Iranian Journal of Medical Physics
ijmp.mums.ac.ir

Performance of different Strength of Aperture Shape Controller on VMAT technique for Head and Neck, Pelvis, and Breast Cancer using Halcyon Machine

Morad Erraoudi[1], El Ghalmi Mohammed[1], Mohamed Yassine Herrassi[2], Yasser Raoui[1], Youssef Bouzekraoui[3*], Farida Bentayeb[1]

1. Faculty of Sciences, LPHE-M&S, Mohammed V University, Rabat, Morocco
2. Private Hospital Casablanca-AKDITAL, Morocco
3. Hassan First University of Settat, High Institute of Health Sciences, Morocco

ARTICLE INFO

Article type:
Original Paper

Article history:
Received: Oct 22, 2022
Accepted: Apr 12, 2023

Keywords:
Target Coverage
Leaf Sequencing
Cancer
Beamlets
VMAT Technique
Aperture Shape Controller
Optimization

ABSTRACT

Introduction: Before starting optimization using the Volumetric Modulated Arc Therapy (VMAT) technique, the choice of the convenient aperture shape controller can be one of the most important factors that affect the plan quality.

Material and Methods: Three different clinical cases were selected: head and neck cancer, pelvic cancer (prostate, cervix, and endometrium), and breast cancer treated with the VMAT technique. By keeping the same conditions, plans were reoptimized by varying aperture shape controllers (OFF, VERY LOW, LOW, MODERATE, HIGH, VERY HIGH). For plans evaluation, the homogeneity index (HI), conformity index (CI), target coverage (D98% and V98%), dose max (DMAX) and near max (D2%), treatment time delivery (MUs), and gamma index passing rate were analyzed.

Results: All the studied localizations treated with the VMAT technique met clinical objectives. The VERY LOW technique achieved the best dose conformity for all localizations. A slight improvement in terms of PTV coverage and max dose is obtained in a VERY LOW technique for pelvic cancer. For breast cancer, almost the same results were obtained. However, for head and neck treatments, better results were observed with the HIGH and VERY HIGH techniques, where coverage and maximum dose improved by up to 6%.

Conclusion: Changing the Strength of Aperture Shape Controller in VMAT optimization can affect dose calculation, especially in concave volumes such as Head and Neck.

► *Please cite this article as:*
Erraoudi M, El Ghalmi M, Herrassi MY, Raoui Y, Bouzekraoui Y, Bentayeb F. Performance of different Strength of Aperture Shape Controller on VMAT technique for Head and Neck, Pelvis, and Breast Cancer using Halcyon Machine. Iran J Med Phys 2024; 21: 168-175. 10.22038/IJMP.2023.68586.2201.

Introduction

Improvements in machine technology for radiotherapy treatment are one of the main factors that contribute to the delivery of high doses to target volume while providing maximum protection to organs at risk. The shape of the beam plays a very important role in improving the accuracy, efficiency, and quality of radiation treatments. Over three decades Multileaf Collimators (MLCs) have been used and considered one of the cornerstones of radiotherapy [1–9]. Initially, beam shapers have been used to eliminate heavy shielding blocks, and then for Intensity Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) [10]. Additionally, various designs of Multi-Leaf Collimators (MLCs) have been introduced throughout the years, with each iteration striving to enhance the efficacy and precision of radiation therapy [4,8,11–13]. In the course of treatment employing IMRT and VMAT techniques, the dose delivered to the target volume is influenced by both leaf positioning and leaf transmission, highlighting the importance of precise control over these factors [5, 8, 14, 15].

Recently, there has been a growing interest in Linear Accelerator (LINAC) improvement of gantry speed, leaf speed, and dose rate that may strengthen the time-efficiency of VMAT delivery. This latter is used in a Halcyon linear accelerator with an O-ring gantry design that can rotate at higher speeds compared to the current C-arm LINACs. This Machine is mainly designed for intensity-modulated radiation therapy and volumetric modulated arc therapy (IMRT/VMAT) because of its specific characteristics such as fast delivery via 4 Rotation/min (4 RPM) with a dose rate of 800 MU/s, Flatting Filter Free (FFF) only beam MLC characteristics and automated daily IGRT workflow. The new model of the Varian (Varian Medical Systems, Palo Alto, CA, USA) Halcyon linear medical accelerator was introduced in May 2017 at

---

*Corresponding Author: Tel: +212623609312; Email: youssef0fsr@gmail.com

the European Society for Radiotherapy & Oncology (ESTRO 36) Meeting, and it was installed in North America and France by mid-2017, as well as in Britain by September 2018 [16,17].

Unlike the other single-layer Varian MLC systems (such as the Millennium™120-leaf MLCs and High Definition 120-leaf MLCs), Halcyon™ has dual-layer MLCs and no beam-shaping jaws, which offer fast beam modulation and substantially reduces leakage between MLC leaves, which ensure accurate dose delivery. Additionally, the Halcyon™ commissioning process is straightforward and streamlined to allow for a short period from installation to treatment. Although the literature has provided descriptions of the Halcyon™ beam output, there is currently no independent characterization available for the unique stacked and staggered dual-layer MLC [16]. A comprehensive characterization of the Multi-Leaf Collimator (MLC) system is crucial for gaining a thorough insight into the limitations of the system. This understanding, in turn, guides the establishment of quality assurance protocols to guarantee precise and accurate radiation deliveries. It is noteworthy that the integration of a reference beam model with the Eclipse treatment planning system was instrumental in the pre-configuration of the HalcyonTM LINAC. Additionally, the beam model parameters concerning small fields and MLC dosimetry exhibit enhanced reliability when there is a strong agreement between the planned and delivered doses [16].

