Electrical Engineering, Cardiology and Physics

Cardiac Imaging Research

KULeuven

UZ Gasthuisberg

Cardiovascular deformation imaging
Part II: cardiac

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Presented at the Third International Conference on the Measurement and Imaging of Tissue Elasticity

Cumbria, UK
October 18th, 2004

Contents

- Cardiac anatomy and function
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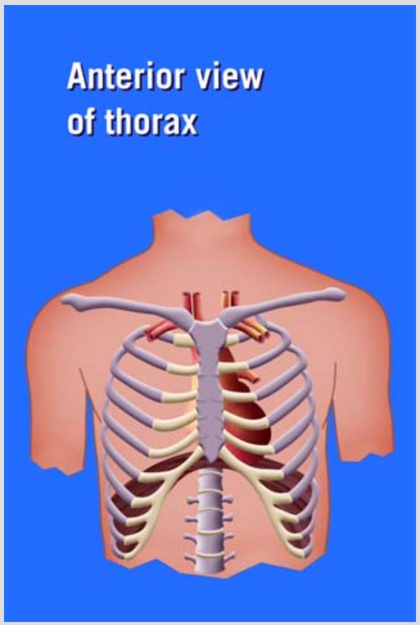
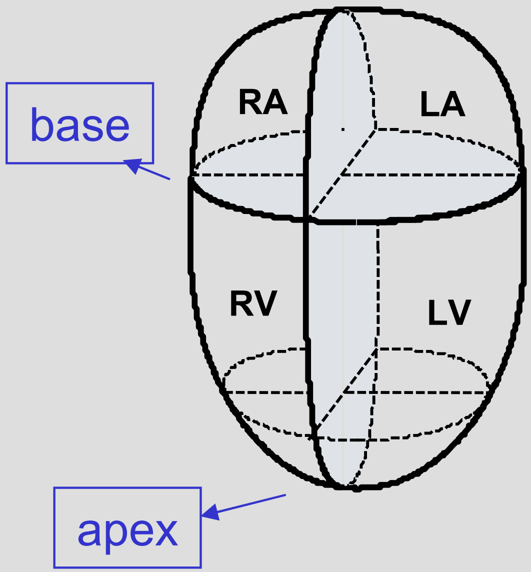
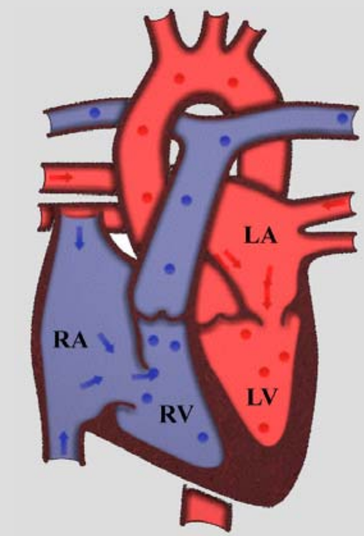
The heart: anatomy

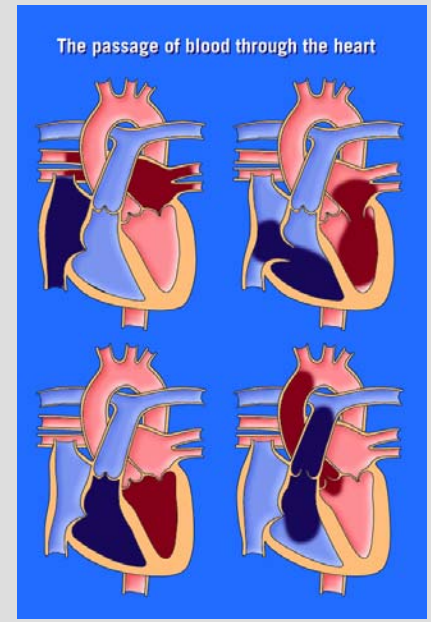
Position of the heart in the human thorax







Circulation



4 compartment “box”:

2 atria

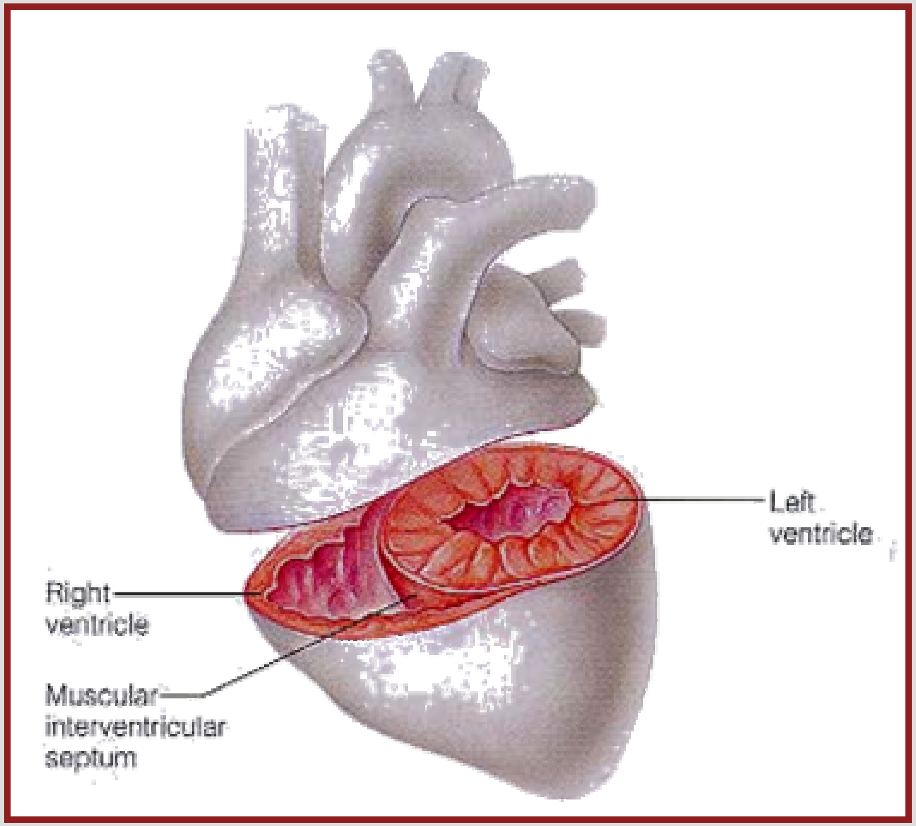
2 ventricles

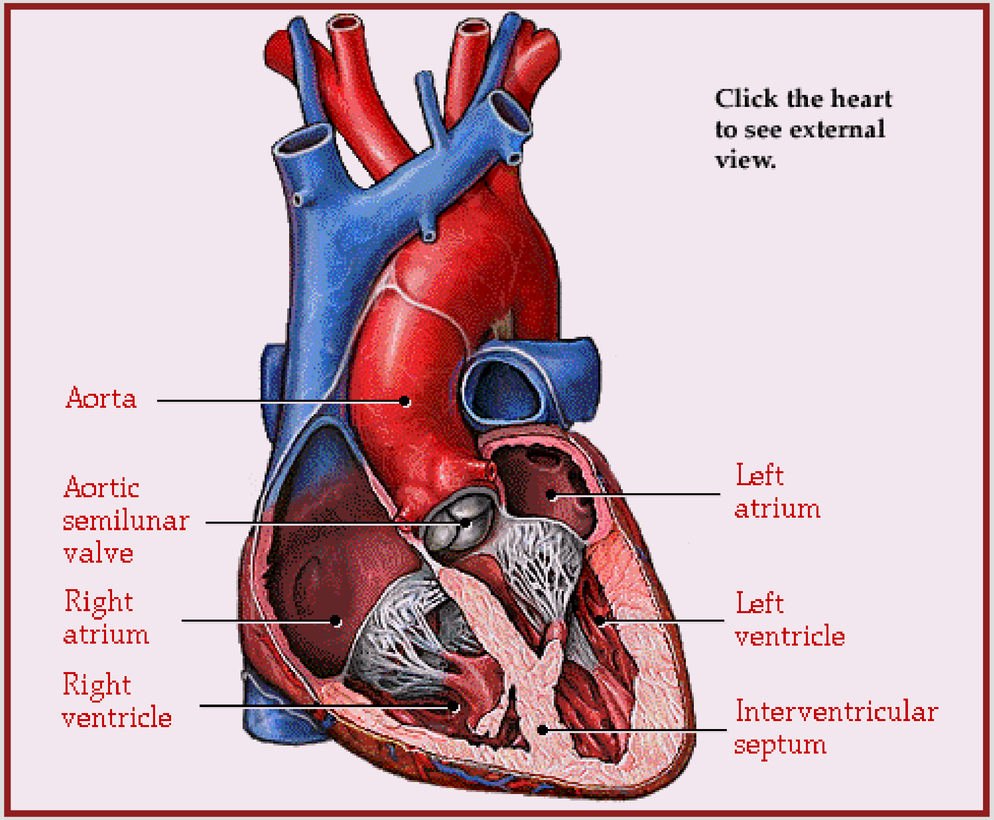
2 pumps in series:

Right heart: lung circulation

Left heart: systemic circulation

The cardiac muscle



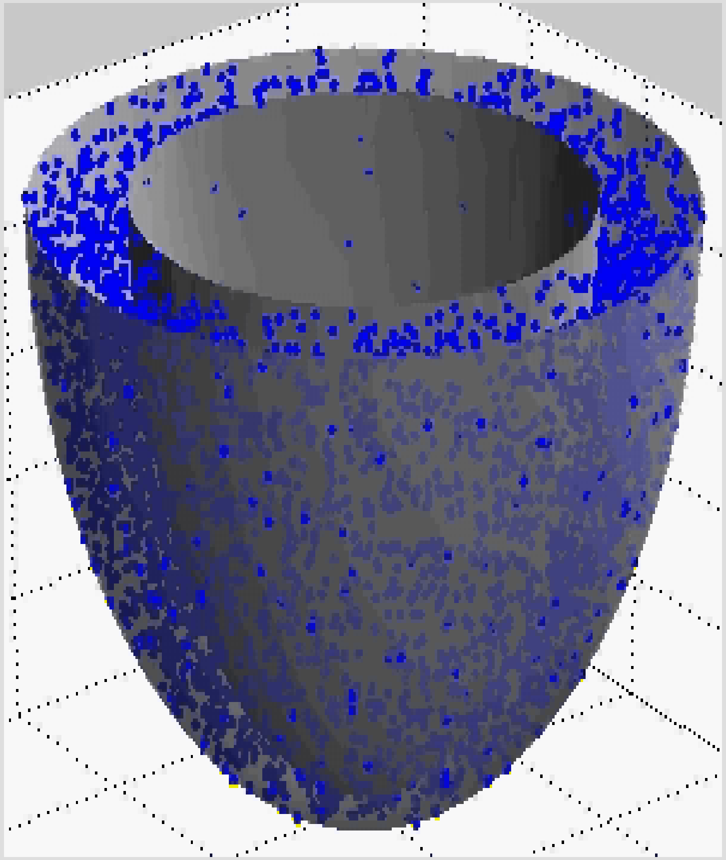


Left ventricle =
Most important cavity of the heart
(systemic circulation)

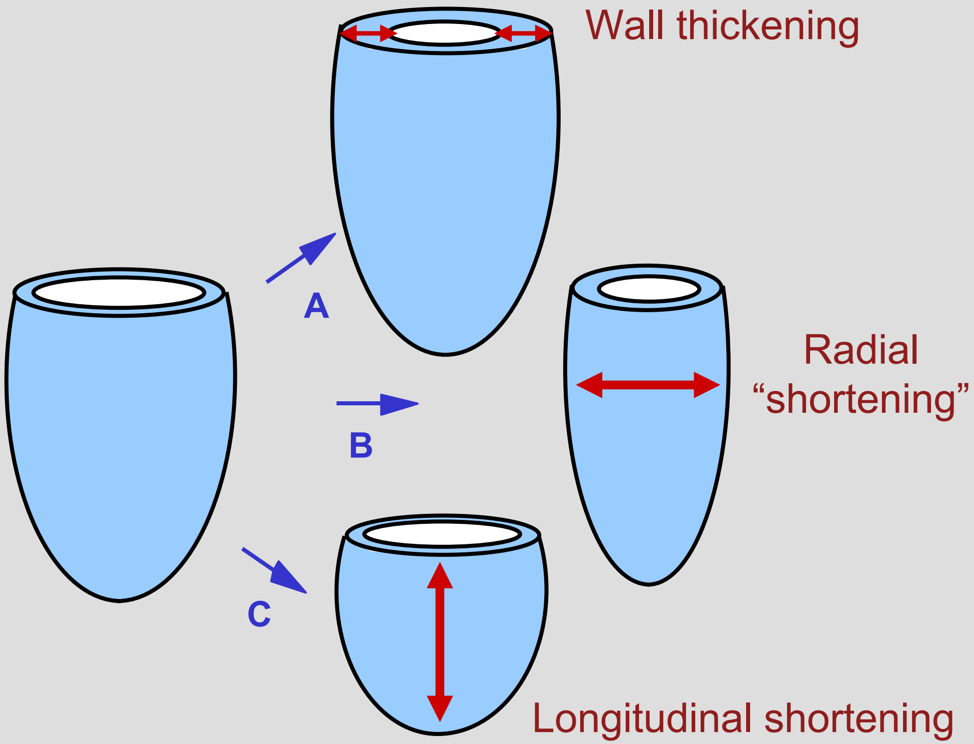
Left ventricle =
Most developed muscle)

