



Dosimetric Characterization of the Dual Layer MLC System for an O-Ring Linear Accelerator

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Abstract

The Halcyon is Varian's latest linear accelerator that offers a single 6X flattening-filter-free beam with a jawless design that features a new dual layer multileaf collimator system with faster speed and reduced transmission. Dosimetric characteristics of the dual layer multileaf collimator system including transmission, dosimetric leaf gap, and tongue and groove effects were measured. Ionization chambers, diode arrays, and an electronic portal imaging device were used to measure various multileaf collimator characteristics. Transmission through both multileaf collimator banks was found to be 0.008%, while the distal and proximal banks alone had transmission values of 0.4%. The penumbra was slightly sharper for fields using only the distal multileaf collimator bank but found to be largely independent of leaf position with values between 2.7 to 3.0 mm at d_{max} for the combined multileaf collimator banks. The dosimetric leaf gap was measured for the proximal and distal multileaf collimator banks both individually and together and found to have values of -0.216 mm, -0.225 mm, and 0.964 mm, respectively. Measurements of dosimetric leaf gap at the leaf edge and midline were also performed. Tongue and groove effects were investigated with both the electronic portal imaging device and a 2-dimensional array of diodes.

Keywords

MLC, multileaf collimator, Halcyon, dosimetric leaf gap, tongue and groove, dynamic beam flattening

Abbreviations

CBCT, cone beam computed tomography; DBF, dynamic beam flattening; DLG, dosimetric leaf gap; IMRT, intensity modulated radiation therapy; MLC, multileaf collimators; MPC, machine performance check; SSD, source-to-surface distance; TPS, treatment planning system; VMAT, volumetrically modulated arc therapy

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Introduction

The Halcyon is Varian's latest linear accelerator with a streamlined design for fast acquisition to clinical deployment. Benefits of the Halcyon include fast implementation and treatment delivery with gantry rotation speeds of 4 rotations per minute, dose rates of 800 MU/min, and leaf speeds of 5 cm/s. The design is a straight-through jawless delivery that uses only dual layer stacked multileaf collimators (MLCs) to collimate the 6 MV flattening-filter-free beam.

The accurate delivery of intensity modulated radiation therapy (IMRT) and volumetrically modulated arc therapy

(VMAT) treatment plans relies on the correct modeling of the MLCs.^{1,2} It is important to characterize MLC parameters such as inter- and intraleaf transmission, dosimetric leaf gap (DLG),

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and their effects on field size and penumbra to determine their effectiveness and dosimetric accuracy when used as the beam collimation system. Prior studies have been performed to characterize MLC systems^{3,4} as well as the impact of different leaf widths,^{5,6} miniature MLC systems,⁷ and the TrueBeam Millennium MLC system.² Dosimetric comparison studies of IMRT and VMAT plans created for various clinical sites using both the TrueBeam and Halcyon MLCs have been performed more recently^{8,9} but did not fully investigate the characteristics needed to accurately model the unique stacked and staggered MLC design.¹⁰

The jawless design features stacked and staggered dual layer MLCs that are 1 cm in width for field conforming. The 1 cm width leaves on the Halcyon have 2 layers, referred to here as “proximal” and “distal” banks for the banks closer to the source and further from the source, respectively.¹¹ Each layer consists of 28 leaves with 0.5 cm offset in the direction perpendicular to the travel of leaves. Maximal field size for clinical treatment is 28 cm by 28 cm. Various features of the MLCs and their function were investigated using each bank separately as well as both banks together (as is the most common use of the MLCs in clinical settings).

