The dosimetric impact of inversely optimized arc radiotherapy plan modulation for real-time dynamic MLC tracking delivery

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Purpose: Real-time dynamic multileaf collimator (MLC) tracking for management of intrafraction tumor motion can be challenging for highly modulated beams, as the leaves need to travel far to adjust for target motion perpendicular to the leaf travel direction. The plan modulation can be reduced by using a leaf position constraint (LPC) that reduces the difference in the position of adjacent MLC leaves in the plan. The purpose of this study was to investigate the impact of the LPC on the quality of inversely optimized arc radiotherapy plans and the effect of the MLC motion pattern on the dosimetric accuracy of MLC tracking delivery. Specifically, the possibility of predicting the accuracy of MLC tracking delivery based on the plan modulation was investigated.

Methods: Inversely optimized arc radiotherapy plans were created on CT-data of three lung cancer patients. For each case, five plans with a single 358° arc were generated with LPC priorities of 0 (no LPC), 0.25, 0.5, 0.75, and 1 (highest possible LPC), respectively. All the plans had a prescribed dose of 2 Gy × 30, used 6 MV, a maximum dose rate of 600 MU/min and a collimator angle of 45° or 315°. To quantify the plan modulation, an average adjacent leaf distance (ALD) was calculated by averaging the mean adjacent leaf distance for each control point. The linear relationship between the plan quality [i.e., the calculated dose distributions and the number of monitor units (MU)] and the LPC was investigated, and the linear regression coefficient as well as a two tailed confidence level of 95% was used in the evaluation. The effect of the plan modulation on the performance of MLC tracking was tested by delivering the plans to a cylindrical diode array phantom moving with sinusoidal motion in the superior–inferior direction with a peak-to-peak displacement of 2 cm and a cycle time of 6 s. The delivery was adjusted to the target motion using MLC tracking, guided in real-time by an infrared optical system. The dosimetric results were evaluated using gamma index evaluation with static target measurements as reference.

Results: The plan quality parameters did not depend significantly on the LPC (p ≥ 0.066), whereas the ALD depended significantly on the LPC (p < 0.001). The gamma index failure rate depended significantly on the ALD, weighted to the percentage of the beam delivered in each control point of the plan (ALDw) when MLC tracking was used (p < 0.001), but not for delivery without MLC.
tracking (p ≥ 0.342). The gamma index failure rate with the criteria of 2% and 2 mm was decreased from > 33.9% without MLC tracking to < 31.4% (LPC 0) and < 2.2% (LPC 1) with MLC tracking. **Conclusions**: The results indicate that the dosimetric robustness of MLC tracking delivery of an inversely optimized arc radiotherapy plan can be improved by incorporating leaf position constraints in the objective function without otherwise affecting the plan quality. The dosimetric robustness may be estimated prior to delivery by evaluating the ALDₜ of the plan. © 2012 American Association of Physicists in Medicine. [DOI: 10.1118/1.3685583]

**Key words**: tumor tracking, intra-fraction motion, arc therapy

### I. INTRODUCTION

Dosimetric uncertainty arising from intrafraction motion can have adverse effects on the treatment outcome of radiation therapy.¹⁻³ Common practice is to treat an extended volume of healthy tissue surrounding a moving clinical target volume to ensure that the tumor is covered with high probability throughout the fraction. Since larger treatment volumes are associated with an increased dose to nearby normal tissues, there has been an increasing interest in developing advanced methods of motion management. As another approach to reduce dose to healthy tissue, inversely optimized arc radiotherapy delivers the treatment in one or several arcs of the gantry, during which the multileaf collimator (MLC) shape, dose rate, and gantry speed are varied. Intensity-modulated arc therapy (IMAT) was introduced by Yu⁴ in 1995 as a treatment technique using multiple superimposed arcs with varying field shapes, while gantry speed and dose rate remained constant. In 2007, the technique was modified by Otto⁵ with a novel aperture-based algorithm for treatment planning optimization. In this study, the RapidArc⁶ (RA) solution implemented by Varian Medical Systems⁶ was used. Complex treatments (e.g., dose painting⁷) with inversely optimized arc radiotherapy are generally characterized by varying field shapes, while gantry speed and dose rate remain constant. Improving the accuracy of MLC tracking delivery based on this factor. The plan modulation was varied using a leaf position constraint and the quality of the treatment plans was evaluated to investigate the applicability of the constraint for increasing the compatibility of highly modulated RA plans with MLC tracking delivery.

