Breathing-Frozen Abdominal Organ at Risk Motion Dynamics Characterized Using Golden-Angle Radially Sampled Magnetic Resonance Imaging and Hierarchical Motion Modeling

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

Christopher Kehayias, PhD; Robert Jones, BSc; Daekeun You, PhD; James Balter, PhD

Department of Radiation Oncology, University of Michigan Hospital, 1500 E Medical Center Dr, Ann Arbor, MI 48109

ABSTRACT

Background: Non-breathing physiological motions of abdominal organs at risk (OARs) are insufficiently characterized to foster quantitative understanding of their dosimetric impact which could reveal needs for monitoring anatomical changes during treatments. We investigated non-breathing abdominal motion dynamics over radiation therapy (RT) time scales.

Approach: Golden-angle radially sampled MRI was acquired for 17 patients (20-minute scans). Hierarchical motion modeling based on prior work removed breathing motion-induced deformations, allowing view-sharing reconstructions of non-breathing motions at fast (4.8 s) and previously-used slow (17 s) temporal resolutions without breathing-induced blurring. Resulting image volumes were aligned sequentially to calculate displacement and velocity magnitudes of voxels within the small bowel, colon, stomach, and duodenum.

Results: Overall median displacement magnitudes for slow temporal sampling were 3.6±1.8 mm, 3.7±2.3 mm, 3.3±1.5 mm, and 3.0±2.4 mm were comparable to those from fast sampling (4.3±1.7 mm, 3.8±2.0 mm, 3.0±1.2 mm, and 2.9±1.3 mm) for small bowel, colon, stomach, and duodenum, respectively. Overall, abdominal anatomy was displaced away from the starting configuration.

Median motion velocities from slower sampling were 1.0±0.5 mm/min, 1.0±1.1 mm/min, 0.7±0.4 mm/min, and 0.9±0.8 mm/min for small bowel, colon, stomach, and duodenum, respectively. Velocities from fast temporal resolution sampling were 3.1±2.6 mm/min, 2.9±2.8 mm/min, 2.8±2.1 mm/min, and 2.9±2.9 mm/min for the same OARs, suggesting that previously reported speeds were underestimated.

Conclusions: Non-breathing abdominal motions were observed to be on the order of millimeters over the course of treatments. The change in rate of displacement suggests potential benefit of delaying IGRT until after several minutes of the patient lying down, and inter-subject variation in motions suggests the possible advantages of individual characterization and/or non-breathing motion monitoring for treatment.

CONTACT

Christopher Kehayias
University of Michigan Medicine
1500 E Medical Center Dr, Ann Arbor, MI 48109 Rm B2 C432D
kehayias@med.umich.edu
(617) 694-7221

MICHIGAN MEDICINE
UNIVERSITY OF MICHIGAN

INTRODUCTION

Abdominal motions due to breathing, peristaltic contractions, and slow abdominal configuration changes pose significant challenges for gastrointestinal (GI) radiotherapy targeting. In addition, these motions could potentially have significant dosimetric consequences, particularly for organs at risk (OARs) directly abutting targets. Breathing accounts for the largest component of overall abdominal motion magnitudes in the upper abdomen and has by far been the most extensively characterized. Non-breathing motions, by contrast, have not been sufficiently investigated despite initial evidence[1-4] of their magnitudes and dosimetric consequences.

Characterizing the spatiotemporal dynamics of non-breathing motions in the abdomen is critical to furthering our understanding of both their dosimetric impact and the need (or lack thereof) for motion management for improved radiation therapy precision.

In this investigation, breathing motion-corrected temporally dynamic magnetic resonance (MR) image volumes were generated from dynamic radial scan data and analyzed to characterize the motion patterns of non-breathing motions of the small bowel, colon, stomach, and duodenum.

METHODS AND MATERIALS

Figure 1 outlines the methodology. 20-minute golden angle radial stack-of-spoke samples of the abdomen were acquired from Dynamic Contrast-Enhanced MR of 17 patients previously scanned under an institutional review board-approved protocol. Scans were acquired using two consecutive 10-minute sequences with a short inter-sequence delay. Breathing-induced deformations were generated for each stack of spokes using a previously published technique and used to correct back projections to remove breathing motion[5]. View-sharing reconstructions at **faster** (**4.8 s**) and **slower** (**17 s**, the time interval used in previous investigations by our group) temporal intervals Δt (with $\sigma_{min} = \Delta t$ and $\sigma_{max} = 2\Delta t$) were generated from the breathing motion-corrected back-projections across the duration of each patient scan[6]. OARs were initially defined on a reference phase reconstruction (the first volume of each imaging series) using an open-source auto-segmentation tool (TotalSegmentator MRI[7]) and then edited manually by experts. Deformable alignment between phases was performed using cubic B-splines (NiftyReg[8]).

