A Rule-Based Multileaf Collimator Algorithm for Dynamic Target Radiotherapy: An Optimized DMLC Leaf Sequencing Approach

K Wan[1]; YL Yang[1]

[1]Institute for Medical Imaging Technology, Ruijin Hospital, Shanghai JiaoTong University School of Medicine

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

ABSTRACT

Purpose:
Respiratory motion during thoracic radiotherapy induces not only target displacement but also non-rigid deformation and tissue density changes, degrading delivered dose. Conventional rigid aperture tracking fails under deformation; iterative re-optimization exceeds real-time latency limits; deep learning lacks robustness against irregular motion. We propose a lightweight, rule-based reference-row guided MLC tracking algorithm to address these challenges.

Methods:
The algorithm dynamically selects a reference row based on residual fluence distribution, propagates its aperture to adjacent rows under physical constraints (leaf speed, gap, inter-leaf distance), and applies online attenuation correction using pre-computed PTV-restricted dose influence matrices. No iteration is required. Validation used 4D-CT data from four lung cancer patients, comparing static, rigid centroid, deformable without correction, and the full proposed method.

Results:
Static delivery severely degraded PTV D98% to 34.36–50.86 Gy (reference: 57.51–59.68 Gy). The full proposed method restored D98% to 56.02–57.72 Gy, with mean dose deviation reduced to −0.51–0.29 Gy, without elevating OAR doses. Inference time was <3 ms per control cycle, confirming real-time feasibility.

Conclusion:
The reference-row guided MLC algorithm with attenuation correction effectively handles tumor deformation and respiration-induced heterogeneity, restoring target coverage while sparing normal tissues. Its non-iterative, millisecond-speed design supports practical clinical deployment for real-time adaptive radiotherapy.

CONTACT

Yingli Yang, PhD, Professor
Ruijin Hospital,
Shanghai Jiaotong University School of Medicine
Email: yyl12920@rjh.com.cn
Phone: 86-18321959799

INTRODUCTION

Respiratory motion during thoracic radiotherapy causes not only target displacement but also non-rigid deformation and tissue density changes, leading to substantial dose degradation. Conventional MLC tracking relies on rigid aperture translation, which fails under tumor stretching or rotation. Online re-optimization methods can handle deformation theoretically, yet their iterative computation takes seconds-far exceeding the latency limit for intrafraction real-time control. Deep learning- based approaches, while promising, often lack robustness against irregular motion patterns such as coughing. Moreover, purely geometric warping neglects respiration-induced variations in beam path length and attenuation, leaving residual dosimetric errors even when the aperture perfectly matches the target projection.

To overcome these limitations, **we propose a lightweight, rule-based reference-row guided MLC algorithm.** It dynamically selects a reference row based on residual fluence, propagates its aperture to adjacent rows under physical constraints (speed, gap, inter-leaf distance), and incorporates online attenuation correction using pre-computed PTV-restricted dose influence matrices. No iterative optimization is required, enabling millisecond-level inference per control cycle. The method is validated on 4D-CT data from four lung cancer patients, demonstrating restored PTV D98% to 56.02–57.72 Gy without elevating OAR doses-confirming its potential for real-time clinical deployment.

METHODS AND MATERIALS

The algorithm operates in discrete control cycles (**Fig. 1**). At each cycle, given the current residual fluence map and leaf positions, three core mechanisms are executed. First, a reference row is dynamically selected based on the residual fluence distribution, and its leaf apertures are determined using a row- specific heuristic. These apertures are then propagated to all adjacent rows under strict physical constraints-maximum leaf speed, inter-leaf distance, and minimum gap-ensuring mechanically feasible motions. Second, an online attenuation correction module compensates for respiration-induced tissue density changes and beam path length variations, using pre- computed dose influence matrices restricted to the PTV. Third, an adaptive jaw dynamically shields rows where fluence delivery has been completed, reducing unnecessary peripheral exposure. This process iterates until the prescribed dose is fully delivered. No iterative optimization is involved, and inference completes within milliseconds per control cycle, supporting realtime operation.

