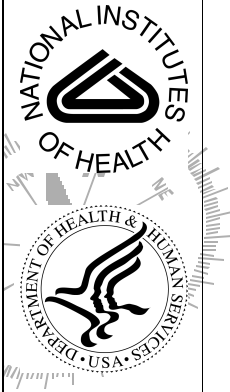


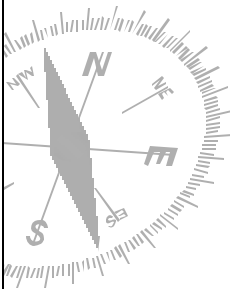


# Imaging Tissue Motion Using MRI DENSE - Displacement Encoding with Stimulated Echo



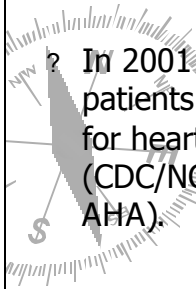
Imaging Physics Section,  
Laboratory of Cardiac Energetics,  
National Heart, Lung and Blood Institute

## MRI Cine, 1997

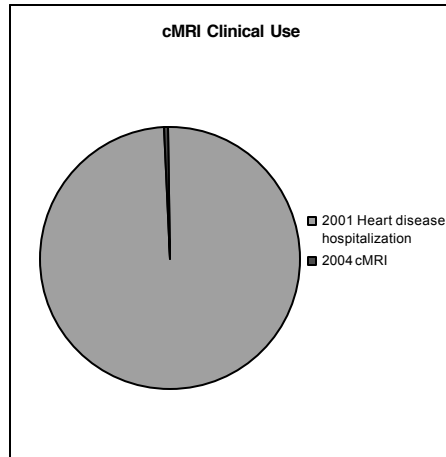


# Challenges for Routine Use of Cardiac MRI

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

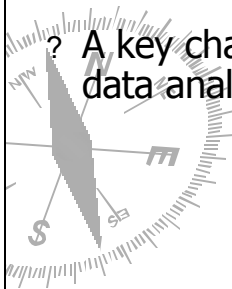


? In 2001 3.4 million patients were hospitalized for heart diseases (CDC/NCHS, published by AHA).



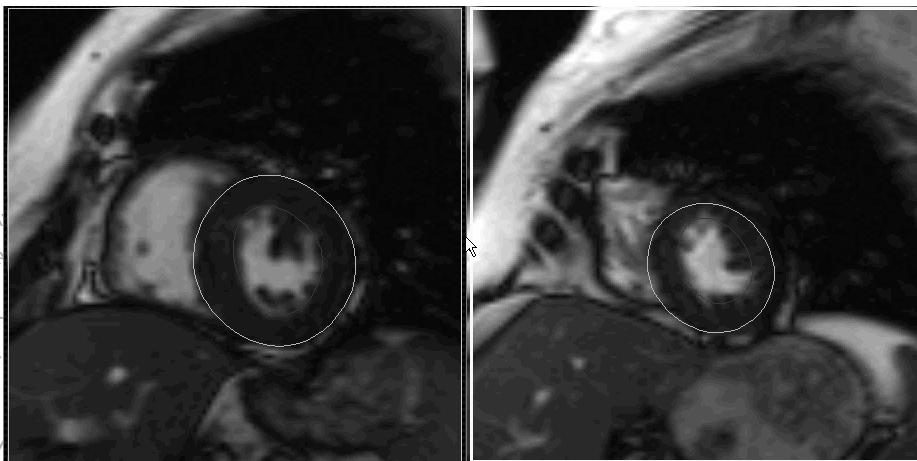
# Translation of MRI Function Imaging from Bench to Bedside

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

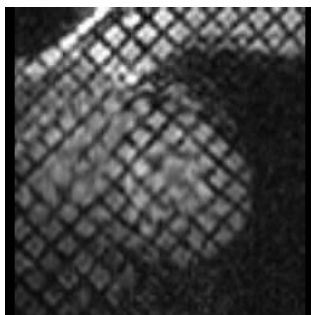
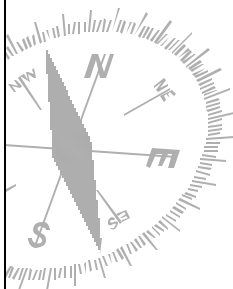


? A key challenge for routine use is automation of data analysis.

## MRI Assessment of Ventricular Function I – Cine Imaging



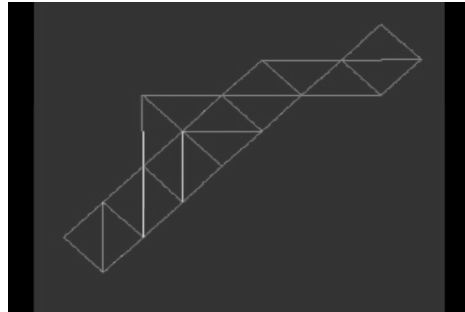
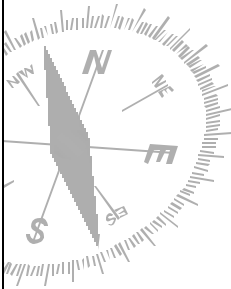
## MRI Assessment of Ventricular Function II – Tagging



Zerhouni, 1988, Axel, 1989.

## MRI Assessment of Ventricular Function II – Tagging

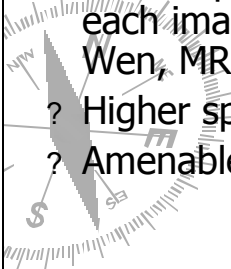
? Tagging measurement resolution is limited due the grid spacing.