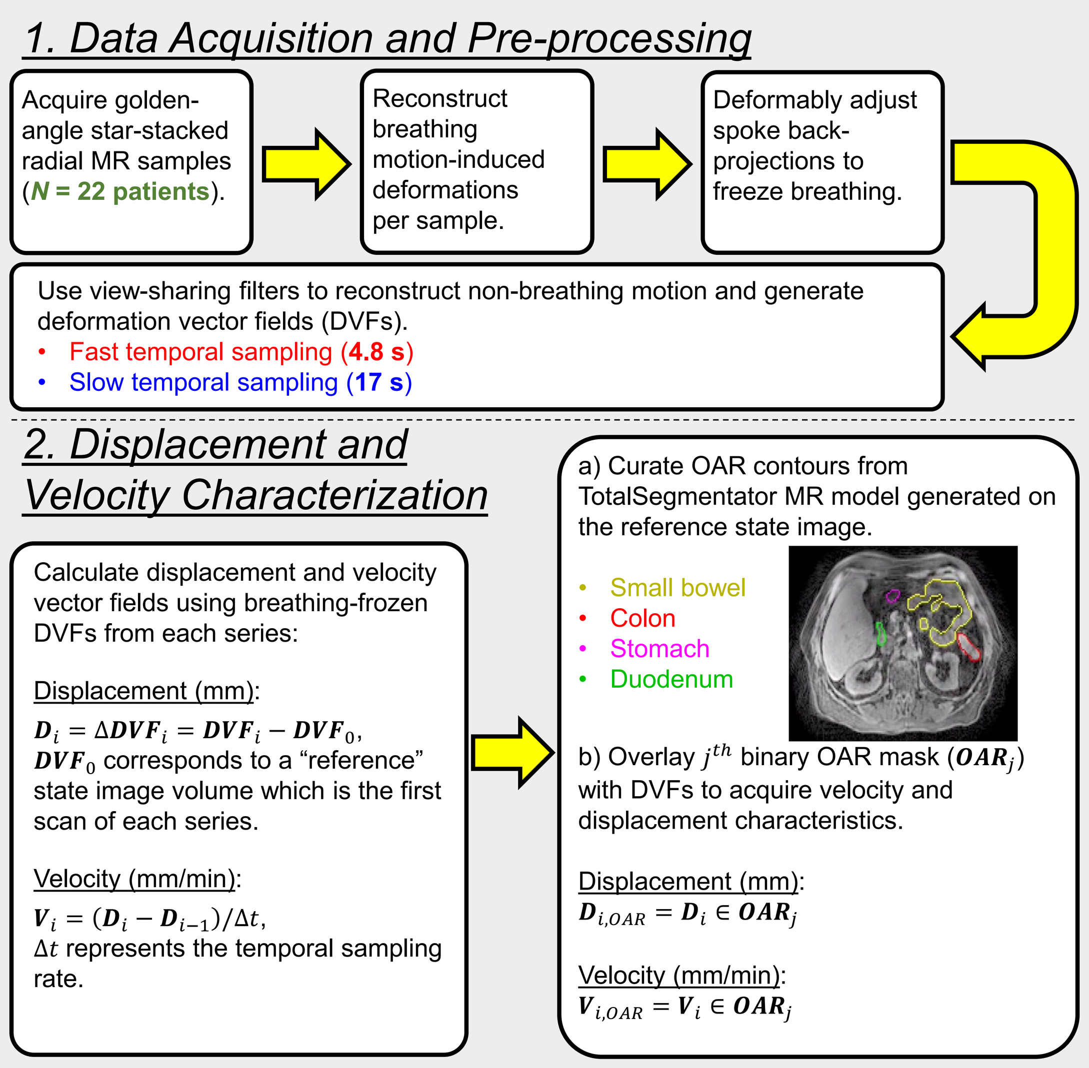

Figure 1. Procedure for slow abdominal configuration displacement and velocity characterization.

