Adapting to the motion of multiple independent targets using multileaf collimator tracking for locally advanced prostate cancer: Proof of principle simulation study

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Abstract

Purpose:
For patients with locally advanced cancer, multiple targets are treated simultaneously with radiotherapy. Differential motion between targets can compromise the treatment accuracy, yet there are currently no methods able to adapt to independent target motion. This study developed a multileaf collimator (MLC) tracking algorithm for differential motion adaptation and evaluated it in simulated treatments of locally advanced prostate cancer.

Methods:
A multi-target MLC tracking algorithm was developed that consisted of three steps: (i) dividing the MLC aperture into two possibly overlapping sections assigned to the prostate and lymph nodes, (ii) calculating the ideally shaped MLC aperture as a union of the individually translated sections, and (iii) fitting the MLC positions to the ideal aperture shape within the physical constraints of the MLC leaves. The multi-target tracking method was evaluated and compared with two existing motion management methods: single-target tracking and no tracking. Treatment simulations of six locally advanced prostate cancer patients with three prostate motion traces were performed for all three motion adaptation methods. The geometric error for each motion adaptation method was calculated using the area of overexposure and underexposure of each field. The dosimetric error was estimated by calculating the dose delivered to the prostate, lymph nodes, bladder, rectum, and small bowel with a motion-encoded dose reconstruction method.

Results:
Multi-target MLC tracking showed an average improvement in geometric error of 84% compared to single-target tracking, and 83% compared to no tracking. Multi-target tracking maintained dose coverage to the prostate CTV D98% and PTV D95% to within 4.8% and 3.9% of the planned values, compared to 1.4% and 0.7% with single-target tracking, and 20.4% and 31.8% with no tracking. With multi-target tracking, the node CTV D95%, PTV D90% and GTV D95% were within 0.3%, 0.6% and 0.3% of the planned values, compared to 9.1%, 11.2% and 21.1% for single-target tracking, and 0.8%, 2.0% and 3.2% with no tracking. The small bowel V57% was maintained within 0.2% to the plan using multi-target tracking, compared to 8% and 3.5% for single-target tracking and no tracking, respectively. Meanwhile, the bladder and rectum V50%
increased by up to 13.6% and 5.2% respectively using multi-target tracking, compared to 2.7% and 1.9% for single-target tracking and 11.2% and 11.5% for no tracking.

**Conclusions:**

A multi-target tracking algorithm was developed and tracked the prostate and lymph nodes independently during simulated treatments. As the algorithm optimizes for target coverage, tracking both targets simultaneously may increase the dose delivered to the organs at risk.
Introduction

Patients with locally advanced cancer can benefit from the irradiation of the primary tumor as well as the associated lymph nodes using radiotherapy.\textsuperscript{1} In many cases, accurately treating multiple tumor targets simultaneously is challenging due to differential motion between targets. For example, for patients with locally advanced prostate cancer, motion of the prostate and associated pelvic lymph nodes are uncorrelated\textsuperscript{2} as the prostate can undergo up to 15 mm of continuous motion\textsuperscript{3,4} during treatment while the lymph nodes remain static as they are fixed to the pelvic vasculature.\textsuperscript{5} For patients with locally advanced lung cancer, the relative movement between the primary lung tumor and the involved mediastinal lymph nodes can be greater than 10 mm.\textsuperscript{6-8}

As targets move independently, when treatment is aligned to a specific target, the dose coverage to the remaining targets will inevitably suffer. Van Elmpt \textit{et al.} found that the fraction of patients treated for lung cancer with nodal involvement who had a loss of dose coverage to the lymph node CTV D99\% was 10\% for a bony anatomy setup, and 13\% when set up to the primary tumor\textsuperscript{9}. Hwang \textit{et al.} found that with a 10 mm prostate displacement during an intensity-modulated radiotherapy (IMRT) treatment, the dose to the prostate D95\% decreased by an average of 14 ± 8\% when motion was not corrected.\textsuperscript{10} When the isocenter was shifted to align with the prostate, the lymph nodes D95\% decreased by an average of 14 ± 6\%. Large CTV to PTV margins are instead needed to compensate for these dosimetric losses.\textsuperscript{2} However, expanded margins do not always encapsulate the motion of the target during treatment.\textsuperscript{11,12}