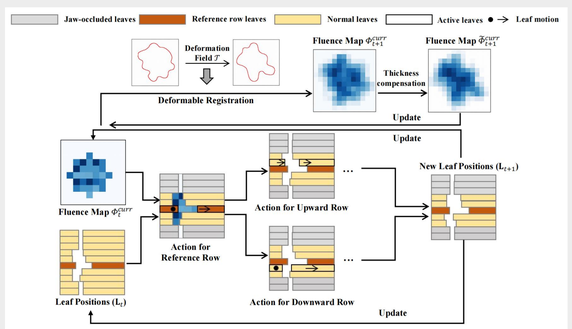

Fig 1. Workflow of the proposed reference-row guided MLC control strategy.

RESULTS

The proposed algorithm was evaluated on 4D-CT data from four lung cancer patients, comparing five delivery strategies: static, rigid centroid tracking, deformable propagation without correction (Def), deformable without adaptive jaw (No Jaw), and the full proposed method with attenuation correction (Def+AC). As summarized in Table 1, static delivery severely degraded target coverage, with PTV D98% falling to 34.36–50.86 Gy (reference: 57.51–59.68 Gy). Rigid centroid tracking partially recovered coverage but remained suboptimal under pronounced tumor deformation. The full proposed method (Def+AC) restored PTV D98% to 56.02–57.72 Gy, closely matching the reference plan, while mean dose deviation was reduced to −0.51–0.29 Gy. Critically, OAR doses (lung, spinal cord, heart, esophagus) remained at reference levels, confirming that target dose restoration was not achieved at the expense of normal tissue sparing. The adaptive jaw effectively reduced peripheral low-dose leakage without compromising core PTV coverage. DVH curves for Def+AC nearly overlapped with the reference plan across all structures (Fig. 2), and the dose difference histograms confirmed that voxelwise deviations were tightly concentrated around 0 Gy (Fig. 3). Inference time was consistently below 3 ms per control cycle, confirming real-time feasibility on standard CPU hardware.

Table 1. Dosimetric metrics of PTV and 10 mm peripheral ring (PTV+10 mm minus PTV) for all four patients. All values in Gy.

Case	Strategy	PTV				PTV 10 mm Peripheral Ring			
		D_{mean}	D_{max}	D_2	D_{98}	D_{mean}	D_{max}	D_2	D_{98}
1	Ref	59.99	60.33	60.15	59.68	43.05	60.68	60.07	7.61
	Rigid	58.35	60.15	59.73	55.14	35.66	59.72	58.08	5.04
	Def	58.79	60.37	59.99	55.56	36.83	60.04	58.42	5.37
	No Jaw	59.59	61.28	60.94	56.96	38.30	61.08	59.62	6.45
	Def+AC	59.48	61.09	60.88	56.02	36.96	60.74	58.96	5.43
	Static	50.72	57.65	57.50	34.36	29.76	56.85	54.87	3.57
2	Ref	59.91	60.59	60.26	58.58	43.17	61.25	59.47	9.08
	Rigid	60.10	61.78	61.12	57.84	42.69	60.87	59.78	12.15
	Def	59.84	63.52	62.05	56.56	41.89	61.70	59.30	10.41
	No Jaw	60.02	63.63	62.16	57.05	42.80	61.77	59.44	14.64
	Def+AC	60.02	63.62	62.21	56.87	41.91	62.12	59.45	10.33
	Static	57.01	60.43	59.60	46.30	37.97	58.92	57.37	8.60
3	Ref	59.77	60.49	60.17	57.51	41.22	59.90	58.63	10.56
	Rigid	60.13	61.79	61.33	56.40	39.62	60.48	58.75	10.45
	Def	60.29	61.94	61.64	56.67	40.40	61.18	59.70	7.05
	No Jaw	60.62	62.24	62.06	57.15	42.24	61.35	60.09	16.17
	Def+AC	59.90	61.80	61.55	55.85	39.98	61.25	59.27	7.01
	Static	53.95	59.50	59.32	36.28	33.83	58.23	56.88	4.65
4	Ref	59.83	60.38	60.20	57.72	38.83	60.20	58.28	6.97
	Rigid	58.20	59.61	59.33	55.51	35.26	57.94	55.98	4.79
	Def	59.33	60.90	60.47	57.30	36.88	59.10	57.41	6.09
	No Jaw	59.71	61.11	60.75	57.48	39.27	59.55	57.92	11.40
	Def+AC	60.12	61.85	61.55	57.72	37.29	60.21	58.16	6.11
	Static	57.01	58.89	58.57	50.86	34.20	57.51	55.64	5.50