### II. MATERIALS AND METHODS

Inversely optimized arc radiotherapy plans were created in a research version of Eclipse™ (version 8.8) treatment planning system (TPS) using the RA technique for delivery using a Novalis TX™ linear accelerator with a high definition MLC (HD MLC). CT-data of three lung cancer patients were used in this study and the target volumes (Table I) were chosen to create treatment plans with varying target size and shape.

The plan modulation was reduced using a leaf position constraint (LPC) that introduced a maximum allowed distance between adjacent leaves (MLD) in the arc optimization. The smallest available MLD was equal to the maximum distance that a leaf can travel between two control points (MLT) (which depends on the distance between the control points, the leaf speed, and the gantry speed). Before the effect on the target coverage and doses to organs at risk had actually been studied, it made sense to also allow for some less stringent constraint on the MLC configuration. This was done considering that if the plan quality was significantly impacted by the side constraint on the MLC in the optimization phase this methodology as a whole would not be attractive, unless the constraint could also be relaxed somewhat. This study investigated if an optimum could be found where the impact on the plan and the leaf positioning accuracy of the MLC tracking are both acceptable. It was estimated that an MLD of 4 times the MLT would leave enough room for an almost free optimization to cover the solution space. The relationship between the MLD and the LPC is given by

\[ \text{MLD} = (1.0 + (1.0 - \text{LPC}) \cdot 3) \cdot \text{MLT}. \]  

(1)

An LPC of 1 gives an MLD equal to MLT and an LPC of 0.25 gives an MLD equal to 3.25 × MLT. Equation (1) is

<table>
<thead>
<tr>
<th>Case</th>
<th>Volume (cm³)</th>
<th>SI</th>
<th>LR</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>108.5</td>
<td>6.8</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>2</td>
<td>18.8</td>
<td>5.4</td>
<td>5.5</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>29.2</td>
<td>7.5</td>
<td>7.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**Table I.** Target volume and size.
only valid for LPC > 0. If LPC = 0, no MLD is applied in the
optimization. For each case, five plans with a single 358° arc
field were created using LPCs of 0, 0.25, 0.5, 0.75, and 1.

All the plans had a prescribed dose of 2 Gy × 30, used a 6
MV beam and a maximum dose rate of 600 MU/min. The
jaws were positioned to have a minimum distance to the field
edge of 1 cm to keep them from blocking the field during the
tracking delivery. The collimator was rotated by 45° or 315°.
The dose volume constraints varied for the three cases to
ensure that the clinical objectives (e.g., 45 Gy maximum
dose to the spinal canal) were fulfilled but were the same for
all plans within the same case. The constraint on the total
number of monitor units (MU) was set to 500 MU for all
plans. To investigate the impact of the LPC on the plan qual-
ity, plans with different LPC priorities within the same case
were compared. The plan quality was assessed by evaluating
the calculated dose distribution (0.1 cm grid size) from the
TPS as well as the number of MU. The dose parameters
investigated were the target volume receiving 95% of the
prescribed dose, the maximum dose to the target, the max-
imum dose to the spinal canal, as well as the mean dose to
each lung and to the heart. To relate the results to those of
the plan with no LPC, the value of each of the investigated
parameters was normalized to the value attained for the
same parameter in the same case with no LPC (e.g., for all
plans, the maximum dose to the target was normalized to the
maximum dose to the target for the plan in the same case
with no LPC). Linear regression was used in the evaluation
and the regression coefficient was calculated. A two tailed
confidence level of 95% was chosen, so p-values less than
0.05 were considered significant. Also, the Spearman’s rank
correlation coefficient (ρ) was calculated to assess the corre-
lations. Statistical analysis used SPSS version 15.0.

To quantify the effect of the LPC on the plan modulation,
the average adjacent leaf distance (ALD) was calculated.
The ALD of a plan was derived by calculating the average
value of the adjacent leaf distance in each control point and
computing the average of this value over all control points in
the plan

$$\text{ALD} = \frac{1}{n} \sum_{i=1}^{n} m_i,$$

(2)

where n is the number of control points and mi is the mean
adjacent leaf distance for control point i. The impact of mi
on the delivered dosimetric accuracy is likely to depend on
the dose delivered at control point i. The ALD was, there-
fore, weighted to the percentage of the beam to be delivered
in each control point

$$\text{ALD}_w = \frac{1}{n} \sum_{i=1}^{n} m_i \cdot w_i,$$

(3)

where wi is the percentage of the beam to be delivered in
control point i. The mean adjacent leaf distance for each con-


$$m = \frac{1}{N} \sum_{j=1}^{N} \left(\frac{|x_j - x_{j-1}| + |x_j - x_{j+1}|}{2}\right).$$

(4)

where xj is the position for leaf j and N is the number of leaves
that are included in the calculation in the specific control
point. N is calculated for each control point and includes
the first and the last open leaf pairs and all leaf pairs in between.