RESULTS

Table 1 shows statistics of median displacement magnitudes over 20 minutes across the patient population from **fast** (**Δt=4.8 s**) and **slow** (**Δt=17 s**) temporal sampling rates at the end of scan time for the OARs of interest (small bowel, colon, stomach, and duodenum).
Figure 2 shows the temporal evolution of medians, 75th percentiles, and 25th percentiles across the patient population of median OAR displacement magnitudes at fast and slow sampling intervals.
Table 2 shows velocity magnitude (speed) statistics for all OARs across each scan from fast and slow sampling intervals.
Figure 3 shows the speeds for fast and slow sampling intervals for all OARs.

Table 1. Statistics of median displacement magnitudes of OARs at the end of scan time across all 17 patients for both fast and slow temporal sampling.

OAR	Median (mm)	Min (mm)	5th %ile (mm)	25th %ile (mm)	75th %ile (mm)	95th %ile (mm)	Max (mm)
Slow Temporal Sampling							
SB	3.6	2.1	2.1	3.1	4.7	8.5	8.8
Colon	3.7	2.0	2.0	3.1	4.9	9.9	11.5
Stomach	3.3	1.2	1.3	2.1	4.2	6.1	6.4
Duodenum	3.0	1.0	1.2	2.1	4.2	9.3	9.3
Fast Temporal Sampling							
SB	4.3	2.0	2.3	3.4	4.7	8.3	9.6
Colon	3.8	1.6	1.8	2.7	4.3	8.8	10.4
Stomach	3.0	2.0	2.1	2.8	4.2	6.0	6.3
Duodenum	2.9	2.0	2.1	2.5	3.4	6.4	7.5

