The impact of leaf width and plan complexity on DMLC tracking of prostate intensity modulated arc therapy

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Purpose: Intensity modulated arc therapy (IMAT) is commonly used to treat prostate cancer. The purpose of this study was to evaluate the impact of leaf width and plan complexity on dynamic multileaf collimator (DMLC) tracking for prostate motion management during IMAT treatments.

Methods: Prostate IMAT plans were delivered with either a high-definition MLC (HDMLC) or a Millennium MLC (M-MLC) (0.25 and 0.50 cm central leaf width, respectively), with and without DMLC tracking, to a dosimetric phantom that reproduced four prostate motion traces. The plan complexity was varied by applying leaf position constraints during plan optimization. A subset of the M-MLC plans was converted for delivery with the HDMLC, isolating the effect of the different leaf widths. The gamma index was used for evaluation. Tracking errors caused by target localization, leaf fitting, and leaf adjustment were analyzed.

Results: The gamma pass rate was significantly improved with DMLC tracking compared to no tracking ($p < 0.001$). With DMLC tracking, the average gamma index pass rate was 98.6% (range 94.8%–100%) with the HDMLC and 98.1% (range 95.4%–99.7%) with the M-MLC, using 3%, 3 mm criteria and the planned dose as reference. The corresponding pass rates without tracking were 87.6% (range 76.2%–94.7%) and 91.1% (range 81.4%–97.6%), respectively. Decreased plan complexity improved the pass rate when static target measurements were used as reference, but not with the planned dose as reference. The main cause of tracking errors was leaf fitting errors, which were decreased by 42% by halving the leaf width.

Conclusions: DMLC tracking successfully compensated for the prostate motion. The finer leaf width of the HDMLC improved the tracking accuracy compared to the M-MLC. The tracking improvement with limited plan complexity was small and not discernible when using the planned dose as reference.

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1. INTRODUCTION

Intensity modulated arc therapy (IMAT) has been shown to facilitate a high degree of efficiency and conformity in radiation delivery.¹ Patient or tumor motion during IMAT delivery may, however, degrade the delivered dose distribution and cause unwanted loss of tumor coverage and increased dose to organs at risk. Prostate motion and its impact on margins and delivered dose distributions in radiotherapy are well studied.^{2–7}

Dynamic multileaf collimator (DMLC) tracking is a method to compensate for intrafraction target motion by real-time adaption of the MLC aperture to the targets movement.^{8–17} Other methods of motion compensation, not

covered in this study, include beam gating, moving the source, and couch tracking. The accuracy of DMLC tracking depends on the alignment between the leaves and the target motion, with motion perpendicular to the leaf travel being more challenging.⁹ There are two reasons for this; (1) the finite leaf width limits the leaf fit to the closest physically possible shape and (2) perpendicular motion can lead to large MLC aperture changes where leaves may be unable to reach the desired position in sufficient time to avoid dose errors.⁹ The leaf width is an inherent limiter of DMLC tracking accuracy, as it defines the smallest possible correction of perpendicular motion. A recent study by Falk *et al.*¹³ showed that optimal tracking performance for IMAT lung treatments with sinusoidal target

motion required restrictions on the plan complexity in terms of limited allowed distances between adjacent leaves. As the characteristics of lung and prostate motion are different, evaluation of the impact of the MLC plan complexity for prostate cases is motivated. The purpose of this study was to investigate the impact of leaf width and treatment plan complexity on delivery accuracy of DMLC tracking of prostate motion.

2. MATERIALS AND METHODS

2.A. Treatment planning

Single-arc IMAT plans were optimized in a research version of a commercial treatment planning system (RapidArc, Eclipse version 10, Varian Medical Systems, Palo Alto, CA). Plans were created for two prostate cancer patients with 2 Gy/fraction prescribed to the PTV. The PTV volumes were 63 and 140 cm³ for patient #1 and patient #2, respectively. To create plans with varying plan complexity, a leaf position constraint (LPC) limited the maximum allowed distance (AD) between adjacent MLC leaves.¹³ The AD was varied between 0.81, 1.44, 2.07, and 2.69 cm (the same for both MLCs). The most stringent constraint, AD = 0.81 cm, corresponded to the maximum distance a leaf could travel between two control points and the other constraints were multipliers of that distance. Additionally, plans were created with no LPC. With the distance between adjacent leaves restricted, the leaves would have a shorter distance to travel to compensate for motion perpendicular to the MLC leaves.