The plans were delivered to the Delta4® dosimetric device
(ScandiDos, Sweden) that measures the 3D dose distribution
using two orthogonal detector arrays surrounded by a cylin-


![Fig. 1. The 1D motion platform carrying the Delta4® dosimetric phantom with the ExacTrac® markers attached to its surface.](https://example.com/delta4-scandios)
results, a measurement with a static target was considered to give the dose distribution that would correspond to optimal motion management. This was, therefore, used as reference in the gamma index evaluation. To avoid the results reflecting discrepancies due to the decrease of interleaf leakage when the MLC tracking system is connected, the static measurement used as reference in the evaluation was made with the MLC tracking system connected for the results with tracking. The reference measurements used for the results without tracking were made with the MLC tracking system disconnected. The gamma index criteria used were the 3% and 3 mm and 2% and 2 mm criteria. The criteria 2% and 2 mm were used as a supplement to the commonly used criteria 3% and 3 mm to thoroughly investigate the dose agreement and to limit the distance to agreement (DTA) to a range smaller than the resolution of the HD MLC (2.5 mm for 32 central leaf-pairs and 5 mm for 28 peripheral leaf-pairs). The dose deviation was evaluated with respect to the isocenter dose and the detector points receiving less than 10% were excluded from the evaluation since these points are likely to pass the evaluation for all cases. The correlation between the gamma index failure rate and the ALD\textsubscript{w} was evaluated to investigate the impact of the MLC motion complexity on the dosimetric accuracy of MLC tracking delivery.

III. RESULTS

The DVH comparison showed similar coverage of the target for the plans with and without the LPC and the variations for the organs at risk appeared to be random (an example is shown in Fig. 2). There was no significant linear dependence of any of the plan quality parameters on the LPC and the Spearman’s rank correlation coefficients was small (|\rho| \leq 0.580) (Table II). The ALD depended significantly on the LPC and had a Spearman’s rank correlation coefficient of –0.917 (Fig. 3, Table II). Note that the LPC does not make the plan approximate a conformal arc, but rather reduces the complexity of the MLC shapes by placing adjacent leaves closer together (Fig. 4). The linear regression coefficient for the plan quality parameters dependence on the LPC was small (|\rho| \leq 0.282).

**TABLE II.** The impact of the leaf position constraint (LPC) on the plan quality and the impact of the weighted average adjacent leaf distance (ALD\textsubscript{w}) on the delivered dosimetric accuracy with and without MLC tracking. The significant correlations are highlighted.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>Coefficient (95% conf interval)</th>
<th>p</th>
<th>Spearman’s rank correlation (\rho)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of MUs</td>
<td>LPC</td>
<td>0.092 (–0.021, 0.206)</td>
<td>0.102</td>
<td>0.329</td>
</tr>
<tr>
<td>Target V\textsubscript{95}</td>
<td>LPC</td>
<td>–0.002 (–0.005, &lt;0.001)</td>
<td>0.066</td>
<td>–0.580</td>
</tr>
<tr>
<td>Target max dose</td>
<td>LPC</td>
<td>–0.004 (–0.013, 0.005)</td>
<td>0.378</td>
<td>–0.361</td>
</tr>
<tr>
<td>Spinal canal max dose</td>
<td>LPC</td>
<td>0.111 (–0.122, 0.345)</td>
<td>0.322</td>
<td>0.361</td>
</tr>
<tr>
<td>Lung R mean dose</td>
<td>LPC</td>
<td>0.036 (–0.021, 0.093)</td>
<td>0.193</td>
<td>0.318</td>
</tr>
<tr>
<td>Lung L mean dose</td>
<td>LPC</td>
<td>0.008 (–0.049, 0.066)</td>
<td>0.758</td>
<td>–0.011</td>
</tr>
<tr>
<td>Heart mean dose</td>
<td>LPC</td>
<td>0.026 (–0.139, 0.191)</td>
<td>0.738</td>
<td>–0.055</td>
</tr>
<tr>
<td>ALD</td>
<td>LPC</td>
<td>–0.323 (&lt;–0.413, –0.233)</td>
<td>&lt;0.001</td>
<td>–0.917</td>
</tr>
</tbody>
</table>