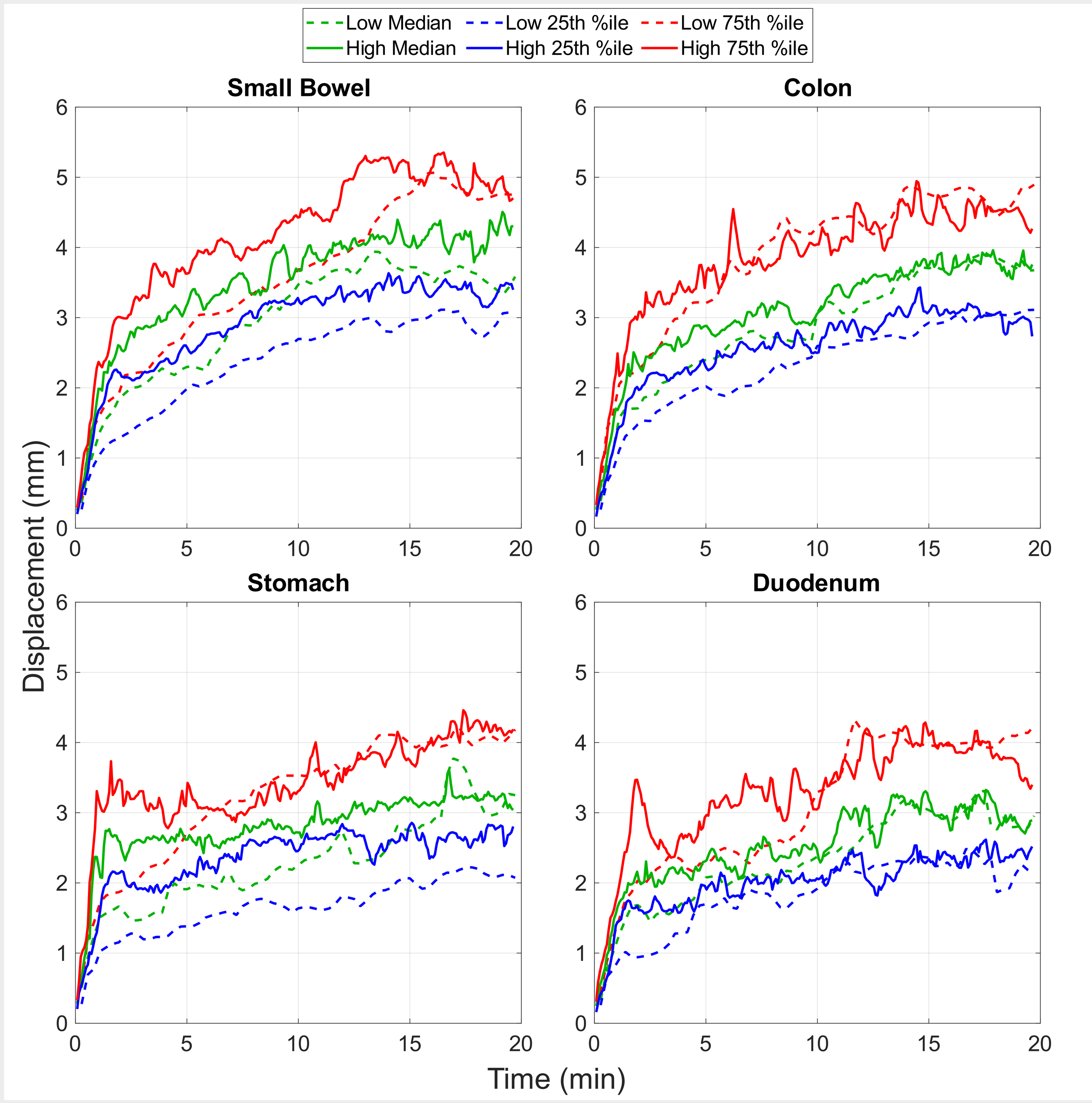

Figure 2. Median, 75th, and 25th percentile displacement magnitudes of OARs throughout the MR scan duration across all 17 patients for both low and fast temporal sampling.

Table 2. Population statistics of OAR speed measurements across all 17 patients for both slow and fast temporal sampling.

OAR	Median (mm/min)	Min (mm/min)	5th %ile (mm/min)	25th %ile (mm/min)	75th %ile (mm/min)	95th %ile (mm/min)	Max (mm/min)
Low Temporal Sampling							
SB	1.0	0.3	0.3	0.6	1.4	2.3	2.5
Colon	1.0	0.2	0.3	0.6	1.5	2.8	3.1
Stomach	0.7	0.2	0.2	0.4	1.1	2.2	2.5
Duodenum	0.9	0.3	0.3	0.6	1.4	2.7	3.0
Fast Temporal Sampling							
SB	3.1	0.9	1.0	1.9	4.4	7.5	8.2
Colon	2.9	0.6	0.8	1.9	4.3	10.2	11.5
Stomach	2.8	0.8	0.9	1.7	4.1	9.4	10.6
Duodenum	2.9	0.7	0.9	1.9	4.0	8.8	10.0

