

Article Type: Radiation Oncology Physics

The Impact of a High-Definition Multileaf Collimator for Spine SBRT

Kelly C Younge, PhD, John R Kuchta, Justin K Mikell, PhD, Benjamin Rosen, PhD, Jeremy S Bredfeldt, PhD, and Martha M Matuszak, PhD

Department of Radiation Oncology, University of Michigan Health System, Ann Arbor, MI

***Corresponding Author:**

Kelly Cooper Younge, PhD

Department of Radiation Oncology

University of Michigan Health System

1500 East Medical Center Drive

Ann Arbor, MI 48109

Phone: (734) 936-4309

Fax: (734) 936-7859

kyoung@med.umich.edu

Running Title: Impact of HDMLC for Spine SBRT

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1002/acm2.12197](https://doi.org/10.1002/acm2.12197)

This article is protected by copyright. All rights reserved

Abstract

Purpose: Advanced radiotherapy delivery systems designed for high-dose, high-precision treatments often come equipped with high-definition multi-leaf collimators (HD-MLC) aimed at more finely shaping radiation dose to the target. In this work, we study the effect of a high-definition MLC on spine stereotactic body radiation therapy (SBRT) treatment plan quality and plan deliverability.

Methods and Materials: Seventeen spine SBRT cases were planned with VMAT using a standard-definition MLC (M120), HD-MLC, and HD-MLC with an added objective to reduce monitor units (MU). M120 plans were converted into plans deliverable on an HD-MLC using in-house software. Plan quality and plan deliverability as measured by portal dosimetry were compared among the three types of plans.

Results: Only minor differences were noted in plan quality between the M120 and HD-MLC plans. Plans generated with the HD-MLC tended to have better spinal cord sparing (3% reduction in maximum cord dose). HD-MLC plans on average had 12% more MU and 55% greater modulation complexity as defined by an in-house metric. HD-MLC plans also had significantly degraded deliverability. Of the VMAT arcs measured, 94% had lower gamma passing metrics when using the HD-MLC.

Conclusion: Modest improvements in plan quality were noted when switching from M120 to HD-MLC at the expense of significantly less accurate deliverability in some cases.

Key words: HD-MLC, spine SBRT, complexity, deliverability

Introduction

The TrueBeam STx and the EDGE linear accelerator from Varian Medical Systems (Palo Alto, CA) are equipped with a number of features designed to facilitate the high-precision, high-accuracy radiation treatment of small targets near critical structures both intra- and extracranially (1). One such feature is the high-definition multileaf collimator (HD-MLC), which uses 32 central 2.5 mm-width leaves and 28 outer 5 mm-width leaves on each MLC bank (widths projected to isocenter). The HD-MLC provides essentially twice the resolution along the axis perpendicular to the leaf travel compared to the standard Varian Millennium MLC (M120) which uses 40 central 5 mm-width leaves and 20 outer 10 mm-width leaves in each bank.

For inversely-optimized treatment plans, the added resolution of the HD-MLC theoretically increases the ability of the optimizer to produce a highly conformal treatment plan, sparing organs at risk (OARs)

while providing adequate target coverage. However, this potential increase in plan quality depends on the ability of the optimizer to efficiently and effectively search the allowed solution space, and additionally is fundamentally limited by the physical properties of the photon beam and MLC leaves.

Our department began using Varian's EDGE linear accelerator for stereotactic treatments in January of 2016. Two of the first treatment types to be transferred almost exclusively to the EDGE were spinal stereotactic body radiation therapy (SBRT) and spinal stereotactic radiosurgery (SRS), both delivered with volumetric modulated arc therapy (VMAT). The geometric complexity of these cases, often with irregularly-shaped target volumes that may include multiple vertebral bodies and can circumscribe the spinal cord, makes them excellent candidates for treatment on this specialized accelerator (2).

With the transfer of these patients to the EDGE, a marked increase in plan modulation was observed, visualized both in the MLC-leaf trajectory sequence in the Eclipse treatment planning system (TPS) as well as quantified by the number of monitor units (MU) and our in-house VMAT complexity metric (3,4). We also observed a sudden increase in plans failing patient-specific quality assurance with the ArcCHECK (Sun Nuclear Corporation, Melbourne, FL).

Because there is often very little extra time built into the workflow for hypofractionated spine treatments, a failing pre-treatment quality assurance measurement can lead to significant disruption in the planned treatment course. The case may either be replanned, which often leads to a delay (or multiple delays) in the patient start date, or the treatment team may elect to proceed with the initial treatment plan and accept the added degree of delivery uncertainty. The goal of this work was to evaluate the change in plan quality and delivery accuracy when switching from the M120 to HD-MLC, and to test the effect of an added optimization objective aimed at reducing plan modulation on these quality indices.