With Halcyon 2.0 came a new feature called dynamic beam flattening (DBF) that utilizes the dynamic motion of the upper leaves (proximal bank) of the MLCs and dose rate modulation for a flat beam profile at depth despite an unflattened native beam profile. The predefined motion of the upper (proximal) MLC bank creates a nonuniform fluence that is lower in the center and higher in the peripheral area of the field to compensate for the radial intensity fall-off from the native nonflattened beam. The impact of the MLC characteristics on the profiles of DBFs is investigated in this study. Lim *et al* characterized Halcyon 1.0 MLC characteristics, and this study aims to investigate the Halcyon 2.0 system. Halcyon 2.0, utilizes the upper layer (proximal bank) of MLCs in modulation as well as the lower layer (distal bank) compared to Halcyon 1.0 where the proximal bank follows the modulation of the distal bank. With this added feature, characteristics of the proximal layer of MLCs should be investigated, including the tongue and groove effect, the DLG, and transmission. Prior studies do not include DLG and tongue and groove measurements for the proximal layer of MLCs which now could have an impact on clinical cases. This work aims to characterize the stacked and staggered dual layer MLCs on the Varian Medical Systems Halcyon (Palo Alto, California, USA) 2.0 platform for key parameters that are of clinical interest and compare them to what is employed in the treatment planning system (TPS).

Methods and Materials

Transmission

Transmission through the MLC banks is important for the Halcyon as there are no jaws and the MLCs are the only beam collimation system available. Adequate blocking of the beam using MLCs is important in providing clinically applicable

treatment plans. Transmission was defined as the amount of charge collected with the closed MLCs for a fixed number of monitor units (MUs) relative to an open field measurement for the same number of MUs. Transmission was measured for the Halcyon MLCs using the portal dosimeter and a CC13 ion chamber with both banks closed, only the distal bank closed, and only the proximal bank closed. Measurements with the CC13 ion chamber were performed with the ion chamber placed under 5 cm of solid water at 95 cm source-to-surface distance (SSD) with 10 cm of solid water for backscatter. The CC13 was utilized for measuring transmission as it allowed for using the same ion chamber for other measurements. Quantified results were compared with the transmission accounted for in the Varian Eclipse treatment planning system (TPS) version 15.6.

Dosimetric Leaf Gap

The DLG was measured using a CC13 ion chamber with swept gaps of various sizes (2, 4, 6, 8, 10, 14, 16, and 20 mm) using both MLC banks, only the distal bank, and only the proximal bank, at 5 cm depth and 95 cm SSD. Since the proximal bank MLCs are offset from the isocenter, DLG was measured both at isocenter (middle of center leaf) and with a 0.5 cm offset (between 2 leaves) with the ion chamber. Dosimetric leaf gap was also measured at both locations under the leaves for proximal, distal, and combined MLC banks using the central measurement from a Sun Nuclear MapCheck2 (Sun Nuclear, Melbourne, Florida) diode array. The advantage of the MapCheck2 is that its finer detector size (0.8 mm in diameter with an active volume of 0.019 mm²) results in reduced volume averaging compared to the CC13, thus allowing for the greater discrimination of discrepancies as a function of position. Only the center detector was used to generate DLG result in this study. Gaps of sizes 2, 4, 6, 10, 14, 16, and 20 mm were swept across the field. Corrected readings were plotted against the gap size and a linear function was fit to the data. Dosimetric leaf gap was determined by the intercept of the linear fits.^{2,12,13} Dosimetric leaf gap is modeled as a single value in the TPS. However, for the dual layer MLC system, DLG should be measured for each of the MLC banks as well as for both banks combined. In order to investigate the leaf rounding effect, DLG was measured for all cases with the detector in the middle of the leaf and with a 5 mm offset to be located between 2 leaves.

Penumbra and Field Size Variation With Depth and Position

Penumbra and field size were measured by scanning a 2 × 10 cm² field with the IBA Razor (IBA Dosimetry, Louvain-la-Neuve, Belgium) diode in water. This detector was used as it is suitable for small fields and regions of high dose gradients. Change in penumbra with leaf position was measured for depths of 10 cm and d_{\max} using both MLC banks, only the proximal banks, and only the distal banks. Penumbra was determined by the distance between 80% and 20% of the max dose across the profile. Three positions in the crossplane direction perpendicular to the direction

of the accelerator waveguide (crossline) were scanned, to see the effects of the leaf ends. Inline scans were offset to measure from the middle of the leaf.

