Clinical Applications of DIR in the Thorax: Verification Using Tagged MR Imaging

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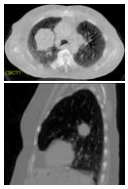
Background



- Patient's anatomy varies during RT, if not properly managed, can lead to mistreatment.
- DIR is becoming increasingly important in RT for managing these variations.
- Clinical applications of DIR in the lung range from 4D-RT, adaptive RT, to response assessment.
- The accuracy of DIR directly impacts the success of the clinical applications.

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Current DIR Assessment Methods

- Expert-determined Landmarks
  - rely on visible features, inter-intra observer variability
  - heterogeneously distributed, limited numbers
- Phantoms (physical and virtual)
  - oversimplified anatomy and deformation models
  - lacking sufficient realism
- FEM Modeling
  - assumes unrealistic homogeneous elasticity
  - challenging to build model, initialize boundary conditions

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Crucial Barriers

- Lack of gold-standard for DIR assessment.
- Current approaches focus on *morphological* similarity but not on the *physiological* plausibility of the deformation.
- Increased morphological similarity of the aligned data does not always imply increased registration accuracy.

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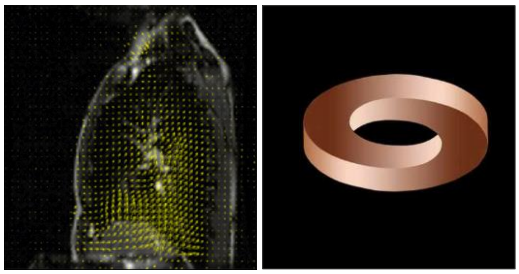

Illusion

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Challenges for the Thorax

- Lung has large volume, but needs to be considered as a whole in dealing with DIR.
- Lung is highly elastic. It moves and deforms in large degree during breathing. Large DIR errors are associated with large displacements .
- Lung respiratory motion is complex: non-uniform and different between different lung lobes.
- Lung has coarse and heterogeneous structures, adversely affecting lung imaging and DIR performance in the lung

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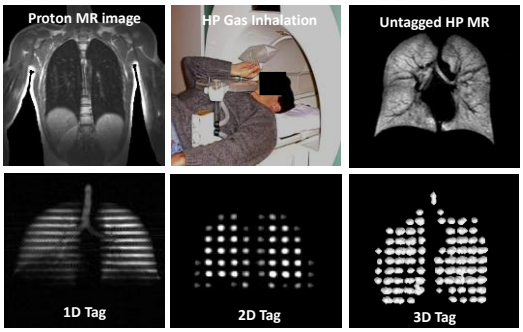
Hyperpolarized (HP) Gas Tagging MRI



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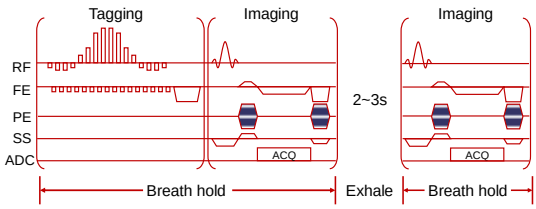
HP Gas Tagging MRI Sequence



- Tagging achieved by applying sinc-modulated RF pulse train with composite flip angle of 90°
- MR images acquired at inhalation (EOI) and exhalation (EOI) during breath hold

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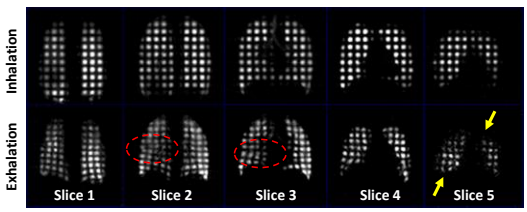
Multi-slice 2D HP Gas Tagging MRI



- Majority of tag-grids persistent at exhalation phase.
- Some tag-grids disappeared in anterior lung (yellow).
- Sliding shear motion between lung lobes (red).