Methods

For this study, 17 previously treated spine SBRT cases employing the M120 were selected for study. A variety of sites (3 C-spine, 11 T-spine, and 3 L-spine) were chosen with geometries representative of that typically seen in our clinic. To ensure consistency in planning and plan quality, all cases chosen were replanned by an expert dosimetrist using the current clinical version of our treatment planning system, Eclipse version 13.6. Each of the cases was inverse planned with VMAT with the Photon Optimizer on a fine (1.25mm) grid using 2 arcs per our institutional standard for spine SBRT. The final dose calculation was done on a 1mm grid with Analytical Anisotropic Algorithm (AAA) version 13.6.23. All plans had a

prescription dose of 30 Gy delivered in three fractions and used 6 MV-only beams. All plans were reviewed by a physicist and physician with experience in spine SBRT. Once an acceptable plan was generated (henceforth referred to as the *M120* plan), for each case, three additional versions of the plan were created, as shown in Table 1. Consistent geometry was used across all plans within a given case (i.e. identical arc rotation length, collimator angles and jaw positions).

The *M120(HD)* plan was created by converting the *M120* plan to HD-MLC by grouping pairs of leaves to identically match the original MLC pattern, and then adjusting the MLC positions outwards (making larger apertures) by 0.7mm to account for the fact that the dosimetric leaf gap (DLG) for the HD-MLC is smaller compared to the *M120* (5). The adjustment amount was chosen empirically by comparing the doses in the *M120* plan to the *M120(HD)* plan. Edits to the MLC positions were performed using an in-house Matlab script (Mathworks, Natick, MA).

The *HD* plan was created by reoptimizing the *M120* plan with the HD-MLC, using identical optimization objectives. The *HD(MU)* plan was the same as the *HD* plan but had an added MU objective (a penalty on an MU value above a given threshold) to reduce the MU down to that of the *M120* plan.

To evaluate plan quality and modulation complexity, the *M120* plan was compared to the *HD* and *HD(MU)* plans. To evaluate delivery accuracy, we compared the *M120(HD)* plan to the *HD* and *HD(MU)* plans. This approach was taken so that in terms of deliverability, all plans could be compared on an equal footing: using the same beam model, calculation algorithm, and delivery and measurement system. This excluded any potential differences in the accuracy of each workflow step for the *M120* MLC versus the HD-MLC from biasing our results. Additionally, with this approach, small deviations in the dose distribution due to changing MLCs (i.e. converting *M120* to *M120(HD)*) had no impact on the results of the study.

To quantify plan quality, several metrics for the target and nearby OARs were used. Conformity index (CI) and gradient index (GI) were used to quantify dose coverage and falloff between the three types of plans. The conformity index used here was the Paddick index, given by:

$$CI = \frac{TV_{PI}^2}{PIV \times TV} \quad (1)$$

Where TV_{PI} is the target volume encompassed by the prescription isodose surface, PIV is the prescription isodose surface volume, and TV is the target volume.

The gradient index was defined as

$$GI = \frac{PI_{50\%}}{PIV} \quad (2)$$

Where $PI_{50\%}$ is the volume encompassed by the 50% dose isodose surface. (6)

To quantify plan complexity, we used a complexity metric developed in-house that analyzes an MU-weighted average of the leaf-side perimeter divided by the aperture area (3). This metric was designed to quantify plan modulation independent of target size, plan dose, arc length, and MLC type, and is defined as,

$$M = \frac{1}{MU} \sum_{i=1}^N MU_i \times \frac{y_i}{A_i}, \quad (3)$$

where the sum is over all control point apertures from $i=1$ to N , MU is the total number of MU in the plan, MU_i is the number of MU delivered through aperture i , A_i is the open area of aperture i , and y_i is the aperture perimeter excluding the MLC leaf tips.

Our portal dosimetry measurements used the digital megavoltage imager (DMI) on the EDGE linear accelerator and the portal dosimetry application within Eclipse. This DMI was clinically commissioned for 6 MV photons with the Portal Dosimetry Image Prediction (PDIP) algorithm version 13.6.23. For the dose comparisons in this study, we used a locally normalized gamma analysis with 10% dose threshold and no region of interest. Local normalization was used to help highlight potential differences in the deliverability between plans. All measurements were auto-aligned to the predicted image by the portal dosimetry software, and our clinical agreement criteria of 4%/1mm were applied.

