

# Real-time tumor tracking during VMAT radiotherapy treatments based on 2D/3D registration using CBCT projections

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**Abstract.** Rotational radiotherapy treatments such as volumetric modulated arc therapy (VMAT) can have superior overall quality while having shorter delivery time with respect to conventional intensity modulated radiotherapy (IMRT). As with conventional treatments, intra-fractional tumor motion is a major source of uncertainty in dose application. To ensure full tumor coverage the planning target volume (PTV) margins are enlarged. Tumor tracking using intensity based 2D/3D registration can reduce uncertainty and would enable margin reduction. The challenge for full arc rotational treatments is the poor tumor visibility at certain irradiation angles. In this work we investigate the feasibility of tumor tracking in VMAT treatments with partial arcs where the tumor is well visible. For three patients, we determined for which subset of angles it was possible to track the tumor using raw projections from CBCT acquisition. We then generated VMAT plans with the obtained partial arcs. Full arc VMAT plans were used as benchmark. For all cases it was possible to track the tumor in two arcs of about 90 degrees, typically with imaging around anterior-posterior (AP) or posterior-anterior (PA) projections. The plans with the partial arcs were clinically comparable to the plans with full arc in terms of target coverage and OAR sparing. The results indicate the feasibility of partial arc VMAT treatments with tumor tracking. Based on this we will investigate generation of plans with reduced PTV margins. These treatments could be delivered by gating the LINAC beam if the tumor motion exceeds a certain margin.

**Keywords:** 2D/3D registration, motion tracking, radiation therapy, VMAT

## 1 Introduction

In radiotherapy, rotational treatments such as intensity modulated arc therapy (IMAT) or volumetric modulated arc therapy (VMAT) have shown superior overall quality while treatment times are shorter [3]. As with conventional treatments, intra-fractional tumor motion remains as one of the main challenges to

solve. The uncertainty due to tumor motion imposes an enlargement on the planned target volume (PTV) in order to assure sufficient dose delivery to the tumor to achieve local control [9]. The PTV enlargement typically leads to increased dose delivery to organs at risk (OAR). In the case of lung tumors, the target site of this work, the main cause for motion is breathing. But, depending on the tumor location heartbeat can also contribute.

Continuous efforts to manage tumor motion have been made especially in the last decade. Management can be done by tracking the tumor position during treatment in order to reduce the uncertainty. Among the different approaches for tumor tracking, purely intensity based 2D/3D registration [11] using x-ray images acquired intra-fractionally is a feasible approach. This technique can deal well with both periodical and non-periodical motion patterns in conventional SBRT treatments [8][7]. However, results for this technique are for the time being limited to specific imaging angles. Investigation at tumor tracking for different gantry angles is underway [13] but early results suggest that for many cases there are imaging angles where tumor tracking will not be possible due to poor visibility. This would limit the applicability of 2D/3D registration for rotational treatments as typically they consist of a full arc rotations around the patient. Tracking approaches using implanted fiducial markers [5] are very successful and have therefore been investigated for VMAT treatments as well [1]. But, implanting markers in the lung has associated complications [4].

In this work we investigate the feasibility of performing partial arc VMAT treatments for lung cases using markerless real-time 2D/3D registration for tumor tracking. The partial arcs consist of the angle intervals where the tumor is well visible and therefore tracking is possible. To assess the feasibility of tumor tracking we used x-ray projections acquired for CBCT reconstruction of the patients under treatment. The projections form a basis for assessing the angle intervals where tracking is possible. Based on individual patient findings, partial arc treatment plans were generated and their clinical relevance compared to a regular full arc VMAT plan. Our aim is to create partial arc treatment plans with reduced PTV margins and to deliver treatment with the tumor under constant monitoring.