In mid-July 2018, the Halcyon™ 2 was introduced to the market, offering upgraded features compared to the previous version. The advancements from Halcyon™ 1 to Halcyon™ 2 include the following features: (a) kilovoltage (kV) imaging capability, see Table 1, (b) maximum treatment length of 36 cm using multiple isocenters, (c) 0.5-cm MLC effective resolution, and (d) dynamic beam flattening sequences that flatten the treatment field beam profiles for three-dimensional (3D) conformal planning. Most other parts remain the same as 1 for hardware, beam data/modeling, MLC characteristics (dimension, Dosimetric gap, transmission, and interleaf leakage), integrated electronic portal imaging device (EPID) with portal dosimetry and treatment workflow [18,19]. Several studies have shown good agreements between measurements and calculated or reference values on Halcyon™ 1 [20, 21].

Due to the lateral scatter equilibrium in small field detectors, the openings of the MLC are significant; therefore, overdosing or underdosing may be detrimental to the outcome of providing safe radiation therapy. To control leaf sequencing; recently, the Strength of Aperture Shape Controller is introduced by (Varian Medical Systems, Palo Alto, CA) to monitor the complexity of the multi-leaf collimator apertures during optimization for VMAT technique [22]. Before starting plan optimization, the user can assign specific leaf adjustments through the options: OFF, VERY LOW, LOW, MODERATE, HIGH, and VERY HIGH. These optimization options may affect plan quality and treatment time. To the best of our knowledge, no precise data are available for the optimal option technique for different treatment sites. Our center has installed Halcyon™ 2 combined with Eclipse™ treatment planning software (v16.1.0) using a 6X FFF energy and 600 MU/min dose rate. Therefore, the purpose of this study is to identify the impact of different Strengths of Aperture Shape Controller, and its effect on planning quality by evaluating the HI, CI, $D_{98\%}$, $V_{98\%}$, $D_{2\%}$, D_{MAX}, MUs and gamma index passing rate. Three distinct sites: Head and Neck, Pelvic (Prostate, Cervix, and Endometrium), and Breast Cancer – were chosen for this study due to their different anatomical shapes and high frequency of occurrence. For each specific plan, six different optimization options were conducted.

Materials and Methods

A retrospective study was conducted on nine consecutive patients representing three different and most frequent cancer sites, including advanced tumors of the nasopharynx, oropharynx, and hypopharynx for Head and Neck, low-risk for Pelvis, and breast cancer. All patients were treated with Halcyon 2.0 using VMAT technique. Treatment plans are generated within Eclipse ™ treatment planning software (v16.1.0) using a 6X flattening filter free (FFF) energy and 600 MU/min dose rate to minimize differences between treatment units and directly compare MLCs.

Table 1. KV cone beam computer tomography characteristics on Halcyon 2

Modes	Clinnical Protocols
Energy	80-140 kVp
Scan time	From 16.6 s (Head, Breast, Thorax modes) To 40.6 s (Pelvis Large mode)
Scan range	24.5 cm
Scan diameter	49.1 cm
Imager	17.5 (cm lateral offset
Bow-tie	Half bow tie/titanium filter
Pixel resolution	1280 x 1280 (43 cm x 43 cm panel)
Reconstruction	2-mm slice thickness Algorithm Conventional FDK (CBCT), iterative process (CBCT; nonlinear/statistical)

Patient's prescriptions

The CT images for all the studied patients were performed in 2 mm slices thickness with Siemens Somatom Sensation Open CT (Siemens, Erlangen, Germany). These images were imported via Varian SOMAVISION Focal workstations v.16.1.0 (Varian, Palo Alto, CA, USA) to delineate organs at risk (OAR) and clinical target volumes and Planning Target Volume (CTV and PTV).

Patients selected for Pelvic Cancer treatment were positioned in a supine posture and aligned with a room laser system based on body markers. Additionally, a personalized immobilization device was employed to enhance treatment precision and patient stability. Patients were imaged with semi-full bladders and empty rectums. The degree of filling was monitored and controlled during each treatment session using Cone Beam Computed Tomography (CBCT) imaging. According to van Herk and our clinical protocol, the CTV-PTV uniform margin recipe of 6 mm was used. The prescription dose for Cervix and Endometrium was 50Gy in 25 treatment fractions and 46Gy with 2Gy/fr for Prostate Cancer.

In breast cancer, a CT scan was performed in a supine position with broad breast immobilization. The prescribed dose for all studied patients was 50 Gy delivered in 25 fractions.

For patients undergoing treatment for head and neck regions, immobilization was achieved using a molded mask with five fixation points, securely attached to a carbon fiber table. Neck lymph nodes and OAR were delineated according to the published guidelines [23,24]. In the treatment, two different dose levels of 2.12Gy/fraction to the PTV-boost and 1.65Gy/fraction to the PTV-elective were prescribed for a total dose of 69·96Gy and 54·45Gy, respectively, delivered in 33fractions with a simultaneously integrated boost (SIB) with VMAT technique.