In all cases shown below, statistical significance in the comparison between plans was determined using the two-tailed Student's t-test.

Results

Figures 1 and 2 illustrate the differences in the MU and modulation complexity for the three types of plans used in this study ($M120$, HD , and $HD(MU)$). The cases are sorted by the MU of the $M120$ plan. One case (case 12) did not have an $HD(MU)$ plan because the MU of the HD plan was already lower than that of the $M120$ plan.

In the majority of cases, the MU-objective in the optimizer was able to reduce the MU in the *HD(MU)* plan down to that of the original *M120* plan. The maximum value that can be used in the MU objective is 4000. There were three cases where the *M120* plan had $MU > 4000$, which resulted in the *HD(MU)* plan having fewer MU than the *M120* plan (see the left-most three cases in Figure 1). The modulation complexity of the *HD* plan was consistently higher than the corresponding *M120* plan. Using the MU objective slightly reduced the modulation complexity in all but one case (**case 3**), but not to the level of the *M120* plan.

Table 2 summarizes the data of Figures 1 and 2. Both the MU and the modulation complexity increased significantly between the *M120* and the *HD* plans. The added MU objective reduced both the MU and the complexity, but these values were still significantly higher than those for the *M120* plans.

Table 3 compares dosimetric parameters for the 17 test cases. Some of the comparisons are statistically significantly different, but the absolute difference may not be clinically relevant. The average gradient index in the *HD* plans was 0.19 lower than in the *M120* plans. Figure 3 illustrates the potential difference in dose distributions for this magnitude of change in GI. There is no clear best type of plan according to these metrics.

Figure 4 shows an example portal dosimetry measurement. Only the predicted images for the *M120* plan are shown. The passing percentage is obtained by computing the number of passing measurement points within the outlined area (defined by a 10% dose threshold). Local analysis can cause exaggerated failures in low dose regions; these points are not included in the pass rate percentage.

Figure 5 and Table 4 show the results of the portal dosimetry analysis for the *M120(HD)*, *HD*, and *HD(MU)* plans. These results are per arc (two arcs per plan). For 2 arcs out of the 34 measured, the *HD* and *HD(MU)* plans had higher passing rates than the corresponding *M120(HD)* plan. For one arc, the *M120(HD)* plan was better than *HD* but worse than the *HD(MU)*. For all other arcs, the *M120(HD)* outperformed the other two. All average passing rates were statistically significantly different from each other. For the portal dosimetry measurements, gamma analysis with local normalization was used to avoid artificially raising the passing rates for highly modulated plans. Average global normalization passing rates for the 51 measured plans are also included in Table 4 for reference.

Discussion

Plan quality

Plans generated with the *HD-MLC* tend to have better spinal cord sparing (about 3% of cord max dose) than the *M120* plans, however, dose fall off and conformity were only marginally better when using the *HD-MLC*. Though some of the differences are statistically significant, they may not be clinically relevant. The MU and complexity score both increased dramatically in order to achieve these modest gains, and using the MU objective was not effective in reducing the complexity though it worked well to reduce the MU to the desired range. We note that the programming of the MU objective was adjusted in version 13.6 of Eclipse and users of earlier versions may not reproduce the same results as seen here.

Deliverability

Portal dosimetry measurements show that the spine plans optimized with the *HD-MLC* have significantly degraded deliverability. Using global normalization (last row of Table 4), the passing rates of the plans generated for this study were very similar to the passing rates we observed with clinical plans prior to the initiation of this study. Using local normalization, over two-thirds of the measured *HD* plans fell below a 95% pass rate threshold. The deliverability was somewhat improved with the added MU objective, but did not match that of the original *M120* plan. This was expected as though the MU were lower for the *HD(MU)* plans, the modulation complexity scores were still high compared to the *M120* plans. We note that all plans used in the comparison of deliverability were calculated using the same beam model and delivered using the same delivery platform. However, because the *HD* and *HD(MU)* plans are more modulated, they are likely to be more sensitive to any weaknesses in the beam model or MLC parameters such as transmission and DLG.