## 2 Materials and methods

### 2.1 Image datasets and Image preprocessing

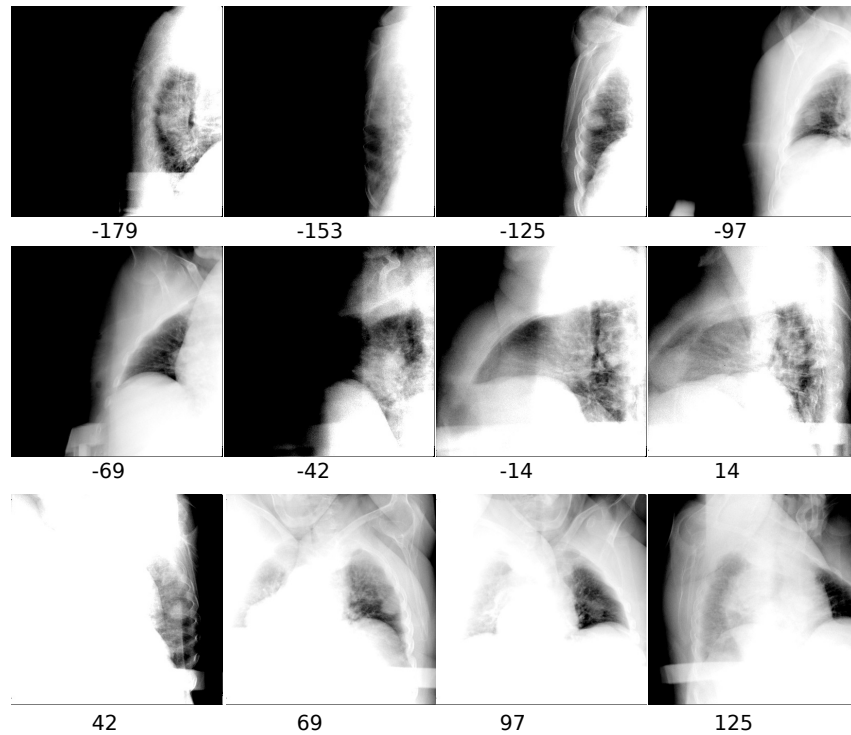
For this investigation we used data from three patients undergoing hypo-fractionated SBRT treatment at our hospital. Each patient was treated with 3 fractions. As a routine at each fraction, a cone beam CT (CBCT) is acquired for the purpose of daily patient positioning. This setup step is well established and guarantees that during treatment, uncertainties in tumor location are typically only due to breathing or heartbeat.

Each of the CBCTs is reconstructed from 657 planar kV x-rays. These x-rays are the ones used in our study. The diaphragm position was manually annotated

in each of the projections and is the basis for deciding when the tumor was correctly tracked or not.

Tumor visibility depends on the x-ray path through the body. Therefore, for optimal tumor tracking the image intensity settings have to be adjusted as a function of each projection angle. An automatic intensity adjustment method based on contrast maximization in the PTV region was used [6]. As an example, figure 1 shows CBCT projections for 12 different gantry angles which are automatically intensity adjusted based on this method.

For creating the new VMAT plans, we used the conventional planning CT which has all the target volumes and organs at risk (OARs) delineated. Both the full and partial arc VMAT plans were generated using these CT datasets.



**Fig. 1.** Illustrative set of x-ray projections obtained during CBCT acquisition for patient 2. The figure shows 12 projections with the angle indicated. All images were automatically intensity adjusted to maximize contrast around the tumor region. The tumor is well visible in projections around the AP or PA directions (angles -153, -125, -97, -69, 42, 69, 97) and not well distinguishable in the other angles.

## 2.2 2D/3D registration

Intensity based 2D/3D registration is an optimization process which aims at finding the spatial transform for a volume dataset of the patient that generates a digitally reconstructed radiograph (DRR) that best matches a real x-ray image acquired during treatment.

The first step of the registration consists of generating an initial DRR from the planning CT. The planning CT is initially aligned by 3D/3D registration to the CBCT volume. The initial transform for the first DRR is defined automatically by using the imaging angle for each of the CBCT projections. The DRR is then compared to the CBCT projection by means of a merit function. An optimizer iterates through the previous steps (new DRR and merit calculation) searching for the rigid spatial transformation  $T$  with the highest similarity between the DRR and the x-ray. The final translational and rotational parameters  $(t_x, t_y, t_z, \omega_x, \omega_y, \omega_z)$  represent the tumor displacement.

The registration was limited to a region-of-interest (ROI) defined as the projection of the PTV on the x-ray images. We selected this ROI mainly because this is the area where we want to track motion and where this motion is assumed to be rigid as our method does not account for deformation. One advantage of using a small ROI is also that rendering a smaller region is much faster.

DRR generation is the most time consuming step therefore we used ray-casting implemented on a general purpose graphics processing unit (GPGPU). We used normalized mutual information [10] or stochastic rank correlation [2] as merit functions. We used the NEUWOA algorithm proposed by Powell [12] for the optimization.