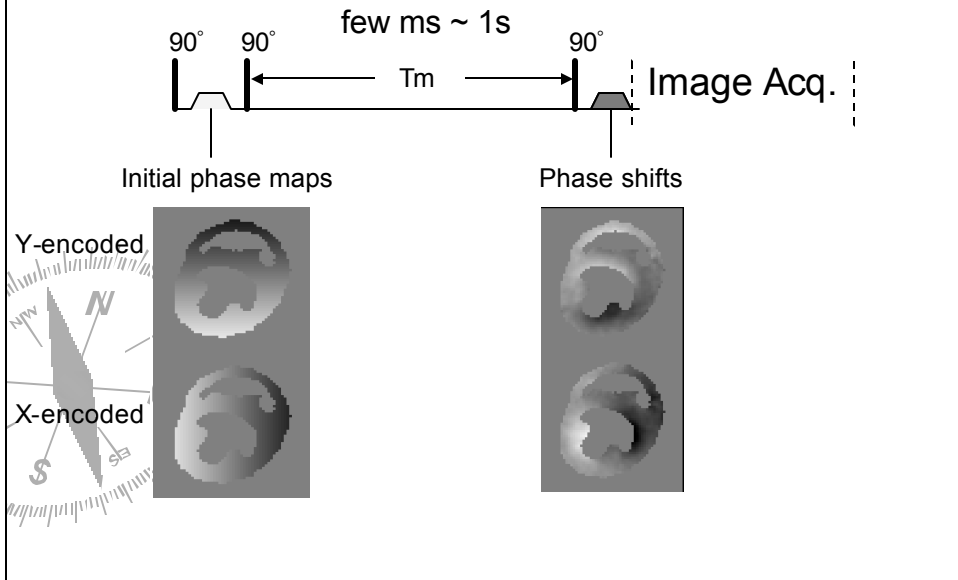
Victor Ferrari, private communication

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

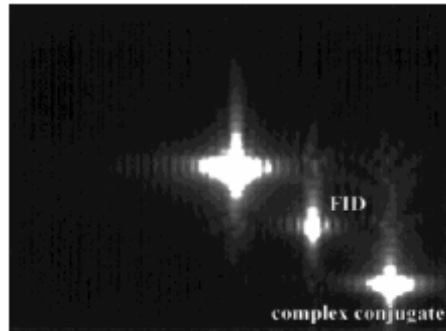
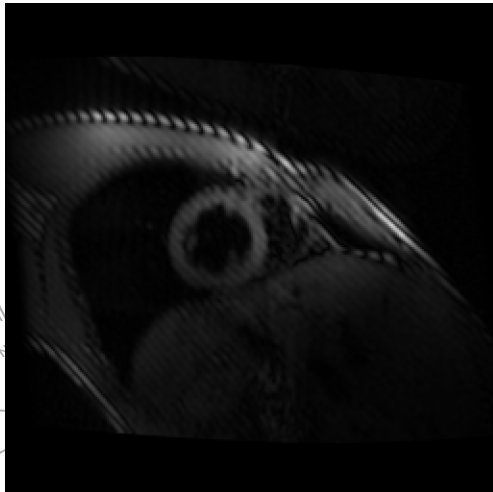
- ? Encode positional information into the phase of each image pixel (Aletras, Ding, Balaban, and Wen, MRM Proc. 1998).
- ? Higher spatial resolution.
- ? Amenable to automatic processing.



# DENSE Pulse Sequence

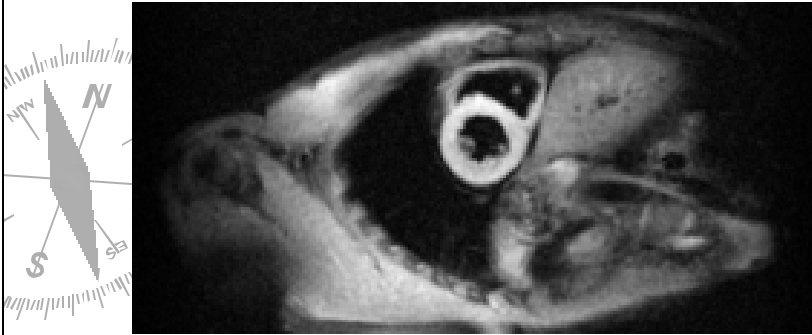


# Striping Artifacts



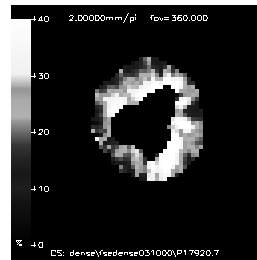
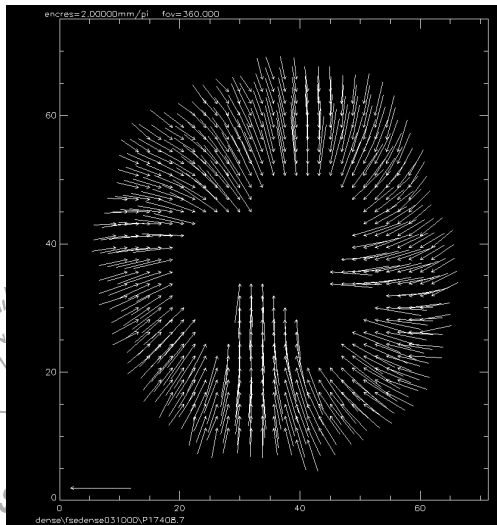
# Removal of Artifacts

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

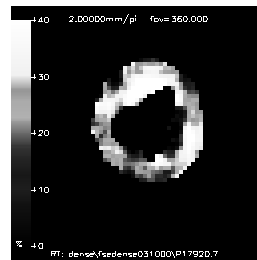


Aletras AH, Wen H. Magnetic Resonance in Medicine 2001; 46(3):523-534.

