2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

4DCT-Based Registration-Guided Dose Accumulation and Tracking Simulation for VMAT-Lattice Radiotherapy

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ABSTRACT

This study proposes a 4DCT-based deformable registration-guided dose accumulation and motion tracking simulation framework to evaluate the impact of respiratory motion on VMAT-Lattice spatially fractionated radiotherapy. The workflow integrates monitor unit (MU) phase mapping, deformable image registration, phase MU resolving, dose accumulation on a reference anatomy, and MLC tracking simulation.

Static VMAT-Lattice plans were evaluated using 4DCT images sorted in ten phases, with comparisons between non-tracking and tracking scenarios, as well as between different deformable registration algorithms. In the tracked scenarios, cumulative dose within high-dose lattice vertices showed improvement, and MLC tracking demonstrated phase-dependent aperture adaptation.

Conclusion: Motion assessment for VMAT-Lattice radiotherapy requires a comprehensive evaluation of control point timing, deformation field uncertainty, dose accumulation, tracking behavior, and peak-to-valley dose ratio (PVDR). This framework supports simulation-based evaluation; future work should focus on balancing dosimetric accuracy and computational efficiency.

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INTRODUCTION

Spatially Fractionated Radiotherapy (SFRT) has emerged as an attractive strategy for improving tumor control while limiting normal-tissue toxicity. Prior work using 4DCT-based simulations and phantom validation has shown that respiratory motion can affect the dosimetric characteristics of VMAT-Lattice radiotherapy, highlighting the importance of motion management for this treatment modality (Slyke et al., 2023). Tumor motion may lead to inadequate target coverage during untracked delivery, whereas MLC tracking can improve geometric alignment between the delivered dose and the moving targets, thereby helping to maintain PTV and vertices dose coverage (Kamerling et al., 2016). Motion-aware VMAT-Lattice dose evaluation therefore requires deformation-based 4D dose accumulation together with time-resolved methods to build phase-specific dose.

In this work, we present a **4DCT-based framework** for motion-aware VMAT-Lattice dose reconstruction that integrates deformable image registration, control-point-resolved MU allocation, and simulated adaptive MLC tracking. The proposed framework reconstructs phase-specific dose delivery and accumulates dose over the respiratory cycle to evaluate motion-induced degradation of lattice dosimetry, with particular emphasis on changes in PVDR.

A deep deformable motion registration (DDMR) model, guided by liver segmentation and lattice-aware weighting, is incorporated to improve local motion and deformation estimation. DDMR is a fast registration method used for repeated phase-specific dose accumulation. This unified workflow provides a practical approach for evaluating respiratory motion effects and supporting future adaptive strategies for VMAT-Lattice radiotherapy.

METHODS AND MATERIALS

A liver 4DCT dataset with a slice thickness of 3mm was used in this study. The 4DCT images were sorted into 10 respiratory phases using phase-based binning. The 50% Phase, corresponding to the end exhalation, was selected as the reference phase for deformable dose accumulation. The target volumes and organs at risk (OARs) were delineated on the average 4DCT image by a radiation oncologist.

The respiratory trace signal was used to assign VMAT control points and their corresponding MUs to individual phase. Two deformable registration approaches were evaluated: an optimization-based method and a learning-based displacement-field prediction method. For both approaches, anatomical segmentation information and lattice-region labels were incorporated to improve local motion estimation in regions relevant to lattice dose delivery. For each respiratory phase, untracked and simulated MLC-tracked phase-specific VMAT sub-plans were generated and imported into Varian Eclipse. Dose was recalculated on the corresponding phase-specific CT images using the AAA algorithm (DUBIN1612), resulting in one dose distribution for each respiratory phase. The phase-specific dose distributions were then deformably mapped and accumulated onto the reference phase to obtain the reconstructed 4D dose.