Studies have found that oligometastatic patients with multiple metastases may have improved long-term survival if all lesions are ablated during surgery or stereotactic ablative radiotherapy (SABR).\textsuperscript{13,14} With higher doses delivered per fraction, SABR requires a higher degree of accuracy and sparing of normal tissue\textsuperscript{15}, making expanded margins for differential motion even less desirable.

While several real-time adaptation methods have been developed including gimbaled\textsuperscript{16} and robotic\textsuperscript{17} tracking, couch tracking\textsuperscript{18}, and multileaf collimator (MLC) tracking\textsuperscript{19}, these methods have been limited to single-target adaptation. There are currently no real-time adaptation solutions that exist on a standard linac, and the only commercial real-time adaptation systems currently available are the CyberKnife\textsuperscript{17} and Radixact treatment systems\textsuperscript{20}. Various studies have investigated online methods that adapt to differential target motion.\textsuperscript{10,21-26} However, these studies were limited to IMRT treatments and only corrected for interfraction displacements between
To date, no method has been developed to address the intrafraction differential motion of multiple targets.

To address the problem of differential motion for multiple targets during radiotherapy treatments, in this study, we have developed a multi-target MLC tracking algorithm and evaluated its use for real-time adaptation for clinical treatment plans. MLC tracking is the only real-time adaptation method that can simultaneously adapt to multiple, independent targets, and the hardware required to implement MLC tracking is already available on modern linear accelerators. The multi-target tracking algorithm was evaluated in silico for locally advanced prostate cancer patients treated with volumetric modulated arc therapy (VMAT) and compared to previously implemented single-target MLC tracking and standard clinical practice through a geometric and dosimetric analysis.

**Methods and Materials**

A multi-target MLC tracking algorithm was developed to adapt to multiple targets independently, described in detail below. The algorithm was evaluated through simulation of treatments using six locally advanced prostate cancer patient plans and three representative prostate motion traces. The performance of the multi-target tracking algorithm was compared to single-target tracking and no tracking through geometric and dosimetric analysis outlined in Figure 1.

**The Multi-Target Tracking Algorithm**

The multi-target tracking algorithm adapts to differential target motion using a three-step process, illustrated in Figure 2 and described below.

The first step divided the area of the MLC aperture into sections corresponding to the respective targets. This step is performed before treatment for the aperture shape at each gantry angle from the patient plan.

At each gantry angle, the projection $p$ of the PTV of target $i$ in the beam’s eye view (BEV) was calculated and represented with a binary function

$$p_i(m,n) = \begin{cases} 1 & \text{if } (m,n) \in \text{PTV of target } i \\ 0 & \text{else} \end{cases}$$  \hspace{1cm} (1)

where the area defined by the jaws was discretized into 1 × 1 mm² square grids with each grid element $(m, n)$. 

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The planned MLC apertures $O$ were similarly discretized using

$$O(m,n) = \begin{cases} 1 & \text{if } (m,n) \in \text{plan aperture opening} \\ 0 & \text{otherwise} \end{cases}$$

Due to the finite leaf width, the planned MLC aperture inevitably exposed some normal tissue surrounding the target structures. These areas $C$ were assigned to the closest PTV.

$$C_i(m,n) = \begin{cases} 1 & \text{if } \sum_i p_i(m,n) = 0, O(m,n) = 1 \\ 0 & \text{and element } (m,n) \text{ is closest to target } i \\ \text{otherwise} \end{cases}$$

Thus, the grid elements that were assigned to target $i$ were:

$$O_i(m,n) = O(m,n) \times p_i(m,n) + C_i(m,n).$$

Note that there could be common area shared by the two targets as the projections of the PTVs in the BEV overlapped.