## Strain Vector Maps

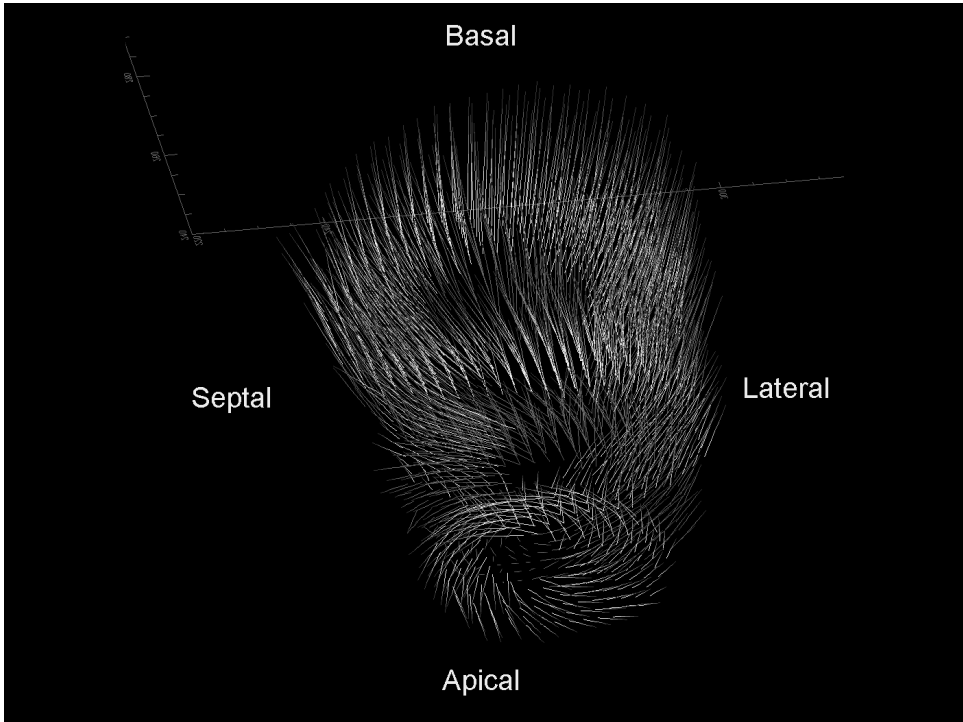


% Circumferential shortening



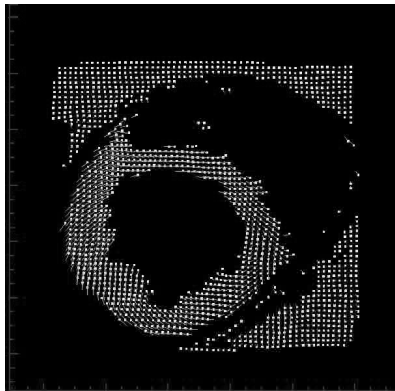
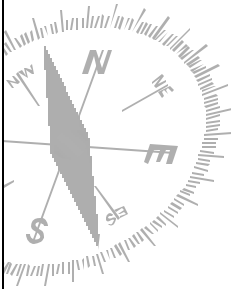
% wall thickening

Aletras, Ding, Balaban, and Wen, JMR 1999



## Time resolved DENSE

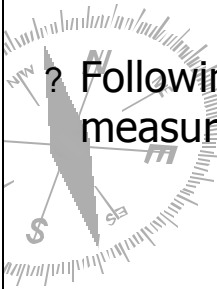
ECG triggered,  
respiratory gated  
scan time = 4  
minutes/slice.



## 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

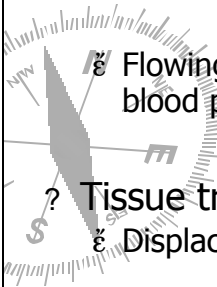
? Automatic masking of solid tissue pixels:

ε Tissue movement should be continuous between neighboring pixels and adjacent time points.

ε Flowing blood appears dark, which aids separation of blood pool and solid tissue.

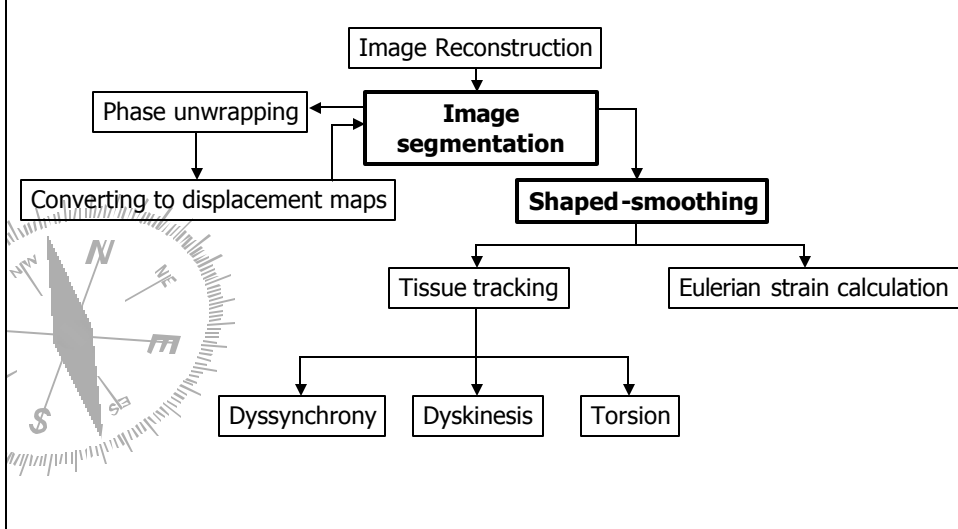
? Tissue tracking-following material points over time

ε Displacement vectors at all time points are available.