Dynamic Beam Flattening

Dynamically flattened and nonflattened square fields were delivered for various field sizes. Profile data was collected using a Sun Nuclear MapCheck2 detector array. The detector spacing in X and Y directions on the MapCheck2 is 1 cm; however, the measurement resolution can be increased by merging the 2 measurements with a 0.5 cm shift of the entire MapCheck2 device. The combined results create a final field profile measurement with an effective detector spacing of 0.5 cm. Central axis data were extracted in the direction perpendicular to MLC leaf travel to investigate the tongue and groove effect on the dynamically flattened fields. Data was taken at depths of both 5 cm and 10 cm for square field sizes ranging from 6 cm to the maximum 28 cm, and profiles across the central axis were compared.

Tongue and Groove Effect

The tongue and groove effect was characterized using MapCheck2 and portal dosimeter. A double-comb plan was designed to highlight the effect of tongue and groove generated by each leaf pair. In the first control point, the even numbered leaves were fully extended and odd numbered leaves fully retracted; this pattern was then reversed (even numbered leaves fully retracted and odd numbered leaves fully extended) to create the second control point. Both control points were assigned to the same MU. The combined output from the 2 control points would equal that of an open field with all leaves retracted if there were no tongue and groove effect, and less than that if the tongue and groove is present. Portal dosimetry and MapCheck2 was used to compare the detected tongue and groove effect to the TPS modeled profiles. MapCheck2 was carefully positioned using kV cone beam computed tomography (CBCT) and MV planar image guidance to make sure each interleaf location aligned with the central array of diodes. MV imaging was used to validate the alignment of the MapCheck2 central diode detector with the central axis, and the CBCT was used to verify vertical alignment and overall rotation.

Results

When measured with the on-board electronic portal imaging device, transmission is 0.25% when delivering 1000 MU in the center for both banks closed, while with only the distal or proximal bank closed the transmission is measured to be around 0.5% (Figure 1). The CC13 ion chamber was also used to measure transmission for 1000 MU delivered, the transmission through proximal, distal, and both MLC banks and are plotted in Figure 1. Using single banks, transmission was found to be less than 0.7%. Use of both banks found very little transmission (<0.4%) indicating use of dual MLCs to

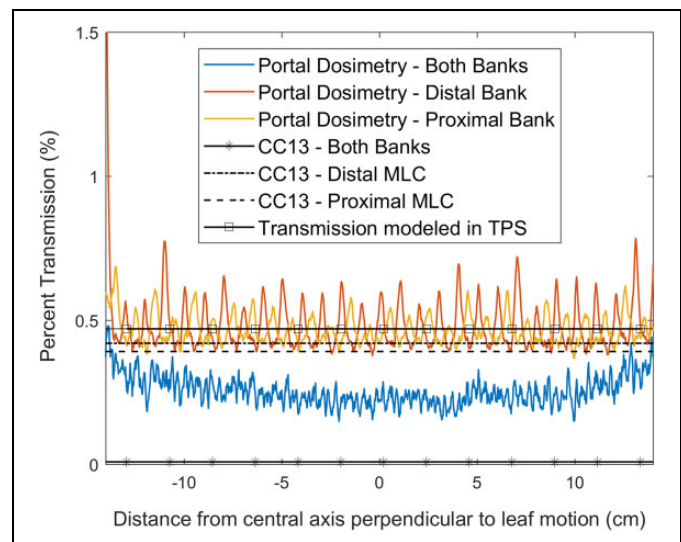


Figure 1. Transmission through both MLC banks, distal bank, and proximal bank measured with the portal dosimeter and a CC13 ion chamber. The value modeled in the TPS (0.47%) is shown with square symbols. MLC indicates multileaf collimator.

Table 1. Dosimetric Leaf Gap for the Proximal, Distal, and Combined MLCs.

MLC Bank	Measurement Location	Dosimetric Leaf Gap (mm)	
		MapCheck2	CC13
Proximal	Leaf midline (Y = 0)	0.053	-0.216
	Leaf edge (Y = 5 mm)	-0.251	
Distal	Leaf edge (Y = 0)	-0.294	-0.225
	Leaf midline (Y = 5 mm)	0.190	
Combined	Y = 0	1.054	0.964
	Y = 5 mm	1.108	

Abbreviation: MLC, multileaf collimator.

be comparable to the conventional collimating jaw and single layer MLC system.

