Gradient Nonlinearity-Corrected 4D MRI for Abdominal Motion Quantification on a 1.5T MR-Linac

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INTRODUCTION

- **Purpose:** Motion-resolved 4D MRI is essential for assessing abdominal tumor and organ motion, but gradient nonlinearity (GNL) causes geometric distortion that reduces spatial fidelity and motion accuracy. This study evaluates GNL correction for 4D MRI on a 1.5T MR Linac.
- **Innovation/Impact**: Gradient nonlinearity (GNL) introduces geometric distortions in 4D MRI, reducing spatial fidelity and motion accuracy that are critical for radiotherapy. Incorporating GNL correction into 4D MRI reconstruction represents a key technical advance for precise motion assessment. The impact of GNL on radial stack-of-stars 4D MRI and derived motion metrics on the MR-Linac has not previously been reported. This study provides the first evaluation of GNL correction on geometric and motion accuracy in pancreatic cancer patients treated on a 1.5T MR-Linac, with implications for improved treatment planning and adaptive radiotherapy.

METHODS AND MATERIALS

- **Data Acquisition**: Free-breathing 3D T1-weighted golden-angle radial stack-of-stars abdominal imaging was performed in 32 pancreatic cancer patients on an Elekta 1.5T Unity MR-Linac (repetition time = 5.0 ms, echo time = 2.1 ms, flip angle = 12°, field of view = 370 × 370 × 200 mm³, voxel size = 1.5 × 1.5 × 4.0 mm³, number of spokes = 905, scan time = 4:14 min).
- **4D MRI Reconstruction**: Motion-resolved 4D MRI with 10 respiratory states was reconstructed from k-space using XD-GRASP[1]. GNL correction generated 3D displacement vector fields from spherical harmonic coefficients for each motion state,[2,3] using body contours as masks for displacement calculation.
- **Patients and Motion Analysis**: Thirty-two pancreatic cancer patients undergoing five-fraction MR-Linac treatment were included. Clinical contours of the gross tumor volume (GTV) and two organs-at-risk (duodenum-stomach, small bowel) were transferred to the first respiratory phase (end-exhale), as shown in **Figure 1**. The contours were propagated to the remaining phases using deformable propagation, and motion range was calculated. The contours were then exported for displacement calculation in MATLAB. Displacement magnitude and motion range were compared before and after GNL correction using paired t-tests, with $p < 0.05$ considered statistically significant.

RESULTS

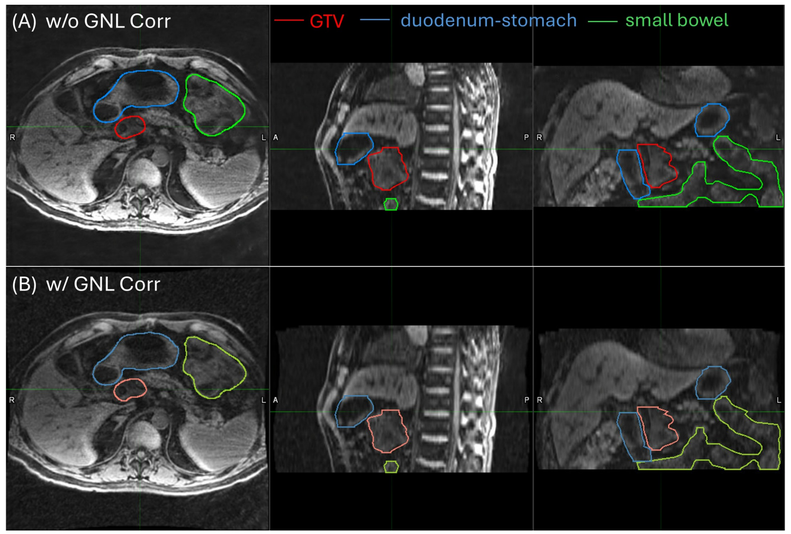

Figure 1: End-exhale phase of 4D MRI from a pancreatic cancer patient showing the gross tumor volume (GTV), duodenum-stomach, and small bowel contours before (A) and after (B) gradient nonlinearity (GNL) correction.