# DENSE-View DV

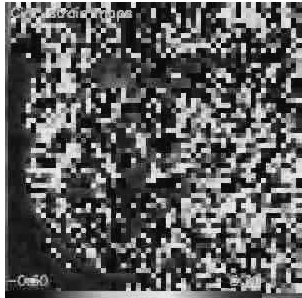
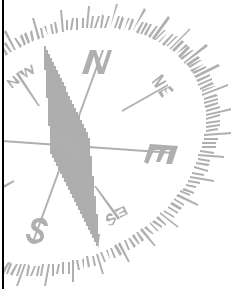


DV		Magnitude	Phase X	Phase Y
	Raw data			
	Phase singularity removed			
	Slip points removed			
	Intensity thresholded and phase unwrapped			

DV

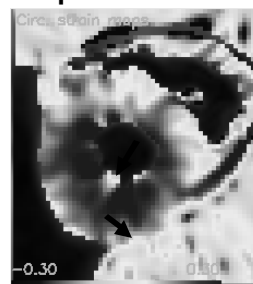
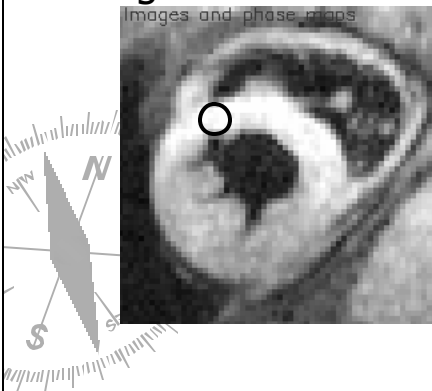
## Unsmoothed Circumferential Strain Movie

? Strain calculation magnifies phase noise in  
the data.



## How to smooth the noisy data?

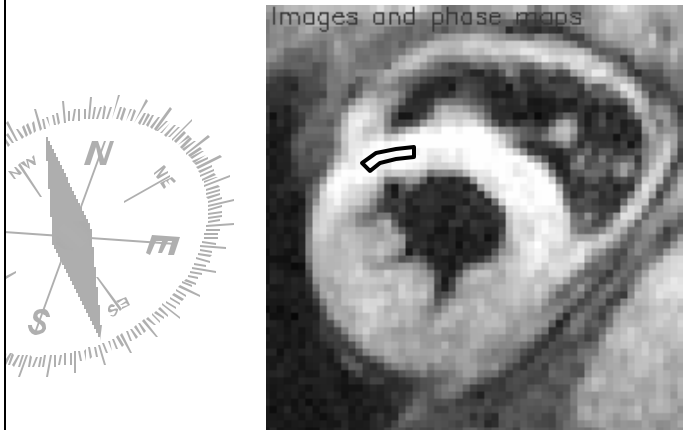
? Low-pass filtering averages over a  
neighborhood of fixed shape



Low-pass filtered

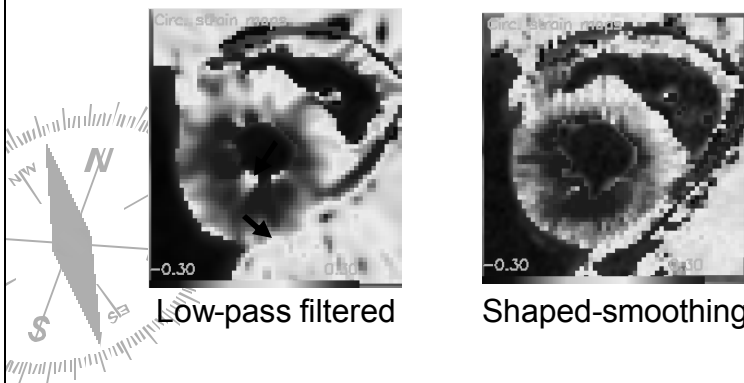
# DV Shaped Smoothing

? Kernel conforms to local anatomical coordinates, preserves transmural resolution.



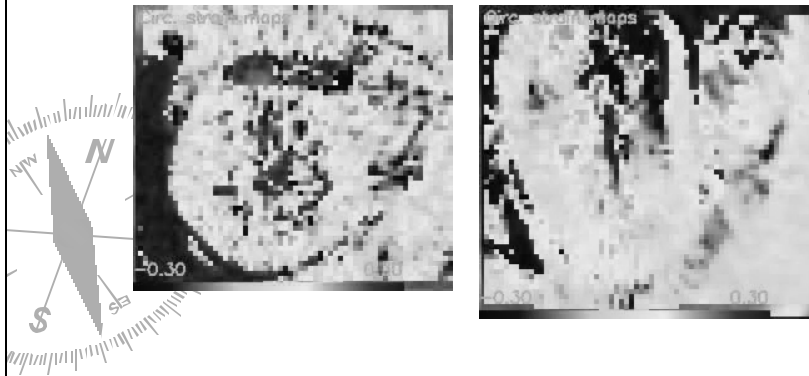
DV

## Shaped-Smoothing is Superior to Low-Pass Filtering



DV

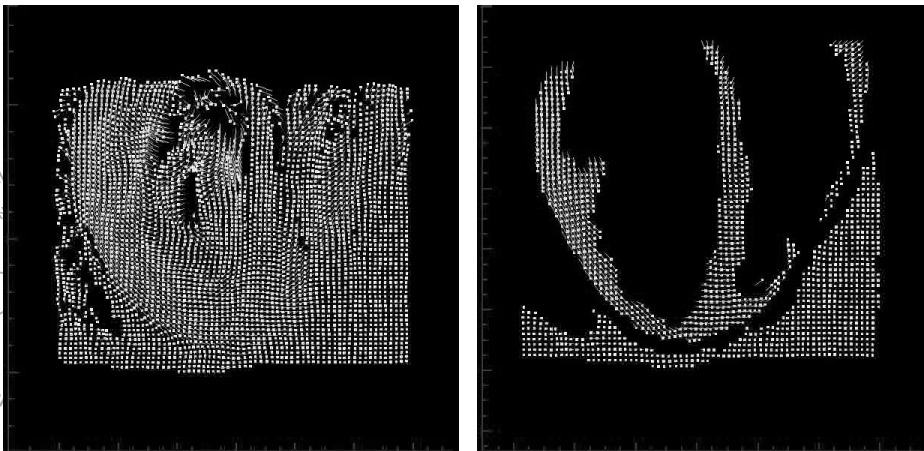
## Strain Maps from Shaped-Smoothed Displacement Fields