Dosimetric leaf gap results are summarized in Table 1. The DLG is larger in magnitude for those measured with the MapCheck2 between leaves at the leaf edge for both the proximal and distal banks of MLCs. The increase in DLG with leaf end measurements highlights the effect of leaf end rounding. With combined MLCs, the difference in DLG measured between leaf ends and at the leaf midline is less pronounced since the proximal and distal banks are offset from one another. In the TPS, the DLG is modeled as one single value of 1 mm, which is very similar to the measured value for the combined leaves. The measured DLG with the CC13 ion chamber does not take into account the positioning of the chamber as the active volume is large enough to cover a leaf width.

Measured penumbra for a 2×10 cm² field at various leaf positions is summarized in Table 2. There is very little difference in penumbra variation across X and Y directions, and the

Table 2. Penumbra (mm) Measured for a $2 \times 10 \text{ cm}^2$ Field at Various Leaf Positions at Depths of 10 cm and d_{max} Using the Proximal, Distal, and Combined MLC Banks.

Leaf Position (cm)	13	7	1	-5	-11
Proximal d_{10}	5.0	4.5	4.6	4.7	5.0
Distal d_{10}	4.1	3.7	3.6	3.7	4.1
Combined d_{10}	3.7	3.6	3.7	3.9	4.0
Proximal d_{max}	3.4	3.2	3.3	3.5	3.7
Distal d_{max}	2.6	2.5	2.6	2.7	2.8
Combined d_{max}	2.7	2.7	2.7	2.8	3.0

Abbreviation: MLC, multileaf collimator.

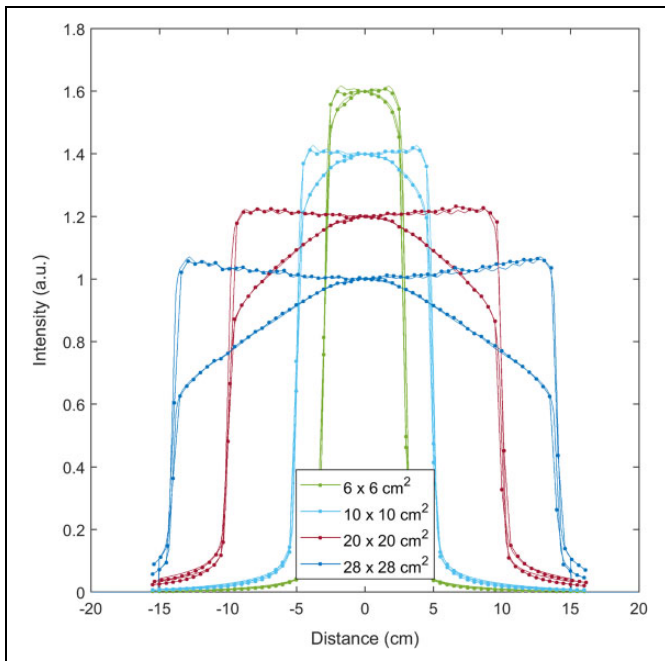


Figure 2. Flattened and nonflattened field profiles in the Y direction measured with MapCheck2 for various field sizes.

degradation is very small. Furthermore, there is a very small difference in penumbra between that measured using only the distal bank and combined banks when compared to the penumbra measured using only the proximal bank; however, its magnitude (at most 1.3 cm) is such that is not likely to be of clinical significance.

Flattened and nonflattened beam profiles are plotted in Figure 2. Profiles for different field sizes along the y-axis are shown with different normalizations so that they can be easily distinguished. The MapCheck2 diode data is shown with dots and the solid lines are the TPS modeled profiles along the direction going across the MLCs. Profiles are from 0.5 cm offset from the central axis so that data is not shown for an area where opposing MLC banks meet.

