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Real-time dynamic MLC tracking for inversely optimized arc radiotherapy

Marianne Falk¹, Per Munck Af Rosenschöld¹, Paul Keall², Herbert Cattell³, Byung Chul Cho², Per Poulsen^{2,4}, Sergey Povzner³, Amit Sawant², Jens Zimmerman¹, and Stine Korreman¹

¹Department of Radiation Oncology, Rigshospitalet, Copenhagen University Hospital, Denmark

²Stanford University, Stanford, CA, USA

³Varian Medical Systems, Palo Alto, CA, USA

⁴Department of Oncology, Aarhus University Hospital, Denmark

Abstract

Background and Purpose—Motion compensation with MLC tracking was tested for inversely optimized arc radiotherapy with special attention to the impact of the size of the target displacements and the angle of the leaf trajectory.

Material and methods—An MLC tracking algorithm was used to adjust the MLC positions according to the target movements using information from an optical real-time positioning management system. Two plans with collimator angles of 45° and 90°, respectively, were delivered and measured using the Delta^{4®} dosimetric device moving in the superior-inferior direction with peak-to-peak displacements of 5, 10, 15, 20 and 25 mm and a cycle time of 6 s.

Results—Gamma index evaluation for plan delivery with MLC tracking gave a pass rate higher than 98% for criteria 3% and 3 mm for both plans and for all sizes of the target displacement. With no motion compensation, the average pass rate was 75% for plan 1 and 70% for plan 2 for 25 mm peak-to-peak displacement.

Conclusion—MLC tracking improves the accuracy of inversely optimized arc delivery for the cases studied. With MLC tracking, the dosimetric accuracy was independent of the magnitude of the peak-to-peak displacement of the target and not significantly affected by the angle between the leaf trajectory and the target movements.

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Author of correspondence: Marianne Falk, Department of Radiation Oncology, 3994, Rigshospitalet, Blegdamsvej 9, DK-2100 København, Phone +45 3545 3545, Fax: +45 3545 3957, Marianne.falk@rh.regionh.dk.

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Conflict of interest

Herb Cattell and Sergey Povzner: Employees of Varian Medical Systems, Inc.

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Keywords

MLC motion tracking RapidArc

Introduction

Treatment of tumours that move intra-fractionally is a well known issue of concern in radiotherapy [1,2]. Cases of lung tumour movements with peak-to-peak displacements of up to 25–30 mm have been presented in the literature [3,4]. Radiotherapy of tumours moving with large amplitudes requires an enlargement of the treated volume to ensure that the tumour is covered throughout the treatment, or alternatively some other compensation for the tumour displacements must be employed. One of the great difficulties in radiotherapy is to give a good treatment of the tumour but at the same time spare healthy tissue and critical organs and an enlargement of the treated volume may not be a favourable solution if the tumour is located close to an organ at risk. Respiratory gating has the disadvantage of increased treatment time since the dose delivery only is asserted when the tumour is within a certain position range [5]. This study is focused on the compensation of tumour movements using the multi leaf collimator (MLC) to reshape the beam according to the instantaneous position of the tumour, referred to as MLC tracking. Several previous studies have reported promising results for this method for IMRT [6,7]. Intensity-modulated arc therapy (IMAT) was first proposed by Yu [8] in 1995 as treatment delivery using multiple superimposed arcs with varying field shapes. The technique was later refined by Otto [9] in 2007 with a novel aperture-based algorithm for treatment planning optimization. For this study, the implementation of this technique by Varian Medical Systems, RapidArc®, was used. RapidArc® plans are created using inverse optimization and delivered in one (or several) rotations of the gantry. The field shape, dose rate and gantry speed are varied during the delivery to give a high dose to the target while minimizing the dose to the surrounding tissues. A 2 Gy fraction can be delivered in less than 2 minutes (one arc) and requires in general fewer monitor units (MU) than IMRT treatments. [10,11] In a study reported earlier, the feasibility of MLC tracking for RapidArc® therapy was shown [12]. The purpose of the present study is to evaluate the performance of MLC tracking for RapidArc® delivery with special attention to the impact of the magnitude of the target movements and the angle of the MLC leaf trajectory with respect to the target movement.