Step 2 occurred in real-time during treatment. As 3D tumor motion is observed during treatment, the motion was transformed into a 2D vector in the BEV coordinate system and the aperture sections for each target were translated independently to correspond to the target’s motion. Thus, the new MLC aperture $g$, for target $i$ was

$$g_i(m,n) = O_i(m + \Delta_{i,m}, n + \Delta_{i,n}).$$

where $\Delta_{i,m}$ and $\Delta_{i,n}$ are the number of grid elements that target $i$ had translated in each direction.

The new ideal MLC aperture shape $G$ was the union of all $g_i$.

$$G = \bigcup_{i=1}^{N} g_i, \text{ where } N \text{ is the total number of targets}$$

If the new location of a grid element was outside of the field defined by the jaw positions, a beam-hold would be asserted.

Lastly, the deliverable MLC leaf positions that best fit to the ideal aperture shape $G$ was determined using a direct optimization leaf sequencing algorithm. Only the physical leaf constraints, i.e. the finite MLC leaf width and the limited formable aperture shapes due to the paired leaf structure, were considered during leaf sequencing in this study. The MU or gantry speed of the control points in the original plan were not changed.
Simulated Treatments

The multi-target tracking algorithm was evaluated using six locally advanced prostate cancer patient plans. Treatment plans included two separate structures, the prostate and stationary pelvic lymph nodes. The prostate PTV was contoured using a 7 mm expansion from the prostate CTV in all directions except posteriorly, where a 5 mm expansion was used, and the lymph node PTV was contoured using a 7 mm expansion from the lymph node CTV in all directions. Each patient was planned to receive VMAT treatment delivered over three arcs on a Varian Trilogy linac (Varian Medical Systems, Palo Alto, USA) equipped with a Millennium 120-leaf MLC. The collimator angles for each arc were set to 10°, 350°, and 0°, and the gantry angles rotated from 181° to 179° over 178 control points. Patients were prescribed 60 Gy to the prostate PTV and 45 Gy to the lymph node PTV delivered in 20 fractions.

Three different motion adaptation methods evaluated:

1. Multi-target MLC tracking
   Treatment was simulated with the patient aligned to the lymph nodes (Figure 3c) at the start of treatment and the multi-target MLC tracking method was used to adapt to both targets’ positions in real-time.

2. Single-target MLC tracking
   Treatment was simulated with the patient aligned to the prostate (Figure 3b) at the start of treatment and a single-target MLC tracking method was used to adapt the entire MLC aperture to the prostate’s motion as previously used to treat low-risk prostate cancer patients.\textsuperscript{28,29}

3. No tracking
   The treatment was simulated according to standard clinical practice with set up to the prostate (Figure 3b) at the beginning of treatment and no intrafraction motion adaptation.

   Treatment was simulated for each patient and motion adaptation method using three different prostate motion traces shown in Figure 4, with the lymph nodes remaining stationary. The motion traces were taken from a patient database with prostate motion measured using Calypso (Varian Medical Systems, Palo Alto, USA).\textsuperscript{3} These traces were selected to represent a range of possible motions that the prostate could undergo during treatment, including a small prostate motion (Figure 4a), a large drift with a substantial and consistent prostate displacement (Figure 4b), and erratic motion where the prostate has sudden, large changes in displacement.
An interfraction prostate displacement relative to the lymph nodes of 3 mm in the posterior direction, and 2 mm in the inferior and right direction was included for each motion trace based on the root mean square deviations of internal prostate displacements with respect to the bony anatomy observed on MVCBCT images by Bylund et al.\textsuperscript{30}

As the single-target and no tracking treatment scenarios were simulated with the patient set up to the prostate at the beginning of treatment, the prostate motion relative to the planned prostate position during the treatment is represented by the top row of Figure 4. The lymph nodes were displaced by 3 mm in the anterior direction, and 2 mm in the superior and left directions as a result of shifting the entire patient to correct for the prostate’s displacement (illustrated in Figure 3). As the patient was simulated with set up to the nodes for the multi-target tracking scenario, the lymph nodes remained in the planned position, while the prostate motion relative to the planned position is shown in the bottom row of Figure 4.

