International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 2022, 11, 189-199
https://www.scirp.org/journal/ijmpcero
ISSN Online: 2168-5444
ISSN Print: 2168-5436

Halcyon™ Acuros XB vs AAA: A RapidArc Planning Comparison for Head & Neck Cancers

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How to cite this paper: Mbewe, J. and Shiba, S. (2022) Halcyon™ Acuros XB vs AAA: A RapidArc Planning Comparison for Head & Neck Cancers. *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, **11**, 189-199.
https://doi.org/10.4236/ijmpcero.2022.114016

Received: August 4, 2022
Accepted: September 26, 2022
Published: September 29, 2022

Abstract

The Halcyon O-ring gantry linear accelerator from Varian Medical Systems is delivered with a hardcoded beam-source model and Analytical Anisotropic Algorithm dose calculation algorithm as standard, while the Acuros XB algorithm is a purchasable option. The models in both algorithms are factory-configured and do not permit fine-tuning by the user. In this study, we compared the two algorithms for sequential boost RapidArc treatment planning of Head & Neck cancers using D98%, D95%, D50%, D2% and maximum dose to assess dose coverage of nodal and tumor planning target volumes (PTV_N and PTV_T, respectively), and cochlear D5%, parotid D20%, D50%, mean dose, and cord maximum dose to evaluate doses to organs-at-risk. The conformity index (CI), homogeneity index (HI) and total number of monitor units (MU) quantified plan quality. We found statistically significant differences in PTV_N D2%, maximum dose, HI, PTV_T D98%, D95%, D2%, Max, HI, and total MU. Statistically significant differences in Cochlear D5% and Parotid mean doses were also encountered. These differences may not necessarily be clinically significant, however. Therefore, we believe that both calculation algorithms are adequate for RapidArc planning of Head & Neck cancers.

Keywords

Halcyon, Acuros XB, AAA, RapidArc, Head and Neck

1. Introduction

Patients undergoing curative radiotherapy for cancers of the head & neck are at risk of developing severe acute and late side-effects owing to the variety and physiological significance of radiosensitive organs within a relatively confined

space [1]. In this regard, radiotherapy with advanced techniques such as Inverse Modulated Radiotherapy (IMRT) and its rotational variant Volumetric Modulated Arc Therapy (VMAT) may lower this risk by shaping the radiation dose distributions away from organs-at-risk while providing superior coverage to target volumes [2]. These qualities have facilitated the introduction of hypofractionated radiotherapy with higher fraction doses and shorter integral treatment durations. The safe delivery of advanced radiotherapy depends significantly on accurately modeling the beam-source and three-dimensional dose distributions in heterogenous patients, as well as moderating systematic and random uncertainties [3].

The Halcyon Ring Delivery System from Varian Medical Systems (Palo Alto, CA, USA) is a single-energy 6 MV Flattening Filter Free (FFF) linear accelerator whose treatment head and imaging systems are mounted on an O-ring gantry. This configuration permits faster imaging and treatment delivery compared to traditional C-arm linear accelerators [4]. The second and third iterations of this system (Halcyon v2.0 and v3.0, respectively) include an on-board kilo-voltage cone beam computed tomography (kV-CBCT) system with a novel iterative reconstruction algorithm for high quality tomographic images. Random uncertainties associated with patient positioning between treatment fractions are minimized on the Halcyon by mandating pretreatment CBCT imaging at every fraction for position verification and correction, while systematic errors associated with incorrect beam-source modeling are also decreased by delivering the system with hard-coded, factory configured beam-source models which the user must validate independently prior to clinical deployment. At our institution, validation was performed according to the recommendations of the Medical Physics Practice Guideline 5.a. of the American Association of Medical Physicists in Medicine (AAPM) [5].

Initially, the Halcyon was delivered with the Analytical Anisotropic Algorithm (AAA) as the sole radiation dose calculation engine. However, Acuros XB (AXB) was released commercially in 2020 as a second purchasable option. Both engines use the same multiple-source model (differing only in the size of the secondary source) but employ fundamentally different principles for radiation transport and dose deposition [6]. AAA is a so-called Class B dose calculation algorithm that uses precomputed dose kernels to predict dose deposition, while AXB—a Class C algorithm, transports radiation and calculates absorbed dose by solving the Linear Boltzmann Transport Equation [7]. In this study, we investigated the performance of the two algorithms and beam-source models for radiotherapy treatment planning of head & neck cancers using RapidArc, an implementation of VMAT by Varian Medical Systems. To the authors' knowledge, no such comparison exists in the literature. A related investigation was previously made, albeit for treatment planning of cervical cancer [8]. Planning comparisons made for the algorithms implemented on C-arm linear accelerators may not hold for the Halcyon as unlike the former, this system does not permit users to fine-tune

or otherwise modify the beam-source models. The results of this study may assist users in their decision to invest in a Halcyon AXB algorithm and beam-source model for use in Head and Neck RapidArc treatment planning.

