Imaging Tissue Motion Using MRI

DENSE - Displacement Encoding with Stimulated Echo

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MRI Cine, 1997
Challenges for Routine Use of Cardiac MRI

According to R. Judd et al. 2005 ISMRM, routine clinical use of cMRI is estimated at less than 20,000 cases this year.

In 2001, 3.4 million patients were hospitalized for heart diseases (CDC/NCHS, published by AHA).

Translation of MRI Function Imaging from Bench to Bedside

There is a need for more data on accuracy and reproducibility from larger trials.

A key challenge for routine use is automation of data analysis.
MRI Assessment of Ventricular Function I – Cine Imaging

MRI Assessment of Ventricular Function II – Tagging

MRI Assessment of Ventricular Function II - Tagging

- Tagging measurement resolution is limited due to the grid spacing.

A New Approach: Displacement Encoding with Stimulated-Echo (DENSE)

- Encode positional information into the phase of each image pixel (Aletras, Ding, Balaban, and Wen, MRM Proc. 1998).
- Higher spatial resolution.
- Amenable to automatic processing.
DENSE Pulse Sequence

Initial phase maps

Phase shifts

few ms ~ 1s

Tm

Image Acq.

Striping Artifacts

Removal of Artifacts

Inversion, through-slice encoding and phase cycling help suppress other echoes and separate out the stimulated echo.


Strain Vector Maps

Aletras, Ding, Balaban, and Wen, JMR 1999
Time resolved DENSE

ECG triggered, respiratory gated scan time = 4 minutes/slice.
Image Processing: from MRI Data to Clinically Useful Parameters

- Image segmentation: removing unwanted pixels.
- Following material points over time to measure peak strain, torsion and timing.

DENSE is Amenable to Automatic Image Processing

- Automatic masking of solid tissue pixels:
  - Tissue movement should be continuous between neighboring pixels and adjacent time points.
  - Flowing blood appears dark, which aids separation of blood pool and solid tissue.
- Tissue tracking-following material points over time:
  - Displacement vectors at all time points are available.
DENSE-View \( \overline{DV} \)

- **Image Reconstruction**
  - Phase unwrapping
  - Converting to displacement maps
  - Image segmentation
  - Shaped-smoothing
  - Tissue tracking
  - Eulerian strain calculation
  - Dyssynchrony
  - Dyskinesis
  - Torsion

<table>
<thead>
<tr>
<th>( \overline{DV} )</th>
<th>Magnitude</th>
<th>Phase X</th>
<th>Phase Y</th>
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<tbody>
<tr>
<td>Raw data</td>
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<td><img src="phase_x_raw_data.png" alt="" /></td>
<td><img src="phase_y_raw_data.png" alt="" /></td>
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<td>Phase singularity removed</td>
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<tr>
<td>Intensity thresholded and phase unwrapped</td>
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<td><img src="phase_y_phase_unwrapped.png" alt="" /></td>
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Unsmoothed Circumferential Strain Movie

Strain calculation magnifies phase noise in the data.

How to smooth the noisy data?

Low-pass filtering averages over a neighborhood of fixed shape.

Low-pass filtered
**DV** Shaped Smoothing

Kernel conforms to local anatomical coordinates, preserves transmural resolution.

**DV**

Shaped-Smoothing is Superior to Low-Pass Filtering

- Low-pass filtered
- Shaped-smoothing
Strain Maps from Shaped-Smoothed Displacement Fields

Tracking Material Points over Time

? Converting Eulerian displacement to Lagrangian displacement
Dyskinesis and Dyssynchrony Maps

Dyskinesis and Dyssynchrony Maps
Patient Data – Epstein Kinase Allele Protocol, NHLBI/NIH

73, F, hypertension 55, M, hypertension

Summary of DENSE Cardiac Function Assessment

? Displacement imaging enables automated Processing for regional ventricular function.

? Future direction: test/retest reproducibility, correlation with echo TDI is being studied in normal volunteers and patients.
Arterial Wall Strain Imaging and Mechanical Instability in Vulnerable Plaques

- A vulnerable plaque is a future culprit plaque - 70% of culprit coronary lesions rupture. (Consensus paper by Naghavi et al., Circ. 108:1664-1672, 1772-1778).

Burke et al., NEJM 1997

Mechanical Aspects Plaque Rupture

- Rupture involves the fissuring of plaque cap in high stress/strain spots.
Tensile Stress Distribution Predicts Rupture Sites in Coronary Balloon Angioplasty

Ohayon, Teppaz, Finet and Rioufol, Coronary Artery Disease 2001, 12:655

Simulation of Strain Patterns for Different Plaque Morphology

Simulation of Strain Patterns of Different Plaque Morphology


Clinical strain imaging with IVUS

IVUS strain mapping in a PCTA procedure patient, Der Korte and Van der Steen, Ultrasonics, 40:859-865, 2002.
Frequency of Regional High Strain Spots Is Correlated with Clinical Indicators

Schaar et al., n = 55, IVUS elastography of culprit vessel before angioplasty (Circ. 109(22): 2716-2719, 2004). Positive correlation with presentation. hsCRP $R^2 = 0.65$.

Circumferentially Averaged Distensibility Is Correlated with Angioscopy Plaque Classification

DENSE Imaging of Registered Strain and Morphology Is Feasible in Human Carotid Artery

DENSE has inherent $T_1$ weighting and dark-blood contrast.

Displacement Field around Carotid Lumen

Current 600µm in-plane resolution, 5 mm slice thickness.
Circumferential Strain around Carotid Lumen

Wen, Vignaud, Rodriguez, submitted to AHA 2005

Another example
Summary of vessel wall strain imaging

Simultaneous strain and morphology imaging of the carotid artery is feasible in humans.

Correlation of MRI findings with other markers needs to be studied in patients with carotid lesions.

The spatial resolution at 1.5T is 500 – 600 µm, and is expected to improve with 3T scanners.
Acknowledgement

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? Clinical application

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