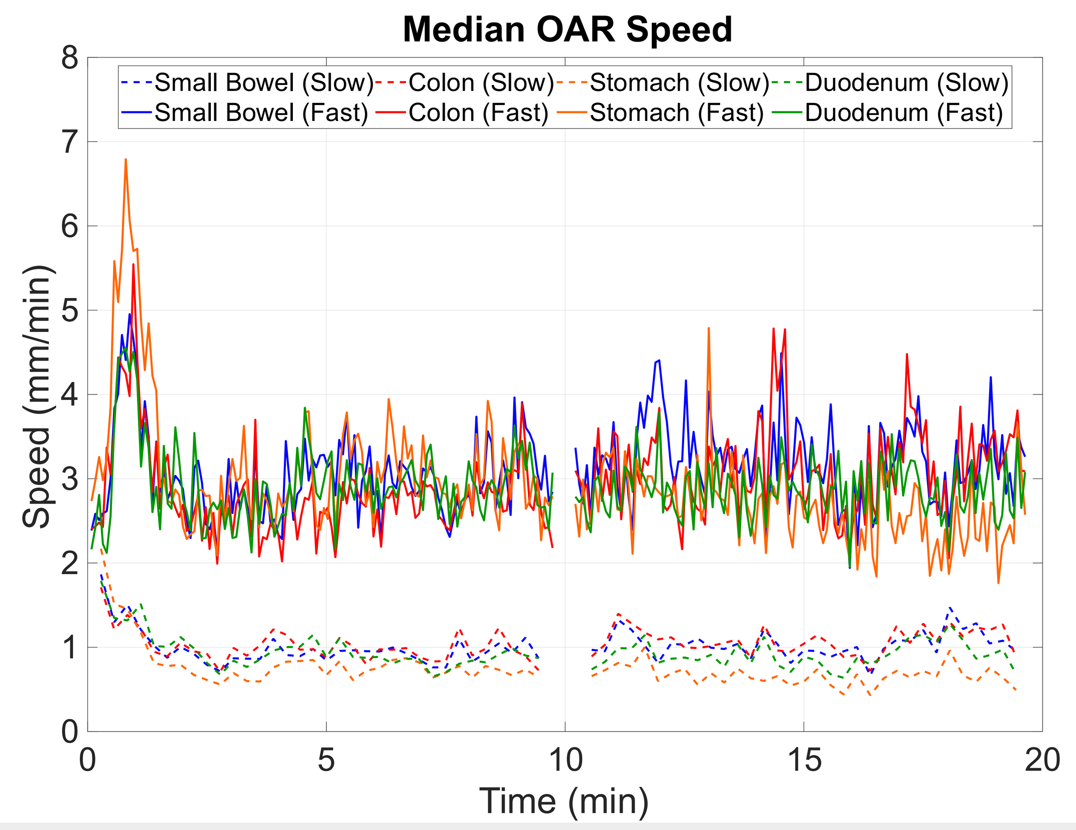

Figure 3. Median OAR speeds with respect to elapsed scan time for slow and fast temporal sampling. The break around 10 minutes represents a short intersequence delay between the two successive 10-minute MR scans.

DISCUSSION

Non-breathing motions were observed for all OARs with cumulative median displacements of small bowel and colon exceeding those of stomach and duodenum. There is an apparent composition of quasi-periodic motions superimposed on a slower motion pattern that appears to settle down after the first 5 – 10 minutes. **This implies a potential advantage of waiting a certain time after setting up the patient on the couch to reduce uncertainties due to motion.**

Median OAR speeds during the first 1 – 3 minutes of scanning generally exceed those throughout the rest of the scan and were approximately 3 times greater for fast temporal sampling relative to slow temporal sampling, **suggesting previously reported velocities were underestimated due to motion blurring.[4]** Despite these differences in median velocities, the cumulative median motions across the population were observed to be similar for fast and slow sampling.

There are several limitations to this study. First, we did not investigate errors in displacement estimation due to deformable registration inaccuracies, which would have propagated to speed estimations. Second, the beginning of each scan was not synchronized with the moment patients were laid on the couch. Third, we cannot safely assume that the introduction of imaging contrast had no effect on the OAR motion or on the quality of deformable registrations.

Future studies will dive further into the observations as well as limitations of our current investigations. We will investigate motion in subjects without contrast and controlled timing from when they lay down and further explore faster temporal resolution reconstructions to improve estimates of true motions.

CONCLUSIONS

1. Abdominal OARs generally drift away from initial configurations.
2. Non-periodic motions appear to slow down over time.
3. Faster temporal sampling yields greater speed estimates but has minimal impact on cumulative displacement estimation.

REFERENCES

1. Alam, S. et al. Inter- and Intrafraction Motion Assessment and Accumulated Dose Quantification of Upper Gastrointestinal Organs during Magnetic Resonance-Guided Ablative Radiation Therapy of Pancreas Patients. Phys. Imaging Radiat. Oncol. 2022, 21, 54–61.
2. Damen, S. L. C. et al. Bowel Tracking for MR-Guided Radiotherapy: Simultaneous Optimization of Small Bowel Imaging and Tracking. Phys. Med. Biol. 2025, 70 (7), 075001.
3. Zhang, Y. Development of an Abdominal Dose Accumulation Tool and Assessments of Accumulated Dose in Gastrointestinal Organs. Phys. Med. Biol. 2023, 68 (7), 075004.
4. Liu, L. Modeling Intra-Fractional Abdominal Configuration Changes Using Breathing Motion-Corrected Radial MRI. Phys. Med. Biol. 2021, 66 (8), 085002.
5. Zhang, Y.; Cao, Y.; Kashani, R.; Lawrence, T. S.; Balter, J. M. Real-Time Prediction of Stomach Motions Based upon Gastric Contraction and Breathing Models. Phys. Med. Biol. 2023, 68 (1), 015001.
6. Johansson, A.; Balter, J. M.; Cao, Y. Abdominal DCE - MRI Reconstruction with Deformable Motion Correction for Liver Perfusion Quantification. Med. Phys. 2018, 45 (10), 4529–4540.
7. Wasserthal, J.; Breit, H.-C.; Meyer, M. T.; Pradella, M.; Hinck, D.; Sauter, A. W.; Heye, T.; Boll, D. T.; Cyriac, J.; Yang, S.; Bach, M.; Segeroth, M. TotalSegmentator: Robust Segmentation of 104 Anatomic Structures in CT Images. Radiol. Artif. Intell. 2023, 5 (5), e230024.
8. Modat, M.; Ridgway, G. R.; Taylor, Z. A.; Lehmann, M.; Barnes, J.; Hawkes, D. J.; Fox, N. C.; Ourselin, S. Fast Free-Form Deformation Using Graphics Processing Units. Comput. Methods Programs Biomed. 2010, 98 (3), 278–284.