## 2.3 Evaluation methodology

The evaluation consists of two steps. The first step is to determine the angle interval for which the tracking is feasible. This was done by applying the 2D/3D registration for each of the CBCT images and comparing the obtained results with the annotated diaphragm motion. The range of angles where tracking is possible was determined to be the range where the correlation of tracking and annotated motion is good. This was determined by visual inspection of the plots shown in Figure 2 and by cross checking with inspection of the CBCT images.

The second step is the creation of a VMAT plan for the partial angle arcs where tracking is possible. Since the kV images are acquired with a fixed 90 degree angle in relation to the treatment beam (gantry), the angle arcs used for planning are perpendicular to the imaging angles. The generated plan is then compared with a clinically "conventional" full arc VMAT plan. If the partial arc plan fulfills the clinical requirements for the given treatment it is then considered accepted.

## 3 Results

Table 1 summarizes the tracking results for all three patients. For all cases, two arcs were defined with the angle intervals where the tumor could be tracked.

The angles were always with imaging roughly around anterior-posterior (AP) and posterior-anterior (PA) directions. The table shows for each patient, the angle interval for imaging around AP, the interval for imaging around PA and the total angle range for which imaging is available. All but one of the partial arcs are over 90 degrees and the total range of angles where tracking is possible exceeds 180 degrees for all three patients. Figure 2 shows for each patient plots of the full tracking sequence from the CBCT projections which was used to determine the arc ranges. Finally, figure 3 shows the obtained plans for full arc (left) the partial arcs (middle) and the corresponding DVHs (right). As it can be seen, the DVHs of the full and partial arc plans are comparable in terms of both target coverage and OAR sparing. The dose distributions for the partial plans are in general acceptable though for patient 1 there is an increase of low dose to the heart which should be better investigated.

Patient	Angles (deg)			Total (deg)
	AP		PA	
1	-136	-25	32	155
2	-160	-65	20	108
3	-141	-48	52	149

**Table 1.** Summary of the angle intervals for which tumor tracking was possible. For each of the patients two arcs were obtained, one around the AP and the other around the PA directions. For these two partial arcs, the minimum and maximum angle where tracking was possible is indicated. The last column shows the total angle range.

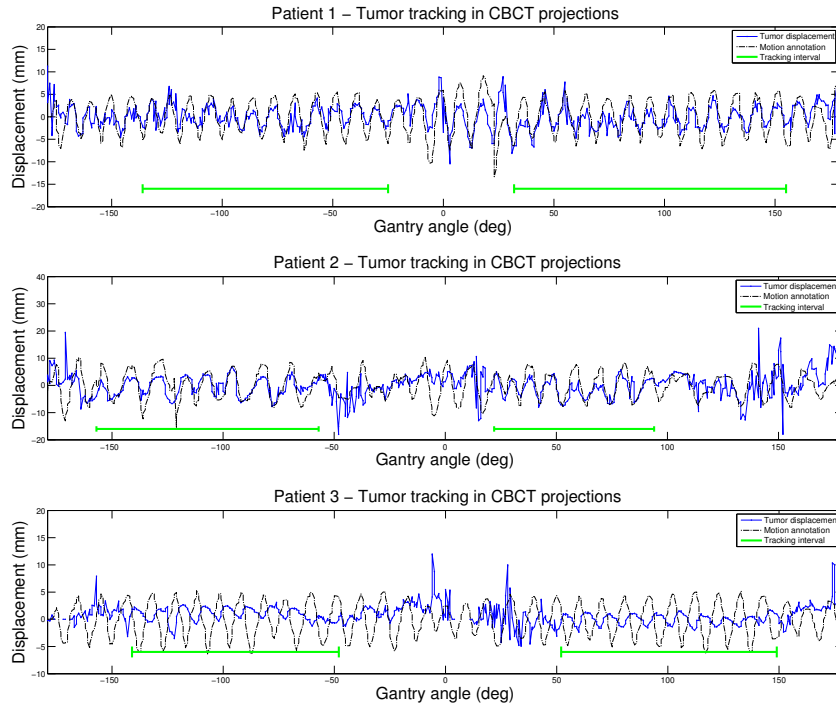
## 4 Discussion and Conclusions

The results obtained in our study suggest that it is clinically feasible to perform VMAT treatments with partial arcs where tumor imaging is possible.

In terms of tumor tracking feasibility, in all cases the total range of angles where imaging is possible exceeded 180 degrees that is, equivalent to over a half of a full arc. The imaging angles are always around the AP or PA directions which is to be expected as this is the direction where the heart or other structures within the mediastinum are not occluding the tumor.