Material and methods

The difference in dosimetric accuracy of RapidArc® plan delivery with and without the influence of MLC tracking was evaluated for a moving target. Two RapidArc® plans were created in Eclipse™ ver. 8.5 treatment planning system (TPS) using inverse optimization. The plans were created with identical settings, apart from the collimator angle which was set to 45° (plan 1) or 90° (plan 2), respectively. Collimator angle 45° has been shown to be preferable for RapidArc® plans [9], while collimator angle 90° has the leaf trajectory parallel to movements in the superior-inferior (SI) direction which has been shown to be favourable for MLC tracking [6]. The plans used a single clock-wise arc with gantry angles spanning 300° from 210° to 150° (to avoid intersection of the incoming beam and the rails of the couch), 6 MV and a maximum dose rate of 600 MU/min. The same CT data of a patient with a lung tumour was used for both plans. The target had a size of about 3.1 cm (SI) × 3.6 cm (AP) × 3.1 cm (LR) (volume of 12.42 cm³) and was located in the right lower lobe. The prescribed dose was 2 Gy and the number of monitor units were 370 (plan 1) and 410 (plan 2). To enable the plans for MLC tracking, the jaws were forced set to 13 cm × 13 cm to prevent them from covering the target as it moved during the delivery (although not necessary for the direction perpendicular to target movement in the 90° collimator rotation

plan, both jaws were retracted for consistency reasons). After the optimization, the plans were recalculated for the Delta⁴® dosimetric phantom (ScandiDos, Inc.), and the dose matrix was imported to the Delta⁴® analysis software.

The plans were delivered using a Varian 2300ix linear accelerator with RapidArc® capabilities. An MLC tracking controller was adjusting the positions of the leaves, using a 3D MLC tracking algorithm to recalculate the planned MLC positions (from the TPS) to best fit the instantaneous location of the target [6,13]. Information about the target location was obtained from the real-time position monitoring system RPM™ (Varian Medical Systems, Inc.). The RPM™ system uses a marker block with two or six reflective markers positioned on the patient/phantom to move in correlation with the target, and the location of the marker block is determined by recording infra-red light reflecting off the markers. For this study, the 6-dot marker block, which is able to track movements in the superior-inferior direction, was used. To minimize the transmission between the closed leaf tips, arising from the extended jaw positions, the non participating leaves were moved to the side by the tracking system, placing the gaps underneath one of the x-jaws. A number of adjacent leaf pairs were kept at the centre in case of the target moving non-parallel to the leaf trajectory and requiring new leaf pairs to be opened. In this case, the next adjacent leaf pair would return from the side to compensate for this and keeping the number of adjacent central leaf pairs constant. The MLC tracking controller is today a non-clinical research tool and the development of it is ongoing.

Lung tumour movement was simulated using a motion platform (Standard Imaging, Inc.) which was programmed to form sinusoidal motion in the superior-inferior (SI) direction with peak-to-peak distances of 5, 10, 15, 20 and 25 mm and a cycle time of 6 seconds. The motion range was chosen to span that observed by Seppenwoolde et al [3] in their fluoroscopic analysis of lung tumour motion, and the cycle time was within the cycle time span reported. The platform carried a Delta⁴® dosimetric device and the plans were delivered to the phantom, which was either static or moving as described above. The Delta⁴® system uses two orthogonal detector arrays with p-Si diodes separated by 0.5 cm in the central 6 cm × 6 cm area of the detector arrays and by 1 cm on the remaining area (in total 20 cm × 20 cm) [14].

Tests of the position monitoring system

First, measurements were performed to test the RPM™ system's position drift, precision and accuracy. The drift was tested by acquiring RPM™ position information of a static marker block for 20 minutes. The experiment was first performed without calibration of the RPM system in between, then the system was calibrated and the whole experiment was repeated another two times. Linear regression was used to estimate the position drift over time. The RPM position precision was investigated in the same measurements by calculating the standard deviation of the measured values. The position accuracy was investigated in four 1 hour measurements during which the marker block was moved between five different positions; 0 cm, +1 cm and -1 cm or 0 cm, +2 cm, -2 cm from the calibration position. The marker block was in total repositioned 30 times for every one hour measurement, and the position was verified using a steel ruler.

States of setup

Dosimetric measurements were then performed in three different states of the setup:

1. Disconnected state

In this state, the MLC tracking controller was not connected, and the MLCs therefore followed the sequence exactly as given from the treatment plan in

Eclipse. Measurements in this state were performed both with a static target and with motion.