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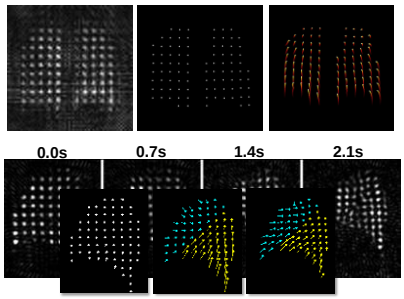
Dynamic 2D HP Gas Tagging MRI



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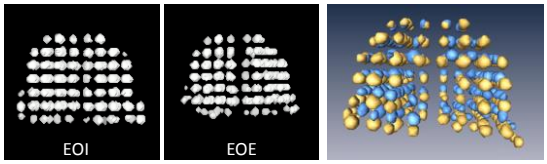
3D HP Gas Tagging MRI



Cai J, et al., Red J, 2007;68:650-653
Cai J, et al., Red J, 2009;75;276-284

3D rending of HP He-3 MR Tagging of the lungs at inhalation (Gold) and exhalation (Blue)

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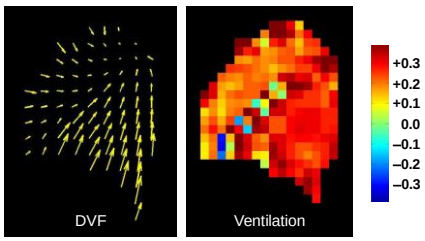
Lung Ventilation Estimation



Ventilation = V_{EOI}-V_{EOE} / V_{EOI}

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Unique Features of HP Gas Tagging MRI for DIR Assessment

- Lung deformation is measured *in vivo* in real human being, providing a *physiological* ground-truth for comparison.
- A large number (300~500) of uniformly distributed landmarks, enabling a complete assessment of DIR throughout the entire lung.
- The tag landmarks have very high SNR (~50) and are easily identifiable, minimizing errors and human uncertainties in landmark identification.

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Purpose

To develop and test a methodology for quantitative evaluation of DIR in the lung using HP gas tagging MRI in a pilot human study.

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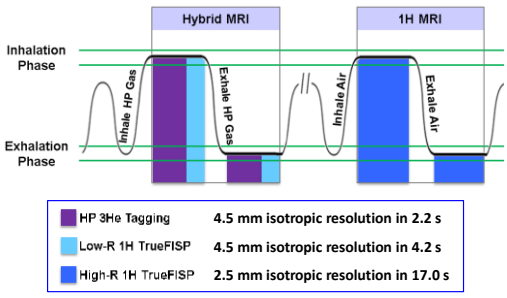
Study Design - MR Imaging



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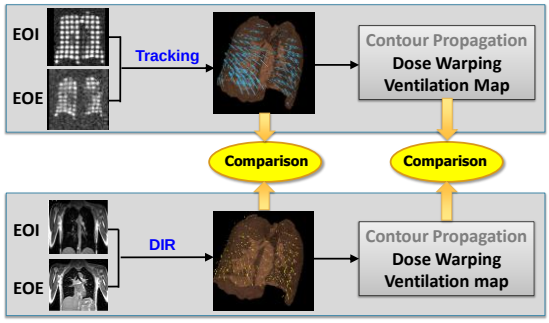
Study Design - Data Analysis



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DIR Algorithms

DIR Algorithms
Multi-pass B-spline
Free Form Deformation
Double Force Demons
Improved Lucas-Kanade
Iterative Optical Flow
Multi-Grid B-spline
Radial-basis Function

- 3 commercial
- 4 in-house developed

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Methods and Materials

- 3 healthy volunteers
- Different breath-hold Levels (1 cm, 2 cm, 4 cm)
- Hyperpolarized gases (He-3, Xe-129)
- Siemens 3T scanner, bellow respiratory system.
- Tag positions were manually determined in Eclipse. Each measured 3 times to minimize error.
- DIR was performed by independent experts.