RESULTS

Compared with the original lattice plan, the untracked delivery showed reduced high-dose coverage of $PTV_{66.7}$, demonstrating the dosimetric impact of respiratory motion. Standard DDMR-based tracking did not substantially recover target coverage in the tracking scenarios, whereas incorporating lattice-guided (Fine) partially restored $PTV_{66.7}$ coverage, with improvements of approximately 4.5%, 7.9%, and 11.9% for ANTs, ANTs-F and DDMR-F, respectively. In contrast, PTV_{20} coverage and OAR DVH metrics showed relatively small variations across reconstruction strategies. As for MU resolving results, the accumulation of untracked dose yielded a PVDR of 1.3. With simulated MLC tracking, the accumulated dose showed improved PVDR values of 1.5, 1.4, 1.6, and 1.4 for ANTs, ANTs-F, DDMR and DDMR-F, respectively. The corresponding dose profiles revealed peak and valley shifts, as well as changes in dose amplitude. These results indicate that translational-based MLC tracking could improve respiratory-motion affected VMAT-Lattice dosimetry. And the assessment of respiratory-motion robustness in VMAT-Lattice radiotherapy should evaluate the preservation of DVH metrics, isodose distributions, and PVDR.

Table 1. Compact dose-metric summary of different track methods

Metric	Ref	Untrack	DDMR	DDMR-F	ANTs	ANTs-F
PTV_66.7 D95% (Gy)	64.7	52.4	45.7	58.3	54.7	56.5
PTV_20 D95% (Gy)	22.1	20.1	21.4	20.3	20.2	20.5
Liver Dmean (Gy)	33.0	29.9	29.1	29.6	29.8	29.9
Kidney_R Dmean (Gy)	22.5	19.9	20.4	20.6	19.9	20.3
Duodenum Dmax (Gy)	35.4	33.0	28.5	32.8	32.7	32.9

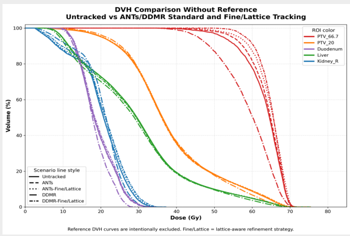

Figure 1. DVH comparisons of different track methods

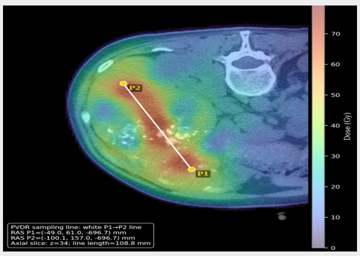

Figure 2. PVDR sampling

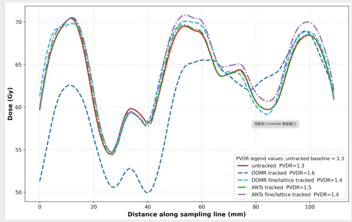

Figure 3. PVDR comparisons

DISCUSSION

This study demonstrates that a control-point–resolved 4D dose accumulation workflow provides a realistic assessment of respiratory motion effects in VMAT-Lattice radiotherapy. Respiratory motion primarily redistributed the lattice peak–valley pattern rather than simply reducing target coverage, indicating that DVH alone cannot fully characterize lattice dose preservation. Registration quality was found to be a major determinant of accumulated dose, with lattice-guided refinement improving target-focused performance, while DDMR offered substantially faster computation than ANTs. Overall, the proposed framework establishes a practical foundation for motion-robust VMAT-Lattice evaluation and future adaptive radiotherapy studies.

CONCLUSIONS

We developed a control-point–resolved 4D dose reconstruction, accumulation and tracking workflow for VMAT-Lattice radiotherapy by integrating respiratory phase sorting, deformable image registration, translation-based MLC tracking, and phase-specific dose accumulation.

Compared with the un-tracked results, simulated tracking generally improved motion-affected dosimetric metrics.

Future work should further quantify the computational efficiency and registration accuracy of different deformable registration methods, particularly for repeated phase-specific dose accumulation and tracking simulation. Such evaluation will be important for determining whether learning-based registration methods can provide accurate and efficient alternatives to conventional optimization-based registration in motion-aware VMAT-Lattice dose assessment.

REFERENCES

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