The tongue and groove effect is shown in the profile plotted in Figure 3. Proximal and distal MLC banks are offset as a visual aid. Measured portal dosimetry (PD) data showed that the calculated portal image overestimates the tongue and

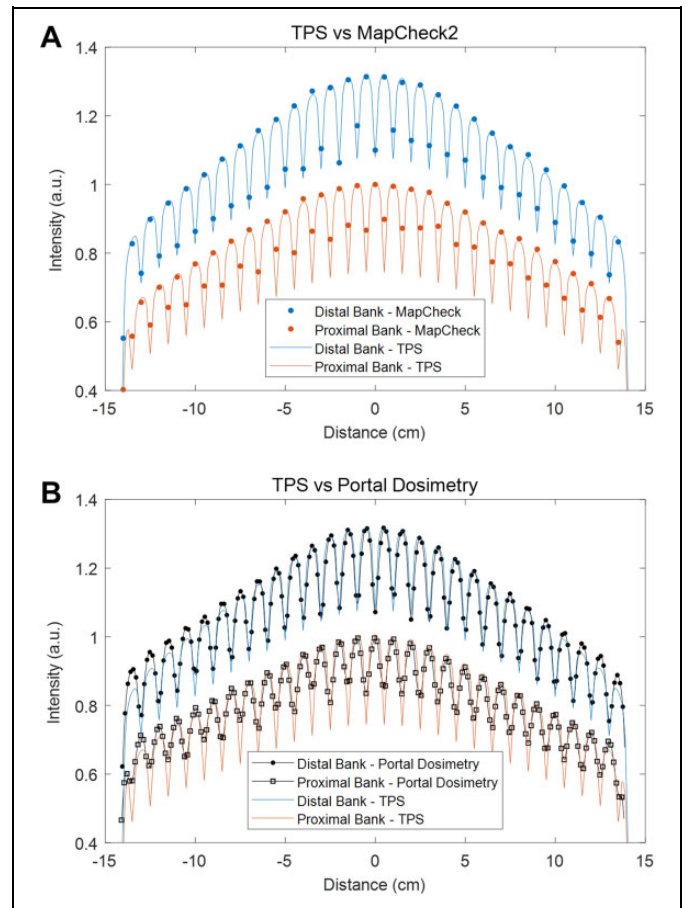


Figure 3. The tongue and groove effect for both proximal and distal banks of MLCs measured with (A) MapCheck2 compared to TPS and (B) portal dosimetry compared to TPS. MLCs indicates multileaf collimators; TPS, treatment planning system.

groove effect by 15.4% for the proximal bank and 3.0% for the distal bank on average across the field. MapCheck2 data indicated that the analytical anisotropic algorithm (AAA) calculated dose agrees well with diode measurement for the distal tongue and groove effect with an average difference of 5.4%. The data measured with MapCheck2 for the proximal bank was different from the AAA calculated dose by an average of 19.1% across the field. The average under-dosing effect as a result of the tongue-and-groove design is 10.7% compared to a region that is not affected.

Uncertainties in the measured values are primarily due to setup and positioning and are minimal. For DLG as well as beam profile measurements, image guidance was utilized to align the detectors. The effect of isocenter uncertainty is also minimal as the Varian machine performance check (MPC) tolerance for isocenter size for the Halcyon is 0.7 mm. The Halcyon is required to pass all aspects of the MPC on a daily basis before treatment delivery is allowed. All measured values were consistent and reproducible with 3 readings and reported values are averages of consecutive readings.

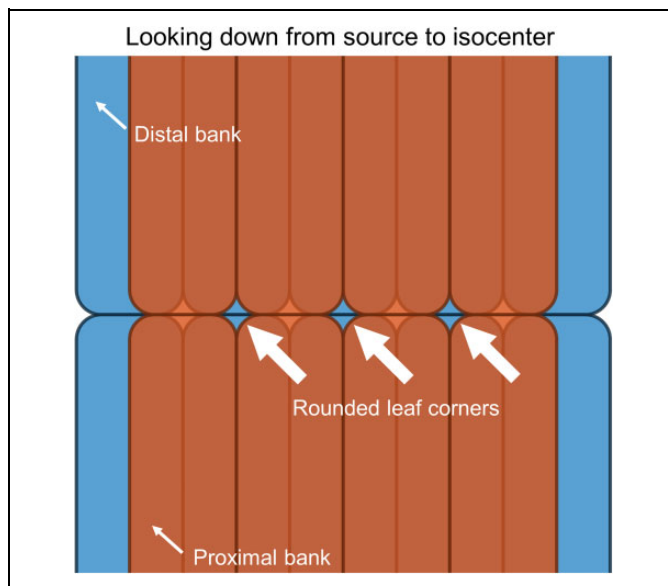


Figure 4. Rounded leaf end schematic.