The plans were optimized for two MLCs; the high-definition MLC (HDMLC) and the Millennium 120 MLC (M-MLC) (Varian Medical Systems, Palo Alto, CA). The HDMLC has 32 2.5 mm central leaf pairs and 28 5.0 mm peripheral leaf pairs. The M-MLC has 40 5.0 mm central leaf pairs and 20 10.0 mm peripheral leaf pairs. Ten plans were made for each patient, five for each MLC with varying LPC. The same planning objectives were used for all plans for each patient, chosen to obtain a similar degree of intensity modulation regardless of the LPC. To isolate the effect of the different leaf widths, the M-MLC plans for patient #1 (with the smaller PTV) were converted for delivery with the HDMLC. The size of the PTV allowed the converted plans to only use the central part of the MLC with 2.5 mm leaves. The jaws were placed approximately 2 cm wider than the PTV projection in order to allow for DMLC tracking. The plans used a 358° arc, 6 MV, and 45° collimator angle.

2.B. Experimental setup

A motion platform with accurate 4D motion capability¹⁴ was used to reproduce four prostate motion traces (average 3D displacement 1.8–4.4 mm, maximal 3D displacement 7.2–13.2 mm), selected from a dataset of 548 motion traces.⁴ The traces represented characteristic types of prostate motion: continuous drift, high frequency excursions, persistent excursion, and transient excursion. The traces are the same as in Keall *et al.*¹⁵ The traces started at isocenter. A dosimetric phantom was mounted on the motion platform (Delta4

with Hexamotion, Scandidos, Uppsala, Sweden). The phantom consisted of two orthogonal diode arrays placed in a cylindrical PMMA phantom, diameter 21.8 cm. The diodes were separated by 0.5 cm in the central 6 × 6 cm of the arrays, and by 1 cm in the peripheral part.

A research DMLC tracking system was used to shape the MLC to the target motion in real-time, considering both longitudinal and lateral motion from the MLCs beams eye view, but also in-depth motion corrected by magnification.⁹ Infrared reflective markers were placed on the phantom and monitored with a stereoscopic optical system (Exactrac, from Brainlab, Germany) to provide positional input to the tracking system. Based on the planned MLC shape, the tracking program adapted the MLC to compensate for the observed motion. The system latency was 260 ms (approximately the same for the two MLCs). No prediction algorithm was used in the experiments as prostate motion cannot be expected to be periodic. Deliveries were made with and without DMLC tracking and with and without target motion. For a single trajectory-plan combination, five repeated measurements were performed with motion and DMLC tracking in order to investigate the reproducibility of the experiments.

2.C. Evaluation

The built-in gamma evaluation function in the Delta4 software was used to calculate the gamma index pass rate, using either the planned dose or the measured dose of a static target as reference (with and without tracking for tracking and no-tracking experiments, respectively, and excluding diodes receiving <5% of the prescribed dose). When planned doses were used, gamma evaluation was done in 3D around the diodes. When measured static doses were used as reference, the gamma calculation was limited to 2D along the diode planes, with the measured dose interpolated between the diodes.

There were two reasons for using static measurements as reference as a supplement to the planned dose. First, it isolated the impact of motion from uncertainties in phantom setup and dose calculation. Second, when controlling the MLC, the tracking software moved unused closed leaves from their planned position to a position either adjacent to an open aperture or beneath the jaws, depending on their distance to the aperture.⁹ In this study, closed leaves within 2 cm from the aperture (i.e., four and two leaf pairs for the HDMLC and the M-MLC, respectively) were kept adjacent to the aperture. Thus, when using measurements as reference, the resulting discrepancy between the planned closed leaf positions and the actual closed leaf positions during tracking was avoided. A statistical analysis of the gamma results comparing MLCs and tracking states was performed using a paired *t*-test, assuming a two tailed distribution and a significance level of 0.05.

