Within Halcyon, AAA had a dose calculation time of 61.800 ± 0.659s, while the AXB had a significantly shorter time of 20.450 ± 0.256s. For TrueBeam, the AAA had a calculation time of 29.550 ± 0.659s, and AXB had a time of 16.250 ± 0.228s. The TB-AXB demonstrated a significantly reduced dose calculation time compared to the other three combinations (Hal-AAA, Hal-AXB, TB-AAA), with $p < 0.001$ indicating that the differences are statistically significant.

Discussion

In this study, the dosimetric comparisons were performed between Hal-AAA, Hal-AXB, TB-AAA, and TB-AXB plans.

Target coverage - CI, HI, $D_{50\%}$, and D_{max}

The AXB resulted in a significantly higher HI, $D_{50\%}$*, and D_{max}*, and lower CI compared to AAA. A higher HI indicates a less uniform dose distribution within the target volume, which may partly be attributed to the greater accuracy of AXB in modelling dose distribution within heterogeneous media. AXB more effectively accounts for tissue density variations, especially in air-tissue or lung-tumour interfaces, which can lead to higher calculated maximum doses and steeper dose gradients.

This could also be explained by the re-calculation and re-optimization process. It was observed that the minimum dose of PTV decreased, and the maximum dose increased when the original plan created using AAA was recalculated with AXB, resulting in a gap between the AXB plan and RTOG protocol criteria. Zhou et al. in 2017 reported a similar effect, where AXB re-calculation decreased the minimum dose of PTV and increased the maximum dose, aligning with our findings [16]. Therefore, it is required to re-optimize and normalize the plan for restoring the compliance of RTOG-0813 or RTOG-0915. Also, in the same study, Zhou et al. in 2017 reported that the CI would be degraded after normalization in the AXB plan [16]. Similar to our result, it can be observed that the AXB has a slightly lower CI than AAA after normalization with significant difference in between (CIAXB = 0.888 ± 0.004, CIAAA = 0.909 ± 0.003 with $p < 0.001$).

In addition, the elevated HI, $D_{50\%}$*, and D_{max}* observed with AXB could also be associated with its ability to more accurately represent dose distribution in heterogeneous media compared to AAA, which tends to overestimate the dose in air-tissue interfaces while underestimating the dose to the PTV [17-20]. In some research studies related to dosimetric verification, measurement, and accuracy for SBRT lung cancer, they indicated that AAA underestimates the dose to the lung tumour by approximately 2-5% compared to AXB, and it tends to overestimate the dose by 1-2% at the lung-and-tissue interface, and by up to 6% in the lung [20-21]. The smaller the tumour size in lung, the severity of overestimation it could be [19].

The dose overestimation in the air-to-tissue interfaces may relate to how AAA models and handles the electronic equilibrium and the tissue density changes in the interface. Radiation dose can penetrate further within the lung as the density in the lung is relatively low. The interaction of radiation is increased in the interface and AAA may not model and handle these changes perfectly. It leads the dose overestimation in these interfaces.

This impact may be crucial in the treatment delivered to some critical structures near the lung. On the other hand, dose underestimation in the PTV may be due to PTV including various tissue types and densities, in which PTV encompasses the tumour with a margin for accounting for the setup variations and internal organ motion. The assumptions related to the tissue homogeneity and radiation scatter may lead to an accuracy reduction of dose calculation. This effect may influence the treatment efficacy potentially.

Also, the lack of stringent constraints on target dose homogeneity during re-optimization may contribute to this effect. As there is no D_{max} constraint stated in both RTOG protocols, it only mentioned the point of maximum dose must exist within the PTV. After a comprehensive review of all treatment plans, it indicates that all D_{max} are localized within the PTV and do not correspond to increased dose to adjacent OARs or affect the $R_{50\%}$.

The statistically significant increased $D_{50\%}$ observed with AXB implies that a greater volume of the tumour receives doses closer to or exceeding the prescribed dose. This could suggest a potential benefit in terms of local control; however, the increased D_{max} indicates a higher maximum dose within the target, which, while it may positively affect tumour control, might also increase the risk of toxicity in adjacent normal tissues. The clinical relevance of these differences warrants careful consideration, as the threshold for clinical significance in the context of RT might differ based on treatment site, tumour type, and clinical endpoints.