Planning Technique

The used VMAT technique for all plans on the fast O-ring linac established two full arcs with one isocenter and the same collimator angles, which can be (45°, 315° or 23°, 293°) in opposite arcs directions. In the treatment of breast cancer, two to four half arcs are used for optimization depending on the volume and the side (left, right) of the patient. However, when multiple lymph nodes are found to be positive in the staging of breast cancer two isocenters might be used if the target volume extended into the supraclavicular-axillary region and occupied a volume bigger than 28cm×28cm.

For each patient, six different optimization plans were performed with variant Strength Aperture Shape Controller (Plan-off, Plan-very low, Plan-low, Plan-moderate, Plan-high, and Plan-very high), and thus the shape of MLC opening to form the size and the number of beams in the same conditions to check their effect on target volume coverage, treatment time, and gamma index passing rate for three different localizations.

Planning Objectives

Our objective for PTV coverage was to guarantee that a minimum of 95% of the prescribed dose covered 98% of the target volume, with the near-minimum dose (D98%) exceeding 95%. This criterion was applied to all the studied patients. Additionally, an upper limit of 107% of the prescribed dose was established for the near-maximum dose of D2%, representing the dose delivered to the 'hottest' 2% volume of each PTV (D2% < 107%). Regarding OARs and healthy tissue, the primary planning objective was to minimize the radiation dose while maintaining maximum homogeneity and conformity of the dose to the PTVs. Subsequently, each plan underwent evaluation based on dose–volume histograms (DVH) of both the PTVs and OARs. the obtained results were then compared against the established planning objectives and constraints specific to each optimization option technique.

To evaluate the HI of each plan, we applied the following formula:

$$HI = (D_{2\%} - D_{98\%}) / D_P \quad (1)$$

Where D_P is the prescribed dose to PTV, [25, 26] Indeed, the optimal value for the Homogeneity Index (HI) is 0. A lower HI indicates improved dose homogeneity within the volume of interest, to minimize variations in radiation dosage across the targeted area.

We calculated the conformity index (CI) as well to estimate the degree of conformity to PTV, this index is defined by Radiation Oncology Group (USA) as follows:

$$CI = V_{RI} / V_{TV} \quad (2)$$

Where: V_{RI} is the Volume for the region of interest and V_{TV} is the Volume of the PTV.

According to this definition, a Conformity Index (CI) value of 1 represents ideal conformity, indicating optimal radiation delivery to the target volume. If the CI exceeds 1, it suggests that healthy tissues may receive excessive radiation. Conversely, if the CI is less than 1, it indicates that the target volume is only partially irradiated.

Furthermore, for evaluating treatment efficiency and planning, the number of monitor units utilized in each technique was also taken into account.

Results

For each of the studied cases (Pelvis, Breast, Head and Neck) the results were investigated for different strength of aperture shape controller (OFF, VERY LOW, LOW, HIGH, and VERY HIGH). A total of 18 VMAT plans were generated to compare different optimization methods. Dosimetric and clinical parameters were calculated and evaluated using DVHs and dose statistics from Eclipse ™ treatment planning software (v16.1.0). Due to the impact of the used algorithm Analytical Anisotropic Algorithm (AAA), some similarities and differences were noted when different optimization methods were used. To highlight the differences when comparing the results for each individual patient, figures, and tables were used.

The Dosimetric results for all the studied patients in Pelvic and Breast cancer cases seem to be different. However, the alteration between the treatment techniques was observed to be very small. Pelvic treatment shows a slight improvement in PTV coverage in the used VERY LOW technique compared to others, by identifying the volume covered by 98% of the prescription dose (D98%), and the percentage of the dose that cover 98% of the Volume (V98%). The value of D98% for all treatment techniques was very close, between 96.5% and 97%, and the higher value was acquired by the VERY LOW technique. these variations were synchronized with V98% which was between 95% and 96% for all techniques except for VERY HIGH which was under 95% Figure 1-a. the Dosimetric parameters that describe PTV coverage (D98% and V98%) show no difference between all techniques in Breast treatment, almost 93% for D98% and 89% for V98% with 1% lower for the OFF technique Figure 2-a. the effect of using different optimization techniques in Head and Neck treatment is more important compared to other localizations, the best results of PTV coverage are obtained in High and VERY HIGH techniques with almost 5% to 6% higher for $D_{2\%}$ and small improvement also found in V2%, except for the OFF technique that was 2% more than HIGH technique Figure 3-a. The same remarque is noted in the analysis of the point dose max (D_{max}) and the near maximum dose $D_{2\%}$ for different localizations and techniques. No significant differences in D_{max} and D2% for Breast treatment. D_{max} was between 110% and 110.5% for all techniques, and between 106% and 106.5% for $D_{2\%}$ always with 0.5% lower in VERY LOW techniques Figure 2-b. For Pelvic treatment, the maxim and near maximum dose variation of 2% between all techniques is clearly shown in Figure 1-b, 106.5% for D_{max} and 103.75% for $D_{2\%}$ always with a lower value in the VERY LOW technique. In the Head and Neck treatment, only a 106% maximum dose is achieved as the best value for the HIGH technique with a gain of almost 3% compared to the worst value obtained in the VERY LOW technique, in the contrary Pelvic case was the best result. The conformity index is always considered one of the fabulous parameters to easily compare the performance of multiple plans and is mostly used in combination with the homogeneity index to check both the uniformity of dose distribution within the target volume and the conforms of reference isodose to the target volume.