2. Methodology

In this retrospective study, we randomly selected from our hospital's Oncology lnformation System, sixteen RapidArc treatment plans of patients that had been prescribed curative courses of radiotherapy. The plans were created by Planning Therapists according to departmental protocols and approved for treatment by clinical oncologists for a range of diagnoses in the head-and-neck region. Prescriptions were patient-specific, but all patients were prescribed at least 64 Gy to the Tumor Planning Treatment Volume (PTV-T) and at least 44 Gy to the Nodal Planning Treatment Volumes (PTV-N) following conventional fractionation of 2.0 Gy per fraction, using the sequential boost technique. The PTV-N in all treatment plans encompassed the submandibular nodes and all the neck nodes extending inferiorly to the supraclavicular nodes. The organs-at-risk evaluated in this study were the parotids (left and right), cochlear (left and right), and spinal cord.

Three-dimensional dose distributions were originally calculated using Halcyon AAA on Eclipse v15.6, reporting absorbed dose as dose-to-water in the medium. For this study, copies of the treatment plans were made, and physical densities assigned to the patient CT image sets using Acuros Physics Material Table version 11. Dose distributions were then recalculated using Halcyon AXB, maintaining the original optimal fluence, arc geometry, normalization to the target-mean dose, calculation grid-size of 2.5 mm, and target margins. Absorbed dose was reported as dose-to-medium in medium, which is the native reporting mode in Halcyon AXB. Dosimetric comparisons were made by assessing the PTV coverage metrics of D98%, D95%, D50%, D2%, mean dose, and plan quality metrics of homogeneity index (HI), conformity index (CI), and the total number of monitor units (MU). The values were extracted from plan-sums of phase 1 and boost treatment plans. For comparing doses to organs-at-risk, cochlear D5%, parotid D20%, D50%, mean dose, and spinal cord maximum dose were used. CI and HI are defined in Equations (1) and (2), respectively.

$$\mathrm{CI} = \frac{\text{Volume of 100\% isodose surface}}{\text{Volume of PTV}} \tag{1}$$

$$\mathrm{HI} = \frac{\mathrm{D2\%} - \mathrm{D98\%}}{\mathrm{D50\%}} \tag{2}$$

The two-tailed Mann-Whitney U test was used for statistical comparison of the dose metrics, with the significance level set at 0.05. P-values < 0.05 were considered statistically significant, corresponding to a 95% confidence level. Statistical analyses were performed on Social Science Statistics [9], a web-based statistics calculator. Approval to access and use patient data was granted by the Human Research Ethics Committee of the University of Cape Town Faculty of Health

Sciences (Reference 162/2022).

3. Results

Table 1 summarises the dose metrics for nodal and tumour planning target volumes calculated by the two algorithms, showing the absolute differences and associated p-values. The data shows that PTV_N dose metrics from both algorithms show no significant differences, except for the maximum dose, where AAA calculated 71.1 Gy and AXB 73.5 Gy. AXB also calculated a more homogenous dose distribution compared to AAA. There were differences observed in PTV_T dose distributions: statistically significant differences were observed at D98%, D95%, D2%, maximum and minimum, and the homogeneity index. AAA calculated higher values of all dose-volume metrics except for D2% and maximum dose, where AXB yielded higher. AXB also calculated a higher homogeneity index. As for PTV_N, differences in the conformity index were not statistically significant.

Table 1. Comparison of dose-volume and plan quality metrics of plans calculated by Halcyon AAA and AXB for nodal planning treatment volumes (PTV_N) and tumour planning treatment volumes (PTV_T). Values are expressed as the median and, in parentheses, the minimum and maximum doses. AAA = Analytical Anisotropic Algorithm, AXB = Acuros XB.