- a. Static target
 - b. Moving target
2. Connected reference state

In this state, the MLC tracking controller was connected, but was not receiving real-time information from the monitoring system. Instead a zero input file was used to simulate an entirely static target. Measurements in this state were only performed with a static target.

3. Connected tracking state

In this state, the MLC tracking controller was connected and receiving input from the monitoring system. Measurements in this state were performed with a moving target.

The measurements with a moving target were compared to static target reference measurements such that state 1b was referenced to state 1a, and state 3 was referenced to state 2. The reason for distinguishing between the disconnected state and the connected state and using two different references for the two, is the feature of the tracking system that moves the non participating leaves underneath one of the jaws to reduce leakage. Since this action was only taken for the delivery in the connected tracking state, there would be a dosimetric difference due to the detector volume receiving leakage dose from those leaves if the disconnected state and the connected states were compared.

Evaluation

Gamma analysis was used for comparison of dosimetric measurements, within the software of the Delta⁴® system. The gamma index evaluation was performed with criteria 3% and 3 mm and 2% and 2 mm, respectively, with the dose deviation evaluated with respect to the isocenter dose. For the measurement with a moving target, detector points with doses in the range of 10% – 500% of the isocenter dose were included in the evaluation.

Margin reduction

The PTV margin is created to account for treatment execution (random) and treatment preparation (systematic) variations. Van Herk et al [15] present a method for deriving PTV margins that accounts for both systematic and random errors and formulas from this study was used to estimate the possible reduction of the PTV margin when using MLC tracking. The difference in the required PTV margin for delivery with and without the use of the MLC tracking method can be described as (using the notation suggested by van Herk et al [15])

$$\beta\sigma_{\text{Disconnected state}} - \beta\sigma_{\text{connected tracking state}} \quad (1)$$

were all other terms in the margin formula are unchanged and cancel out in the subtraction. The term $\beta\sigma_{\text{Disconnected state}}$ represents the random PTV margin component needed for treatment of a lung tumour with no motion compensation and $\beta\sigma_{\text{Connected tracking state}}$ represents the random PTV margin component needed when MLC tracking is used for the same treatment. $\beta\sigma$ represents the distance between the 95% and 50% isodose surface of the dose distribution with σ describing the total SD for all random variations, and β is equal to 1.64 (van Herk et al. [15]):

$$\sigma^2 = \sigma_{motion}^2 + \sigma_{setup}^2 + \sigma_{penumbra}^2 \quad (2)$$

The SD for the setup of lung cancer patients, σ_{setup} , was set to be 4.6 mm in the SI direction, as suggested in the literature [16]. The SD describing the width of the dose distribution penumbra in the lung, $\sigma_{penumbra}$, was found by measuring the distance between the 95% and 50% isodose surface for several plans in the TPS and then dividing the average value with β . The SD for the target motion, σ_{motion} , was then the only unknown in the calculation of the total σ^2 , and will be found based on the measurements for the connected tracking state and the disconnected state respectively. σ_{motion} was estimated from the measurements by calculating the average value of $\beta\sigma$ for all the Delta^{4®} measurements with a moving target in the different states of the tracking system for plan 1, $\beta\sigma_{measured}$. The value of σ_{motion} could then be derived by the relation

$$\sigma_{motion} = \sqrt{\left(\frac{\beta\sigma_{measured}}{\beta}\right)^2 - (\sigma_{setup, D4}^2 + \sigma_{penumbra, D4}^2)} \quad (3)$$

(using equation (2) with SDs for the Delta^{4®} setup and dose distribution). Dose information from detectors along the central line in the SI direction of one of the detector arrays of the Delta^{4®} was used to calculate this value. The standard deviation for the variations in setup and the width of the penumbra for the Delta^{4®} measurements, $\sigma_{setup, D4}$ and $\sigma_{penumbra, D4}$ were estimated by calculating $\beta\sigma$ for static measurements in the connected tracking state for plan 1. The possible reduction of the PTV margin with MLC tracking was calculated for both the superior and for the inferior side of the tumour separately, and for all the magnitudes of the peak-to-peak displacements studied in this work.