2.D. Error contribution

There are three main sources of errors in DMLC tracking of a moving target: (1) target localization error, (2) leaf

fitting error, and (3) leaf adjustment error.¹⁶ Target localization error is caused by system latency and uncertainties in the monitoring system. Leaf fitting error occurs when the desired MLC shape is fitted unto the closest physically possible MLC shape and is caused by the finite leaf width. Leaf adjustment error is the difference between the actual and the requested leaf positions and is caused by the finite leaf speed.

To investigate the relative contribution of the abovementioned errors, log files from the DMLC tracking software and the linear accelerator, the treatment plan, and the motion trace were analyzed. The method is explained in detail by Poulsen *et al.*¹⁶ The analysis allowed for computing over- and underexposed areas, A_o and A_u (cm^2), which were the areas from the beams eye view that were not shielded by a MLC leaf when they should have been, and vice versa. The dose weighted A_o and A_u were calculated for each error source and for the combined effect of all errors, which was not a linear sum of the three contributing terms as errors sometimes partially cancelled each other out.

2.E. Average leaf distance

To measure the impact of applying leaf position constraints and to quantify plan complexity, the dose weighted average

adjacent leaf distance (ALDw) was calculated for each plan.¹³ The mean distance to the two adjacent leaves for all leaves used in an open MLC aperture was calculated for each control point, weighted to the dose delivered at the control point, and averaged for the entire plan. The metric has previously been shown to correlate with DMLC tracking performance for sinusoidal target motion.¹³ In order to offer a reasonable comparison between the MLCs, as twice as many leaves were available for the HDMLC compared to the M-MLC, the ALDw was normalized to the (central) leaf width.

3. RESULTS

The gamma pass rate for the two MLCs and range of ADs with static measurements as reference and gamma criteria of 1%, 1 mm is shown in Fig. 1 (top left). For both MLCs, the pass rate with $\text{AD} = 0.81$ cm and $\text{AD} = 1.45$ cm were significantly higher ($p < 0.05$) than the pass rate with no LPC, while no significance was found between $\text{AD} = 2.07$ cm and no LPC, and $\text{AD} = 2.69$ cm and no LPC. The pass rate with no LPC for the HDMLC ($90.8\% \pm 3.0\%$) was the same as the pass rate with $\text{AD} = 0.81$ cm for the M-MLC ($90.8\% \pm 3.2\%$). With gamma criteria of 2% 2 mm (Fig. 1, bottom left), $\text{AD} = 0.81$ cm gave significantly higher pass rate than

FIG. 1. Gamma pass rate for the two MLCs and different allowed distances (ADs) to adjacent MLC leaves, using measurement with a static phantom as reference (left) or the planned dose as reference (right) with 1%, 1 mm gamma criteria (top) and 2%, 2 mm criteria (bottom). Each data point represents the average of eight measurements (two patients and four motion traces per patient). The error bars show standard deviation.

TABLE I. Average gamma index pass rates (in per cent) with and without DMLC tracking with different gamma criteria. Each value represents the average of 40 measurements (all combinations of two plans, four traces, and five LPCs) with range shown in brackets. Also presented are p -values from HDMLC vs M-MLC t -tests.

	Motion vs static			Motion vs planned		
	1%, 1 mm	2%, 2 mm	3%, 3 mm	1%, 1 mm	2%, 2 mm	3%, 3 mm
With tracking						
HDMLC	92.6 [86.0–97.9]	98.7 [95.1–100]	99.8 [99.0–100]	77.9 [70.0–86.6]	95.0 [88.7–99.1]	98.6 [94.8–100]
M-MLC	87.6 [77.5–95.6]	97.0 [93.3–100]	99.4 [98.0–100]	67.8 [58.2–80.2]	92.2 [88.5–96.4]	98.1 [95.4–99.7]
p -value	<0.001	<0.001	<0.001	<0.001	<0.001	0.013
No tracking						
HDMLC	48.9 [37.9–68.8]	72.0 [61.0–85.6]	87.4 [77.9–95.2]	44.2 [33.8–63.9]	73.4 [61.3–87.1]	87.6 [76.2–94.7]
M-MLC	52.0 [38.8–70.9]	74.7 [61.0–88.8]	88.8 [78.1–96.3]	49.3 [38.7–67.8]	78.0 [66.6–90.5]	91.1 [81.4–97.6]
p -value	0.002	0.002	0.06	<0.001	<0.001	<0.001

no LPC for both MLCs while AD = 1.45 cm vs no LPC was significant only for the M-MLC.