Comparison to previous studies

Many other groups have performed planning studies to examine the benefit of the smaller *HD-MLC* leaf width. Chae et al. found that for artificially contoured spine lesions, the *HD-MLC* significantly improved GI but not CI, but that the results more notable for IMRT vs VMAT. The biggest gains were seen for complex target shapes (7). Tanyi et al. performed a planning study comparing the *M120* to *HD-MLC* for liver and lung with 3D, IMRT, and VMAT treatment plans and found small differences between the MLC types with the biggest difference being the faster dose fall-off with the *HD-MLC* (8). Dhabaan et al. examined the benefit of the *HD-MLC* for intracranial radiosurgery planning with dynamic conformal arcs and found that conformity and dose gradients were both improved with the *HD-MLC* (9).

Though there is no question that the *HD-MLC* may provide a benefit for certain body sites and certain types of target geometries, there have been very few studies looking at the deliverability impact of the

HD-MLC. Wu et al. used CT-based polymer gel dosimetry to show that for a 2.5 cc radiosurgery volume treated with IMRT, CI and dose fall-off were both improved with the smaller MLC. (10). Kairn et al. did not use the HD-MLC but studied delivery accuracy for the treatment of spinal metastases using portal dosimetry and radiochromic film (11). They found that IMRT plans tended to be more deliverable than dosimetrically similar VMAT plans even though the delivery time was longer. Similar to the present study, the authors were able to improve delivery accuracy by limiting the MU of the plans.

We note that one weakness of this study is that the PDIP algorithm is a standalone algorithm that is configured independently of the AAA algorithm (although it does have some shared beam data), and therefore does not directly verify the dose calculation of AAA (12). While our clinical ArcCHECK experience appears to support the findings in this work that deliverability is reduced with the HD-MLC, the ArcCHECK is a coarse measurement compared to the target size of most of the spine plans studied. Further analysis of these plans could be performed using film to more thoroughly verify the AAA dose calculation strengths and weaknesses.

The solution found by the optimizer for the *M120* plans is part of the solution set available for the *HD* and *HD-MU* plans, however, the optimizer tends to choose more highly modulated plans. This is partially a result of the fact that the optimizer does not have direct feedback about the modulation in the plan, outside of the number of MU, and therefore is not able to directly limit the modulation (3). The MU objective is not a sufficient tool for ensuring the deliverability of plans while at the same time effectively searching for an acceptable dose distribution.

In practice when using the HD-MLC, the user will not typically have a comparison *M120* plan, so it is difficult or impossible to effectively judge the modulation complexity versus the plan quality to find an acceptable solution. Using a complexity metric like the one employed here aids in comparing newly created plans to past plans that have previously been measured for delivery accuracy. Besides analyzing complexity post-optimization, planners need improved tools for limiting modulation when it is not needed in order to ensure an accurate delivery of the dose. One potential solution is to penalize complexity during the optimization in order to help guide the optimizer into the solution space that is represents an acceptable compromise between plan quality and deliverability (3). Though in this work the HD-MLC plans exhibit modest gains in the quality of the dose distribution, this improvement will come at a cost in terms of calculation accuracy, delivery accuracy, and delivery efficiency. Additionally, if calculation and delivery accuracy are sacrificed, one cannot be sure that the promised dosimetric gains are in fact realized.

Conclusion

The HD-MLC theoretically allows improved dose distributions through added degrees of optimization freedom, however, care must be taken during the optimization process to avoid needlessly increasing the level of plan modulation. We have shown that increased plan complexity may lead to increased delivery uncertainty while at the same only modestly improving the dosimetric quality of the plan.

Acknowledgements

We gratefully acknowledge assistance with this work from Steven Kronenberg, Robin Marsh, Joseph Foy, and Matthew Schipper.

Conflict of interest: none

1. Glide-Hurst C, Bellon M, Foster R, et al. Commissioning of the Varian TrueBeam linear accelerator: A multi-institutional study. *Med Phys*. 2013;40:031719.
2. Sahgal A, Larson DA, and Chang EL. Stereotactic Body Radiosurgery for Spinal Metastases: A Critical Review. *Int J Radiat Oncol Biol Phys*. 2008;71(3):642-665.
3. Younge KC, Roberts D, Janes LA et al. Predicting deliverability of volumetric-modulated arc therapy (VMAT) plans using aperture complexity analysis. *J Appl Clin Med Phys*. 2016;17(4):124-131.
4. Younge KC, Matuszak MM, Moran JM, et al. Penalization of aperture complexity in inversely planned volumetric modulated arc therapy. *Med Phys*. 2012;39:7160.
5. Kielar KN, Mok E, Hsu A, et al. Verification of dosimetric accuracy on the TrueBeam STx: rounded leaf effect of the high definition MLC. *Med Phys*. 2012;39(10):6360-6371.
6. Paddick I. A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. *J Neurosurg*. 2000;93(3):219-222.
7. Chae SM, Lee GW, and Son SH. The effect of multileaf collimator leaf width on the radiosurgery planning for spine lesion treatment in terms of the modulated techniques and target complexity. *Radiat Oncol*. 2014;9(72).