**Geometric Analysis**

The geometric accuracy of each motion adaptation method was evaluated by calculating the area of overexposure and underexposure as described by Poulsen et al.\textsuperscript{31} The ideal MLC aperture shapes for each motion trace were calculated by shifting the MLC aperture section belonging to each target to the corresponding target’s position at each control point, without any MLC leaf limitations. The geometric accuracy of each treatment method was then assessed by calculating the area of the treated MLC apertures that were incorrectly inside of the ideal MLC aperture (overexposure $A_O$), and the area incorrectly outside the ideal MLC aperture (underexposure $A_U$). The total geometric error, $A_O + A_U$, was calculated at each control point to assess the total area of mismatch between the delivered and ideal MLC apertures.

**Dosimetric Analysis**

Each motion adaptation method was also assessed dosimetrically using a dose reconstruction method previously described by Poulsen et al.\textsuperscript{32} The original DICOM treatment plans were exported from the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, USA) and modified using a computer program developed in MATLAB (MathWorks, Natick, MA, USA). Motion was encoded into the original treatment plan by dividing the treatment into several sub-arcs with shifted isocenters that corresponded to the prostate positions, using 1 mm bins. The MLC positions that were output by the MLC tracking software were encoded into the treatment plan instead of the original planned MLC positions to calculate the dose delivered using multi-
target tracking and single-target tracking (Figure 1). The modified DICOM treatment plan was imported into the treatment planning system to calculate the dose delivered. The isocenter shift method was used to reconstruct the dose to structures that were considered moving which included the prostate CTV and PTV, the rectum, and the bladder. A separate dose reconstruction without motion encoding was used to evaluate the dose to static structures including the node CTV, PTV and GTV, and the small bowel.

Results

Geometric results
The mean $A_O + A_U$ across the six patients for each motion trace is shown in Figure 5. Multi-target tracking had the smallest geometric error with average improvements over single-target tracking of 79%, 91% and 82% for small motion, large drift, and erratic motion, respectively. Multi-target tracking had average improvements over no tracking of 78%, 88% and 84% for small motion, large drift, and erratic motion, respectively.

Dosimetric results
The difference in planned doses and delivered dose using multi-target tracking, single-target tracking, and no tracking is shown in Figure 6. Percentage differences are relative to the prescription dose of 3 Gy per fraction. Across all three prostate motion traces, the maximum reduction from the planned dose to the prostate CTV $D_{98\%}$ and PTV $D_{95\%}$ using multi-target tracking was 4.8% and 3.9% respectively, compared to single-target tracking which maintained the doses to within 1.4% and 0.7% respectively. Meanwhile, the prostate CTV $D_{98\%}$ and PTV $D_{95\%}$ were decreased by up to 20.4% and 31.8% when large prostate motion was not tracked. The node CTV $D_{95\%}$, PTV $D_{90\%}$ and GTV $D_{95\%}$ with multi-target tracking were within 0.3%, 0.6% and 0.3% respectively. Tracking the prostate using single-target tracking decreased the node CTV $D_{95\%}$, PTV $D_{90\%}$ and GTV $D_{95\%}$ by up to 9.1%, 11.2% and 21.1% respectively. The interfraction prostate displacement simulated in this study decreased the node CTV $D_{95\%}$, PTV $D_{90\%}$ and GTV $D_{95\%}$ by up to 0.8%, 2.0% and 3.2% respectively when the patient was set up to the prostate and motion was not tracked.