The homogeneity index recognized no gain between techniques for all localizations, except for head and neck in the application of HIGH and VERY HIGH, the HI=0.2 against 0.25 to 0.3 for others, on the other hand, the best conformity index attained in the VERY LOW and VERY HIGH techniques for Pelvic and Breast with CI ranges from 0.97-0.99 Figure 1-c, Figure 2-c and 0.97 for Head and Neck Figure 3-c. Monitor units calculation achieved the best results when using the off technique for Pelvic and Breast treatment with 565 MUs and 523MUs respectively Figure 1, 2-d, for head and neck the off technique was the worst with 585MUs and the best result was obtained with the high and very technique with 480MUs. Quality control shows no significant differences between all techniques in all cases when a 3mm distance to agreement and 3% dose difference is used.

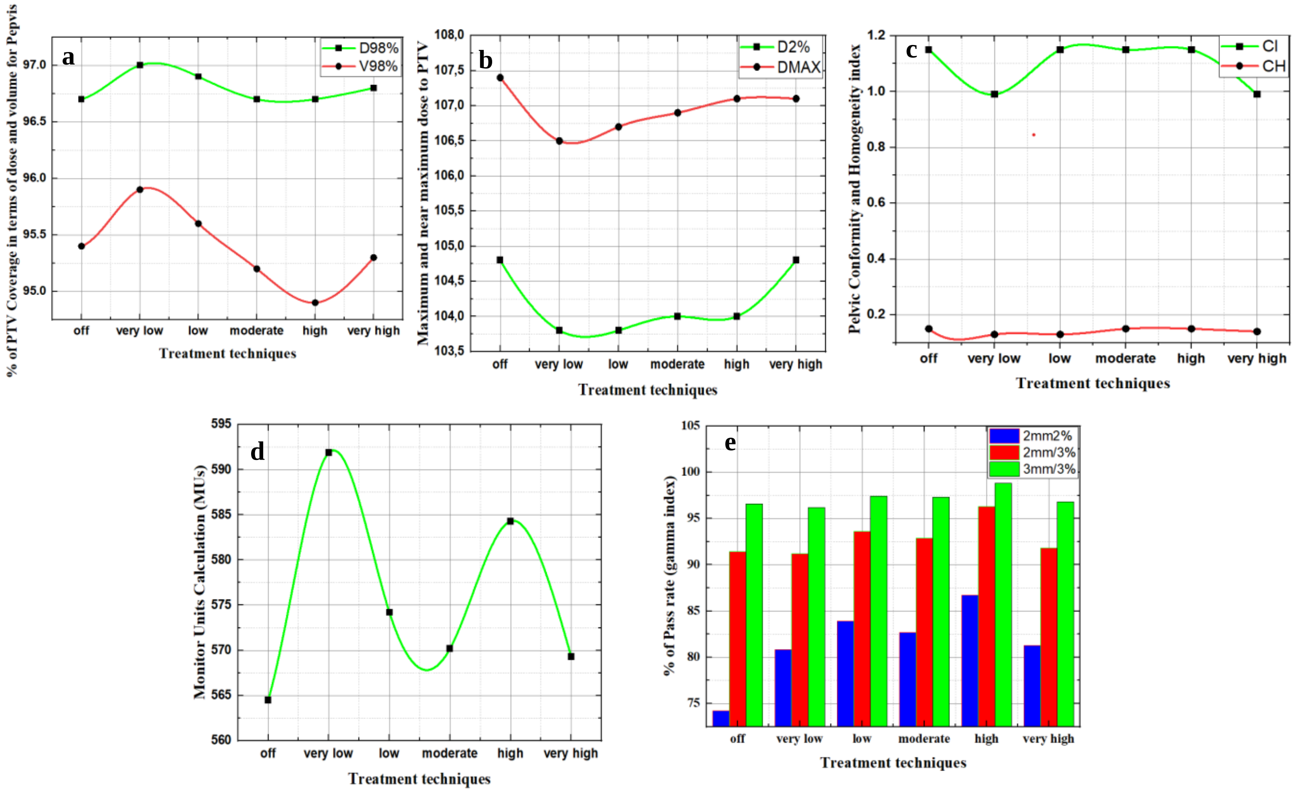

Figure 1. Dosimetric parameters for pelvic treatment using different Strength of Aperture Shape Controller: OFF technique, VERY LOW technique, LOW technique, MODERATE technique, HIGH technique, and VERY HIGH technique