Changing reference from the static measured dose to the planned dose in the gamma evaluations added uncertainties associated with dose calculation and phantom setup. No trend of increased pass rate with more stringent LPC was observed, neither using 1%, 1 mm (Fig. 1, top right) nor 2%, 2 mm gamma criteria (Fig. 1, bottom right)

The gamma pass rates with both references and 1% 1 mm, 2% 2 mm, and 3% 3 mm criteria are presented in Table I. The pass rate for tracking with the HDMLC was significantly higher than the M-MLC for all used gamma criteria and using either reference. Without tracking, HDMLC plans had consistently lower pass rate than M-MLC plans. The pass rate was also significantly higher with tracking than without tracking ($p < 0.001$). Measurements without motion showed a slightly worse agreement to the planned dose with tracking than without tracking. The average pass rate with tracking a static target was 99.3% (3%, 3 mm) and 95.6% (2%, 2 mm) and the corresponding pass rates without tracking were 99.9% and 98.3% ($p < 0.001$).

An example of the leaf fitting step for the plans with AD = 0.81 cm for patient #1 is shown in Fig. 2 with the M-MLC plan (Fig. 2, left), the same plan converted to HDMLC (mid-

dle) and the plan optimized for the HDMLC (right). The figure illustrates the benefit of halving the leaf width, as well as examples of plan optimizations with the most stringent LPC. The primary tracking errors contribution was leaf fitting, which was decreased by 42% when the M-MLC plans were converted for delivery with the HDMLC (Fig. 3). More stringent ADs decreased all individual errors as well as the total error with tracking, which was approximately two times larger without tracking than with tracking.

The gamma pass rate with tracking using 1%, 1 mm and measurements as reference is plotted versus the normalized ALDw for patient #1 in Fig. 4. The impact of LPC on ALDw is visualized as more stringent LPC leads to decreased ALDw. The gamma pass rates for patient #1 was significantly higher for the HDMLC plans and the converted plans compared to the M-MLC plans ($p < 0.001$), while no difference was found between the HDMLC plans and the converted plans ($p = 0.31$).

Five repeated measurements were performed with DMLC tracking for the high frequency excursions motion trace and a HDMLC plan with AD = 1.44 cm. With a single static measurement as reference, the gamma pass rate was 92.4%–94.4% (1%, 1 mm), 98.8%–99.6% (2%, 2 mm), and 100% (3%, 3 mm).

FIG. 2. Example of the leaf fitting step. The ideal shape based on target motion is shown as an outline. This shape is not achievable due to the finite MLC leaf width. The leaves are positioned to the optimal compromise position, leaving residual underexposed (A_u) and overexposed (A_o) areas. The converted plan delivered the M-MLC plan with the HDMLC, using two HDMLC leaves for each M-MLC leaf. The plans shown in the figure were optimized with a maximum distance to adjacent leaves of 0.81 cm.

FIG. 3. The individual error contributions for DMLC tracking for patient #1, quantified as the mean sum of over- and underexposed areas (A_u , A_o), averaged for four motion traces. The converted plans were M-MLC plans converted and delivered with the HDMLC.

