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Performance of Unity 1.5 T MR-Linac Gating System Across Anatomical Sites and Motion Management Strategies

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ABSTRACT

Comprehensive Motion Management (CMM) enables automatic beam gating on the 1.5 T MR-Linac, and recent commissioning studies have characterized its performance using modeled respiratory waveforms [1]. This work extends validation to clinically realistic conditions, evaluating tracking accuracy, latency, and gated dosimetry across gastrointestinal, genitourinary, and thoracic sites. CMM acceptance and commissioning were performed with the IBA QUASAR™ Modus programmable motion phantom using vendor-defined workflows. End-to-end dosimetry employed three MR-compatible small-volume detectors, with gating consistency verified by radiochromic film and a four-channel scintillator array. To assess performance under realistic motion, respiratory traces from 20 previously treated Unity patients were converted to phantom waveforms and delivered in clinical treatment mode. Anatomical Position Monitoring (APM) met the ±2 mm tolerance in all axes (95th percentile ≤1.85 mm). Beam-on/off average latency with motion prediction (respiratory strategies) was within specification (−23.7/−18.2 ms); without prediction (non-respiratory strategy), latency increased to ~350 ms. Point-dose agreement was <1.8%, gamma pass rates exceeded 95% (3%/2 mm). These results provide a practical benchmark for clinical implementation of MR-guided gating radiotherapy.

INTRODUCTION

Intrafraction target motion remains a principal source of geometric uncertainty in radiotherapy of thoracic and abdominal tumors. MRI-guided adaptive radiotherapy on the 1.5 T Elekta Unity can directly monitor the anatomical position of the target during treatment with no additional imaging dose. Early commissioning reports have characterized tracking accuracy, latency, and gated dosimetry relying largely on modeled or idealized waveforms [1]. Whether commissioning-level performance translates to the breathing irregularity of real patients, across anatomical sites and gating strategies, remains an open question. In this work we evaluated CMM performance for three anatomically distinct sites (GI, GU, lung) and define capabilities and limitations under clinically realistic conditions.

METHODS AND MATERIALS

- Measurements performed at 1.5 T MR-Linac with IBA QUASAR™ Modus phantom (Figure 1) per TG-142 and institutional quality control tests.
- Four types of phantom cylindrical inserts were used for MR-compatible detectors: Semiflex 3D MR 31024, PinPoint 3D MR 31025, MedScint HS-RP200 and Gafchromic™ EBT4 film.
- CMM log files were analysed with target respiratory motion traces extracted for pancreas (2 traces), liver (4) and lung (4) anatomical sites, and non-respiratory motion traces for 10 prostate patients.
- APM tracking accuracy and latency for free-breathing and exception-gating strategies were measured by running extracted motion traces on motion phantom in translation-only mode, while executing CMM acceptance tests per vendor-defined workflows (Figures 2).
- End-to-end test with dosimetry measurements for adapted plans performed in clinical mode with 3 point-dose detectors and 2 plane detectors (film and MRI4D Scintillation Detector Cassette) and compared to the target mean dose from treatment planning system.

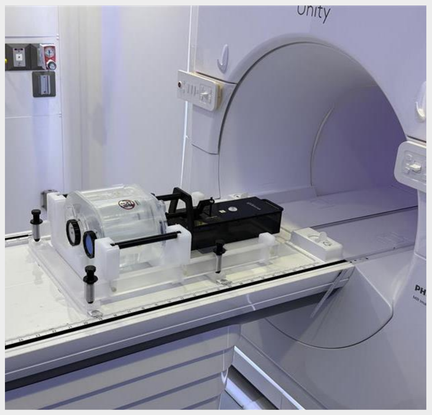

Figure 1. Motion phantom setup on the Unity couch.

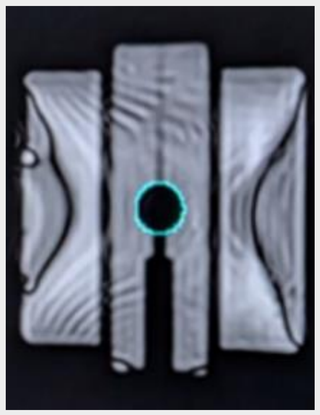

Figure 2. 2D MR cine of the phantom; reconstructed target in cyan.

RESULTS

APM tracking accuracy (Figure 3) was well within the 2 mm tolerance for all sites, with mean y-displacements of 1.35 ± 0.23 mm (GI, n = 6), 0.18 ± 0.25 mm (GU, n = 10), and 1.15 ± 0.35 mm (Lung, n = 4); the largest single deviation was 1.6 mm. With the predictive algorithm enabled, gating latency (Figure 5) for GI and Lung averaged −23.7 ± 6.8 / −15.8 ± 4.0 ms and −21.0 ± 3.6 / −18.2 ± 2.6 ms (beam-on/beam-off) respectively, with a single beam-on measurement (−34 ms) exceeding the ±30 ms tolerance. Without prediction, GU latency (Figure 6) was 352.0 ± 15.4 / 357.9 ± 18.5 ms against the 380 ms tolerance, with one beam-off measurement (387 ms) slightly above the limit. End-to-end dosimetric agreement was within tolerance for all measurements (Figure 4): small-volume detectors (Semiflex 3D, PinPoint, scintillator) deviated by ≤1.8% (tolerance ±2%), and film and scintillator-array measurements deviated by ≤4.1% (tolerance ±5%) across all sites.