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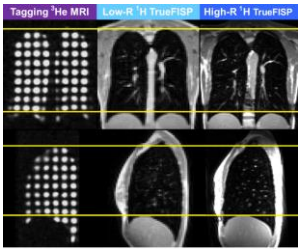
MR Images



- Good match in lung volume between breath-holds
- Rich internal lung features in TrueFISP MRI

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Fused Images at EOI

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Fused Images at EOE

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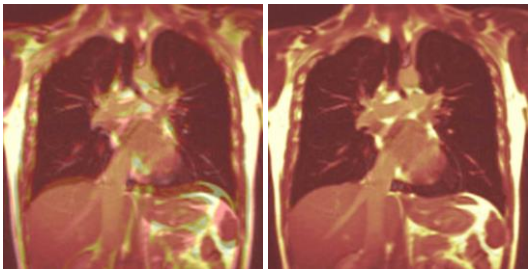
Proton MRI DIR Registration



Before After

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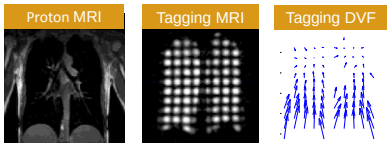
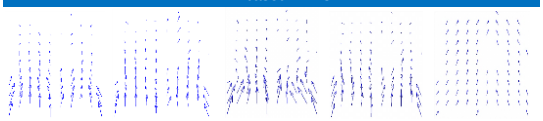
DVF Comparison



DIR-based DVFs



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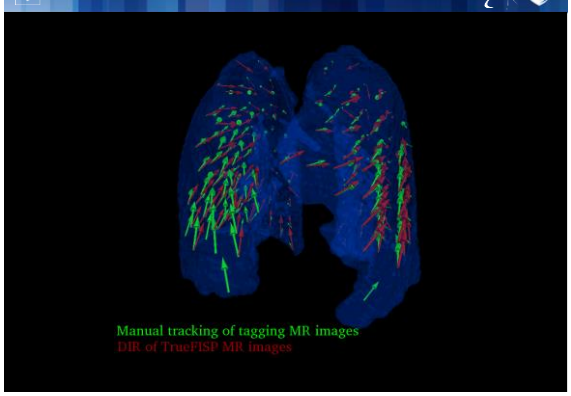

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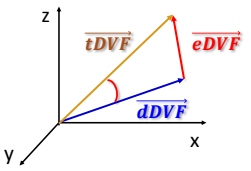
Methods: Data Analysis



$\overrightarrow{eDVF} = \overrightarrow{tDVF} - \overrightarrow{dDVF}$

- Magnitude (*Em*)
- Angle (*Ea*)

- Global Analysis
  - DVF frequency
  - DVF error frequency
  - DVF correlation
- Regional Analysis
  - DVF error ~ motion
  - DVF error spatial distribution
- RT Applications
  - Dose warping
  - Lung ventilation

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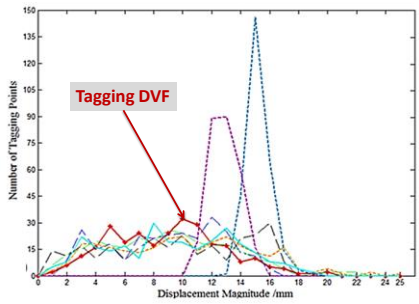
DVF Magnitude Frequency Distribution



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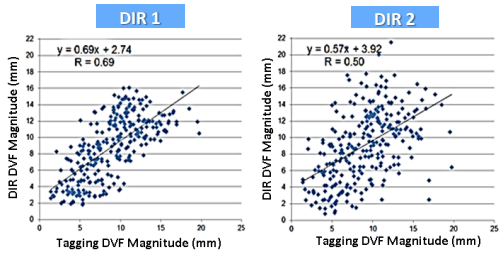
DVF Magnitude Correlation



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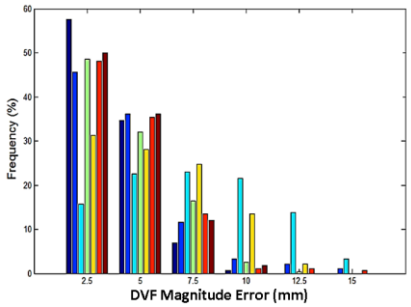
DVF Error Frequency Distribution



