Dose-Free Functional Lung Imaging: Comparing Deformable Image Registration Algorithms for MR-Only Ventilation Mapping

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

T. Maurer[1], O. Hugh[1], R. Andosca[1], C. Miller[1], F. Han[2], A. Lee[1], D. Moghanaki[1], J. Lamb[1], D. Low[1], D. Maziero[1], and M. Lauria[1]
[1]Department of Radiation Oncology, University of California, Los Angeles, Los Angeles, CA
[2]Siemens Healthineers, Los Angeles, CA

ABSTRACT

Purpose: Recent advances in MRI could offer patients with benign lung disease whole-lung ventilation mapping that may serve as a surrogate for pathophysiological changes such as increased airway resistance and decreased lung compliance. Ventilation maps can be derived from deformable image registration (DIR) algorithms, but DIRs remain underexplored in MRI lung scans. This work evaluates and compares the registration of MRI lung scans across five DIR algorithms for the purposes of ventilation mapping.

Methods: Free-breathing, non-contrast, 3D lung scans of five participants were acquired on a 1.5T MRI Siemens Magnetom Sola. An ultra-short echo time stack-of-spirals sequence, with reconstructed golden-angle radial sparse parallel and prospective gating, accounted for respiratory motion through acquiring k-space data over inhale and exhale phases. Five open-source DIR algorithms were used to measure exhalation to inhalation deformation vector fields (DVFs): dense displacement sampling (deeds), advanced normalization tools (ANTs), elastix, MATLAB's demons, and MATLAB's total variation (TV). Each registration was evaluated following AAPM TG-132 guidelines. The ventilation was characterized using the Jacobian determinate and compared across algorithms using the structural similarity index measure (SSIM).

Results: Aside from MATLAB TV, the DIR algorithms met the tolerances of AAPM TG-132. Deeds and ANTs were the top performing DIR algorithms overall. The ventilation maps varied widely based on the DIR algorithm used, with deeds and elastix producing the most similar ventilation maps at a participant-averaged SSIM of 0.51±0.06.

Conclusion: Though four of five DIR algorithms were TG-132 compliant, the ventilation revealed disparities across all DIR algorithms, necessitating further investigation. Immediate next steps include rigorous DIR algorithm optimization. Future work will also focus on using 4DCT as a benchmark to better understand ventilation in MRI and to explore its clinical relevance as a non-ionizing alternative to regional ventilation imaging.

INTRODUCTION

- Recent advances in MRI could offer patients with benign lung disease whole-lung ventilation mapping
  - May serve as surrogate for pathophysiological changes such as…
    - ➢ Increased airway resistance
    - ➢ Decreased lung compliance
- Ventilation maps can be derived from deformable image registration (DIR) algorithms[1]
  - But DIRs underexplored in MRI lung scans
- This work evaluates and compares registration of MRI lung scans across five DIR algorithms for purposes of ventilation mapping

METHODS AND MATERIALS

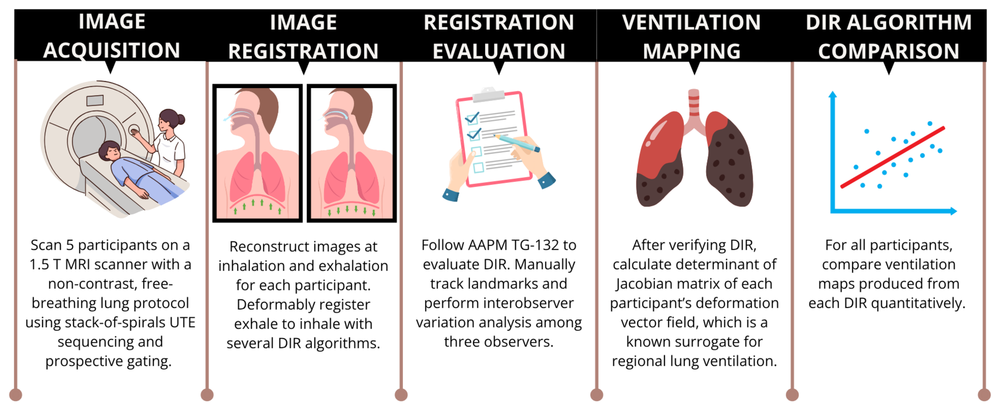

Figure 1. Methodology. DIR: deformable image registration.

