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What Works and What Breaks:

Real-World Performance & Limitations of Comprehensive Motion Management on a 1.5 T MR-Linac

Ruiqi Li; Fan-chi Su; Mu-han Lin; Jie Deng; Chris Kabat

Department of Radiation Oncology, University of Texas Southwestern Medical Center, Dallas, TX

ABSTRACT

MR-guided adaptive radiotherapy allows intrafraction motion to be monitored in real time, yet the real-world performance of Comprehensive Motion Management (CMM) across disease sites is not well characterized.

We retrospectively analyzed 2,382 fractions (590 patients) delivered on a 1.5 T Elekta Unity MR-Linac with CMM enabled, quantifying delivery efficiency, tracking reliability, and the causes of beam interruption from system log files.

The mean duty cycle was 85.2 ± 15.1%. Prostate was most stable (89% duty cycle, 98% tracking success), whereas mobile abdominal and thoracic sites were less efficient, with kidney lowest. Most beam holds (62.5%) were driven by target motion exceeding tolerance.

CMM integrates seamlessly into routine adaptive workflows and provides a quantitative framework for intrafraction motion assessment, governed by site-specific motion and tracking-structure design.

CONTACT

Ruiqi Li
Department of Radiation Oncology,
UT Southwestern Medical Center, Dallas, TX
ruiqi.li@utsouthwestern.edu

INTRODUCTION

- MR-guided adaptive radiotherapy now allows intrafraction motion to be monitored in real time, yet the real-world performance of CMM across disease sites is not well characterized.
- CMM combines cine-based surrogate tracking, a user-defined tolerance envelope, and automatic beam control, holding the beam when the tracked structure leaves its envelope or tracking confidence falls.
- We evaluated how efficiently CMM delivers, how reliably it tracks, and why it interrupts the beam, to define what works, what fails, and the practical lessons for routine use.

METHODS AND MATERIALS

- We retrospectively analyzed 2,382 fractions (590 patients) delivered with daily online adaptive (ATS) radiotherapy on a 1.5 T Elekta Unity MR-Linac with CMM enabled, spanning six disease-site groups.
- Each site used a surrogate tracking target, registration region, and tolerance envelope matched to its anatomy and expected motion (Table 1).
- Log files and motion traces quantified, per fraction, the duty cycle and tracking success rate; every beam hold was classified by cause (Figure 1).

Table 1. Site-specific CMM configuration.

Site	Mode	Target	Envelope	Registration region
Prostate	Non-resp.	CTV (±SV)	CTV + 2–3 mm	CTV + 10 mm, excl. bladder
Liver	FB	ITV / GTV	PTV (ITV+5)	ITV + 5–20 mm, avoid ribs/vessels
Pancreas	FB	ITV / GTV	PTV (ITV+5)	ITV + 5–20 mm + stable renal
Kidney	FB	ITV / GTV	PTV (ITV+3–5)	ITV + 0–5 mm + ipsi. kidney
Lung	FB	ITV / GTV	PTV (ITV+3–5)	ITV + 5–10 mm + lung
Other	—	Case-dep.	Case-dep.	Case-dependent

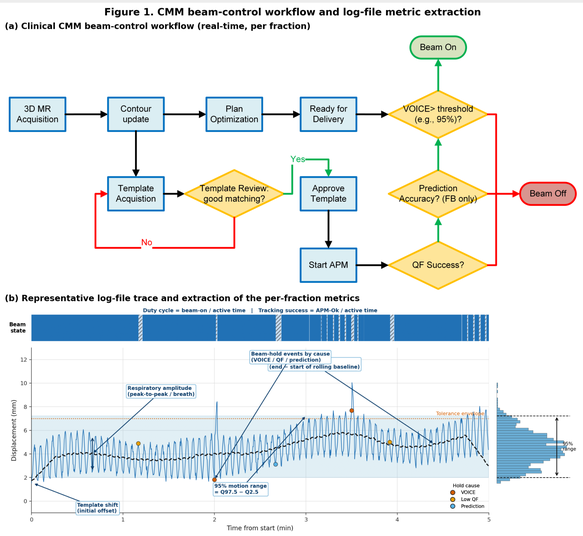

Figure 1. CMM beam-control workflow and log-file metric extraction.

RESULTS

- CMM initialized successfully in 95% of sessions and was applied across 2,382 fractions, with a mean duty cycle of 85.2 ± 15.1%, confirming it integrates into routine delivery without compromising efficiency (Table 2).
- Prostate was most stable, with the highest duty cycle (89%) and tracking success (98%), reflecting slow drift and minimal respiratory motion (Table 2, Figure 2).
- Duty cycle stayed high while 3D motion remained within the tolerance envelope but fell sharply beyond it; the 95th-percentile SI motion range was the strongest predictor (r = -0.64), so mobile sites (kidney lowest) were most affected (Figure 4).
- Most holds reflected genuine target motion rather than tracking artifact: overall 62.5% from motion exceeding tolerance, 17.6% from free-breathing prediction failure, and 16.8% from low registration quality (Figure 3).