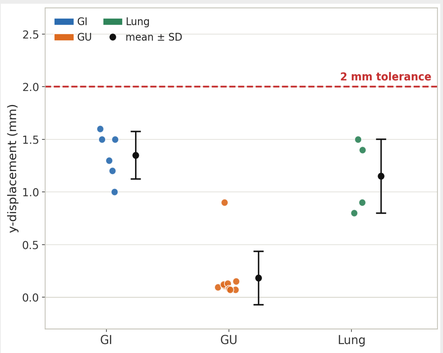

Figure 3. APM tracking accuracy along the Y-axis.

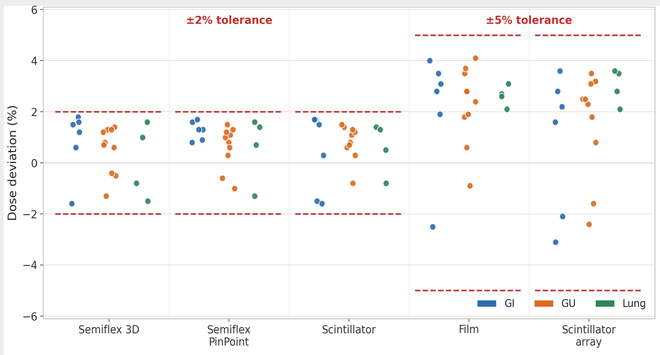

Figure 4. Dose deviation between TPS and measured dose for 5 detectors during end-to-end test.

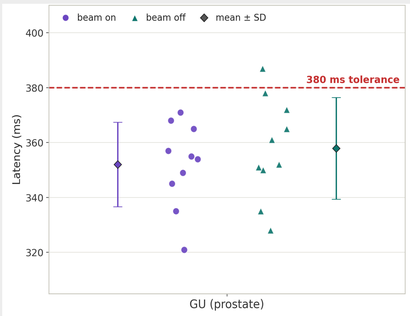

Figure 5. Beam latency during exception-gating strategy (without prediction).

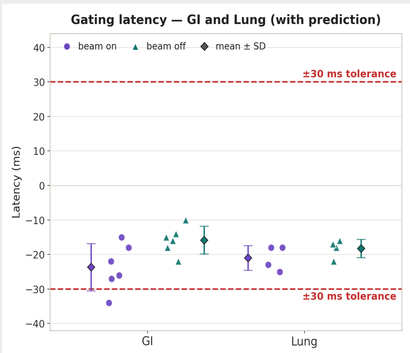

Figure 6. Beam latency during respiratory-gating strategy (with prediction).

DISCUSSION

- The site-specific measurements obtained in this work were consistent with the values established during acceptance and commissioning of the CMM system, supporting the stability of its performance under clinically realistic conditions.
- Maximum observed tracking errors in the y-direction (1.6 mm for GI, 1.5 mm for Lung) were comparable to the commissioned APM tracking accuracy of 1.57 mm, and all measurements remained within the 2 mm acceptance tolerance. The notably smaller displacements observed for the GU case (0.18 ± 0.25 mm) reflect the limited intrafraction motion characteristic of prostate targets rather than a difference in system performance.
- Latency measurements showed similar agreement. The agreement between commissioning values and current measurements across both APM tracking and latency metrics suggests that CMM performance has remained stable since clinical release, and that the commissioned baseline values are representative of routine clinical operation.
- End-to-end dosimetric agreement within detector-specific tolerances at all sites further supports this conclusion.
- Several limitations should be noted: phantom motion was programmed exclusively along the y-axis and modest number of measurements per site.

CONCLUSIONS

- ✓ Site-specific performance testing of the Unity CMM system across GI, GU, and thoracic cases demonstrated tracking accuracy, gating latency, and end-to-end dosimetric agreement consistent with values established at acceptance and commissioning.
- ✓ APM tracking errors remained within the 2 mm tolerance for all sites, latency was within specification with and without motion prediction.
- ✓ The agreement between current and commissioned values indicates that CMM performance has remained stable in clinical operation and supports the use of commissioned baselines as reference values for routine QC.
- ✓ These results provide a practical benchmark for institutions implementing MR-guided gated radiotherapy

REFERENCES

Smith BR, St-Aubin J, Hyer DE. Commissioning of a motion management system for a 1.5T Elekta Unity MR-Linac: A single institution experience. J Appl Clin Med Phys. 2025;26:e70005.

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