Repeatability of Ventilation In the Lung Using MR-Based Imaging

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INTRODUCTION

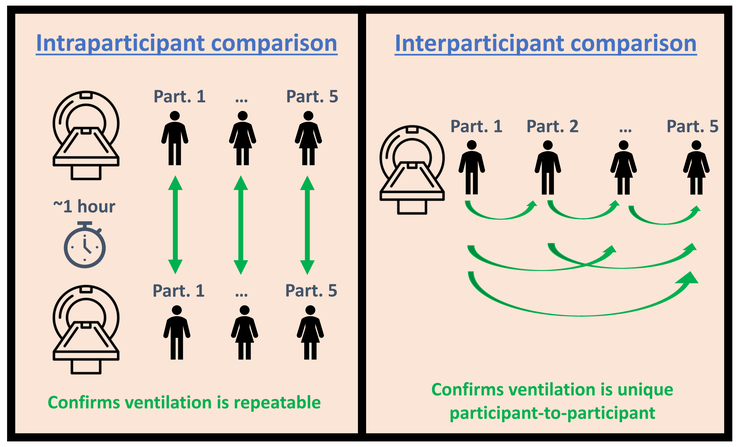
- Recent advances with MRI allow for motion-based, non-contrast ventilation imaging of the entire lungs
  - Repeatability of ventilation imaging in PET and CT have been studied, but MRI emerging
    - ➢ In lieu of regional ventilation ground truth, repeatability necessary to establish
- Deformable imaging registration (DIR) basis of motion-based ventilation
  - But algorithm choice, even when AAPM TG-132 compliant[1], can greatly influence final ventilation (see Poster TU-310-BRP-12 and VAMPIRE challenge[2])
- This work evaluates repeatability and reproducibility of MR-based ventilation imaging across four AAPM TG-132 compliant DIRs

METHODS AND MATERIALS

- Non-contrast, free-breathing, whole-lung scans of 5 participants acquired on 1.5T MRI with UTE stack-of-spirals sequence
- Deformably registered exhale-to-inhale phases with 4 DIRs: advanced normalization tools (ANTs), dense displacement sampling (deeds), elastix, and MATLAB's demons
- From DIR, used deformation vector fields (DVFs) t_1, t_2, and t_3 (associated with each cardinal plane) at voxel $\vec{x}$ to calculate the Jacobian[3]

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

- Jacobian of DVF → surrogate for regional ventilation (voxel-wise volume change)
- Compared ventilations via structural similarity index measure (SSIM): intraparticipant (repeat) and interparticipant scans



- One additional participant scanned in multiple sessions longitudinally
  - Ventilations compared across DIRs for reproducibility check
- All repeat ventilations registered to first ventilation and normalized by inhale-to-exhale volume ratio to allow for direct comparison
  - Interparticipant comparison also used registration and normalization

RESULTS

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

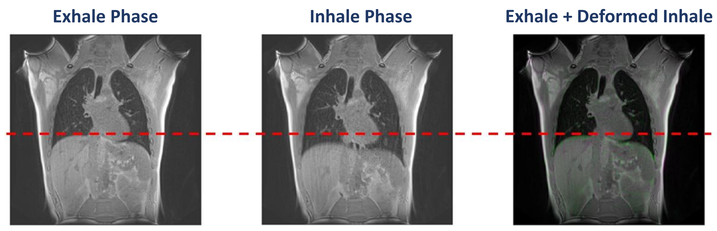


Figure 1. Representative exhalation and inhalation phases for the mid-coronal slice of a participant, along with the exhalation overlaid with the inhalation deformed to exhalation via DIR (deeds). A red dashed horizontal line shows the diaphragm position in the exhalation and is extended across panels for reference.

- Elastix showed moderate repeatability in ventilation
  - Deeds, ANTs, and demons showed no similarity in repeat ventilation (SSIM < 0.7)

Table 1. SSIMs for each ventilation comparison, intra- (n=5) and inter-participant (n=10 combinations), averaged (± one standard deviation) over comparison pairs and evaluated across DIRs. Bolded green text shows the largest SSIMs.