DIR of exhale-to-inhale phases for each participant with 5 different algorithms:

1. Dense displacements sampling (deeds)
2. Advanced normalization tools (ANTs)
3. Elastix
4. MATLAB's demons
5. MATLAB's total variation (TV)

- Each DIR evaluated with AAPM TG-132 metrics[2]: target registration error (TRE), mean distance to agreement (MDA), Dice similarity coefficient (DSC), percent of Jacobians less than or equal zero, and consistency

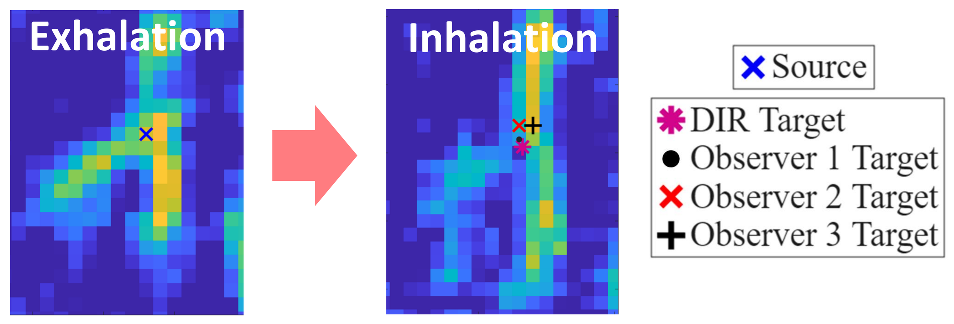

Figure 2. Example of three observers tracking a landmark across the exhalation and inhalation states for the TRE ground truth.

- Upon validating DIR with AAPM TG-132, can use its deformation vector fields (DVFs) t_1, t_2, and t_3 (for each cardinal plane) at voxel $\vec{x}$ to calculate the Jacobian[1]

$$J(\vec{x}) = \det \begin{bmatrix} 1 + \frac{\partial t_1(\vec{x})}{\partial x_1} & \frac{\partial t_1(\vec{x})}{\partial x_2} & \frac{\partial t_1(\vec{x})}{\partial x_3} \\ \frac{\partial t_2(\vec{x})}{\partial x_1} & 1 + \frac{\partial t_2(\vec{x})}{\partial x_2} & \frac{\partial t_2(\vec{x})}{\partial x_3} \\ \frac{\partial t_3(\vec{x})}{\partial x_1} & \frac{\partial t_3(\vec{x})}{\partial x_2} & 1 + \frac{\partial t_3(\vec{x})}{\partial x_3} \end{bmatrix}$$

- Jacobian of DVF → surrogate for regional ventilation (voxel-wise volume change)

→ **Because motion-based ventilation derived from DIR, verifying DIR accuracy requisite**

RESULTS

- Prospective gating provided distinct exhale and inhale phases, and DIR deformed inhalation to exhalation geometry

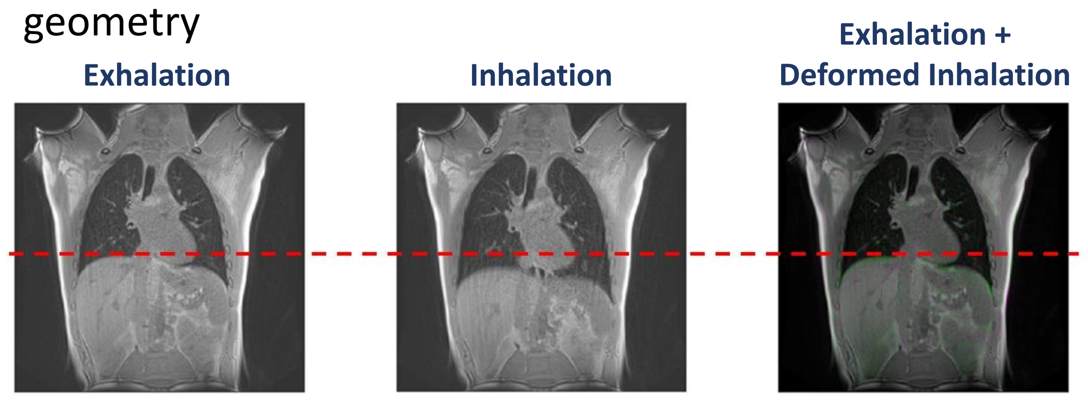

Figure 3. Representative exhalation and inhalation phases for the mid-coronal slice of a participant, along with the exhalation overlaid with the inhalation deformed to exhalation via DIR. A red dashed horizontal line shows the diaphragm position in the exhalation and is extended across panels for reference.