PTV_N	AAA (Gy)	AXB (Gy)	Difference	P-value
Mean (Gy)	60.9 (48.5, 66.6)	60.3 (48.5, 67.2)	0.6	0.08
D98%	47.2 (45.6, 56.7)	47.1 (37.2, 56.3)	0.1	0.30
D95%	47.9 (46.0, 57.2)	47.8 (45.7, 56.7)	0.1	0.13
D50%	64.8 (48.4, 69.4)	64.0 (48.3, 70.3)	0.8	0.18
D2%	69.5 (52.5, 72.0)	70.1 (52.5, 74.2)	−0.6	0.02
Max (Gy)	71.1 (54.7, 74.2)	73.5 (54.8, 83.2)	−2.4	<0.01
Min (Gy)	42.2 (19.1, 50.5)	42.2 (18.6, 52.1)	0.0	0.33
HI	0.35 (0.14, 0.43)	0.36 (0.14, 0.58)	−0.01	0.02
CI	1.56 (0.57, 1.92)	1.51 (0.53, 1.92)	0.05	0.91
PTV_T				
Mean (Gy)	68.0 (56.3, 70.2)	67.9 (54.7, 68.9)	0.1	0.51
D98%	66.3 (60.5, 68.2)	65.7 (60.4, 68.5)	0.4	<0.01
D95%	66.7 (61.5, 68.9)	66.1 (60.5, 68.2)	0.6	<0.01
D50%	68.0 (64.0, 70.3)	68.0 (64.1, 71.1)	0.0	0.60
D2%	69.9 (65.3, 72.2)	70.5 (66.6, 78.6)	−0.6	<0.01
Max (Gy)	71.8 (66.4, 74.3)	73.5 (69.0, 83.2)	−1.5	<0.01
Min (Gy)	60.7 (42.2, 64.3)	59.5 (41.9, 63.7)	1.2	0.04
HI	0.06 (0.04, 0.51)	0.08 (0.07, 0.22)	−0.02	0.01
CI	0.52 (0.01, 1.58)	0.53 (0.01, 0.90)	−0.01	0.85
MU	1116 (517, 1321)	1120 (524, 1335)	−4	0.04

Table 2 repeats this summary for selected organs-at-risk, where statistically significant differences were observed for LT and RT cochlear D5%, LT parotid mean dose and D50%, and RT parotid mean dose. In all instances, AAA predicted higher values than AXB. The difference in values of the maximum spinal cord dose is not statistically significant.

Figure 1 and Figure 2 are box-and-whisker plots comparing AAA and AXB calculated dose distributions for PTV_T and PTV_N, respectively.

Table 2. Comparison of dose-volume metrics of dose distributions calculated by Halcyon AAA and AXB for selected organs-at-risk. Values are expressed as the median and, in parentheses, the minimum and maximum doses. AAA = Analytical Anisotropic Algorithm, AXB = Acuros XB.

Structure	AAA (Gy)	AXB (Gy)	Difference	P-value
Lt Cochlear				
D5%	3.1 (0.0, 23.7)	2.9 (0.0, 23.4)	0.2	<0.01
Rt Cochlear				
D5%	3.0 (0.00, 32.3)	2.8 (0.0, 32.0)	0.2	0.01
Lt Parotid				
Mean	29.8 (5.8, 52.7)	28.9 (5.6, 52.7)	0.9	<0.01
D50%	24.8 (5.7, 67.3)	24.0 (5.6, 67.0)	0.8	<0.01
D20%	49.2 (7.5, 68.5)	49.1 (7.2, 68.6)	0.1	0.75
Rt Parotid				
Mean	26.3 (7.1, 46.9)	25.5 (7.0, 47.3)	0.8	0.02
D50%	20.6 (6.9, 54.6)	19.8 (8.2, 69.5)	0.8	0.94
D20%	46.0 (8.2, 69.5)	45.8 (8.1, 70.3)	0.2	0.94
Spinal cord				
Max	34.3 (5.7, 45.0)	34.3 (5.5, 45.0)	0.0	0.80

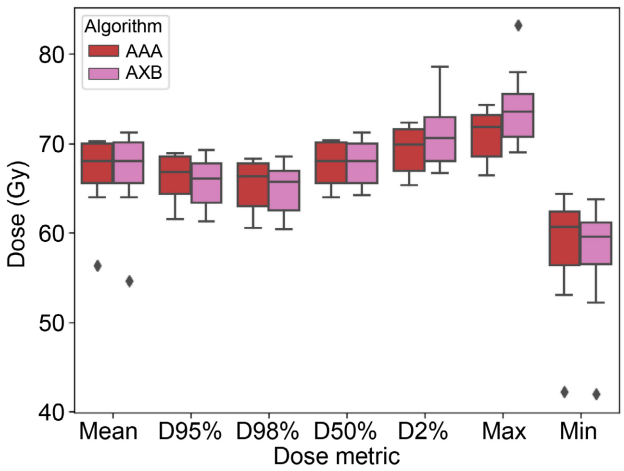

Figure 1. Boxplots comparing PTV_T dose metrics calculated by AAA and AXB. PTV_T = Tumour Planning Treatment Volume, AAA = Analytic Anisotropic Algorithm, AXB = Acuros XB. Outliers those values lying outside 1.5 times the Interquartile range (IQR) above the upper quartile and below the lower quartile.