- **Imaging Off-center Distance**: The imaging off-center distance (mean ± SD) was 27.78 ± 18.72 mm, 16.01 ± 11.99 mm, and 10.64 ± 7.30 mm in SI, AP, and LR directions.
- **Displacements**: The displacement within body contours was 2.82 ± 0.75 mm, 3.76 ± 1.75 mm for the GTV, 1.36 ± 0.67 mm for the duodenum-stomach, and 5.56 ± 2.01 mm for the small bowel. **Figure 2** presents a pancreas patient before and after GNL correction.
- **Motion Range**: Motion range before GNL correction was 3.37 ± 1.64 mm, 5.93 ± 2.32 mm, and 5.27 ± 2.18 mm, and after correction was 3.37 ± 1.69 mm, 6.07 ± 2.19 mm, and 7.04 ± 1.30 mm for the GTV, duodenum-stomach, and small bowel, respectively. Changes were not significant for the GTV ($p = 0.829$) or duodenum-stomach ($p = 0.145$) but were significant for the small bowel ($p = 0.048$).

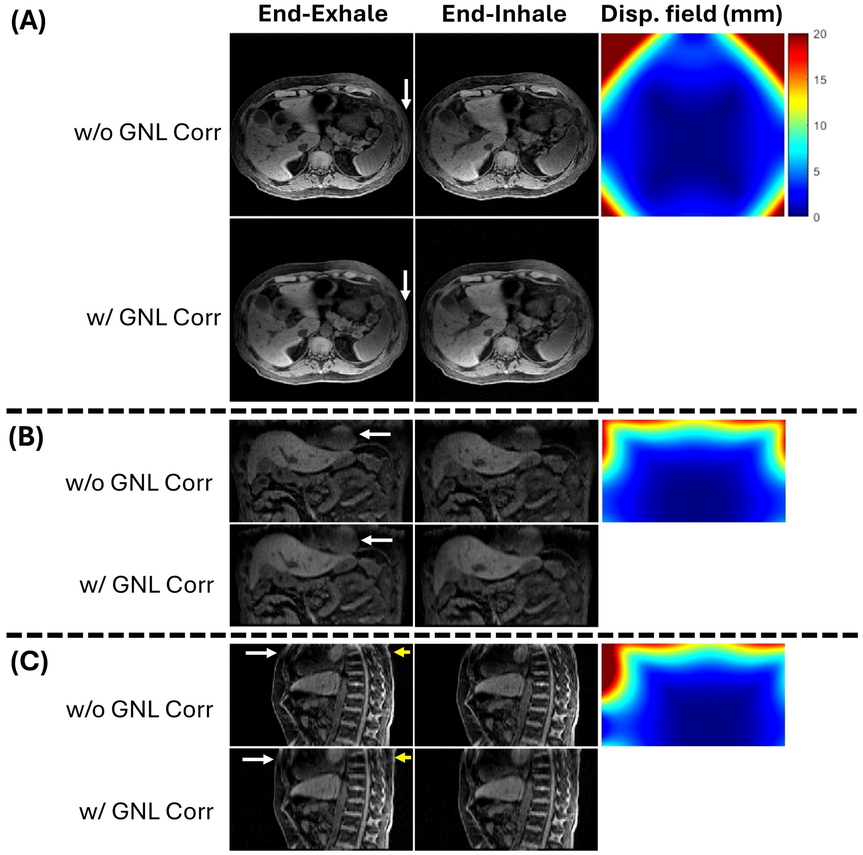

Figure 2: End-exhale and end-inhale respiratory phases in 4D MRI before and after gradient nonlinearity (GNL) correction. GNL correction improves geometric accuracy (arrows), particularly in regions with large displacement fields.

- Small bowel showed a significant increase in SI motion range after GNL correction (3.60 ± 1.84 mm vs. 5.94 ± 1.73 mm, $p = 0.006$), leading to a larger center-of-mass shift (5.27 ± 2.18 mm vs. 7.04 ± 1.30 mm, $p = 0.048$).

CONCLUSIONS

- Gradient nonlinearity correction improves 4D MRI geometric accuracy on the 1.5T MR-Linac.
- This study highlights the importance of GNL correction for accurate geometric and motion assessment using 4D MRI in abdominal radiotherapy.

REFERENCES

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