Treatment Delivery

The statistically significant difference in total MU* and BOT between the Halcyon and TrueBeam can be attributed to their design and technology differences. Halcyon is designed as a streamlined workflow with fewer customizable options, and different dose rates, MLC, and field size, which might lead to a higher total MU and longer BOT to achieve a similar dose distribution [4]. As the stacked and staggered MLC system is used in Halcyon, it provides less interleaf leakage in nominal 6MV-FFF transmission, which is 0.01% in Halcyon MLC and 1.36% in Millennium 120. Therefore, it may require more MUs for Halcyon [4].

Shorter BOT and lower total MU in TrueBeam might be influenced by its more advanced beam modulation capabilities, such as a higher dose rate (1400MU/min) and larger field size for modulation, allowing for more efficient treatment delivery. The significant difference in BOT, with a p-value of less than 0.001, underscores a potential advantage of TrueBeam in reducing patient treatment time, which can reduce the dose uncertainties due to the patient's motion during the treatment.

Besides, although Halcyon provides comparable dosimetric differences to TrueBeam, TrueBeam has the potential for dual-energy (photon and electron) irradiation for various applications in radiation therapy while Halcyon has only single 6MV photon.

Dose Calculation Time

AXB demonstrated significantly shorter dose calculation times (18.35 ± 0.376 s) compared to AAA (45.68 ± 2.62 s; $p < 0.001$). This notable dose calculation time reduction by AXB could be associated with the utilization of Graphics Processing Unit (GPU). Similarly, TrueBeam showed superior dose calculation times (22.90 ± 1.12 s) than Halcyon (41.13 ± 3.33 s; $p < 0.001$), attributed to TrueBeam's higher dose rate and simpler single-layer MLC design compared to Halcyon's stacked-and-staggered dual-layer MLC.

When combining both calculation algorithms and RT equipment, AXB consistently outperformed AAA on both TrueBeam and Halcyon (p-value < 0.001), with a more pronounced improvement on Halcyon, suggesting better optimization of AXB for Halcyon. These findings highlight the clinical efficiency of GPU-based AXB, allowing faster treatment planning and adjustments, particularly beneficial in high-volume centers.

Conclusion

There were significant differences in CI, HI, D_{mean}, D_{max} and dose fall-off between different calculation algorithm

of AAA and AXB across both RT equipment. AAA generally achieved better conformity and homogeneity in target and AAA also achieved a fast fall-off outside the target. However, there was no significant difference of the above endpoints was observed between Halcyon and TrueBeam equipment. For OARs, both AAA and AXB can be used interchangeably on either the Halcyon or TrueBeam equipment without significant variations in dose delivery to the OARs.

When comparing treatment delivery efficiency and BOT, there was no significant difference between AAA and AXB. However, when comparing Halcyon and TrueBeam, a significant difference was found in both total MU per fraction and BOT. Halcyon required more total MUs per fraction and longer BOT compared to TrueBeam. The GPU-based AXB significantly reduced dose calculation time. TrueBeam with GPU-based AXB calculation algorithm can achieve accuracy and efficiency in treatment delivery for SBRT treatment of lung cancer.

Conflicts of Interest

The author declares no conflicts of interest.

Funding

This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

Acknowledgments

Thank KWH hospital for providing patient data and Tung Wah College for providing Varian Eclipse TPS for carrying out the study.