Gamma index failure rate with criteria 3% and 3 mm

| With tracking | ALD\textsubscript{w} | 48.645 (37.413, 59.876) | <0.001 | 0.949 |
| No tracking   | ALD\textsubscript{w} | –1.382 (–13.149, 10.384) | 0.804 | –0.077 |

Gamma index failure rate with criteria 2% and 2 mm

| With tracking | ALD\textsubscript{w} | 61.454 (44.348, 78.559) | <0.001 | 0.854 |
| No tracking   | ALD\textsubscript{w} | 7.769 (–9.245, 24.782)  | 0.342 | 0.282 |
IV. DISCUSSION

The dosimetric results indicated a strong potential of motion management for the cases studied. MLC tracking proved to accurately adjust the treatment to the target movements for the plans with low and intermediate ALD\textsubscript{w} but for the highly modulated plans, the tracking performance was decreased. This was especially apparent for the plan with no LPC for case 1. The ALD\textsubscript{w} value for this plan was higher than for the other two cases, which might be due to the larger target volume for this case (109 cm\textsuperscript{3}) compared with the target volumes for the other two cases (19 cm\textsuperscript{3} and 30 cm\textsuperscript{3}). It should be noted that the targets used in this study were selected to generate complex treatment plans and many RA plans may have a lower ALD\textsubscript{w} than the cases in this study even without the use of an LPC. The strong correlation between the tracking performance and the ALD\textsubscript{w} suggests that a good indication of the dosimetric accuracy of MLC tracking delivery can be given by calculating the ALD\textsubscript{w} of the plan. However, the results vary for the different cases for plans with similar ALD\textsubscript{w} which implies that other factors may affect the results as well.

The 2\% and 2 mm criteria emphasized the motion induced effects for delivery with no motion management while the results with MLC tracking had a similar gamma index failure rate for the two criteria. This suggests that some of the motion induced effects when no motion management was used were hidden with the coarse criteria 3\% and 3mm and that a very accurate delivery is possible with MLC tracking for plans with low ALD\textsubscript{w}.

The Spearman’s rank correlation test indicated that the relationship between the variables could be described as a monotonic function only in the cases where there was also a strong linear dependence. Linear regression showed that the impact of the LPC on the plan quality was not statistically significant, which suggests that it can be used to increase the compatibility of highly modulated plans with MLC tracking delivery. The target V\textsubscript{95} and the LPC had a Spearman’s rank correlation coefficient and a two-tailed significance level for the linear regression that might indicate a weak correlation ($\rho = -0.580$, $p = 0.066$). However, since the linear regression coefficient was close to zero ($\rho = 0.002$) and the difference between the minimum and maximum value of the target V\textsubscript{95} for plans within the same case was found to be less than 1\% of the target volume, a possible effect of the LPC is unlikely to be of clinical significance. The observed variations in the treatment plans might be due to the intrinsic stochastic component in the RA optimization that allows variations to avoid traps in local minima.\textsuperscript{32}
In this study, the plan MLD was restricted in the optimization but other options could be investigated in a future study, such as applying a constraint on the average leaf distance or the root mean square of the leaf distance. More details could be included in the optimization, such as the amount of motion observed during pretreatment imaging, as well as the leaf dynamics (velocity and acceleration), to better determine the appropriate plan on an individual basis.

V. CONCLUSION

The intrafraction motion had adverse effects on the delivered dose distributions of the plans in this study when it was not compensated for. MLC tracking proved to be a suitable tool for motion management for the plans with low and intermediate plan modulations (small and intermediate average adjacent leaf distance) but for the highly modulated RapidArc plans (large average adjacent leaf distance), the tracking performance was decreased. The results indicate that the dosimetric robustness of MLC tracking delivery of a RapidArc plan can be estimated prior to delivery by evaluating the plan modulation complexity. The leaf position constraint was shown to increase the accuracy of MLC tracking delivery of highly modulated RapidArc plans without significantly compromising the plan quality. In cases of exceptionally high modulation, the leaf position constraint was shown to be essential for accurate MLC tracking.

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