Cardiac function

Cardiac ejection/filling through myocardial deformation



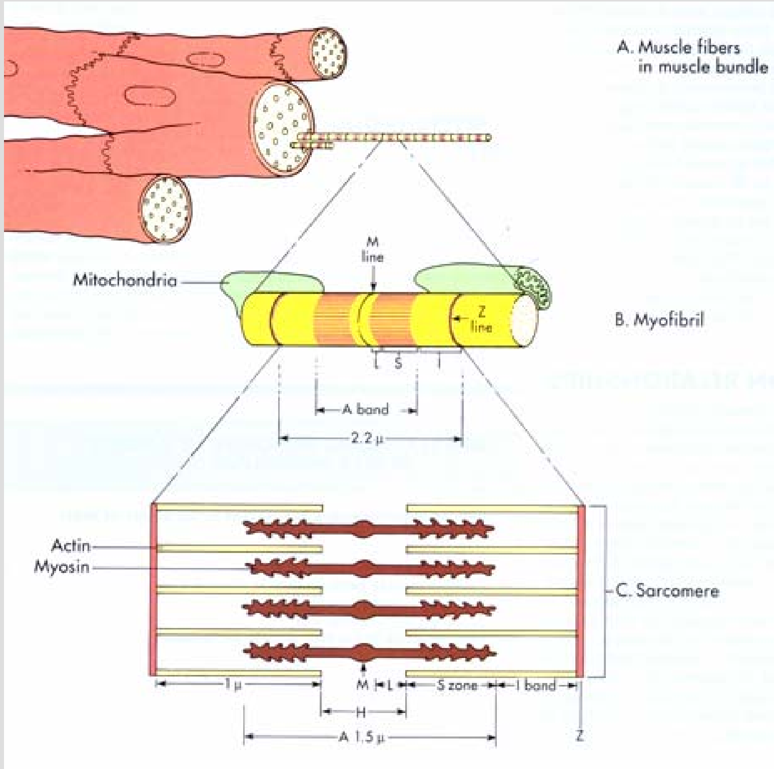
Courtesy: S.I.Rabben, Univ. of Oslo, Norway



