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First Clinical Experience with All Four Comprehensive Motion Management Gating Strategies in a 1.5 T MR-Linac in Treatment of a Heart-Proximal Lung Lesion

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ABSTRACT

Lung lesions near the heart introduce dual-motion challenges—respiratory and cardiac—that compromise predictive gating in MRgRT using Comprehensive Motion Monitoring (CMM), leading to risks of beam interruptions and prolonged on-couch time. This case demonstrates that a non-predictive exception-gating strategy is more robust in the presence of cardiac motion and pulsation MRI artifacts.

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INTRODUCTION

Magnetic resonance-guided radiotherapy (MRgRT) with a 1.5 T MR-Linac enables real-time tumor tracking but poses unique challenges for lung targets near the heart, where cardiac and respiratory motion coexist. This study reports the first patient treated with all four Comprehensive Motion Management (CMM) gating strategies and evaluates their performance in addressing complex motion uncertainties.

METHODS AND MATERIALS

A 53-year-old female with secondary malignant lymph node metastases adjacent to the bronchial tree and great vessels underwent MRgRT (60 Gy/15 fractions) using CMM. The GTV was tracked in real-time with a 5 mm PTV margin in all directions except 3 mm posteriorly as the envelope, and the Volumetric Overlapping Criterion (VOICE) was set to 100%. Tumor motion trajectories were quantified via Welch's spectral analysis to isolate respiratory and cardiac contributions.

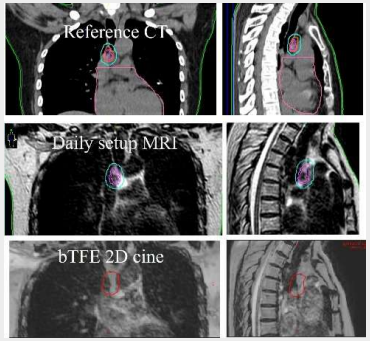

Fig 1. Patient planning CT, daily MRI using T2 TSE 3D sequence, and bTFE 2D cine image for motion monitoring.

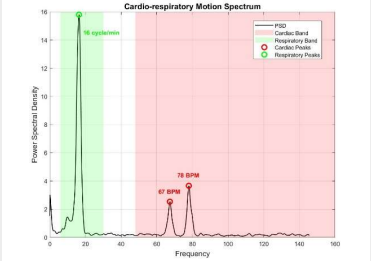

Fig 2. Spectral analysis identified dominant respiratory and cardiac motion components from a representative fraction.

RESULTS

Pre-treatment drill session tested three respiratory gating strategies (respiratory, breath-hold, exhale). Without visual biofeedback, breath-hold gating showed the poorest performance (59.3% of time spent in low accuracy). Initial chosen exhale gating was discontinued after treating two fractions due to a low duty cycle caused by cardiac motion and MRI artifacts (pulsation and inflow enhancement). Subsequent treatment used exception gating. Exception gating markedly increased the mean duty cycle from 8.5% to 36.6%, decreased time in low accuracy from 70.4% to 25.1%, and reduced low-quality periods from 35.7% to 5.4%. Retrospective spectral analysis identified dominant respiratory motion (14.6 cycles/min) and significant cardiac motion (60.9 beats/min). Higher respiratory rates positively correlated with improved duty cycle ($p < 0.001$), while increased anterior-posterior motion variability negatively impacted duty cycle ($p = 0.007$).

Tumor displacement was 0.2 ± 0.5 mm (LR), 0.1 ± 0.7 mm (SI), and 0.6 ± 0.9 mm (AP), while the 95th percentile (range) was 2.0 (0 to 3.2) mm, 3.4 (2.1 to 5.1) mm, and 3.5 (0.6 to 9.1) mm, respectively.

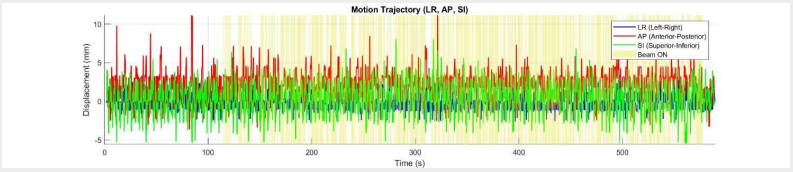

Fig. 3. Tumor motion trajectories in LR, AP, and SI directions during a representative fraction using exception gating. Yellow shading denotes beam-on periods. Beam holds occurred when the CMM-detected accuracy was low, the quality factor was low, or VOICE < 100%, or the IMRT delivery required MLC inter-segment motion or gantry rotation.

Correlation analysis revealed critical relationships between motion characteristics and delivery efficiency. Increased AP motion variability negatively affected delivery ($r = -0.52$, $p = 0.007$). Higher respiratory rates were positively correlated with improved duty cycle ($r = 0.74$, $p<0.001$).

Exception gating dramatically improved delivery metrics compared to exhale gating: duty cycle increased from 8.5% to 36.6%, while time in low accuracy (70.4% to 25.1%) and low quality (35.7% to 5.4%) substantially decreased. VOICE < 100% time reduced from 38.0% to 13.5%.

Though exception gating introduces longer system latency (within 500 ms) that potentially could compromise dose accuracy near the gating envelope, it overcomes cardiac interference, establishing that physiology-informed gating selection is critical for heart-proximal targets.

	Session duration (s)	Duty cycle (%)	Low Accuracy (%time)	Low Quality (%time)
Respiratory (n=1)	887.2	NA	39.8	20.6
Breathold (n=1)	698.8	NA	59.3	55.3
Exhale (n=7)	798.3 ± 507.9	8.5 ± 13.8	70.4 ± 26.1	35.7 ± 24.3
Exception (n = 18)	607.7 ±260.9	36.6 ±24.7	25.1 ± 28.6	5.4 ± 6.4

	VOICE<100% (%time)	SI P95 (mm)	Cardiac (cycle/min)	Resp (BPM)
Respiratory (n=1)	19.5	3.2	50.8	12.7
Breathold (n=1)	56.6	32.8	81.8	7.1
Exhale (n=7)	38.0 ± 13.0	2.8 ± 1.1	78.2 ± 36.4	11.8 ± 3.5
Exception (n = 18)	13.5 ± 8.9	3.4 ± 0.8	60.9 ± 7.6	14.6 ± 4.4

Table1. Mean and SD of the patient treatment session data using respiratory, breath-hold, exhale, or exception gating.

CONCLUSIONS

Exception gating without motion prediction overcame cardiac motion interference and enabled beam delivery with a reasonable duty cycle. This comparative dataset demonstrates that gating strategy selection must be individualized based on motion patterns rather than applied uniformly, providing a practical framework for optimizing MRgRT delivery near the heart.

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