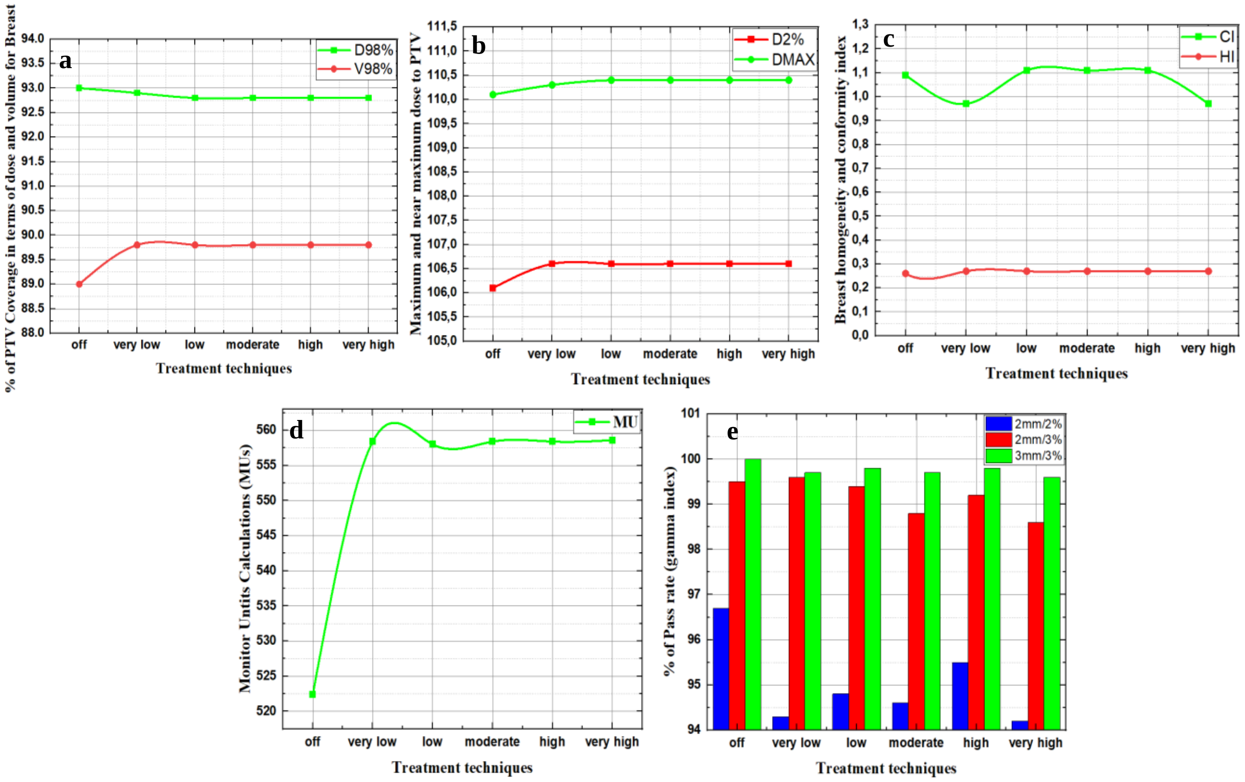

Figure 2. Dosimetric parameters for Breast treatment using different Strength of Aperture Shape Controller: OFF technique, VERY LOW technique, LOW technique, MODERATE technique, HIGH technique, and VERY HIGH technique

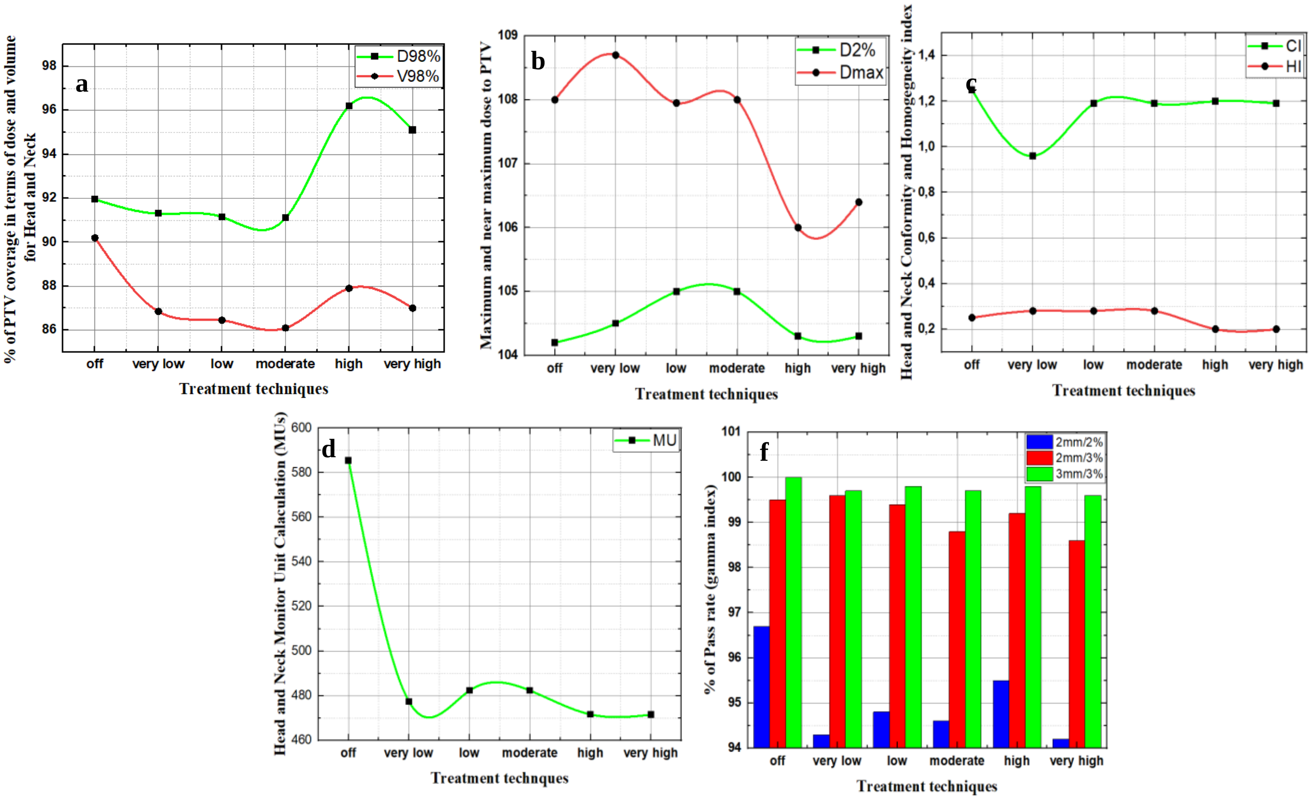

Figure 3. Dosimetric parameters for Head and Neck treatment using different Strength of Aperture Shape Controller: OFF technique, VERY LOW technique, LOW technique, MODERATE technique, HIGH technique, and VERY HIGH technique