Results

Tests of the position monitoring system

The positional drift of the RPM system was found to be in the range of 0.0063 mm/min to 0.015 mm/min and the direction of the drift varied between the measurements. For this study, the built-in temporal averaging used clinically to reduce the noise level of the RPM system, was disabled in order to reduce the system latency. This was expected to affect the noise level which was found to be consistent over time, and the standard deviation (position precision) was in the range of 1.01 mm to 1.16 mm. The test of the position accuracy showed errors in the position estimation of the marker block in the range of 0 mm to 4.3 mm with a mean of 1.1 ± 0.9 mm in the SI direction. The calculated means of the RPM position estimation for the one hour displacement measurements are plotted together with the ruler measurements in fig. 1 for one measurement series. The differences seen in fig. 1 between expected position and measured position exceed the precision variations within the measurements given above.

Profile shift

A shift of the dose profiles was noted for some of the dosimetric measurements and appeared to be related to instabilities in the RPM system (as described above). An example of such an observed shift is shown in fig. 2. The shift of the dose profiles was found to be as large as 4.25 mm in the SI direction for measurements in the connected tracking state. The measurements with a profile shift larger than 1.3 mm were excluded from the following evaluation to give a fair description of the MLC tracking systems capabilities rather than reflecting the shortcomings of the RPM system. The threshold of 1.3 mm was based on an

observed strong linear dependence above this threshold between the profile shift and the gamma index pass rate for criteria 2% and 2 mm. For values over 1.3 mm, the shift started to dominate the results of the dosimetric accuracy. This resulted in 23.2 % of the measured results in the connected tracking state being excluded from the evaluation. Five measurements for plan 1 and four measurements for plan 2 were included in this analysis.

Dosimetric results

The dose-smearing arising from the target movements was clearly reduced by the MLC tracking system. This is illustrated by the measured dose profiles for measurements in the disconnected state and the connected tracking state shown in fig. 3. The pass rates of the gamma index evaluation as a function of the peak-to-peak displacements of the target are shown in fig. 4. The mean pass rate values of all measurements are shown for each displacement and measurement state along with error bars indicating the pass rate standard deviation of the measurements. There was a clear increase in pass rate of the gamma index evaluation when MLC tracking was used for the delivery of the plans (fig. 4a–b) compared to no tracking. For both plans, the pass rate was above 98% for the 3% and 3 mm criteria and above 93% for the 2% and 2 mm criteria for all magnitudes of the peak-to-peak displacement of the target for measurements in the connected tracking state. Plan 2 (90° collimator angle) had a slightly higher pass rate than plan 1 (45° collimator angle). For measurements without tracking (fig. 4a–b) the gamma index pass rate decreased markedly with increasing peak-to-peak displacement. For a displacement of 25 mm, the average pass rate for plan 1 was reduced to 75% for the 3% and 3 mm criteria, and to 45% for the 2% and 2 mm criteria.

Margin reduction

The mean values of $\sigma_{penumbra, lung}$ were calculated to 8.2 mm (cranial side) and 14.7 mm (caudal side). The distance between the 50% and the 95% isodose surface in the measured dose profiles in the Delta⁴® are shown in table 1. For the static target measurements in the connected tracking state, the average value of this distance was calculated to 6.76 ± 0.78 mm (cranial side) and 6.70 ± 0.13 mm (caudal side). The possible margin reduction when using MLC tracking was found to be 2.72 ± 0.43 mm (cranial side) and 1.66 ± 0.34 mm (caudal side) for 15 mm peak-to-peak displacement and 5.46 ± 1.15 mm (cranial side) and 3.58 ± 1.15 mm (caudal side) for 25 mm peak-to-peak displacement (fig. 5).

Discussion

The results of the gamma index evaluation showed a strong increase in delivery accuracy when MLC tracking was used for RapidArc® delivery to periodically moving targets. The frequently used criteria 3% and 3 mm was used for the evaluation as well as the criteria 2% and 2 mm to take a closer look at the dosimetric accuracy achievable with MLC tracking. The stringent criteria of 2% and 2 mm resulted in a lower pass rate for both states and both plans, with a larger decrease for the measurements in the disconnected tracking state. The high (>93%) pass rate for the measurements in the connected tracking state for 2% and 2 mm criteria gives a good illustration of the great potential of MLC tracking for target motion compensation. The results did not show a decrease in tracking performance depending on the magnitude of the peak-to-peak displacement of the target. The benefit of positioning the MLC parallel to the target movements was shown to be minimal. Results of calculations suggest that MLC tracking possibly can enable reduction of the PTV margin for large motion amplitudes.