4. DISCUSSION

This study investigated the impact of leaf width and plan complexity on the delivery accuracy of DMLC tracking. The DMLC tracking accuracy was for the first time directly compared between MLCs with different leaf widths by using MLCs with either 0.25 cm (HDMLC) or 0.50 cm central leaf width (M-MLC). The HDMLC gave consistently higher DMLC tracking accuracy than the M-MLC. The plan complexity was varied by applying leaf position constraints (LPCs) in the plan optimization. Decreased plan complexity increased the DMLC tracking accuracy when using static measurements as reference, which isolated the effect of motion from uncertainties arising from dose calculation and

phantom setup. However, no difference was seen when the reference was changed to the planned dose, i.e., any benefit from decreased plan complexity was overshadowed by calculation or phantom setup uncertainties, suggesting that the impact of LPC, although measurable, would be small for prostate DMLC tracking. These results are in clear contrast to the previous study of LPC and lung motion,¹³ and the characteristics of prostate motion likely reduced the need of a LPC. Thus, leaf width is a more crucial parameter than plan complexity for prostate DMLC tracking.

A deviation from the delivery without tracking was caused by the tracking software moving unused leaves from their planned position to either a position beneath the jaws or next to an open aperture. In Pommer *et al.*,¹⁷ this effect was isolated (by keeping the planned positions for all MLC leaves) without any improved agreement to the planned dose, suggesting other causes for the deviation. The agreement with the planned dose can thus possibly be improved with future versions of the tracking software.

When tracking was not used, regardless of gamma criteria and reference, the HDMLC showed more deteriorated dose distributions than the M-MLC. This was likely caused by the finer leaf width allowing more complex delivery patterns and, therefore, an increased interplay effect.

This study investigated two of the approaches for improved DMLC tracking accuracy suggested by Keall *et al.*¹⁵ and Poulsen *et al.*¹⁶ thinner leaves and robust planning. The abovementioned studies used clinically applicably target monitoring systems, whereas this study utilized external markers placed on the phantom. The performance of the optical system used in this study and the electromagnetic-guided system used in Keall *et al.*¹⁵ were comparable,^{18,19} and by

FIG. 4. The gamma pass rate (1%, 1 mm, measurement as reference) for patient #1, averaged for four motion traces and plotted against the average adjacent leaf distance (ALDw), normalized to the leaf width. The converted plans delivered the planned MLC shape for M-MLC plans with the HDMLC, using two HDMLC leaves for each M-MLC leaf. The leaf position constraint decreased the ALDw and the plans are thus from left to right showing more to less stringent LPC.

using external markers, the impact of target localization error was minimized. As this study investigated the impact of leaf width and plan complexity, patient-specific characteristics were not the focus. Therefore, plans were made for only two patients. A previous study with four patients showed very small difference in DMLC tracking performance among the different patients.¹⁷

The decreased tracking error with more stringent LPC in Fig. 3 was expected: target localization errors result in a shift of the adapted MLC aperture relative to the ideal MLC aperture, which gives errors along the circumference of the aperture. This contribution increases with the length of the circumference and thus with less stringent LPC. Similarly, leaf fitting errors are approximately proportional to the part of the aperture circumference that is formed by leaf sides (Fig. 2), which also increases with less stringent LPC. Finally, leaf adjustment errors are proportional to the average distance that leaves have to travel to adapt to target shifts, which also increases with less stringent LPC. Since the M-MLC plans and the converted M-MLC plans in Fig. 3 have identical apertures the target localization errors in Fig. 3 would be identical for the plans if they were delivered identically with the same absolute phantom position and synchronization between gantry and phantom position. This was, however, not the case as there was a small difference in delivery time between the two linear accelerators used. We ascribe the small differences in localization errors to this.

5. CONCLUSION

DMLC tracking successfully compensated for the studied prostate motion and was able to reproduce the planned dose for a static target. The tracking accuracy was significantly higher with the HDMLC than the M-MLC. Limiting the plan complexity increased the dosimetric accuracy only when the effect of motion was isolated by using static measurements as reference in the gamma evaluation, suggesting that the impact of plan complexity for prostate DMLC tracking is small. Tracking error analysis indicated that leaf fitting was the major cause of tracking error, and decreased almost by half when the leaf width was halved.