References

1. World Cancer Research Fund (2023) Lung cancer statistics.
2. American Cancer Society (2024) Lung metastases.
3. Zheng J, Xia Y, Sun L (2022) A comprehensive evaluation of the application of the Halcyon (2.0) IMRT technique in long-course radiotherapy for rectal cancer. Technology in Cancer Research & Treatment 21: 1075-1081.
4. Lim TY, Dragojević I, Hoffman D, Flores-Martinez E, Kim GY (2019) Characterization of the Halcyon™ multileaf collimator system. Journal of applied clinical medical physics 20(4): 106-114.
5. Li T, Scheuermann R, Lin A, Teo BK, Zou W, et al. (2018) Impact of multi-leaf collimator parameters on head and neck plan quality and delivery: a comparison between halcyon™ and truebeam® treatment delivery systems. Cureus 10(11): e3648.
6. Lim TY, Dragojević I, Hoffman D, Flores-Martinez E, Kim GY (2019) Characterization of the Halcyon™ multileaf collimator system. Journal of applied clinical medical physics 20(4): 106-114.
7. Kim DW, Park K, Kim H, Kim J (2020) History of the photon beam dose calculation algorithm in radiation treatment planning system. Progress in Medical Physics 31(3): 54-62.
8. Hung HM (2021) Dosimetric Impact of Using the Acuros XB for Planning of SBRT of Centrally Located NSCLC. Journal of Thoracic Oncology 16(3): 274-275.
9. Pokhrel D, Visak J, Critchfield LC, Stephen J, Bernard ME, et al. (2021) Clinical validation of ring-mounted halcyon linac for lung SBRT: comparison to SBRT-dedicated C-arm linac treatments. Journal of Applied Clinical Medical Physics 22(1): 261-270.
10. Tsuruta Y, Nakata M, Nakamura M, Matsuo Y, Higashimura K, et al. (2014) Dosimetric comparison of Acuros XB, AAA, and XVMC in stereotactic body radiotherapy for lung cancer. Medical physics 41: 081715.
11. Zhang J, Jiang D, Su H, Dai Z, Dai J, et al. (2019) Dosimetric comparison of different algorithms in stereotactic body radiation therapy (SBRT) plan for non-small cell lung cancer (NSCLC). OncoTargets and therapy 12: 6385-6391.
12. Ong CC, Ang KW, Soh RC, Tin KM, Yap JH, et al. (2017) Dosimetric comparison of peripheral NSCLC SBRT using Acuros XB and AAA calculation algorithms. Medical Dosimetry 42(3): 216-222.
13. Bezjak A, Papiez L, Bradley J, Gore E, Gaspar L, et al. (2019) Radiation Therapy Oncology Group RTOG 0813 seamless Phase I/II study of stereotactic lung radiotherapy (SBRT) For early stage, centrally located, non-small cell lung cancer (NSCLC) in medically inoperable patients. J Clin Oncol 37: 1316-1325.
14. Guckenberger M, Andratschke N, Dieckmann K, Hoogeman MS, Hoyer M, et al. (2017) ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer. Radiother Oncol 124(1): 11-17.
15. Videtic GM, Hu C, Singh A, Chang JY, Parker W, et al. (2013) Radiation Therapy Oncology Group (RTOG) protocol 0915: a randomized phase 2 study comparing

2 stereotactic body radiation therapy (SBRT) schedules for medically inoperable patients with stage I peripheral non-small cell lung cancer. International journal of radiation oncology, biology, physics 87(2): S3.

16. Zhou C, Bennion N, Ma R, Liang X, Wang S, et al. (2017) A comprehensive dosimetric study on switching from a Type-B to a Type-C dose algorithm for modern lung SBRT. Radiation Oncology 12: 1-1.

17. Hu Y, Byrne M, Archibald-Heeren B, Collett N, Liu G, Aland T (2020) Validation of the preconfigured Varian Ethos Acuros XB Beam Model for treatment planning dose calculations: A dosimetric study. Journal of Applied Clinical Medical Physics 21(12): 27-42.

18. Gete E, Teke T, Kwa W (2012) Evaluation of the AAA treatment planning algorithm for SBRT lung treatment: comparison with Monte Carlo and homogeneous pencil beam dose calculations. Journal of Medical Imaging and Radiation Sciences 43(1): 26-33.

19. Lobb E, Plypoo A (2022) Limits for the therapeutic application of the analytical anisotropic algorithm in the context of ablative lung radiotherapy near the minima of lung density and tumor size. Journal of Applied Clinical Medical Physics 23(7): e13634.

20. Muñoz-Montplet C, Marruecos J, Buxó M, Jurado-Bruggeman D, Romera-Martínez I, et al. (2018) Dosimetric impact of Acuros XB dose-to-water and dose-to-medium reporting modes on VMAT planning for head and neck cancer. Physica Medica 55: 107-115.

21. Ding GX, Duggan DM, Lu B, Hallahan DE, Cmelak A, et al. (2007) Impact of inhomogeneity corrections on dose coverage in the treatment of lung cancer using stereotactic body radiation therapy. Medical physics. 34(7): 2985-2994.