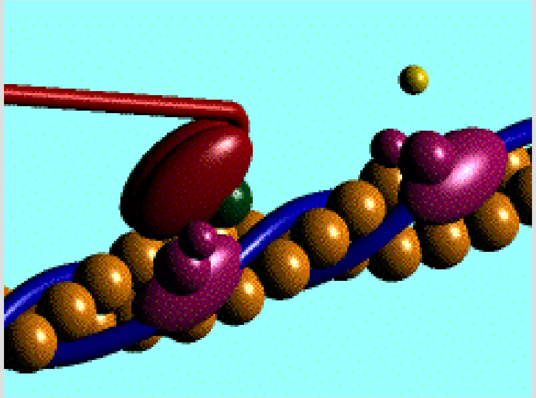
Ultrastructure

Fiber orientation

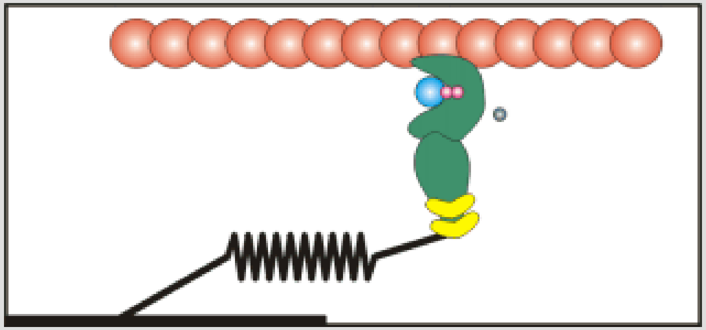
Ultra-structure



Actin-myosin interaction

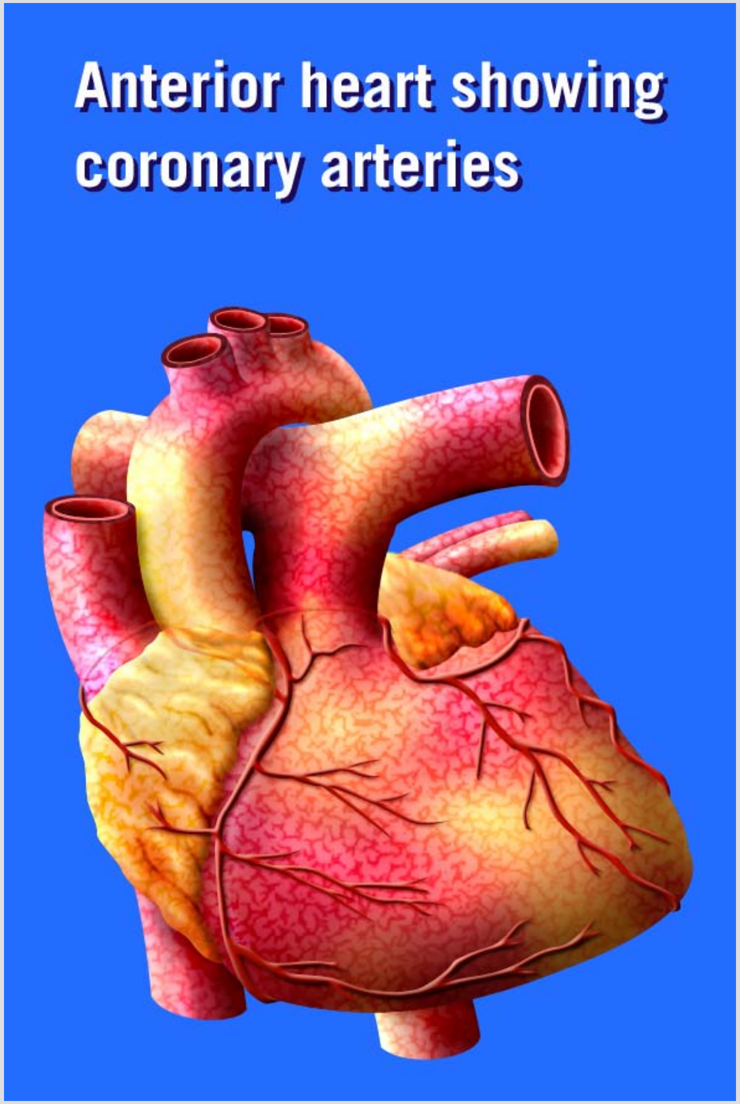


Actin-myosin interaction



Coronary arteries

Coronary arteries



Most common cardiac pathology:

Coronary Artery Disease (CAD)

Therapy depends on:

- Severity
- Localization
- Period of time
- ....

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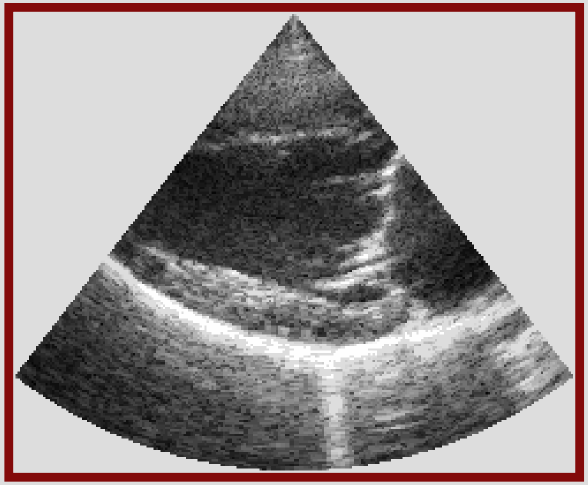