Treatment simulated using multi-target tracking increased the bladder V50% by up to 13.6% during a large prostate drift (Figure 4b) and increased the rectum V50% by up to 5.2% during the small prostate motion (Figure 4a). The dose to the small bowel remained within 0.2%. Using single-target tracking, the bladder and rectum V50% were increased by up to 2.7% and
1.9% respectively. When motion was not tracked, the bladder and rectum V50% were increased by up to 11.2% and 11.5% respectively. No large increases in the small bowel V57% were observed, however deviations from the planned doses of up to 8% and 3.5% were seen when treatment was simulated using single-target tracking and no tracking, respectively.

An example of the delivered dose distributions using each motion adaptation method for a patient experiencing a large prostate drift is shown in Figure 7.

Discussion
This study developed and tested a novel method that tracks multiple, independently moving targets in real-time using a new MLC tracking algorithm. Multi-target tracking was the only method that was able to track both the prostate and lymph nodes for locally advanced cancer patients, advancing the previous implementation of MLC tracking which includes translation, rotation and deformation.

Multi-target tracking had the lowest overall geometric error compared to single-target tracking and no tracking, as shown in Figure 5. Since multi-target tracking involved patient setup to the static nodes, it nearly eliminated both geometric and dosimetric errors for the nodes (Figure 5, Figure 6). Single-target tracking and no tracking, both involving patient alignment to the prostate, resulted in large geometric errors for the nodes caused by the correction for the interfraction shift of the prostate relative to the nodes, and for single-target tracking by translating the whole MLC aperture with the prostate’s motion.

However, the patient setup to the nodes for the multi-target tracking simulations resulted in larger prostate errors than with single-target tracking, and even without tracking when the intrafraction motion was small (Figure 5a). This difference was due to the finite MLC leaf width of 5mm. When patients were aligned to the lymph nodes, the initial prostate displacement was 3 mm in the posterior direction, and 2 mm in the inferior and right directions (Figure 4). This displacement resulted in a BEV prostate position that was often offset by half a leaf width, as shown in Supplementary Figure 1. When prostate motion was small, errors resulting from the finite leaf width (up to 2.5 mm errors) were larger than the error resulting from the prostate displacement (maximum 1.6 mm). These results are consistent with the MLC tracking literature where leaf fitting errors have been found to be the biggest contributor to geometric errors for prostate MLC tracking.
As the multi-target treatment method aligns the patient to the nodes at the beginning of treatment, the magnitude of the interfraction prostate displacement can affect the accuracy of MLC tracking. The effect of the interfraction prostate displacement on geometric accuracy is demonstrated in Supplementary Figure 2, where treatments with small intrafraction prostate motion and varying interfraction prostate displacements were simulated for comparison to Figure 5a.

These results were also reflected in our dosimetric analysis, shown in Figure 6. Multi-target tracking was mostly able to simultaneously maintain dose coverage to the prostate CTV and PTV, as well as the node CTV, PTV, and GTV. Similar to the geometric results in Figure 5, the largest deviation from the planned prostate dose was seen with the small motion trace (Figure 4a). Single-target tracking was able to maintain high dose coverage for the prostate CTV and PTV but resulted in considerable decreases in dose to the node CTV, PTV, and GTV, in particular with the large drift motion, which had prostate drift in the same direction as the interfraction prostate displacement (Figure 4b). Without tracking, the prostate and rectum doses decreased, and the bladder dose increased during the large (inferior-posterior) prostate drift (Figure 6b), while the rectum dose increased when prostate motion was erratic (Figure 6c). The node PTV D90% decreased, however, by only a small amount compared to the nodal volume. Due to the large node CTV to PTV margin (7 mm) compared to the interfraction prostate displacement, dose coverage was maintained to the node CTV. The small bowel V57% decreased for both single-target tracking and no tracking with the interfraction prostate shift being in the inferior and posterior direction. A patient setup to a prostate displacement in the opposite direction may instead increase the small bowel dose.