8. Tanyi HA, Summers PA, McCracken CL, et al. Implications of a high-definition multileaf collimator (HD-MLC) on treatment planning techniques for stereotactic body radiation therapy (SBRT): a planning study. *Radiat Oncol.* 2009;4:22.
9. Dhabaan A, Elder E, Schreibmann E, et al. Dosimetric performance of the new high-definition multileaf collimator for intracranial stereotactic radiosurgery. *J Appl Clin Med Phys.* 2010;11(3):197-211.
10. Wu CS, Kessel J, and Xu Y. 3-D dosimetric evaluation of 2.5 mm HD120® multileaf system for intensity modulated stereotactic radiosurgery using optical CT based polymer gel dosimetry. *J. Phys.: Conf. Ser.* 2009;164:012056.
11. Kairn T, Papworth D., Crowe S, et al. Dosimetric quality, accuracy, and deliverability of modulated radiotherapy treatments for spinal metastases. *Med Dosim.* 2016;41(3):258-266.
12. Varian Medical Systems. Eclipse Photon and Electron Algorithms Reference Guide, Chapter 12 Portal Dose Algorithms, 2015;258-284.

Figure 1: Comparison of MU for the *M120*, *HD*, and *HD(MU)* plans. The graph is ordered from highest MU to lowest MU for the *M120* plan.

Figure 2: Comparison of modulation complexity for the *M120*, *HD*, and *HD-MU* plans. The data are ordered identically to Figure 1.

Figure 3: Comparison of two plans with differing gradient indices. The plan on the left (A) has a gradient index of 5.23 and the plan on the right has a gradient index of 5.01. The color wash ends at 50% of the prescription dose.

Figure 4: Example portal dosimetry measurement for one case with arcs named CW (clockwise) and CCW (counter clockwise). The predicted images are shown on the left (for the *M120* plan), with gamma maps (4% / 1mm, local normalization) on the right. The 10% dose threshold is outlined in red. Orange pixels indicate failing measurement points ($\gamma > 1$).

Figure 5: Difference in per arc gamma passing percentages between the *M120(HD)* plans and the *HD* and *HD(MU)* plans. Positive values mean that the *M120(HD)* arc had a higher passing rate than the

comparison arc. The graph is ordered from highest difference between M120(HD) and HD to lowest difference between M120(HD) and HD passing percentage.

Table 1: Description of plans used in this study.

Plan name	Description
<i>M120</i>	Original plan using M120 MLC
<i>M120(HD)</i>	<i>M120</i> plan recreated with HD-MLC by pairing the MLC leaves
<i>HD</i>	<i>M120</i> plan reoptimized with identical objectives on HD-MLC
<i>HD(MU)</i>	<i>HD</i> plan reoptimized with MU objective to reduce MU to that of the <i>M120</i> plan

Table 2: Average MU and Complexity values for the 17 test cases

	<i>M120</i>	<i>HD</i>	<i>HD(MU)</i>	<i>P-value</i>		
				<i>M120 vs HD</i>	<i>M120 vs HD(MU)</i>	<i>HD vs HD(MU)</i>
Average MU	3370±585	3783±613	3315±507	<0.001	.07	<0.001
Average Complexity (mm ⁻¹)	0.18±0.02	0.28±0.03	0.25±0.03	<0.001	<0.001	<0.001