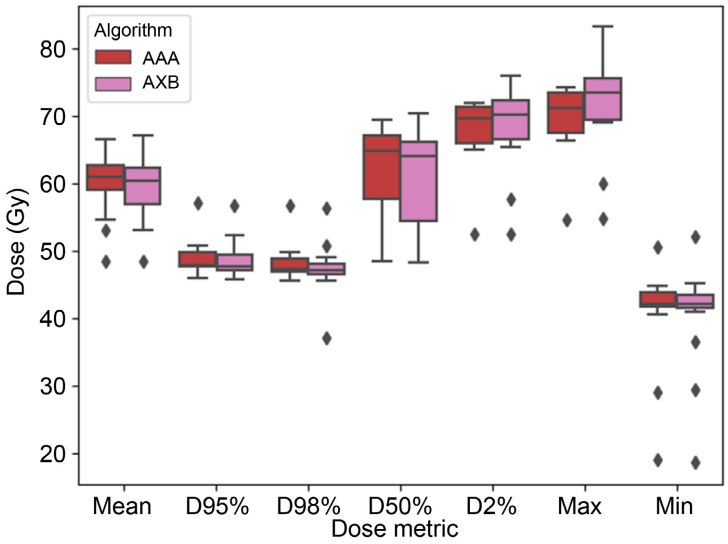

Figure 2. Boxplots comparing PTV_N dose metrics calculated by AAA and AXB. PTV_N = nodal planning treatment volume, AAA = Analytic Anisotropic Algorithm, AXB = Acuros XB. Outliers those values lying outside 1.5 times the Interquartile range (IQR) above the upper quartile and below the lower quartile.

Figure 1 shows that except for the mean dose and D50%, all dose-volume metrics demonstrate a negatively skewed statistical distribution. The box-and-whisker plots at the maximum PTV_T dose demonstrate a clear difference between the algorithms.

In Figure 2, only the AAA calculated mean doses appear to be normally distributed, whereas the D95%, D98%, and minimum dose from both algorithms demonstrate tight, positively skewed distributions. The distributions of the remaining dose-volume metrics negatively skewed, while the difference in the maximum doses is evident.

Variation plots of the dose-volume metrics to PTV_T and the organs at risk are shown in Figures 3-8.

In Figure 9, representative dose histograms of PTV_T, LT and RT cochlea, LT and RT parotids, and the spinal cord is shown. There are no obvious differences between the algorithms in dose distributions calculated for the organs-at-risk. However, Halcyon AXB appears to predict better coverage, superior dose heterogeneity and lower hotspots to the PTV_T.

4. Discussion

In accordance with the recommendations of AAPM TG 329 [10], AXB dose calculations were reported as dose-to-medium in medium, a mode of reporting which is inherent to Halcyon AXB. The same report advises against switching to dose-to-water reporting option because the process would introduce additional uncertainties in the result. Halcyon AAA dose calculations are inherently reported as dose-to-water, seeing that this algorithm is type B and alternative dose