Conforming with standard clinical practice, the patient plans in this study had a pelvic lymph node CTV to PTV margin of 7 mm, which would have accounted for a majority of the error caused by the interfraction prostate displacement simulated in this study. With multi-target tracking enabled, these margins could potentially be reduced as indicated by the high node PTV coverage in Figure 6, which would decrease the total dose delivered to the patient during treatment. Reduced PTV margins would also reduce the common MLC aperture area shared by the prostate and node PTVs, potentially reducing the overdosing error seen with multi-target tracking. However, if this algorithm was implemented in a clinical setting, there would be some uncertainties associated with the target localization method and patient setup. Methods such as
Calypso or Kilovoltage Intrafraction Monitoring have been measured to have sub-millimeter 3D target localization accuracy. \(^{36-38}\) While this uncertainty is small, PTV margins would still be needed to account for localization and adaptation uncertainties.

Using the current margins, we found that the proposed multi-target tracking method did result in delivering higher doses to the prostate. The additional dose delivered was a result of the common area shared between the prostate and node PTVs in the BEV when the aperture is divided into sections. As described in step 2 of the multi-target tracking algorithm (Figure 2), the aperture sections are translated according to the targets’ motion and the ideal aperture is formed by the union of the translated sections. Thus, the shared aperture shape between each PTV will be repeated in the translated area of the MLC aperture that corresponds to the new target position. This increase in open aperture area results in an increase in dose to the targets in the region that they overlap, which can be seen in Figure 7. As a consequence, the dose to the rectum and bladder volumes near the overlap of the prostate and node PTVs were also increased, depending on the direction of prostate motion. This is the main limitation of the multi-target tracking method, and applications of multi-target tracking should aim to minimize dose to the bladder and rectum to prevent toxicity which may lead to quality of life issues such as urinary incontinence, sexual dysfunction, bowel incontinence, or rectal irritation. \(^{39-41}\) The small bowel was unaffected, with dose delivered within 0.2% of the original plan when multi-target tracking was implemented.

In future work, real-time replanning methods using MLC tracking could look at adapting the MLC aperture shape to adjust for dosimetric errors occurring during treatment in real-time. Wisotzky et al.\(^ {42}\) developed and tested a novel MLC tracking algorithm that optimized leaf sequencing based on a 2D dose map for IMRT plans. An MLC tracking method optimized by the 3D delivered dose would be preferable to correct for tracking errors arising from the finite MLC leaf widths and speeds. The multi-target MLC tracking algorithm could also potentially be optimized by favoring a particular tumor target or balancing trade-offs between target dose delivery and OAR avoidance. Moore et al.\(^ {43}\) evaluated an MLC tracking algorithm that implemented a cost-density function that could assign imbalanced weights to overexposure and underexposure for IMRT plans and can be generalized for multiple targets.

While this current work focusses on the prostate and the associated lymph nodes, this multi-target tracking method could have applications for other locally advanced treatments, such as for lung cancer, or the oligometastatic treatment setting. The multi-target tracking algorithm
described in this study can be generalized to an arbitrary number of independently moving targets. The development of MLC tracking to adapt to multiple targets can potentially increase the number of patient eligible for adaptive treatment to include those with high risk cancer.

One of the limitations of this study was the rigid dose reconstruction method. The dose to the moving structures, the prostate, bladder, and rectum were reconstructed separately from the static lymph nodes and small bowel. The method utilized in this study shifts the isocenter, simulating rigid motion for the prostate, as well as the bladder and rectum. However, in reality, the bladder and rectum would deform as they are filled, inducing the prostate motion. The clinical scenario envisaged is the implementation of multi-target tracking on a standard linear accelerator, where the prostate position is determined from kilovoltage intrafraction motion monitoring of the prostate markers, and the node position is determined from the pelvic bony anatomy. In standard linear accelerator scenario, there is only target and node positional information, and no additional information available to implement a deformable dose reconstruction method. In a more advanced clinical scenario, such as on an MRI-Linac, sufficient information may be available to perform a deformable dose reconstruction.