Discussion

In this study, a Halcyon fast-rotating O-ring linac with fast-moving leaves was used to treat three different localizations with VMAT technique. Six different Strength of Aperture Shape Controller were used to optimize plans for each patient. In view of the fact that the Halcyon^{TM} 2 mounted with Eclipse^{TM} treatment planning software (v16.1.0) has newly been used, this investigation represents an initiative to compare the performance of each optimization technique in the studied localizations.

The prime objective of this study is to select the best Strength of Aperture Shape Controller prior to starting optimization for each localization. Our results of Pelvic treatment recognize some variations when the Strength of Aperture Shape Controller, changed and used for optimization. As seen from the plans quality review (Table 2), CI for all the studied patients who achieved good results and ranges between 0,99 to 1,15 and almost similar HI is obtained, always with the advantage of the VEY LOW and VERY HIGH optimization technique. These results were comparable to that of KIM et all, for gynecological cancer treatments [27]. Better coverage and hot spot reduction are obtained by the VERY LOW technique, on the other hand, more treatment time was needed to perform this accomplishment. Pretreatment patient-specific QA was performed with portal dosimetry with an electronic portal imaging device (EPID), 3mm/3%, 2mm/3%, and 2mm/2% were evaluated. Our pretreatment QA results ranged from 96,2% to 98,8% for 3mm/3% criteria and from 91,2% to 96,3% for 2mm/3% passing rate. These results were consistent with the recent report by De Roover et al [28] that achieved between 92,5% and 96,5% for 2mm/3% using Halcyon 1. The evaluation of 2mm/2% is identified to clarify the strength between techniques in a small area as shown in Figure 1-e, since the VERY LOW and VERY HIGH techniques showed some advantage compared to others in terms of PTV coverage and dose conformity, the difference between them was not significant and achieved just 0,6% better using the VERY HIGH technique. Variation between all techniques in Breast treatment was not meaningful in the used dosimetric parameters in this study, but in terms of Conformity index, the VERY LOW and VERY HIGH techniques were clearly better with 12,6% compared to the LOW, MODERATE, and HIGH techniques, and 11% compared to the OFF technique Table 2.

Our results for treating complicated shapes of target volume as head and neck achieved, a remarkable advantage when the size of the beamlet increased by using the HIGH and VERY HIGH techniques Figure 4. More than 100 MUs reduction is obtained compared to the OFF technique, where the small size of the beamlet is applied to irradiate the target volume. However, our results in dose conformity for HIGH and VERY HIGH were comparable to those obtained by S. Michiels et al, for PTV$_{elective}$ coverage and improved the maximum dose [29]. The study performed by Diana Binny et al, tested only three Strength of Aperture Shape Controller options; Low, High, and Moderate. For the studied cases MU reduction was found, likewise, plan complexity marginally improved when these three Strength of Aperture Shape Controller options are used [30].

The VERY LOW technique recorded the best conformity index for all localizations, Smaller beamlet sizes in the applied VMAT Plans offer the potential to upgrade dose conformity and homogeneity. The current constraints on applying smaller beamlet sizes to clinical planning practice are largely rooted in computational limitations. However, it is anticipated that these restrictions will diminish over time, primarily due to advancements in computational speed. As technology progresses, the ability to employ finer beamlet sizes in clinical planning is expected to improve.

this study investigated only three different cases at our institute for planning target volume assessment during optimization, without taking organs at risk analysis into account which may change the quality of the obtained results. Further work would be to include organs at risk and a larger number of cases to better understand the effect of using different strength of aperture shape controller on treatment plans.

Table 2. Conformity index and homogeneity index for Pelvic and Breast cancer

Technique	Pelvic		Breast	
	CI	HI	CI	HI
OFF	1,15	0,15	1.09	0.26
VERY LOW	0,99	0,13	0.97	0.27
LOW	1,15	0,13	1.11	0.27
MODERATE	1,15	0,15	1.11	0.27
HIGH	1,15	0,15	1.11	0.27
VERY HIGH	0,99	0,14	0.97	0.27