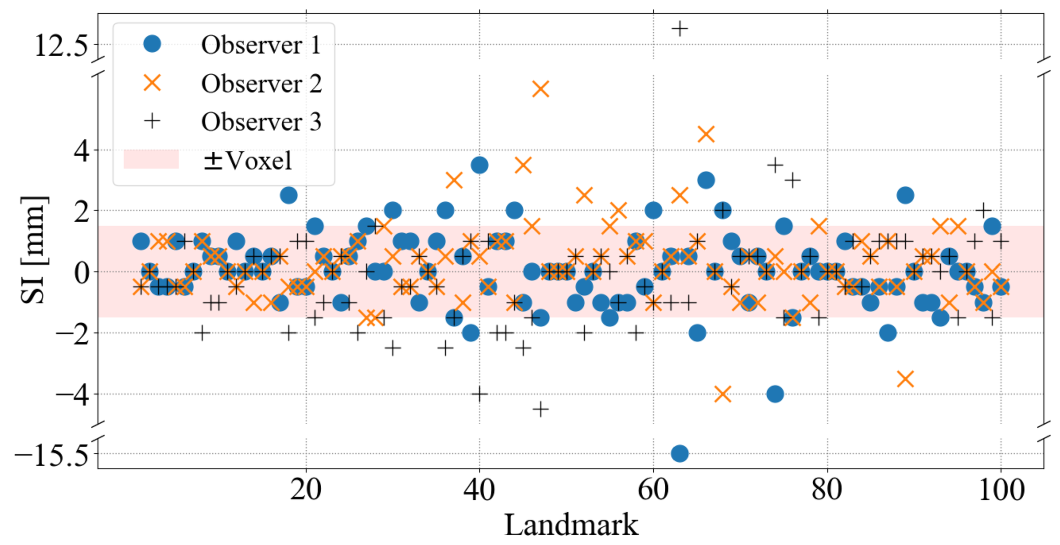

Figure 4. The interobserver deviation from the ground truth landmarks, which was the observer average, for the axial direction (Superior-Inferior). The shaded area corresponds to ± one voxel (1.5 mm).

- Three observers tracked landmarks across exhalation and inhalation phases for each participant for TRE ground truth
  - The interobserver uncertainty was 1.33 mm in landmark selection (all directions)

Table 1. Participant-averaged AAPM TG-132 metrics for each DIR ± one standard deviation, except for the TRE, where the uncertainty was determined from the interobserver study of the ground truth. *Seven voxels within the lung contour had negative Jacobians. Bolded red text indicates tolerance violation.

Tolerance	TRE (mm) ≤ 1.5	MDA (mm) ≤ 3	DSC (%) ≥80-90	Jacobian ≤ 0 (%) $= 0$	Consistency (mm) ≤ 1.5
ANTs	1.5 ± 1.4	1.71 ± 0.49	94.4 ± 1.4	0	0.16 ± 0.14
Deeds	1.7 ± 1.5	2.04 ± 0.54	93.3 ± 1.5	0	0.14 ± 0.22
Elastix	2.2 ± 1.4	1.64 ± 0.62	94.6 ± 1.9	0	**1.53 ± 1.20**
Demons	2.3 ± 1.5	1.89 ± 0.60	93.9 ± 1.8	**0***	1.29 ± 1.04
TV	**4.9 ± 1.5**	2.52 ± 0.77	91.8 ± 0.77	**0.4 ± 0.2**	**1.72 ± 1.73**

Table 2. The structural similarity index measure (SSIM) of the ventilation maps produced from one DIR compared to another for the same participant. The participant-average SSIM is reported ± one standard deviation.

	Demons	ANTs	Elastix	TV
Deeds	0.38 ± 0.01	0.42 ± 0.01	0.39 ± 0.01	0.37 ± 0.01
Demons	-	**0.47 ± 0.01**	0.43 ± 0.02	0.42 ± 0.01
ANTs	-	-	0.40 ± 0.01	0.44 ± 0.02
Elastix	-	-	-	0.35 ± 0.02

RESULTS (CONTINUED)

- Averaged across participants…
  - ANTs and deeds were AAPM TG-132 compliant
  - Demons and elastix were largely AAPM TG-132 compliant
  - TV not AAPM TG-132 compliant
- No inter-DIR algorithm agreement in ventilation mapping, seen visually and quantitatively
  - Demons and ANTs had largest inter-DIR algorithm agreement in ventilation mapping (SSIM = 0.47), but still indicated no agreement (≤ 0.7)
- However, globally ventilation was within expectations for typical lung physiology metrics