Echocardiography: introduction



Strong points

- Real-time
- Non-invasive
- Relatively cheap
- Portable / bed-side
- Excellent temporal resolution

Clinical use

- Anatomy
- Blood flow
- Function (= performance)

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Standard echocardiographic views

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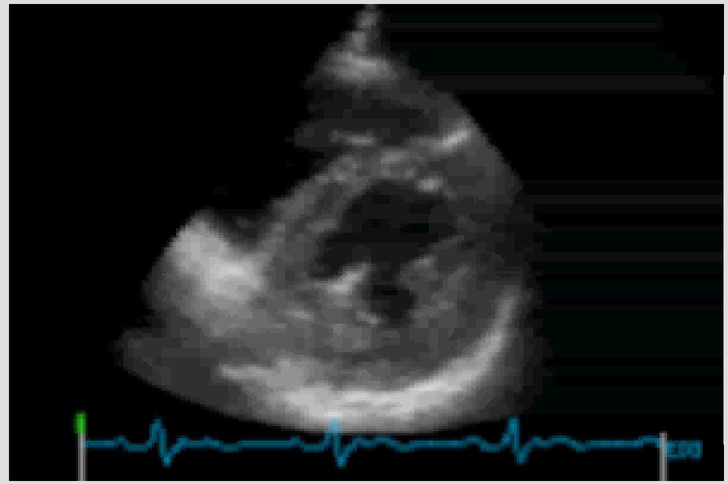
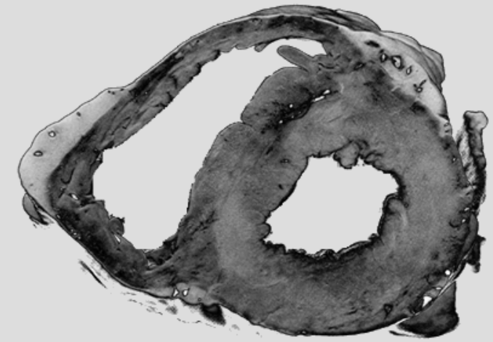
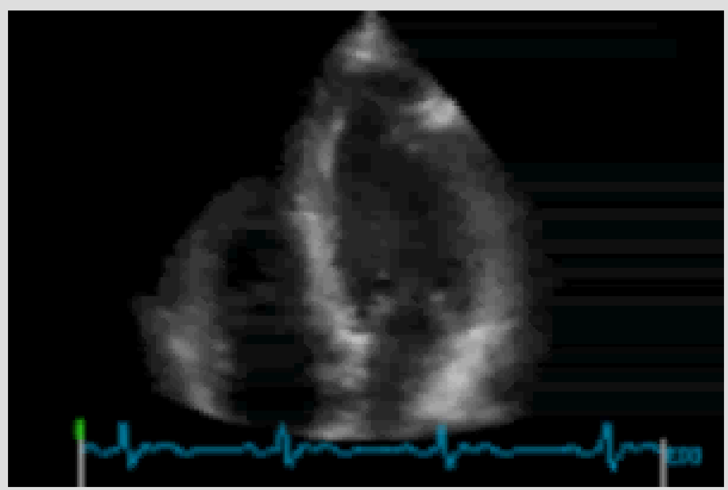
Parasternal long axis (M-mode)