The treatment strategies investigated in this study were only simulated for three, selected prostate motion traces to understand what may be observed in a range of scenarios. These dosimetric results may not be representative of the total dose received by a patient over the course of treatment delivered in multiple fractions. Hsu et al. simulated the impact on dose coverage of interfraction prostate shifts when setting the patient up to the prostate for five, 25 fraction IMRT plans, and found the dosimetric impact of random shifts to be negligible in the absence of a significant systematic shift. However, this may not be the case if the planning CT has captured a non-representative patient anatomy. Tumor motion can also have a larger impact on the total delivered dose as treatments tend toward hypofractionation.

**Conclusion**

A method to simultaneously track targets with differential motion in real time has been developed and evaluated in silico. This study has demonstrated the advantages of a multi-target MLC tracking method as well as the shortcomings which will drive future development. Once clinically realized, this method could improve patient outcomes by allowing for margin reductions to minimize healthy tissue toxicity while ensuring dose coverage of all independent cancerous targets.
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Conflict of Interest
PJK is an inventor on US patents 7,469,035 and 8,971,489 that are related to MLC tracking. Patent 7,469,035 is unlicensed; patent 8,971,489 is exclusively licensed to Asto CT.
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(a) Small motion

(b) Large drift

(c) Erratic motion
(a) Small motion

(b) Large drift

(c) Erratic motion
Figure 1. Evaluation of multi-target tracking for clinical VMAT plans. Treatments for six locally advanced prostate cancer plans with three prostate motions were each simulated using multi-target tracking, single-target tracking, and no tracking. Simulated treatments were assessed through geometric and dosimetric analysis.

Figure 2. The three steps involved in the multi-target MLC tracking algorithm. Step 1 divides the MLC aperture into sections belonging to each corresponding target in the beam’s eye view. Step 2 translates each section of the aperture individually and recombines them to obtain the ideal MLC shape. Step 3 recalculates the MLC aperture to form the deliverable MLC aperture.

Figure 3. The relative positions of the prostate PTV, node PTV and the treatment isocenter under different scenarios. (a) The position of each structure in the planning CT. (b) The position of the structures at the beginning of a fraction with an interfraction prostate displacement compared to the planned position, indicated by the arrow. To align the patient to the prostate, the whole patient is shifted, instead displacing the node PTV. This setup was used in the single-target tracking and no tracking scenarios. (c) The position of the structures with an interfraction prostate displacement, with the patient set up to the nodes. This setup was used in the multi-target tracking scenario.

Figure 4. Three motion traces from Langen et al. used to represent patient prostate motion. Top row: Prostate motion relative to the set-up position for single-target tracking and no tracking scenarios. Bottom row: Prostate motion relative to the set-up position for multi-target tracking with initial alignment of the lymph nodes. This motion includes an interfraction prostate displacement relative to the lymph nodes of 3 mm posterior and 2 mm inferior and right.
Figure 5. The total area of underexposure and overexposure for (a) small motion, (b) large prostate drift and (c) erratic motion, for multi-target tracking, single-target tracking, and no tracking treatments.

Figure 6. The differences in dose from the planned doses for multi-target tracking, single-target tracking and no tracking for six patients whose prostate underwent (a) small motion, (b) a large drift, and (c) erratic motion. The dose is normalized to the prescription dose. The whiskers represent the minimum and maximum values.

Figure 7. The reconstructed dose distributions for treatment delivered using multi-target tracking, single-target tracking, and no tracking for a patient undergoing a large prostate drift. The dose wash ranges from 95% to 121.6% for the moving structures, and from 75% to 121.6% for the static structures.