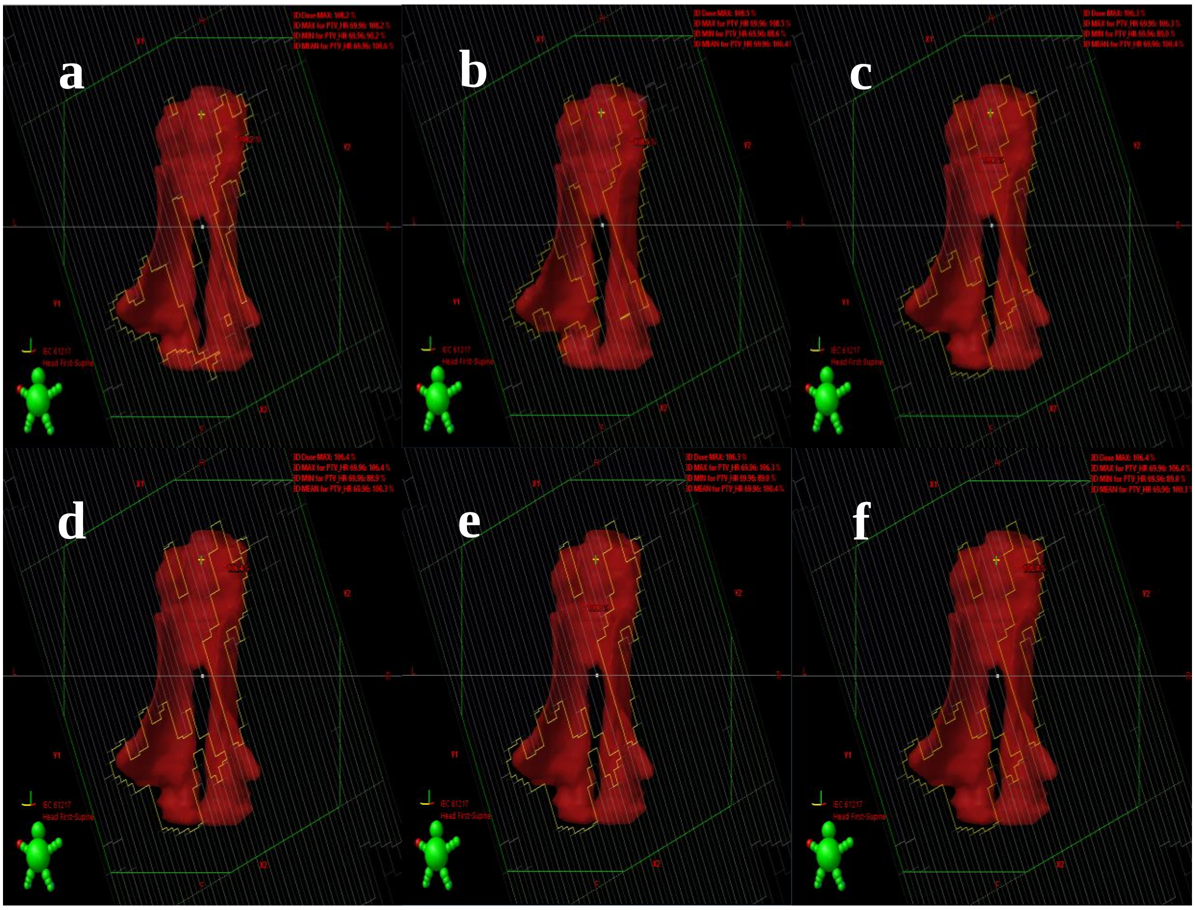

Figure 4. Head and Neck beamlet variation sizes for different Strength of Aperture Shape Controller from the same gantry rotation angle a) OFF technique b) VERY LOW technique c) LOW technique d) MODERATE technique e) HIGH technique f) VERY HIGH technique

Conclusion

The primary goal of employing the strength of the aperture shape controller, specifically through leaf sequencing, is to improve the quality of VMAT treatment plans. The results of this study showed that, adjusting the Strength of Aperture Shape Controller during the optimization of VMAT can have a significant impact on dose calculation. The present study indicated that selecting the appropriate Strength of the Aperture Shape Controller option during VMAT optimization significantly enhances the quality of the treatment plan. The results disclosed that using the HIGH and VERY HIGH techniques for the Head and Neck can improve the dose coverage, and dose max and significantly reduce the treatment time compared to the LOW technique.

The VERY LOW technique showed some advantages for the treatment of Pelvis and Breast cancer to balance between treatment time and target volume coverage.

References

1. Arnfield M, Siebers J, Kim J, Wu Q, Keall P, Mohan R. A method for determining multileaf collimator transmission and scatter for dynamic intensity modulated radiotherapy. Med Phys. 2000;27:2231–41.
2. Zygmanski P, Rosca F, Kadam D, Lrenz F, Nalichowski A, Chin L. Determination of depth and field size dependence of multileaf collimator transmission in intensity-modulated radiation therapy beams. JAppl Clin Med Phys. 2007;8:2693.
3. Lorenz F, Nalichowski A, Rosca F, Kung J, Wenz F, ZygmanskiP. Spatial dependence of MLC transmission in IMRT delivery. Phys MedBiol. 2007;52:5985–99.
4. Thompson C, Weston S, Cosgrove V, Thwaites D. A dosimetric characterization of a novel linear accelerator collimator. Med Phys. 2014;41:031713.
5. Galvin J, Smith A, Lally B. Characterization of a multileafcollimatorsystem. Int J Radiat Oncol Biol Phys. 1993;25:181–92.
6. Maleki N, Kijewski P. Analysis of the field defining properties of amultileaf collimator. Med Phys. 1984;11:390.
7. Helyer S, Heisig S. Multileaf collimation versus conventional shieldingblocks − a time and motion study of beam shaping in radiotherapy.Radiother Oncol. 1995;37:61–4.