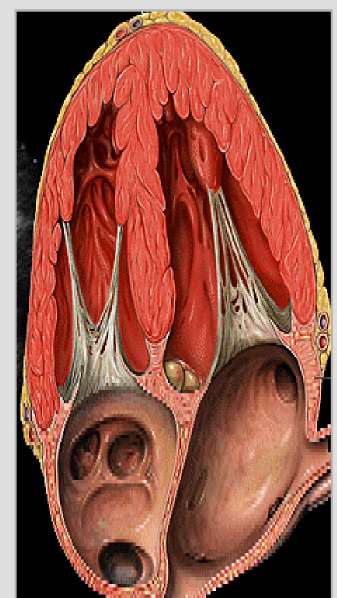
Parasternal short axis



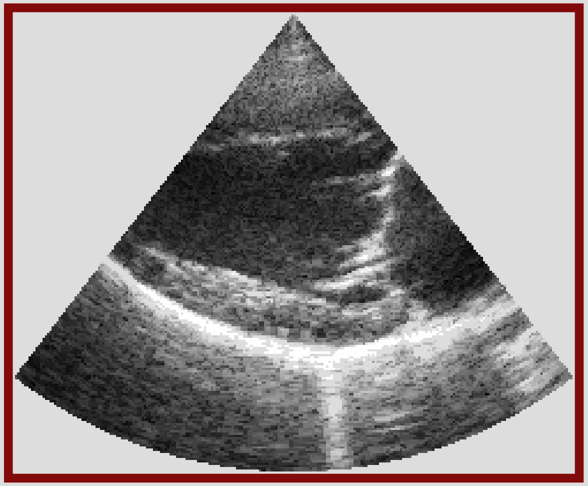


4 chamber view





Echocardiography: function



Qualitative

Visual assessment and appreciation of regional wall motion

Quantitative

- Ejection fraction
- Fractional shortening
- Atrio-ventricular plane motion
- E/A ratio blood Doppler
- …

→ Global measures!

⇨ The quantitative assessment of *regional* myocardial function remains an important goal in clinical cardiology

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17 segment model of the heart (LV)

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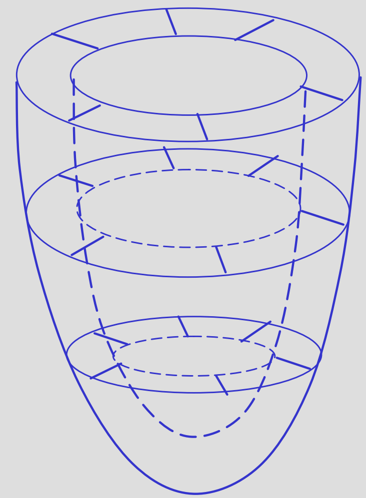
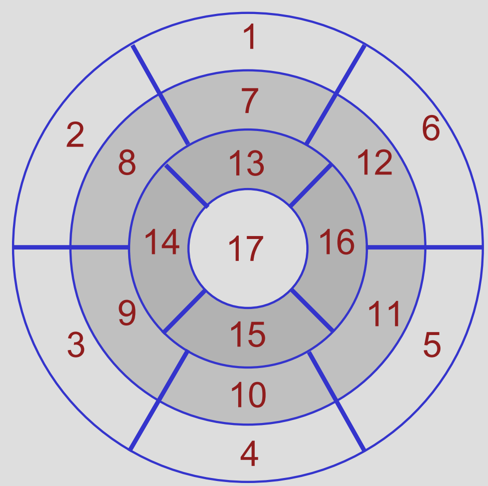
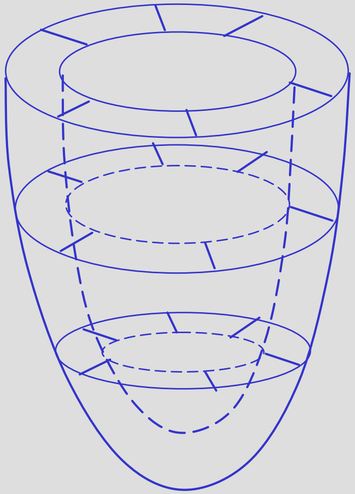
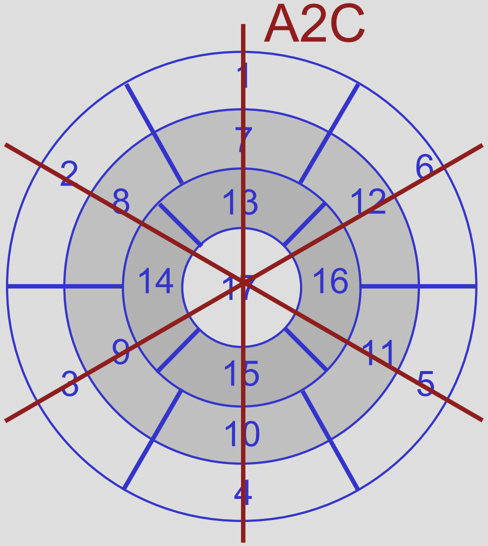