DV

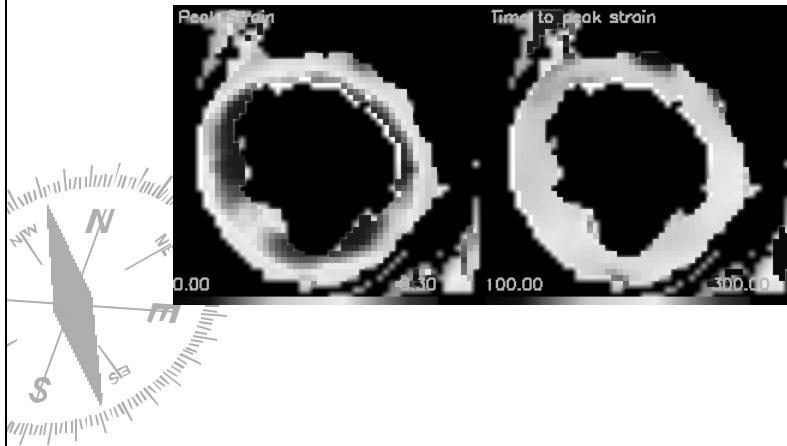
## Tracking Material Points over Time

? Converting Eulerian displacement to Lagrangian displacement



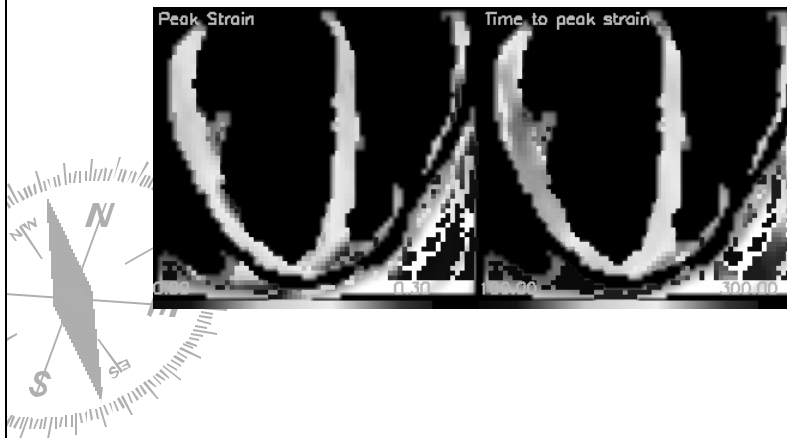
DV

## Dyskinesis and Dyssynchrony Maps



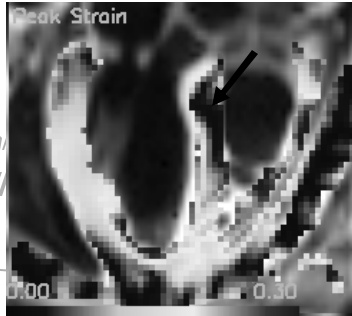
DV

## Dyskinesis and Dyssynchrony Maps

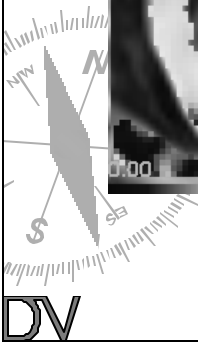
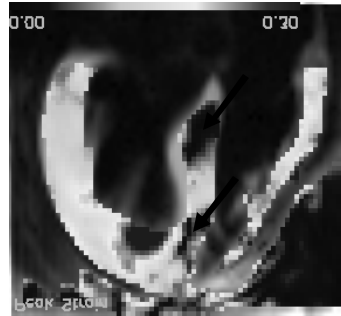


## Patient Data – Epstein Kinase Allele Protocol, NHLBI/NIH

73, F, hypertension

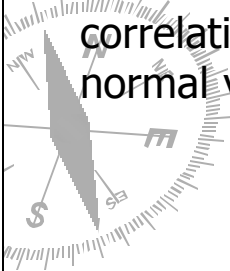


55, M, hypertension



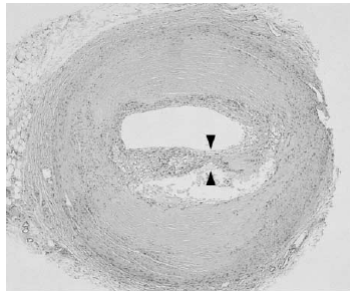
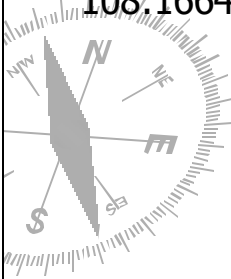
## Summary of DENSE Cardiac Function Assessment

- ? 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

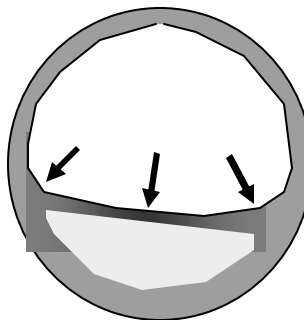
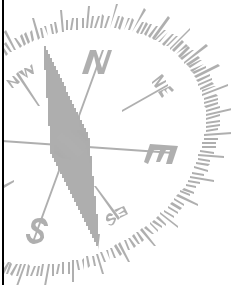
? A vulnerable plaque is a future culprit plaque - 70% of culprit coronary lesions rupture. (Consensus paper by Naghavi et al., *Circ.* 108:1664-1672, 1772-1778).