	Deeds	ANTs	Elastix	Demons
Intraparticipant SSIM (-)	0.55 ± 0.06	0.51 ± 0.02	**0.82 ± 0.12**	0.55 ± 0.10
Interparticipant SSIM (-)	0.46 ± 0.08	0.39 ± 0.06	**0.58 ± 0.12**	0.40 ± 0.07

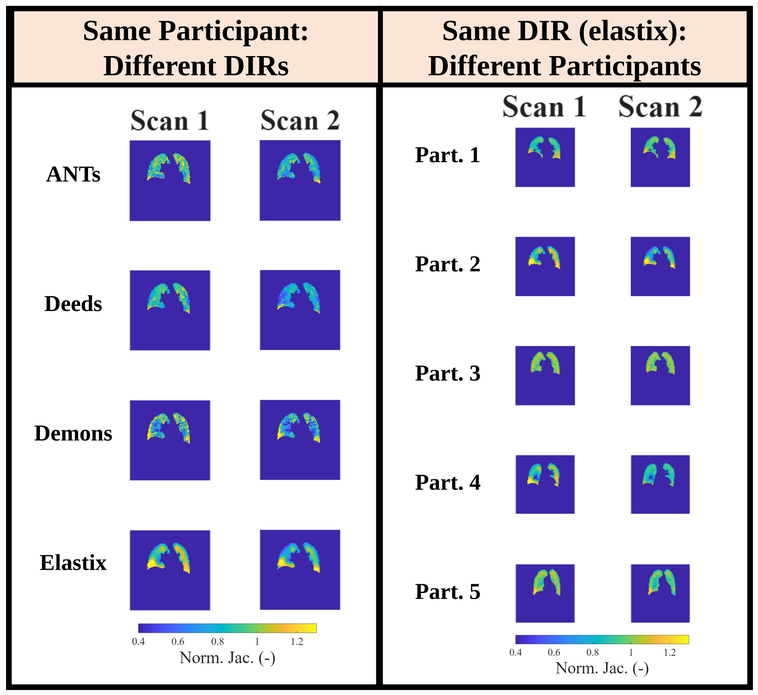
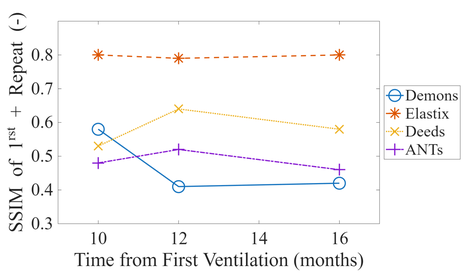


Figure 2. Ventilations normalized by the inhale-to-exhale lung volume ratio shown for repeated scans of (left) the same participant but different DIRs and (right) the same DIR (elastix) but different participants. The same coronal slice is shown for visualization, but ventilation was derived for the entire lung.



- Elastix generated most reproducible ventilation over time, SSIM ≈ 0.8 even over 16-month gap
- Other DIRs not reproducible with time (SSIM < 0.7)

Figure 3. Reproducibility of longitudinal ventilations of the same participant shown for each DIR. Reproducibility was computed as the SSIM of the first ventilation and a ventilation acquired later (~months) for the same participant.

DISCUSSION

- Elastix ventilation repeatability (intraparticipant SSIM > 0.7) not at expense of unique regional information (interparticipant SSIM < 0.7 and seen visually across participants)
- Reproducibility findings over time mirrored repeatability conclusions, but study limited to one participant
- Previous work (Poster TU-310-BRP-12) and the VAMPIRE challenge[2] showed DIR algorithm choice affects motion-based ventilation, even when DIR algorithm accuracy validated according to AAPM TG-132
  - This repeatability (and reproducibility) work serves as initial validation for motion-based ventilation that goes beyond DIR accuracy evaluation
    - ➢ Can inform proper DIR choice when DIR accuracy metrics alone not enough

Fundamental differences between DIR algorithms:

- Deeds: Markov random field discrete optimization
- ANTs: continuous, symmetric diffeomorphic optimizer
- Demons: optical flow
- Elastix: continuous B-spline
  - ➢ Elastix smoothed over ROI of 7 voxels, more than all of the other DIRs

CONCLUSIONS

For non-contrast, free-breathing, whole-lung MRI…

- Elastix most suitable DIR investigated for ventilation imaging
  - Moderate repeatability in ventilation
  - Maintained differences between participants
- ANTs, deeds, and demons did not show repeatability in ventilation
- Elastix only DIR studied that showed moderate reproducibility over time
- Future work can benchmark elastix-based ventilation using 4DCT
  - Establishing non-ionizing, non-contrast regional ventilation imaging expands prognostic and surgical intervention tools available for patients

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