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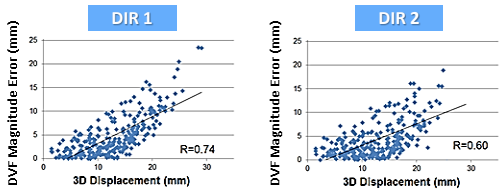
DVF Magnitude Error ~ Lung Motion



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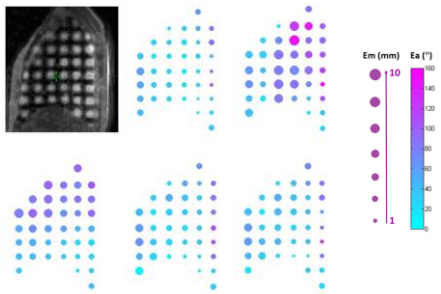
Spatial Distribution of DVF Error



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DVF Error Summary

- DVF magnitude error (*Em*)
  - Range: 0.1mm - 29.3 mm
  - Range of mean value: 4.5 mm - 10.7 mm
- DVF angle error (*Ea*)
  - Range: 0.9° - 177.8°
  - Range of mean value: 36.7° - 70.9°

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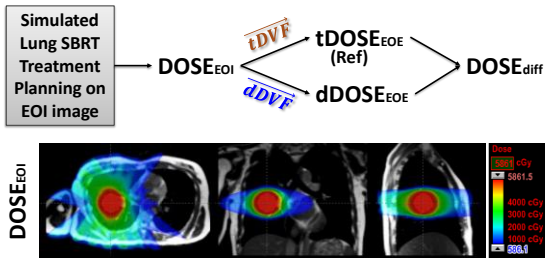
Dose Warping



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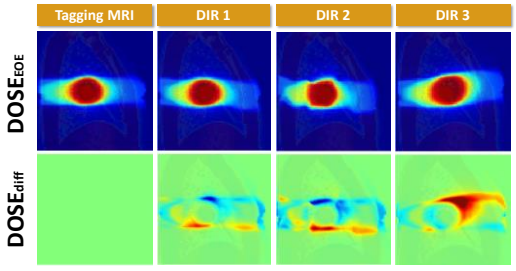
Dose Warping



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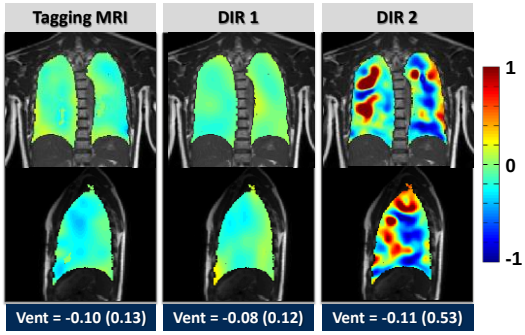
Lung Ventilation Estimation



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Limitations and Future Studies

- Limited number of subjects
- Only healthy subjects, no cancer patients
- MR images used for DIR, performance of DIR may be different than that on CT images
- Potential error in HP gas tagging MRI DVF (human error, gas diffusion, inter-BH variability)
- Evaluated only two respiratory phases
- Sub-optimal spatial resolution of MR images

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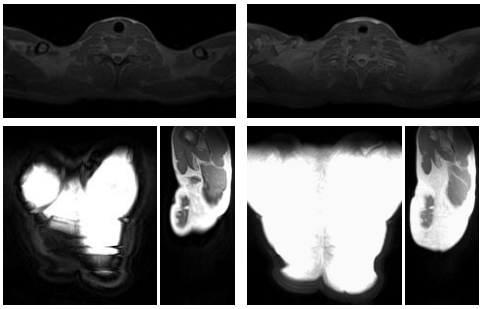
Ultra-resolution TrueFISP MRI



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Conclusions

- A methodology for evaluating DIR in the lung using HP gas tagging MRI has been developed, and its feasibility has been tested on healthy subjects.
- Large differences in lung DVF between the tagging MRI method and various DIR algorithms and large variations among DIR algorithms were observed.
- Lung DVF errors may lead to significant errors in RT applications of DIR.
- It is important to consider the *physiological* plausibility of the deformation when developing and evaluating DIR algorithms in the lung.

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