Discussion

Most of the measurements showed that TPS modeling is fairly accurate. The transmission factor is for a single bank of MLCs is 0.4% and is similar to the value of 0.47% which is used in the TPS. However, the transmission measured for both MLC banks was 0.008% which is much lower than what is modeled in the TPS. Furthermore, the TPS does not model transmission separately for each MLC layer. Tongue and groove measurement also confirmed TPS modeling in AAA 15.6.03. Previous AAA versions underestimate the tongue and groove effect by $\sim 4\%$ as shown by the researchers from the University of California San Diego.^{8,11} Based on the measured MapCheck2 data, it does appear that the TPS over modulates the tongue and groove effect; however, there are limits to the measurement resolution using the MapCheck2. The portal dosimetry results agree with the MapCheck2 results with an average deviation of 3% across the field.

Dosimetric leaf gap measurements showed differences between distal, proximal, and both banks. The results for the dual layer stacked MLCs are likely sensitive to measurement devices, contrary to previous findings.¹³ Since the magnitude is very small, omitting large gaps (eg 1 and 2 cm) and use of smaller detectors might help with consistency. The DLG was shown to be dependent on measurement location (midline of leaf or leaf end) and dependent of MLC bank used. Proximal and distal MLCs had smaller DLG values than that measured for the combined banks. While the TPS models DLG as one value that cannot be modified or optimized for Halcyon, patient-specific quality assurance (QA) results indicate its adequacy for clinical use and dosimetric accuracy. For other systems such as the TrueBeam, the DLG is a sensitive parameter for dosimetric accuracy and can be optimized for a wide range of different types of plans and degrees of modulation.¹³⁻¹⁵

Additionally, detailed analysis on portal images demonstrated that the Halcyon MLC leaves have pronounced leaf corner rounding when looking at beam's eye view as shown in Figure 4. As a result, leaf openings measured at interleaf locations is likely to be slightly larger than measured at leaf midline. This will happen when measurement is with a fine resolution detector at the isocenter for distal banks, and at 5 mm away from isocenter in Y direction for proximal banks. This DLG measurement difference based on measurement location is also evident in Table 1, where DLG values are larger if measured at these leaf-corner locations and smaller if measured midleaf. The effect is more produced for Halcyon MLC than for TrueBeam for 2 reasons: (1) The Halcyon MLC is closer to the source therefore has a larger magnification of the rounded leaf end at the isocenter plane; and (2) the magnitude of Halcyon MLC DLG is much smaller compared to TrueBeam values (1-2 mm), therefore the impact of slight variation in leaf opening is enhanced.

Even though DLG was measured to be dependent on MLC layer and the TPS uses only one fixed value for DLG that cannot be modified, the patient-specific QA results appear to be passing with the clinically relevant 3%/3 mm accuracy, indicating sufficient dosimetric accuracy of the TPS DLG value. For breast, head and neck, thoracic, abdominal, and pelvic treatment sites, individual fields were passing 94.8% to 100% with portal dosimetry based QA. Prior studies have shown that patient-specific QA measurements in absolute dose mode with the ArcCheck (Sun Nuclear) met the stricter 2%/2 mm criterion gamma index metric with a 90% passing rate and 10% low dose threshold for spine stereotactic body radiation therapy treatment plans generated for the Halcyon.¹⁶ Further validation of the Medical Physics Practice Guideline 5.a. tests were summarized for the Halcyon using a gamma criterion of 2%/2 mm by De Roover *et al* and show adequate passing results, further justifying dosimetric accuracy of the TPS model.^{17,18}

With DBF, the Halcyon can be used to deliver a flat beam; however, beam delivery requires more MUs and the dose rate is reduced, resulting in less efficient use of the beam. The delivery time of a flattened 20×20 cm² field is much longer than that of a nonflattened field to deliver the same dose, as the required MU are 2.4 times that of a nonflattened field.¹⁹ Dynamic beam flattening is not only less efficient, but also suffers from the tongue and groove effect as seen on the profiles in Figure 2. Due to these characteristics, it is not recommended that DBF be used for those patients who require deep inspiration breath-hold motion management.