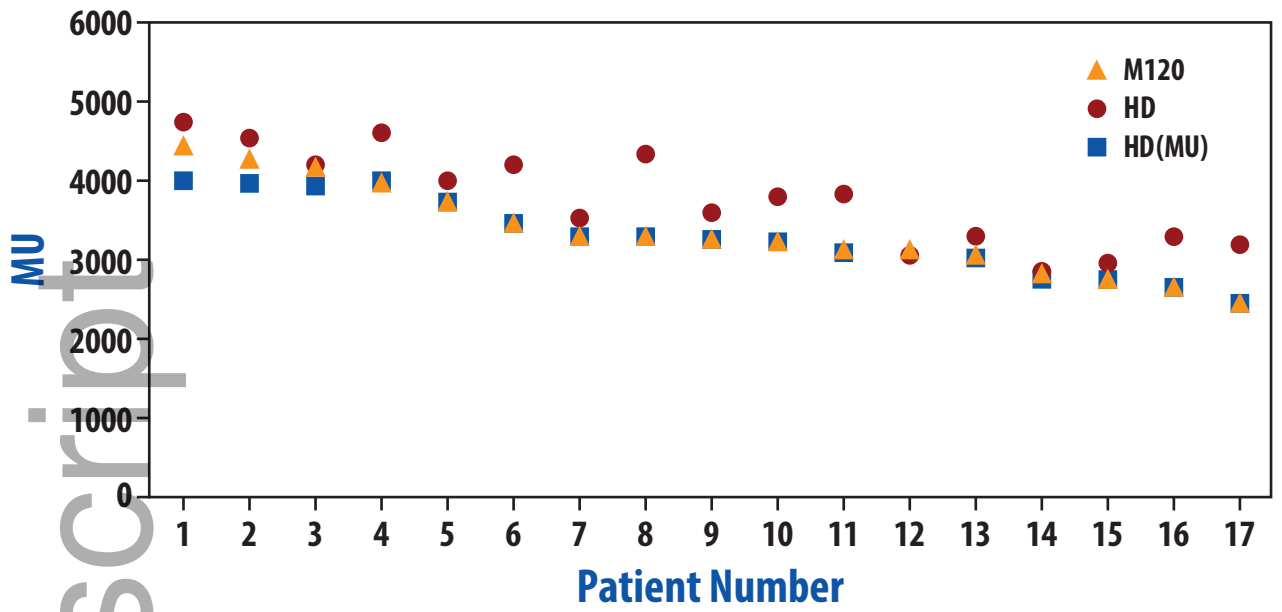
Table 3: Plan quality parameters of *M120* and *HD-MLC* plans.

Quality Metric	<i>M120</i>	<i>HD</i>	<i>HD(MU)</i>	<i>P-Value</i>		
				<i>M120 vs HD</i>	<i>M120 vs HD(MU)</i>	<i>HD vs HD(MU)</i>
CI	0.72±0.10	0.74±0.10	0.73±0.10	0.01	0.003	0.17
GI	5.08±0.96	4.88±0.96	4.86±0.91	0.01	<0.001	0.43

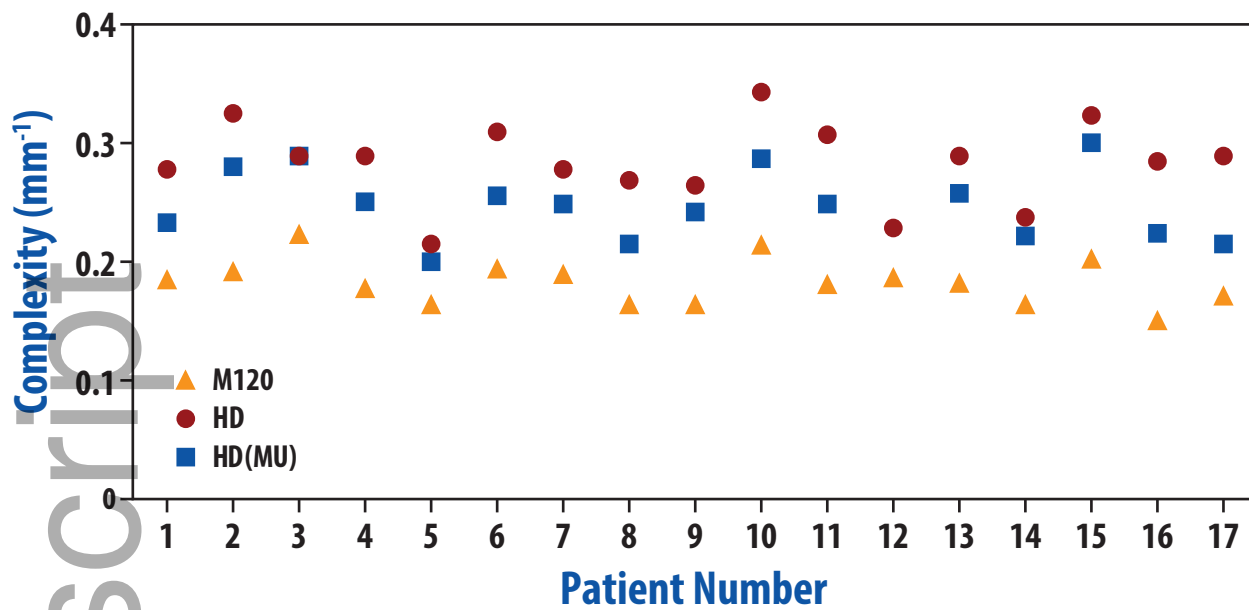
PTV D98 (Gy)	22.7±5.1	22.3±5.3	22.7±5.1	0.02	0.96	0.01
PTV D90 (Gy)	28.6±3.0	28.6±2.9	28.5±3.0	0.56	0.10	0.40
Spinal Cord 0.1cc (Gy)	16.6±1.1	16.1±0.9	16.5±0.9	0.01	0.69	0.01