The RPM tests in this study were only performed in the SI direction. Clinically the RPM system is mainly used to track movements in the Anterior-Posterior (AP) direction and can

be used for gating purposes only based on AP movements. The accuracy of the system in the SI direction measured here is within specifications for this motion direction, but appears to be insufficient for the purpose of MLC tracking in the SI direction. The RPM system has a larger tolerance for variations in the SI direction than in the other directions, because SI displacement can only be quantified in terms of changing distance between reflective markers in the recorded images. An additional reason why the RPM system may not be the best position monitor for MLC tracking is the need to correlate the movements of the external marker to the internal tumour movement, which has been shown to be nontrivial and subject to baseline shifts [17].

The use of an RPM system, with the current characteristics, does not provide an adequate monitoring of the target position for MLC tracking, due to instabilities of the system. There is therefore a strong need for an alternative positioning monitoring system with higher accuracy in all three directions of motion. A position monitoring device that will be tested with MLC tracking for RapidArc delivery in the near future is the ExacTrac® system (BrainLAB) [18]. This system uses a combination of x-ray imaging and infrared tracking to estimate the position of the target in a stereoscopic view facilitating high accuracy in all directions.

Sinusoidal paths, as studied in this work, are good approximations for lung tumour movements, but when moving towards clinical applications, real patient specific tumour movements need to be considered. Studies of MLC tracking during RapidArc delivery for complex tumour movement in 3D are therefore required.

The 3D MLC tracking algorithm has a prediction algorithm that can account for temporal latencies in the system and thus possible further improve the tracking performance. For this study however, no prediction was used. The time consumption of detecting target motion, calculating the new leaf positions and the time for the leaves to respond was about 160 ms [6]. The temporal latency may have had a minor smearing effect on the dose distributions and the effect is likely to increase with target speed. To minimise the effect of the system latency, the cycle frequency was set to a value at the lower end of the range presented in the literature [3]. The temporal latency did not show any effect on the results for the different target speeds (due to the different peak-to-peak displacements with fixed cycle time) used in this study.

Conclusion

The dosimetric accuracy when treating a moving target with fluence modulated technique is clearly worsened as the size of the peak-to-peak displacements increases when the motions are not compensated for. MLC tracking has been shown to improve the accuracy of RapidArc® delivery for the cases studied. The benefits of the method are more apparent when using gamma index criteria of 2% and 2 mm than the more commonly used 3% and 3 mm criteria which suggests that a very accurate dose delivery is possible with MLC tracking. The method is not largely affected by the size of the peak-to-peak displacement or the angle of the leaf trajectory with respect to the target movements.

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Figure 1. Mean position estimation of the marker block by the RPM system compared to the positions measured with a ruler.

Figure 2.

Example of a profile shift. The measured values in the connected tracking state are shifted with respect to the reference measurement with a static target.

Figure 3.

Dose profiles in the SI direction of measurements in the disconnected state (a) and the connected tracking state (b). Dose profiles are shown for 5 mm, 15 mm and 25 mm displacement of the target.

Figure 4.

a–d The result of the gamma index evaluations for plan 1 with criteria 3% and 3 mm (a) and 2% and 2 mm (b) are shown above. A comparison of the gamma index pass rate of the two plans when delivered using MLC tracking are shown in (c) for gamma criteria of 3% and 3 mm and in (d) for gamma criteria of 2% and 2 mm. The error bars indicate one standard deviation of the measured values. Note the different scales on the y-axis between a,b and c,d.

Figure 5. Calculated reduction of the PTV margin for treatment delivery with MLC tracking to a moving tumour.

Table 1

The distance between the 50% and 95% isodose surface for plan delivery with and without MLC tracking

Size of target displacements [mm]	Cranial side		Caudal side	
	$\beta\sigma_{CTS,D4}$ [mm]	$\beta\sigma_{DS,D4}$ [mm]	$\beta\sigma_{CTS,D4}$ [mm]	$\beta\sigma_{DS,D4}$ [mm]
5	6.41 ± 0.47	6.65 ± 0.64	7.29 ± 0.44	7.15 ± 0.37
10	6.32 ± 0.41	9.69 ± 1.03	7.97 ± 0.44	9.70 ± 1.90
15	6.82 ± 0.31	11.72 ± 0.71	7.85 ± 0.47	12.2 ± 1.06
20	6.64 ± 0.84	13.28 ± 0.47	8.14 ± 0.61	13.28 ± 0.84
25	6.70 ± 0.61	15.55 ± 1.41	8.38 ± 0.82	16.33 ± 1.88