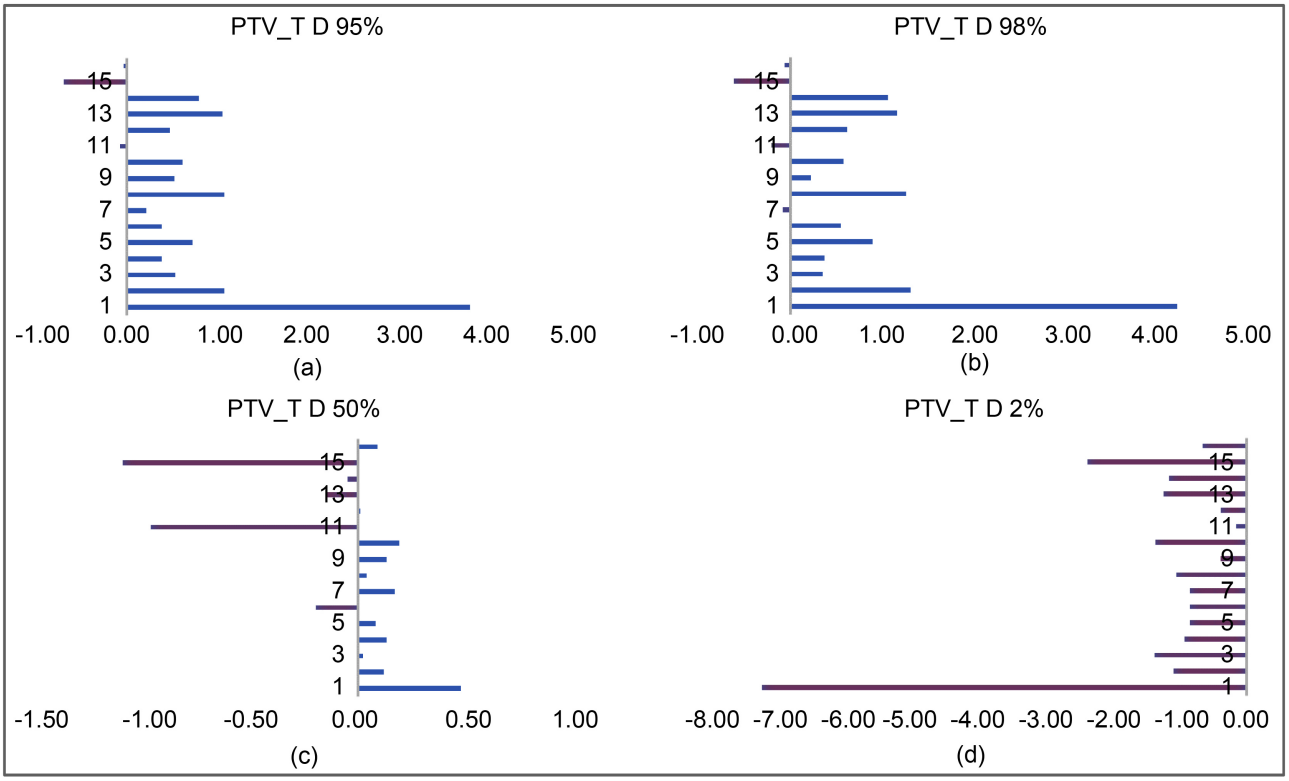

Figure 3. Variation plots for (a) D95%, (b) D98%, (c) D50% and (d) D2% of the tumour planning treatment volume (PTV_T). The bars indicate the instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher values.

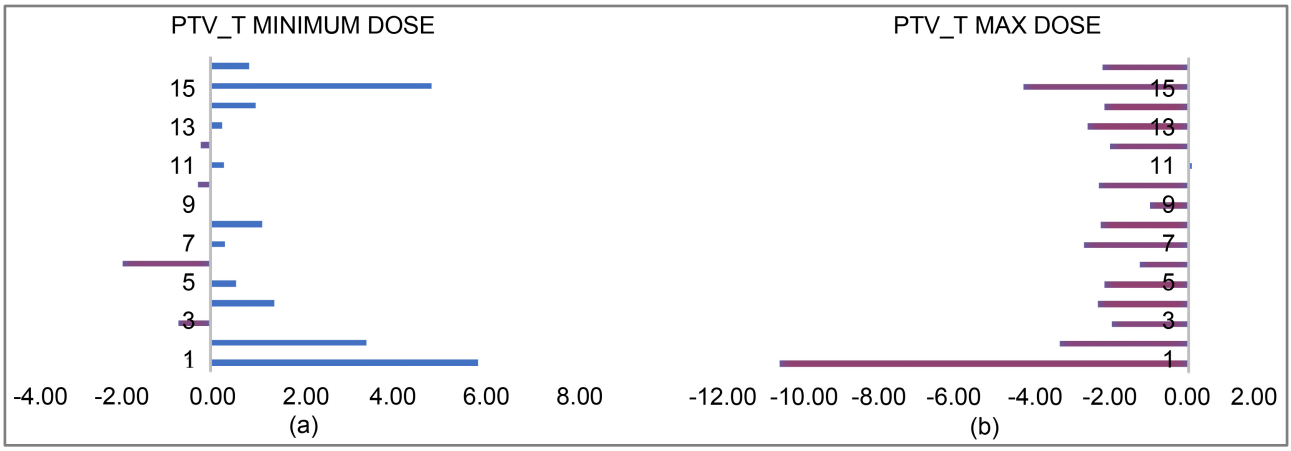

Figure 4. Variation plots for (a) minimum and (b) maximum dose to the tumor planning treatment volume (PTV_T). The bars indicate the instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher value.