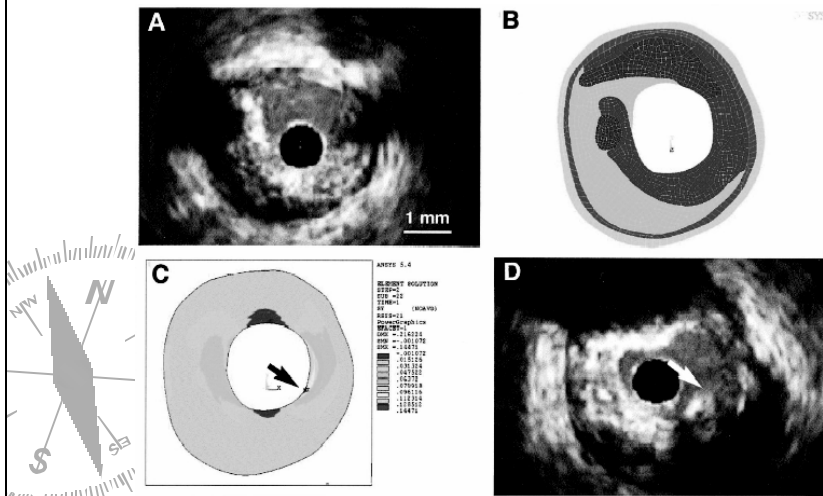
Burke et al., NEJM 1997

## Mechanical Aspects Plaque Rupture

? Rupture involves the fissuring of plaque cap in high stress/strain spots.

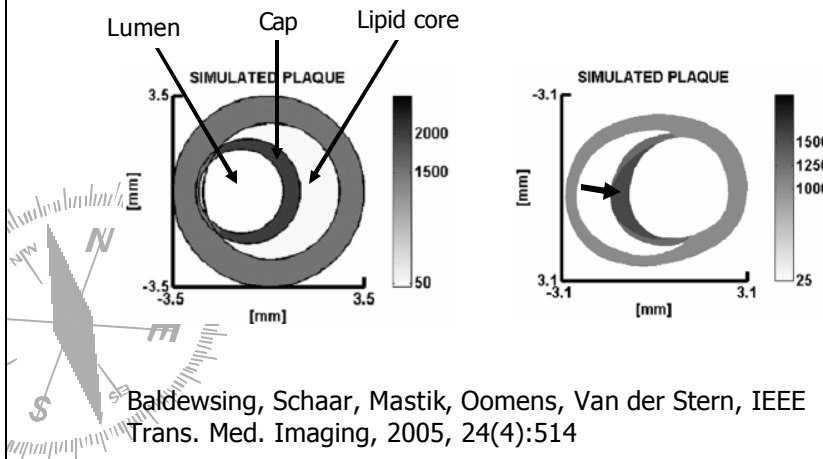


## Tensile Stress Distribution Predicts Rupture Sites in Coronary Balloon Angioplasty



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

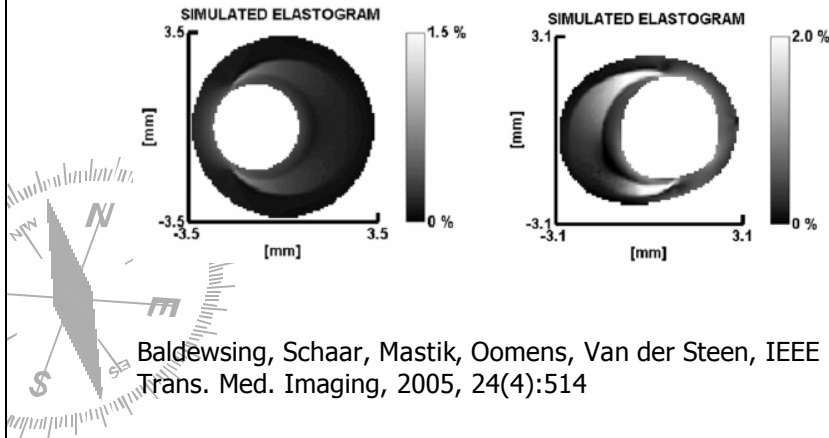
## Simulation of Strain Patterns for Different Plaque Morphology



Baldewsing, Schaar, Mastik, Oomens, Van der Stern, IEEE Trans. Med. Imaging, 2005, 24(4):514