Because of the larger tongue and groove effect compared to TrueBeam,² it is recommended that the collimator be set to nonzero values for both IMRT and VMAT plans so that the cold regions do not fully overlap. Figure 5 shows an example of a gynecologic IMRT case where all collimator angles were set to zero. Pronounced cold strips were identifiable in the dose colorwash. Overall, the tongue and groove effect is more pronounced than in the TrueBeam and is clinically visible for the 0 degree collimator IMRT plans. Clinical manifestation of the

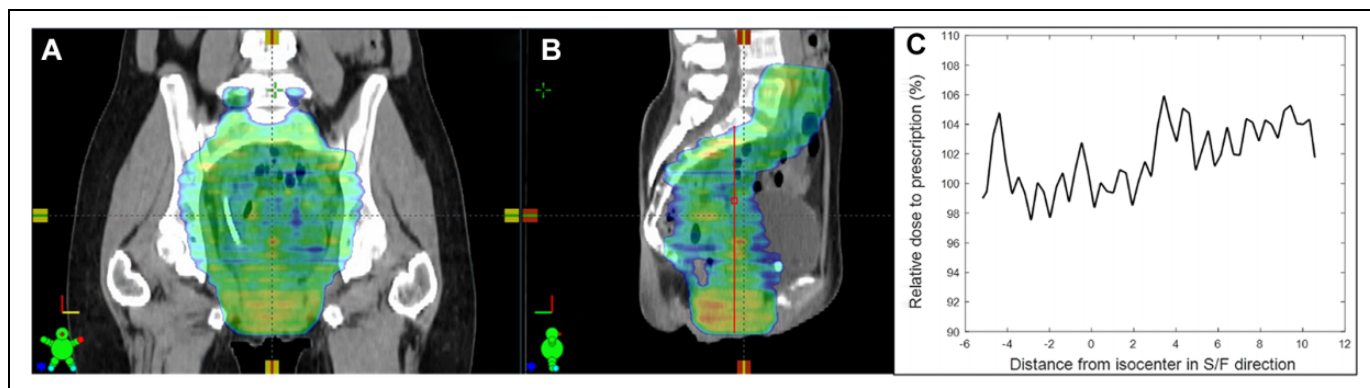


Figure 5. Example of tongue and groove effect with collimator angles set to 0. The dose color wash for pelvis treatment is shown for the (A) coronal and (B) sagittal views along with the (C) dose profile to highlight the tongue and groove effect.

tongue and groove effect can be seen in the flattened beam profiles in Figure 2. The TPS has conservatively overmodeled this effect, as seen from the measurements with both MapCheck2 and with portal dosimetry in Figure 3. It is recommended that the collimator be rotated for both IMRT and VMAT plans to reduce potential underdosing due to the tongue and groove effect.

The measured penumbra is larger at a depth of 10 cm compared to that measured at d_{\max} and varies minimally depending on the position of the field within the $28 \times 28 \text{ cm}^2$ maximum MLC-defined field size. This is particularly useful for large treatment areas or those involving multiple isocenters. The penumbra is smaller for fields made with both MLC banks than with the proximal or distal bank alone. Furthermore, the proximal banks create a larger penumbra than compared to the distal penumbra due to the proximity of the bank to the source.

Conclusions

The new dual-layer stacked MLC system for the Varian Halcyon 2.0 linear accelerator was investigated for dosimetric and physical characteristics that are relevant for use in clinical treatment settings. Current TPS modeling of these characteristics were found to be within a reasonable range from measured data, and acceptable dosimetric accuracy for VMAT and IMRT plans based on patient-specific QA results. Multileaf collimator characteristics were investigated for each individual stacked MLC layer and their impact on the dynamic beam flattening feature was examined.

Authors' Note

Our study did not require an ethical board approval because it did not contain human or animal trials.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article. Dr Lei Dong reports personal fees from Varian Medical Systems Speakers Bureau and other from Varian Medical Systems (PI of Master Research Agreement between the University of Pennsylvania and Varian Medical Systems), outside the submitted work. Dr James

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