reporting options do not exist. The distributions of most of the dose-volume metrics were skewed, thereby justifying our choice to use the median and range as measures of location and spread, respectively. We have found that that except for D2% and maximum dose, the median PTV dose-volume metrics calculated by Halcyon AAA were higher or equal to those of Halcyon AXB. A statistically significant difference was observed at PTV_N maximum dose, where AXB calculated a higher median value. However, this value translates to only about 3%

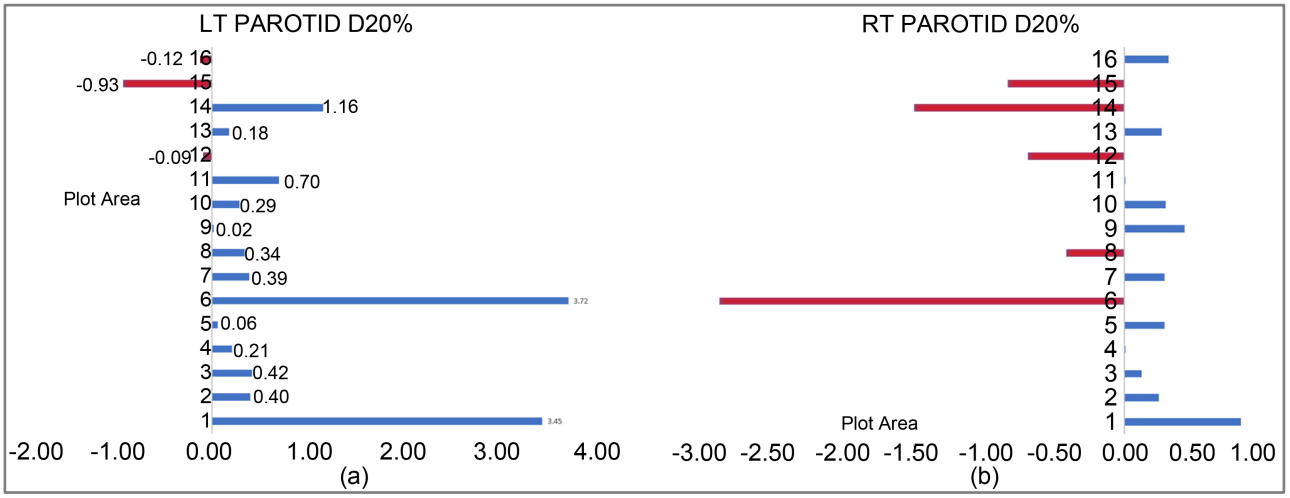

Figure 5. Variation plots for D20% of the left parotid gland (a) and right parotid gland (b). The bars indicate the instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher values.

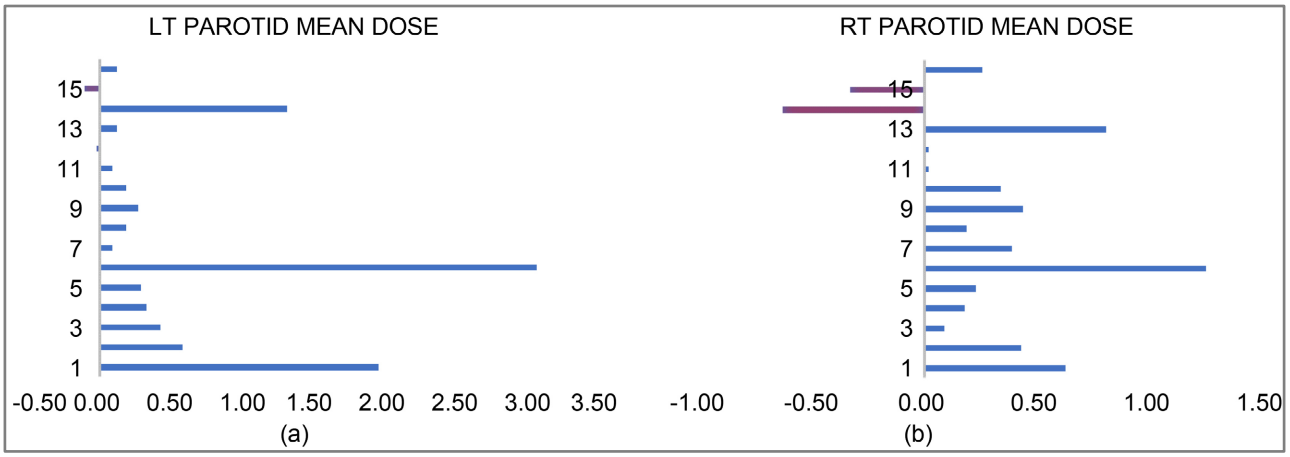

Figure 6. Variation plots for D50% of the left parotid gland (a) and right parotid gland (b). The bars indicate the instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher values.