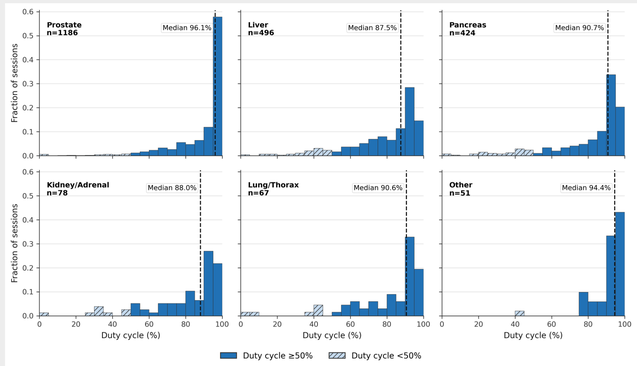

Figure 2. Duty-cycle distribution by disease site.

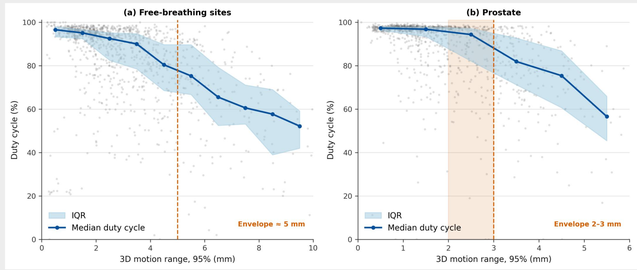

Figure 4. Duty cycle vs. 3D motion relative to the tolerance envelope.

DISCUSSION

- CMM integrated smoothly into routine adaptive workflows and provided quantitative motion information that complements, rather than replaces, visual cine review.
- Performance closely followed the underlying motion, so drift-dominant prostate delivered efficiently while respiratory sites saw more frequent interruptions.
- Because most holds were driven by true target motion, CMM behaves as intended; free-breathing prediction failure was the second cause, pointing to surrogate selection, envelope design, and motion mitigation (e.g., abdominal compression) as the main levers.
- Limitations: a surrogate may not capture true target deformation, static envelopes may not fit every fraction, dosimetric impact is not yet quantified, and this is single-institution experience.

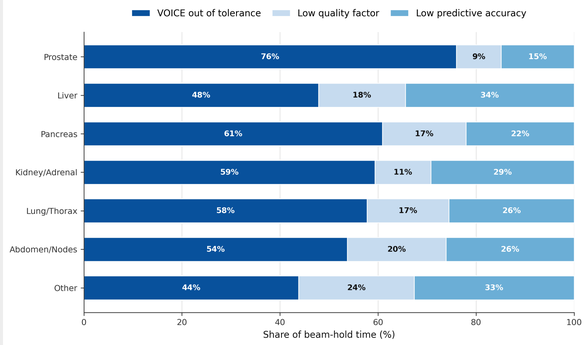

Figure 3. Cause of beam interruption by disease site.

CONCLUSIONS

- CMM offers a practical, low-burden, quantitative framework for assessing intrafraction motion during MR-guided adaptive radiotherapy.
- Site-specific differences in duty cycle, tracking success, and beam-hold mechanisms show performance depends on both motion characteristics and tracking-structure design.
- These findings support safer adaptive delivery and guide surrogate selection, envelope configuration, and motion mitigation for mobile abdominal targets.

Table 2. Site-specific CMM performance, intrafraction motion, and suggested margins.

Site	N	Duty cycle (%)	Track. success (%)	Mean shift AP / SI / LR (mm)	95% range AP / SI / LR (mm)	Margin LR / AP / SI (mm)
Prostate	1186	89.3 ± 14.1	97.5 ± 10.2	0.6 / -1.6 / 0.1	2.2 / 2.7 / 0.7	2.0 / 4.0 / 3.5
Liver	496	79.6 ± 18.7	88.9 ± 13.6	1.0 / 0.1 / -0.1	4.9 / 10.8 / 3.2	4.5 / 5.5 / 9.5
Pancreas	424	81.6 ± 20.1	93.5 ± 10.4	0.1 / -0.1 / -0.2	2.8 / 8.2 / 2.9	5.5 / 4.5 / 8.0
Kidney	78	79.8 ± 20.6	91.2 ± 12.8	0.6 / -1.2 / 0.0	4.3 / 9.6 / 2.4	3.5 / 4.5 / 9.0
Lung	67	80.3 ± 20.8	92.8 ± 10.7	1.0 / 0.5 / 0.0	3.7 / 6.4 / 3.0	4.0 / 4.5 / 7.5
Other	131	86.5 ± 15.2	93.4 ± 10.1	0.2 / -0.7 / 0.2	3.1 / 6.7 / 2.3	4.5 / 4.5 / 7.5

Duty cycle = beam-permitted fraction of active time; tracking success rate = fraction of active time with APM state OK. Suggested margin (van Herk): $M = 2.5\Sigma + 0.7\sigma$, where Σ = between-fraction SD of the per-fraction mean shift and σ = RMS of the per-fraction shift SD. Motion values are AP/SI/LR; margins LR/AP/SI.

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