During actual treatment, scatter from the treatment beam will have a negative effect on the kV images so they will actually contain more noise than these CBCT projections. Nevertheless, in our previous work, the same scatter was present when using simultaneous kV-MV acquisition but the additional noise had a small impact on tracking accuracy [7].

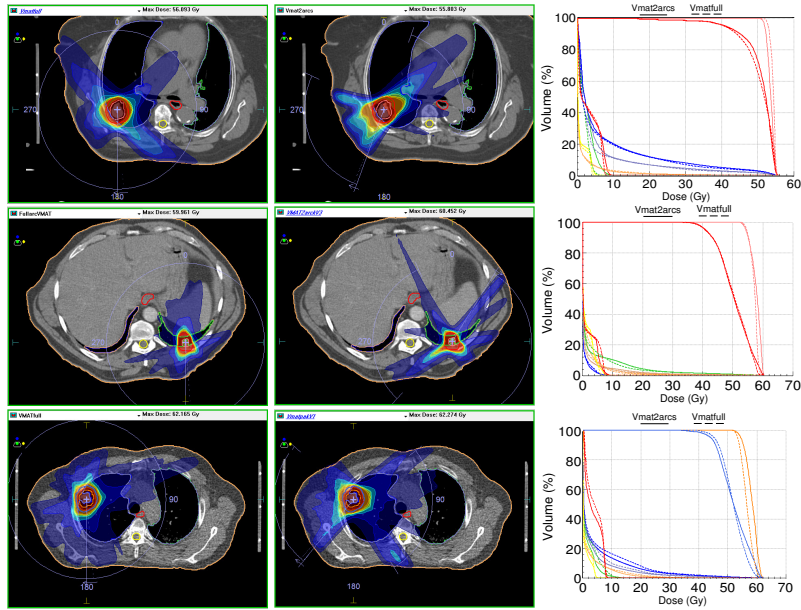
The treatment plans that were generated based on the tumor visibility show DVHs which are clinically acceptable. The dose distributions however need to be closely analyzed. In the case of patient 1, there is an increased low dose



**Fig. 2.** Tumor tracking in the full range of 360 degrees (657 CBCT x-ray projections). The tracking results (blue line) are compared to the annotated diaphragm motion (dashed black line). The angles where the tumor could be tracked is shown in green.

delivered to the heart. Since there is no contour of the heart on this dataset (as it was not considered an OAR for the SBRT planning), it was for the time being not possible to evaluate the amount of delivered dose. With a contour it would be possible to optimize treatment planning to minimize the dose. For this and subsequent cases, relevant organs will be additionally delineated and used as constraints in treatment planning. In all three cases higher doses were observed close to the spinal cord. Though the study is promising, these plans have to be considered as preliminary and need careful plan optimization and clinical validation by a radiation oncology expert.

In terms of clinical implementation, tracking the tumor position in the CBCT projections was done retrospectively and can therefore be seen as a planning step. The tracking method used was the same which is to be used intra-fractionally which means that as long as there are no important anatomical changes, the tumor can be tracked during treatment for the same angles. In terms of workflow this means that for each patient, a partial arc and a full arc plans would be generated and the decision of which one to use would be based on the CBCT acquired immediately before treatment.



**Fig. 3.** Comparison of full arc VMAT (left) partial arc VMAT (middle) dose distributions and corresponding DVHs (right) for the three patients in the study.

Also, in a clinical scenario, imaging and registration latency will have to be taken into account. The imaging latency could be up to a few hundred milliseconds while one registration takes slightly less than 100 ms. This means that a motion prediction scheme will have to be used to estimate the true tumor position at a given time.

The method shown here is dependent on the availability of a CBCT prior to irradiation. CBCT is commonly available as it is used for patient setup. In cases where it might not be available, an alternative approach could be used. The planning CT can be used to generate DRRs in the full 360 degree arc. These DRRs could then be the base to assess on which angle arcs tumor tracking would be possible.

The final aim will be to create treatment plans with reduced PTV margins. As the tumor position will be known during treatment, margins can be reduced and the plan delivered as long as the tumor moves within the expected limits. If this is not the case, the beam can be turned off until the tumor position is again within limits. In the future, the dosimetric benefits of margin reduction have to be weighted against the additional dose burden imposed by kV imaging and the additional planning time required to implement this approach.

Despite the preliminary nature of these results, they represent a very positive indication that tracking during VMAT treatments is feasible, bringing the benefit of shorter delivery times, high conformal dose distributions and reduced margins.

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