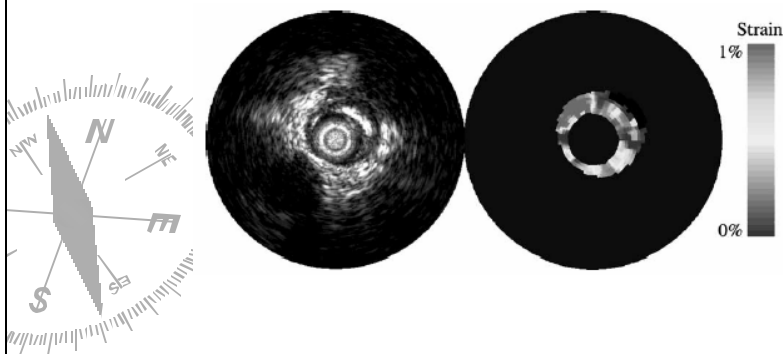


# Simulation of Strain Patterns of Different Plaque Morphology



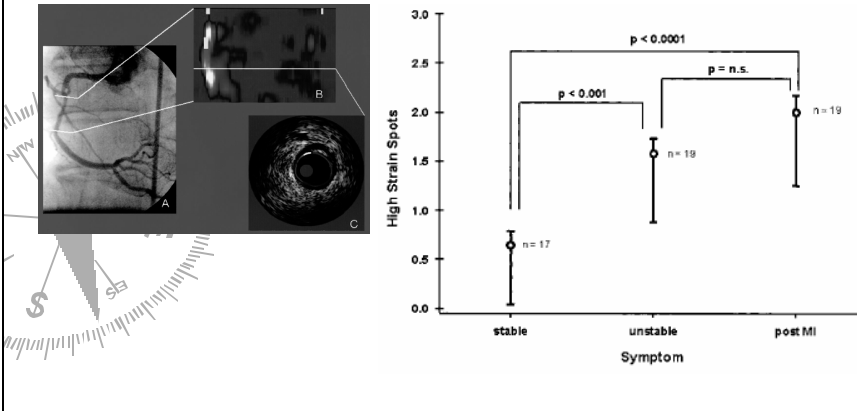
# Clinical strain imaging with IVUS

IVUS strain mapping in a PCTA procedure patient, Der Korte and Van der Steen, Ultrasonics, 40:859-865, 2002.



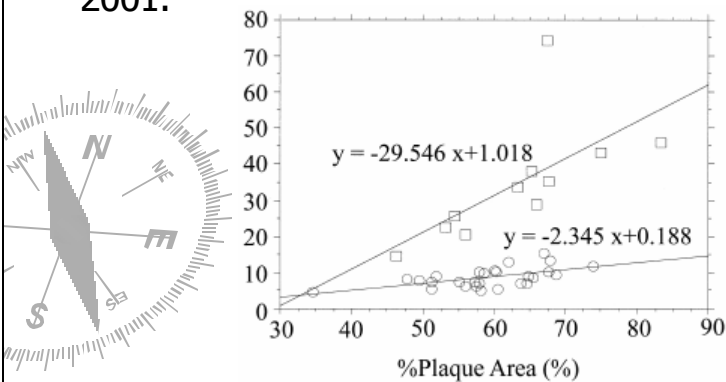
## Frequency of Regional High Strain Spots Is Correlated with Clinical Indicators

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



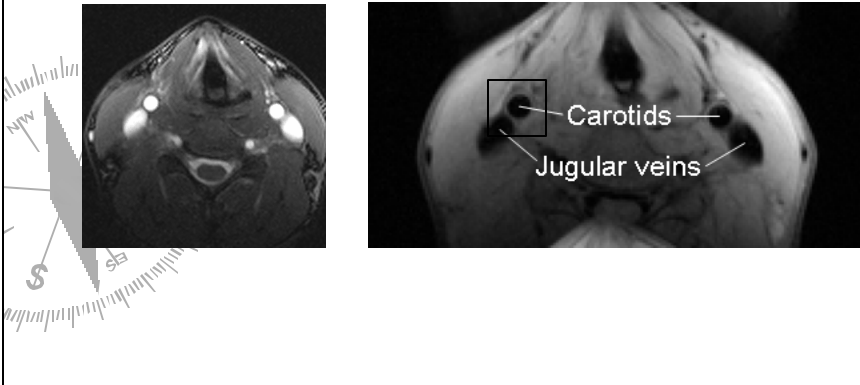
## Circumferentially Averaged Distensibility Is Correlated with Angioscopy Plaque Classification

Takano et al., n = 38, post ACS. JACC 38(1):99-104, 2001.



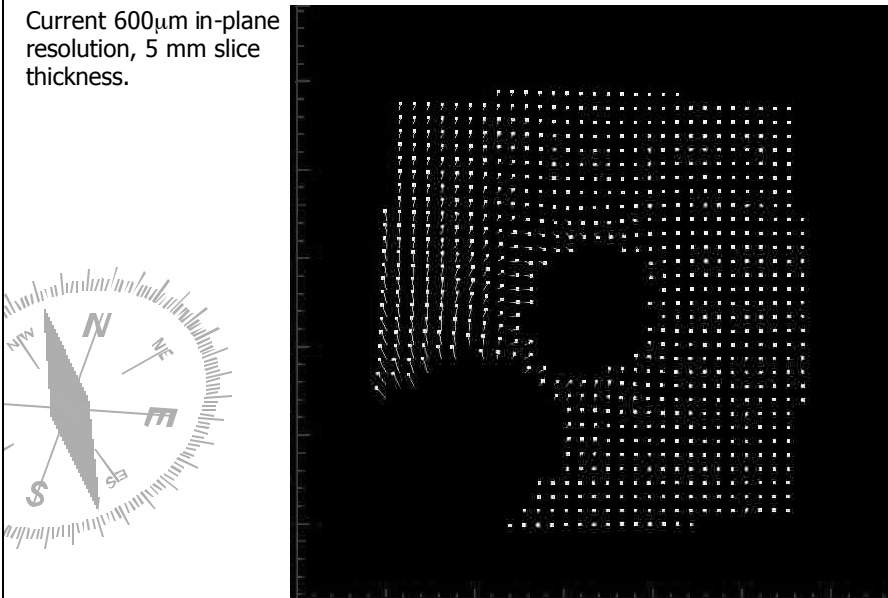
## DENSE Imaging of Registered Strain and Morphology Is Feasible in Human Carotid Artery