8. Huq M, Das I, Steinberg T, Galvin J. A dosimetric comparison of various multileaf collimators. Phys Med Biol. 2002;47:N159−N70.
9. Jin J, Yin F, Ryu S, Ajlouni M, Kim J. Dosimetric study using differentleaf-width MLCs for treatment planning of dynamic conformal arcsand intensity-modulated radiosurgery. Med Phys. 2005;32:405−11.
10. Losasso T. IMRT delivery performance with a varianmultileaf collimator. Int J Radiat Oncol Biol Phys. 2008;71:S85S88.
11. Webb S. A new concept of multileaf collimator (the shuttling MLC) −an interpreter for high-efficiency IMRT. Phys Med Biol. 2000;45:3343−58.
12. Tacke M, Nill S, Haring P, Oelfke U. 6 MV dosimetric characterization of the 160 MLC, the new Siemens multileafcollimator. MedPhys. 2008;35:1634−42.
13. Cai B, Li H, Yang D, Rodriguez V, Curcuru A, Wang Y, et al. Performance of a multi leaf collimator system for MR-guided radiation therapy. Medical physics. 2017 Dec;44(12):6504-14.
14. Fiveash J, Murshed H, Duan J. Effect of multileafcollimator leaf width on physical dose distributions in the
15. treatment of CNS and head and neck neoplasms withintensity modulated radiation therapy. Med Phys. 2002;29:1116−9.
16. Cosgrove V, Jahn U, Pfaender M, Bauer S, Budach V, WurmR. Commissioning of a micro multi-leaf collimator and planningsystem for stereotactic radiosurgery. Radiother Oncol. 1999;50:325−36.
17. Bernard V, Fafi S, Nguyen D, Khodri M. 33 Commissioning and dosimetric characteristics of new halcyon system. Physica Medica: European Journal of Medical Physics. 2018 Dec 1;56:54.
18. Withers D, Kidane G, Crees L, Farmakidis D, Greenwood J, Isaacs É, et al. Treatment planning for a 6MV FFF Halcyon linac as a replacement for a 10MV-capable Clinac. InRadiotherapy and Oncology. 2018 Apr 1;127: 1073.
19. Halcyon System. Available from: https://www.varian. com/oncology/products/treatment-delivery/halcyon.
20. RDS Treatment Planning Instructions for Use Eclipse 15.1.1. Report No.: P1017375-004-D.
21. De Roover R, Crijns W, Poels K, Michiels S, Nulens A, Vanstraelen B, et al. Validation and IMRT/VMAT delivery quality of a preconfigured fast-rotating O-ring linac system. Medical physics. 2019 Jan;46(1):328-39.
22. Lloyd SA, Lim TY, Fave X, Flores-Martinez E, Atwood TF, Moiseenko V. TG-51 reference dosimetry for the Halcyon™: a clinical experience. Journal of applied clinical medical physics. 2018 Jul;19(4):98-102.
23. Binny D, Spalding M, Crowe SB, Jolly D, Kairn T, Trapp JV, Walsh A. Investigating the use of aperture shape controller in VMAT treatment deliveries. Medical Dosimetry. 2020 Sep 1;45(3):284-92.
24. Grégoire V, Ang K, Budach W, Grau C, Hamoir M, Langendijk JA, et al. Delineation of the neck node levels for head and neck tumors: a 2013 update. DAHANCA, EORTC, HKNPCSG, NCIC CTG, NCRI, RTOG, TROG consensusguidelines. Radiother Oncol. 2013;110:172−81.
25. Brouwer CL, Steenbakkers RJHM, Bourhis J, Budach W, Grau C, Grégoire V, et al. CT-based delineation of organs at risk in the head and neck region: DAHANCA, EORTC, GORTEC, HKNPCSG, NCIC CTG, NCRI, NRG Oncology and TROG consensus guidelines. Radiother Oncol. 2015;117:83−90.
26. Kataria T, Sharma K, Subramani V, Karrthick K P, Bisht SS. Homogeneity Index: an objective tool for assessment of conformalradiation treatments. J Med Phys. 2012; 37: 207−13.
27. Yoon M, Park SY, Shin D, Lee SB, Pyo HR, Kim DY, et al. A new homogeneity index based on statistical analysis of the dose−volume histogram. Journal of applied clinical medical physics. 2007 Mar;8(2):9-17.
28. Kim H, Huq MS, Lalonde R, Houser CJ, Beriwal S, Heron DE. Early clinical experience with varian halcyon V2 linear accelerator: Dual-isocenter IMRT planning and delivery with portal dosimetry for gynecological cancer treatments. J Appl Clin Med Phys. 2019 Nov;20(11):111-20.
29. De Roover R, Crijns W, Poels K, Michiels S, Nulens A, Vanstraelen B, et al. Validation and IMRT/VMAT delivery quality of a preconfigured fast-rotating O-ring linac system. Medical physics. 2019 Jan;46(1):328-39.
30. Michiels S, Poels K, Crijns W, Delombaerde L, De Roover R, Vanstraelen B, et al. Volumetric modulated arc therapy of head-and-neck cancer on a fast-rotating O-ring linac: Plan quality and delivery time comparison with a C-arm linac. Radiotherapy and Oncology. 2018 Sep 1;128(3):479-84.
31. Binny D, Spalding M, Crowe SB, Jolly D, Kairn T, Trapp JV, et al. Investigating the use of aperture shape controller in VMAT treatment deliveries. Medical Dosimetry. 2020 Sep 1;45(3):284-92.