Table 4: Summary of portal dosimetry results. A passing arc is defined as a defined as an arc with a gamma pass rate of greater than 95%. A passing plan is defined as a plan where both arcs pass. All measurements are locally normalized unless otherwise stated.

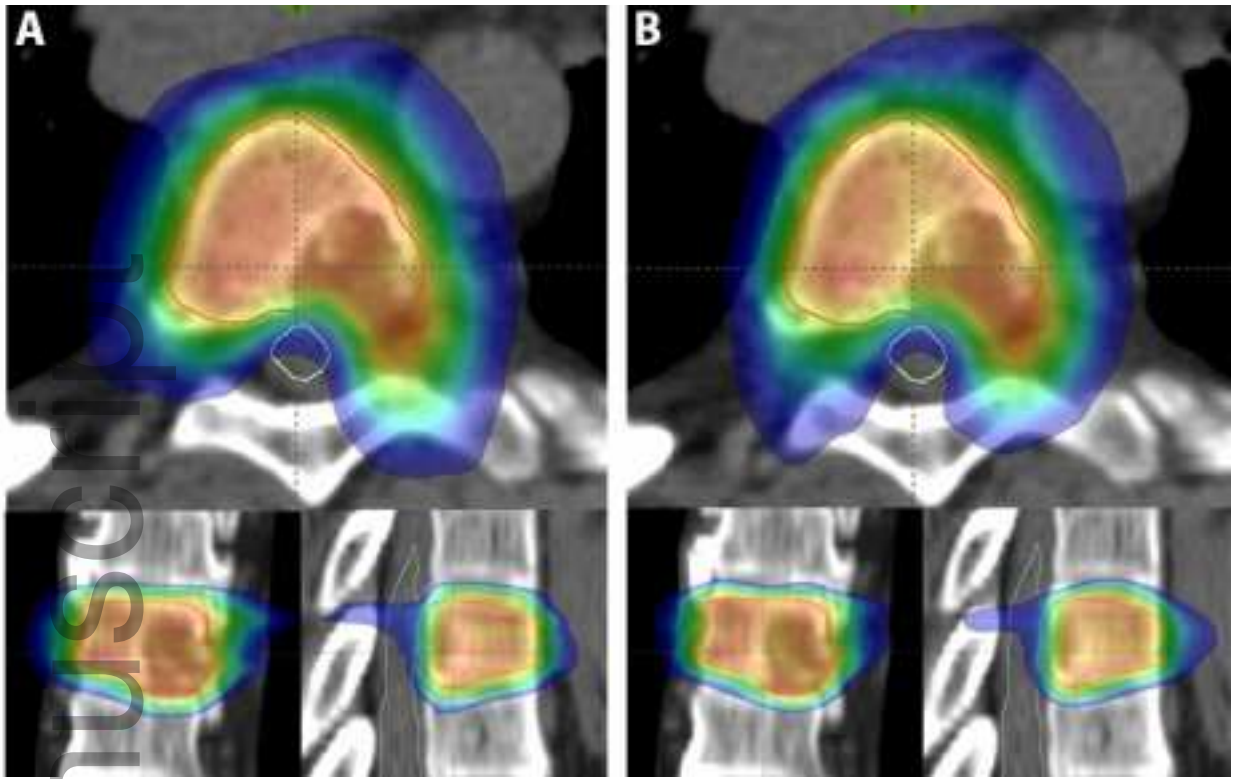
	<i>M120(HD)</i>	<i>HD</i>	<i>HD(MU)</i>
Average arc pass rate	99.1±1.0 (<i>P</i> <0.001 vs <i>HD</i>)	94.4±2.3 (<i>P</i> <0.001 vs <i>HD(MU)</i>)	95.5±2.3 (<i>P</i> <0.001 vs <i>M120(HD)</i>)
Percentage of passing arcs	94.1%	41.2%	58.8%
Percentage of passing plans	94.1%	29.4%	52.9%
Percentage of passing plans (using global normalization)	94.1%	78.9%	85.7%