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

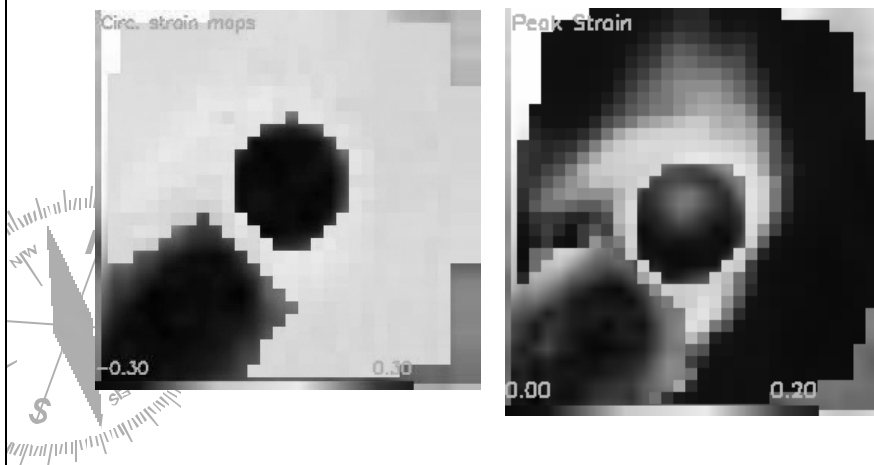


## Displacement Field around Carotid Lumen

Current 600 $\mu$ m in-plane resolution, 5 mm slice thickness.

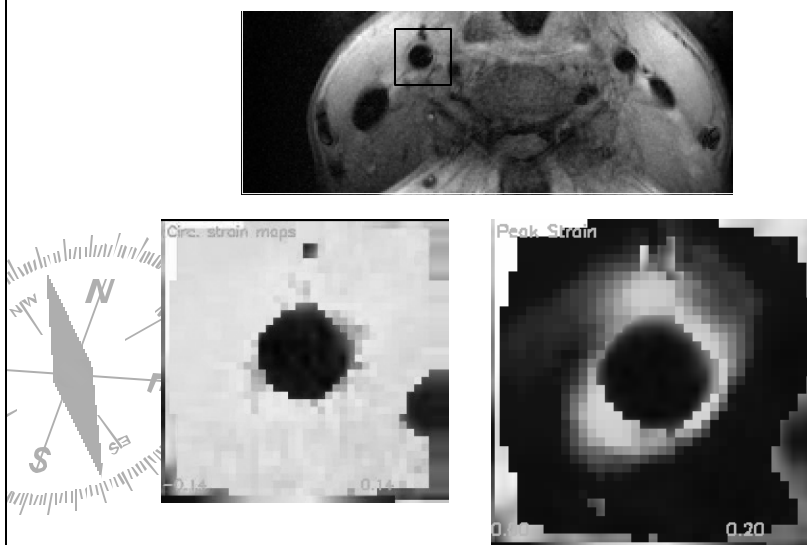


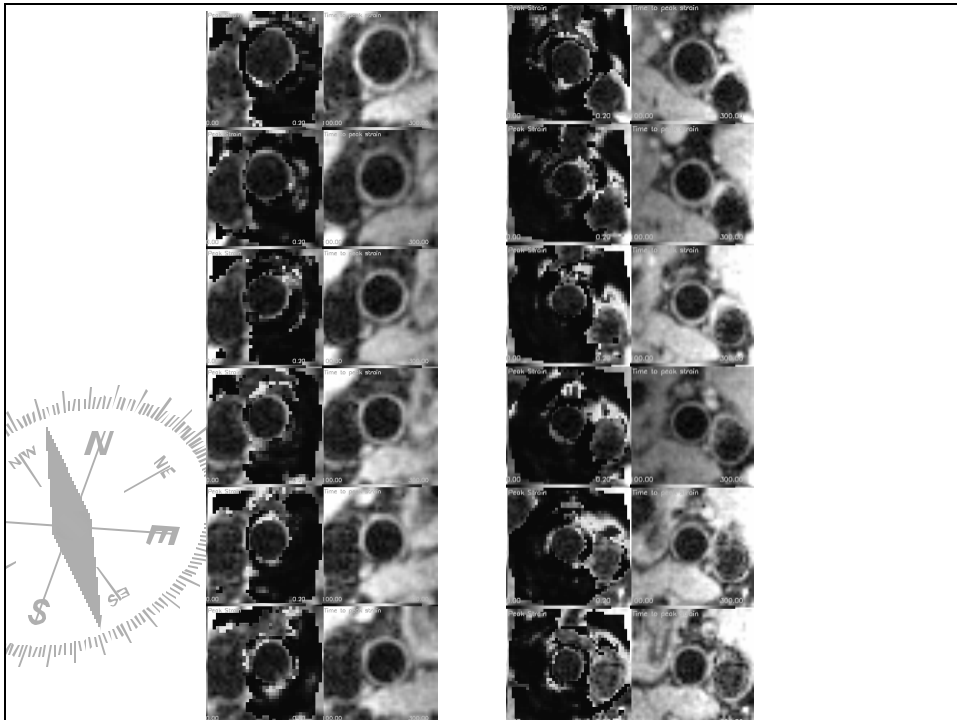
# Circumferential Strain around Carotid Lumen



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  $\mu\text{m}$ , and is expected to improve with 3T scanners.

# Acknowledgement

## ? Engineering

Shujun Ding, PhD, NIH

Anthony Aletras, PhD, NIH

Vinay Pai, PhD, NYU

Ignacio Rodriguez, PhD, NIH

Alex Vignaud, PhD, NIH

Eric Bennett, MS, NIH

## ? Clinical application

Jon Plehn, MD, NIH/GW

Neal Epstein, MD, NIH

Andrew Arai, MD, NIH