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- ¹K. Otto, "Volumetric modulated arc therapy: IMRT in a single gantry arc," *Med. Phys.* **35**, 310–317 (2008).
- ²E. Huang *et al.*, "Intrafraction prostate motion during IMRT for prostate cancer," *Int. J. Radiat. Oncol., Biol., Phys.* **53**, 261–268 (2002).
- ³P. Kupelian *et al.*, "Multi-institutional clinical experience with the Calypso System in localization and continuous, real-time monitoring of the prostate gland during external radiotherapy," *Int. J. Radiat. Oncol., Biol., Phys.* **67**, 1088–1098 (2007).
- ⁴K. M. Langen *et al.*, "Observations on real-time prostate gland motion using electromagnetic tracking," *Int. J. Radiat. Oncol., Biol., Phys.* **71**, 1084–1090 (2008).
- ⁵H. S. Li *et al.*, "Dosimetric consequences of intrafraction prostate motion," *Int. J. Radiat. Oncol., Biol., Phys.* **71**, 801–812 (2008).
- ⁶P. Zhang, D. Mah, L. Happersett, B. Cox, M. Hunt, and G. Mageras, "Determination of action thresholds for electromagnetic tracking system-guided hypofractionated prostate radiotherapy using volumetric modulated arc therapy," *Med. Phys.* **38**, 4001–4008 (2011).
- ⁷D. W. Litzenberg *et al.*, "Prostate intrafraction translation margins for real-time monitoring and correction strategies," *Prostate Cancer* **2012**, 130579 (2012).
- ⁸P. J. Keall *et al.*, "Geometric accuracy of a real-time target tracking system with dynamic multileaf collimator tracking system," *Int. J. Radiat. Oncol., Biol., Phys.* **65**, 1579–1584 (2006).
- ⁹A. Sawant *et al.*, "Management of three-dimensional intrafraction motion through real-time DMLC tracking," *Med. Phys.* **35**, 2050–2061 (2008).
- ¹⁰M. B. Tacke, S. Nill, A. Krauss, and U. Oelfke, "Real-time tumor tracking: Automatic compensation of target motion using the Siemens 160 MLC," *Med. Phys.* **37**, 753–761 (2010).
- ¹¹D. McQuaid and S. Webb, "Target-tracking deliveries using conventional multileaf collimators planned with 4D direct-aperture optimization," *Phys. Med. Biol.* **53**, 4013–4029 (2008).
- ¹²B. Sun, D. Rangaraj, L. Papiez, S. Oddiraju, D. Yang, and H. H. Li, "Target tracking using DMLC for volumetric modulated arc therapy: A simulation study," *Med. Phys.* **37**, 6116–6124 (2010).
- ¹³M. Falk *et al.*, "The dosimetric impact of inversely optimized arc radiotherapy plan modulation for real-time dynamic MLC tracking delivery," *Med. Phys.* **39**, 1588–1594 (2012).
- ¹⁴M. Falk, P. Keall, B. Cho, S. Korreman, and P. Munck af Rosenschöld, "Real-time dynamic mlc tracking during arc therapy: A dosimetric comparison for irregular and regular tumour motion," *Radiother. Oncol.* **99**, S187 (2011).
- ¹⁵P. J. Keall *et al.*, "Electromagnetic-guided dynamic multileaf collimator tracking enables motion management for intensity-modulated arc therapy," *Int. J. Radiat. Oncol., Biol., Phys.* **79**, 312–320 (2011).
- ¹⁶P. R. Poulsen, W. Fledelius, B. Cho, and P. Keall, "Image-based dynamic multileaf collimator tracking of moving targets during intensity-modulated arc therapy," *Int. J. Radiat. Oncol., Biol., Phys.* **83**, e265–e271 (2012).
- ¹⁷T. Pommer *et al.*, "Dosimetric benefit of DMLC tracking for conventional and sub-volume boosted prostate intensity-modulated arc radiotherapy," *Phys. Med. Biol.* **58**, 2349–2361 (2013).
- ¹⁸J. M. Balter *et al.*, "Accuracy of a wireless localization system for radiotherapy," *Int. J. Radiat. Oncol., Biol., Phys.* **61**, 933–937 (2005).
- ¹⁹L. T. Wang, T. D. Solberg, P. M. Medin, and R. Boone, "Infrared patient positioning for stereotactic radiosurgery of extracranial tumors," *Comput. Biol. Med.* **31**, 101–111 (2001).