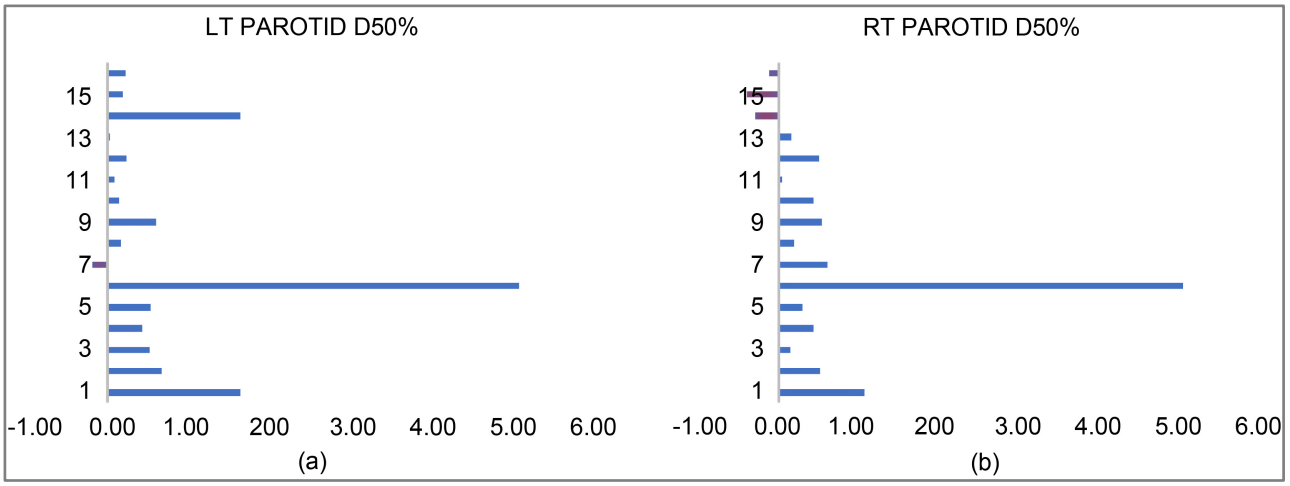

Figure 7. Variation plots for the mean dose to the left parotid gland (a) and right parotid gland (b). The bars indicate the instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher values.

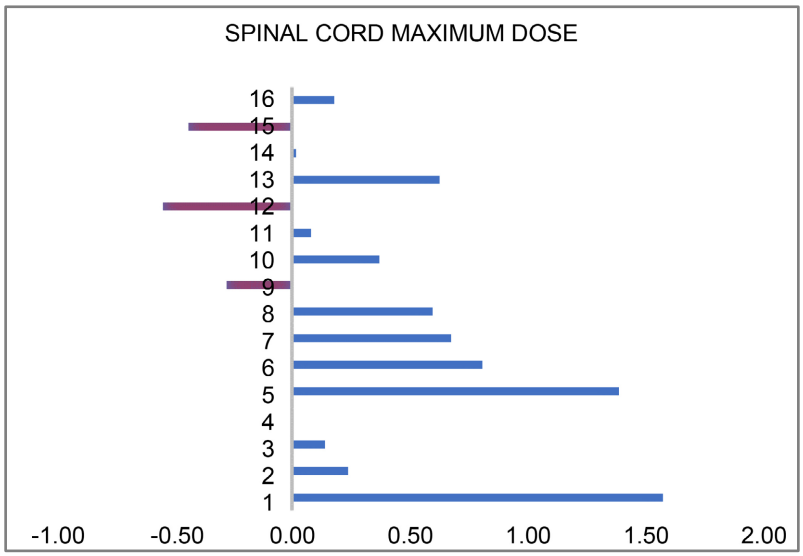

Figure 8. Variation plots for maximum dose to the spinal cord. The bars indicate instances when Halcyon AAA (red) or Halcyon AXB (blue) calculated higher values.