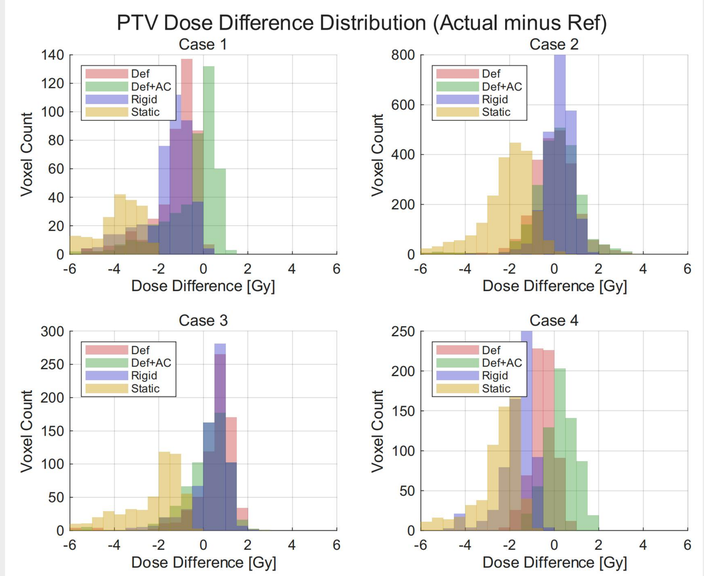

Fig 3. PTV dose difference distribution histograms.

DISCUSSION

The proposed reference-row guided MLC tracking with attenuation correction addresses three fundamental limitations of existing approaches: the inability of rigid aperture translation to handle non-rigid deformation, the excessive latency of iterative re-optimization, and the neglect of tissue attenuation changes during respiration. By propagating leaf positions from a dynamically selected reference row under physical constraints, the algorithm maintains aperture coherence while respecting mechanical limits. The attenuation correction module, using pre-computed PTV-restricted dose influence matrices, compensates for respiration-induced beam path variations with minimal online computation—a key differentiator from purely geometric warping.

The dosimetric results demonstrate that the full proposed method restores PTV coverage to near-reference levels without elevating OAR doses, a critical requirement for safe clinical translation. The sub-3 ms inference time confirms that the algorithm can operate within the latency constraints of real- time MLC control. While validated on periodic 4D-CT data of four lung cancer patients, the algorithm does not assume periodicity and can accept arbitrary deformation sequences. Future work should address irregular breathing patterns, registration uncertainties, and larger multi-site cohorts to further establish clinical robustness.

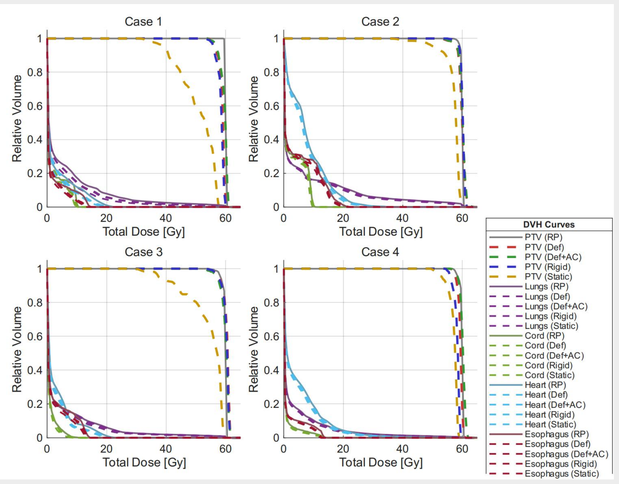

Fig 2. DVH curves of PTV and OARs for all cases.

CONCLUSIONS

The proposed reference-row guided MLC tracking algorithm with attenuation correction effectively handles tumor deformation and respiration-induced tissue heterogeneity, restoring PTV coverage to near-reference levels (56.02–57.72 Gy) without increasing OAR doses. Its rule-based, non-iterative design ensures sub-3 ms inference per control cycle, meeting real-time clinical latency requirements. The adaptive jaw further reduces peripheral exposure without compromising target dose. Validated on lung cancer 4D-CT data, the method offers a lightweight, practical solution for real-time MLC tracking in adaptive radiotherapy, with future work needed to verify robustness across irregular motion patterns and larger patient cohorts.