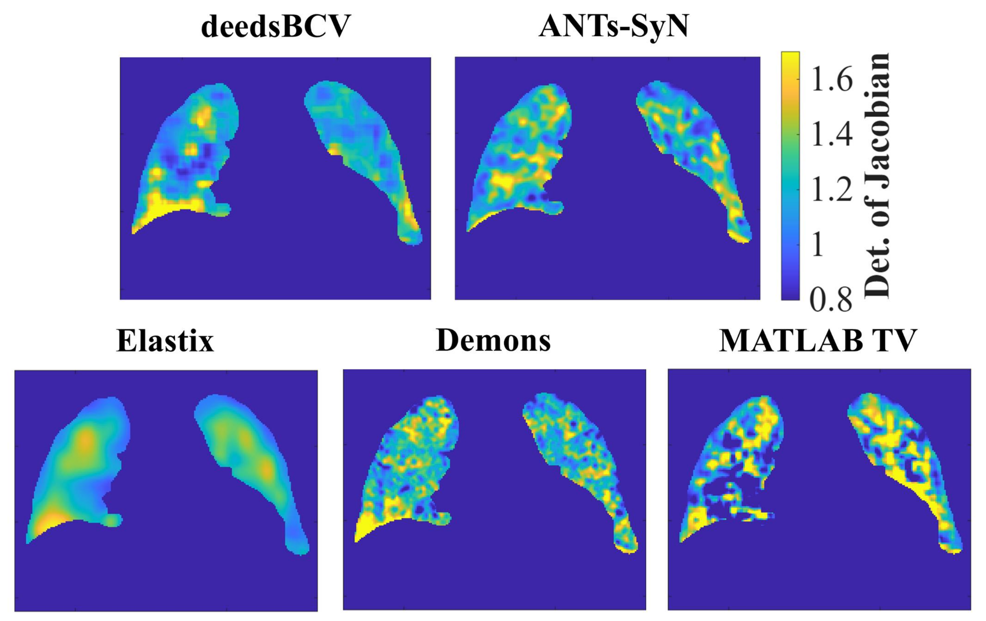

Figure 5. The unnormalized ventilation maps produced from 5 DIR algorithms, shown at mid-coronal slice for **Participant 3**, who had the **largest** inter-DIR algorithm ventilation agreement.

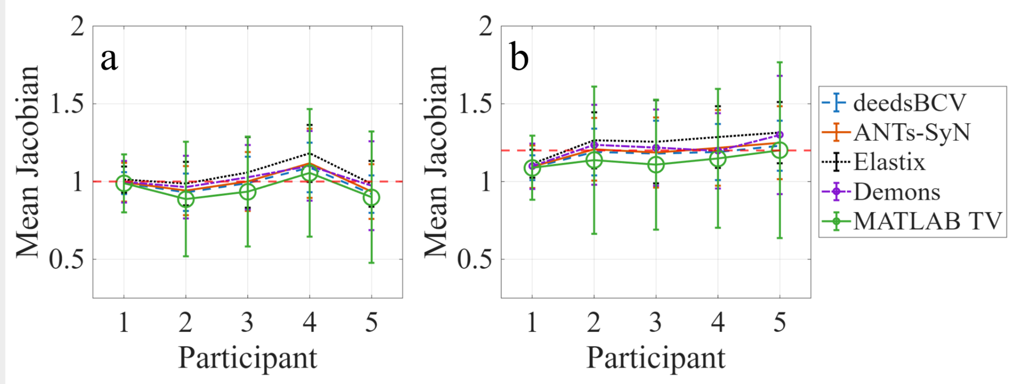

Figure 6. The mean Jacobian determinant for each participant and for each DIR algorithm (a) normalized by the inhale-to-exhale lung volume ratio and (b) unnormalized. The error bars represent one standard deviation. The red dashed horizontal lines represent reference values for typical ventilation distributions.

CONCLUSIONS

- Four of five DIR algorithms were largely AAPM TG-132 compliant
  - Although global ventilation consistent with typical lung physiology, regional ventilation revealed disparities across all DIR algorithms, despite AAPM TG-132 compliance
  - Necessitates further investigation into precise DIR algorithm evaluation and image quality
  - Future work will focus on 4DCT benchmarking to better understand ventilation in MRI
- This work important step in exploring MRI's clinical relevance as a non-ionizing alternative to regional ventilation mapping

REFERENCES

1. Castillo R, Castillo E, Martinez J, Guerrero T. Ventilation from four-dimensional computed tomography: density versus Jacobian methods. Phys Med Biol. 2010;55(16):4661-4685. doi:10.1088/0031-9155/55/16/004
2. Brock KK, Mutic S, McNutt TR, Li H, Kessler ML. Use of image registration and fusion algorithms and techniques in radiotherapy: Report of the AAPM Radiation Therapy Committee Task Group No. 132. Med Phys. 2017;44(7):e43-e76. doi:10.1002/mp.12256

CONTACT

Tessa Maurer
Department of Radiation Oncology, University of California, Los Angeles
Los Angeles, CA
TMaurer@mednet.ucla.edu