acm2_12197_f1.eps

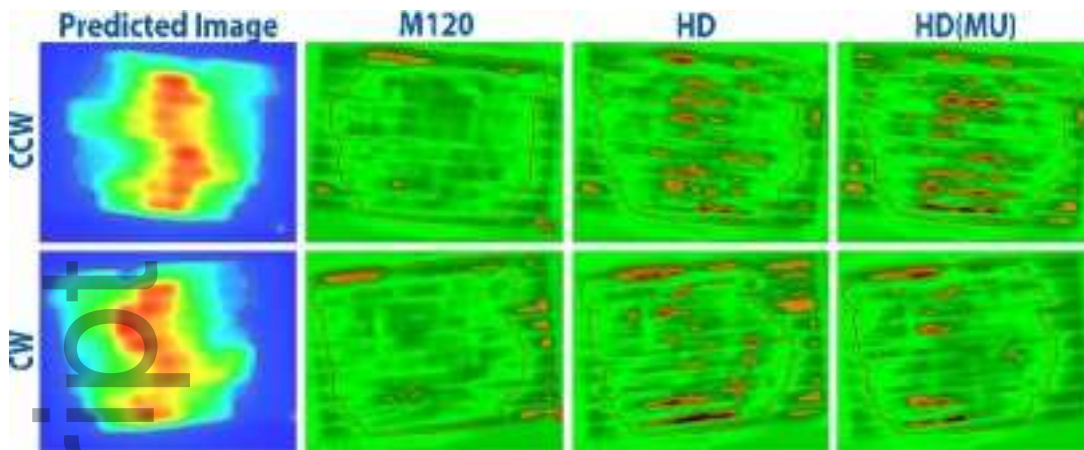


acm2_12197_f2.eps



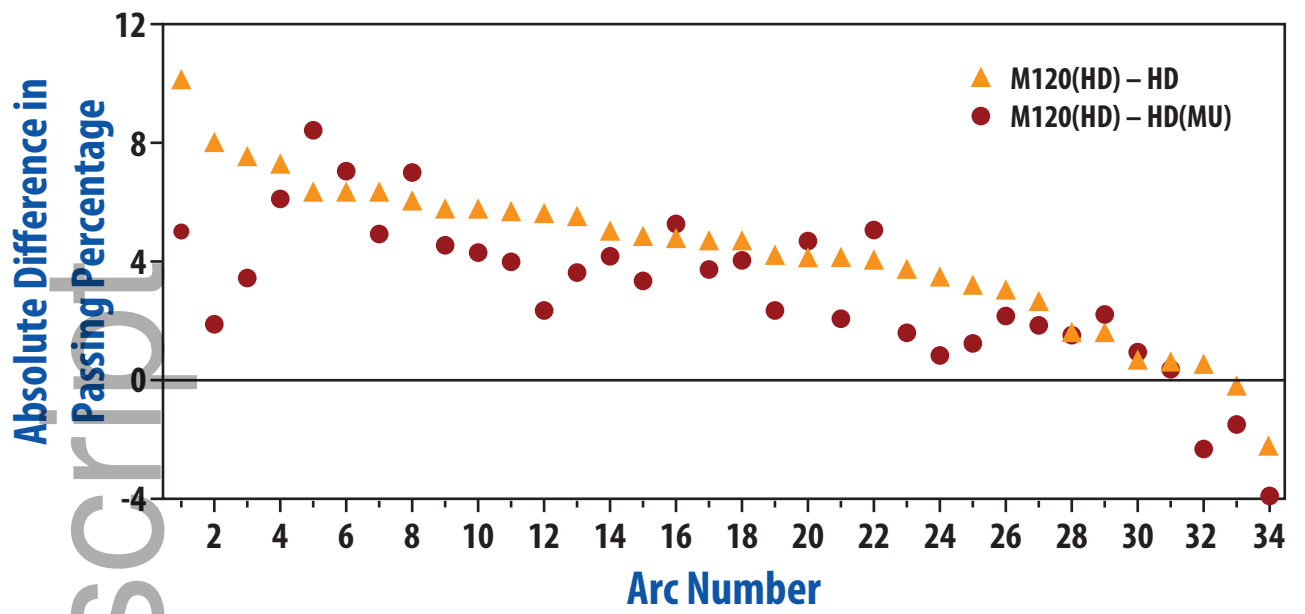
acm2_12197_f3.jpg

Author Manuscript



acm2_12197_f4.jpg

Author Manuscript



acm2_12197_f5.eps