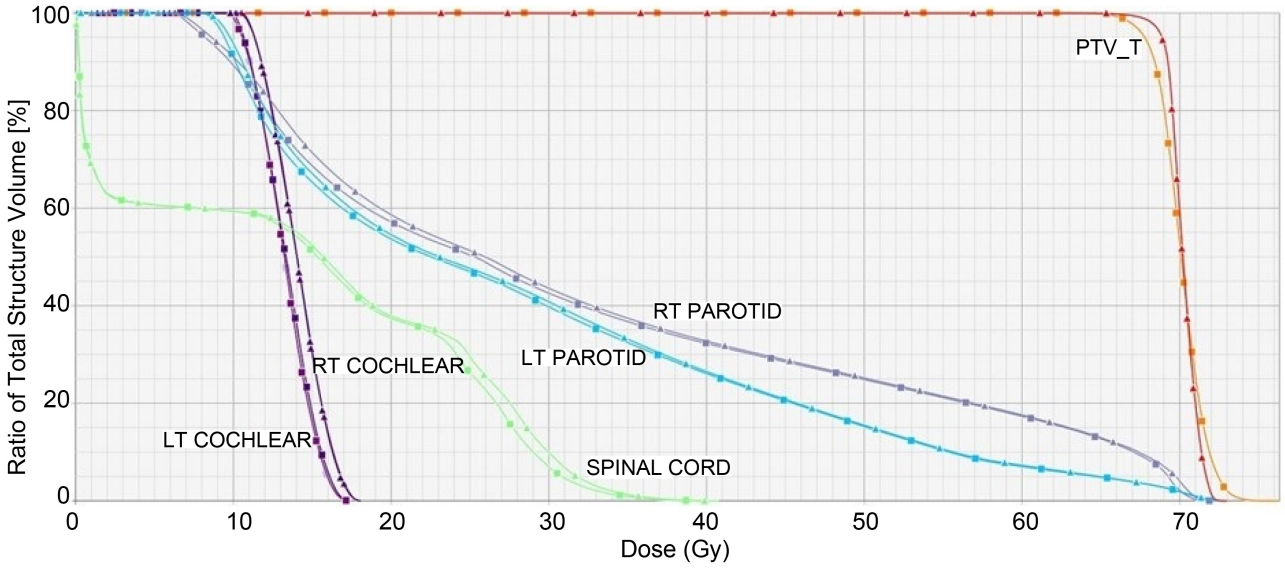

Figure 9. Cumulative dose-volume histogram showing dose distributions calculated by AAA (squares) and AXB (triangles) for tumour planning target volume (PTV_T) and selected organs-at-risk. RT = right, LT = left.

of the median PTV_N dose and therefore the clinical significance may not be remarkable. Statistically significant differences were observed at PTV_T D98%, D95%, D2%, maximum, and minimum doses. Again, the clinical significance may not be astounding, judging by the values of the absolute differences. Table 2 shows that Halcyon AAA consistently calculated higher OAR median dose-volume metrics than AXB. Statistically significant differences were observed for bilateral Cochlear D5%, bilateral parotid mean dose, and Lt parotid D50%. Clinically, these differences may not be significant because the absolute differences are miniscule. However, this assessment may not be valid in general as only a

selected number of OAR were assessed in this study.

No systematic trends in differences between PTV and OAR dose metrics calculated by the two algorithms were observed (Figures 1-8). The superior PTV_T dose coverage and homogeneity calculated by AXB in

Figure 9 appears to be peculiar to this specific case. In this regard, our findings are in keeping with those of Munoz-Montplet, *et al.* [11] who conducted a similar study albeit for the regular C-arm AAA and AXB.

5. Conclusion

A dosimetric plan comparison between Halcyon AAA and AXB algorithms was conducted for RapidArc head-and-neck plans created using the sequential boost technique. Although statistically significant differences were observed for several dose-volume metrics in the PTVs and organs-at-risk, we found that these differences may not be clinically remarkable. Therefore, both Halcyon AAA and AXB may be adequate for RapidArc planning of Head & Neck cancers with acceptable metrics of target coverage, OAR sparing, and plan quality.

6. Limitations

The small sample size used in this study may be a limitation. In addition, the sequential boost technique instead of the more contemporary Simultaneous Integrated Boost was used for creating the treatment plans. It is our belief that the choice of either one or the other technique does not influence the outcome.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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