M.D. Cerqueira *et al*., *Circulation* 105(4):539-542, 2002

17 segment model of the heart (LV)

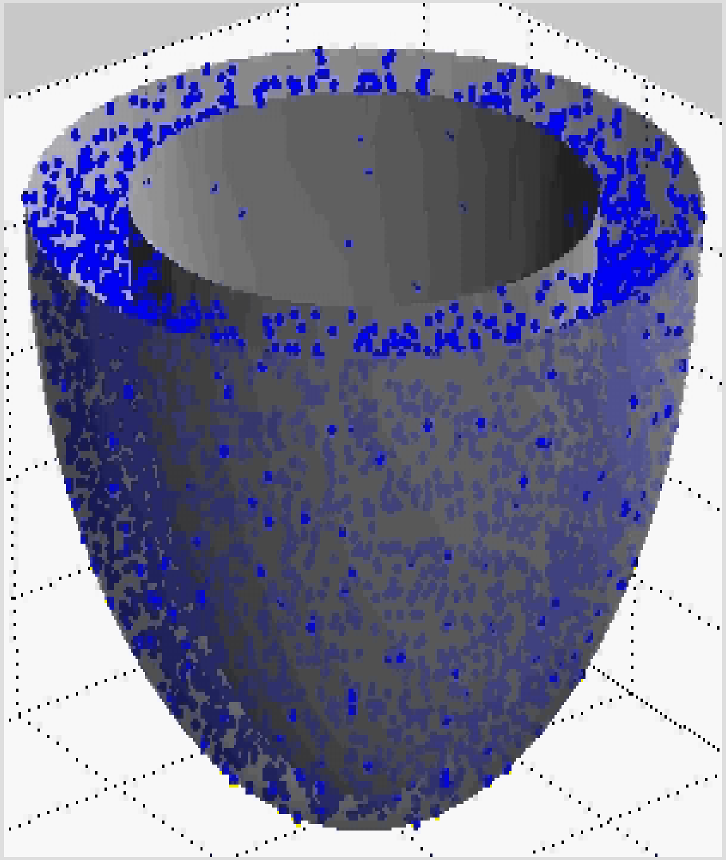




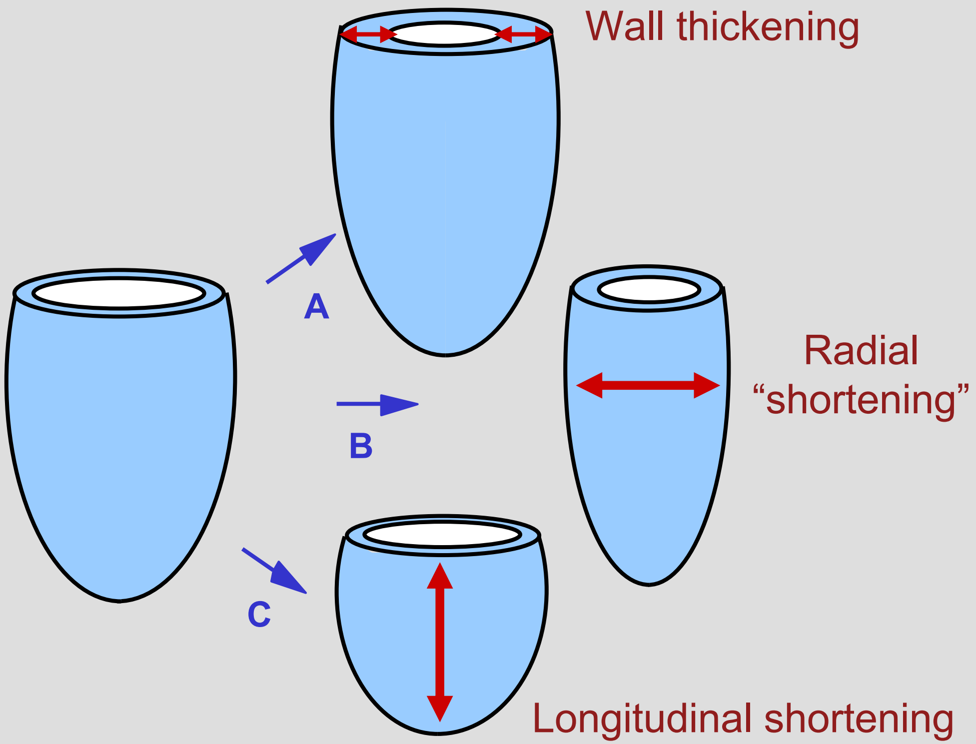
M.D. Cerqueira *et al.*, *Circulation* 105(4):539-542, 2002

Regional myocardial function

Cardiac ejection/filling through myocardial deformation

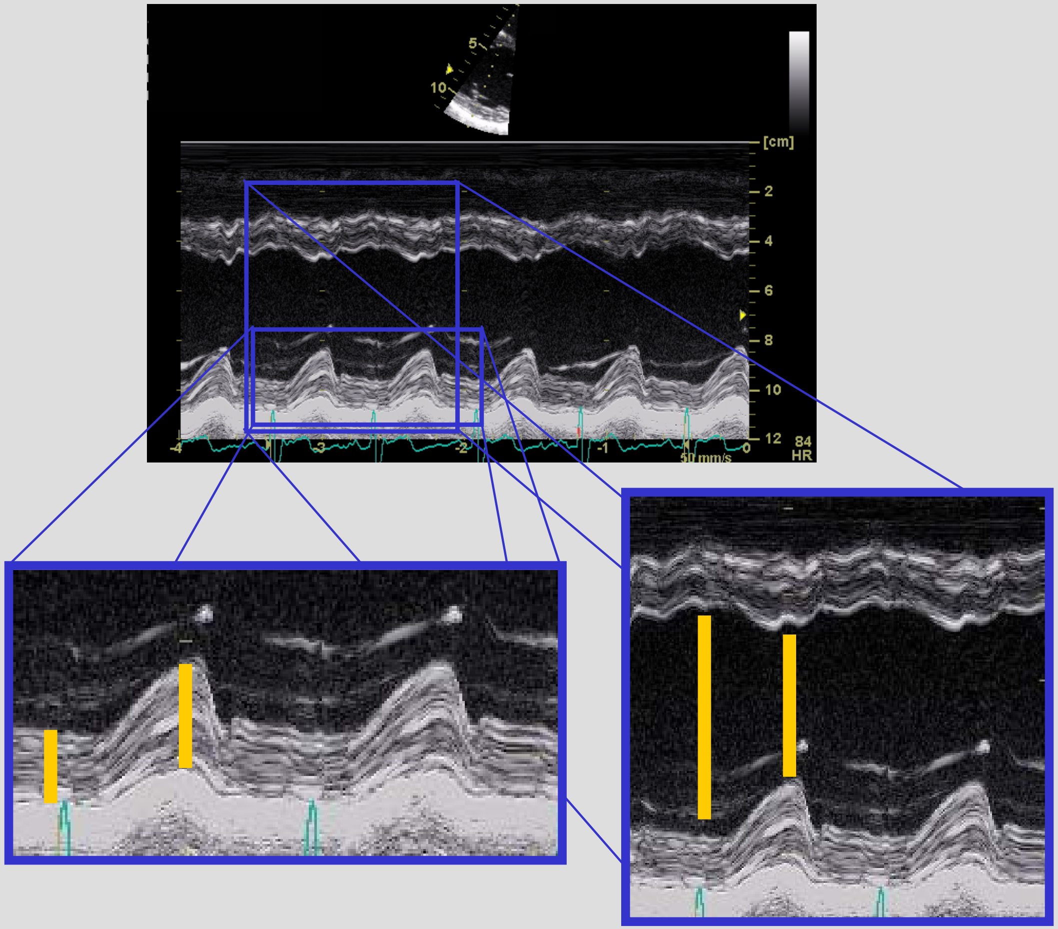


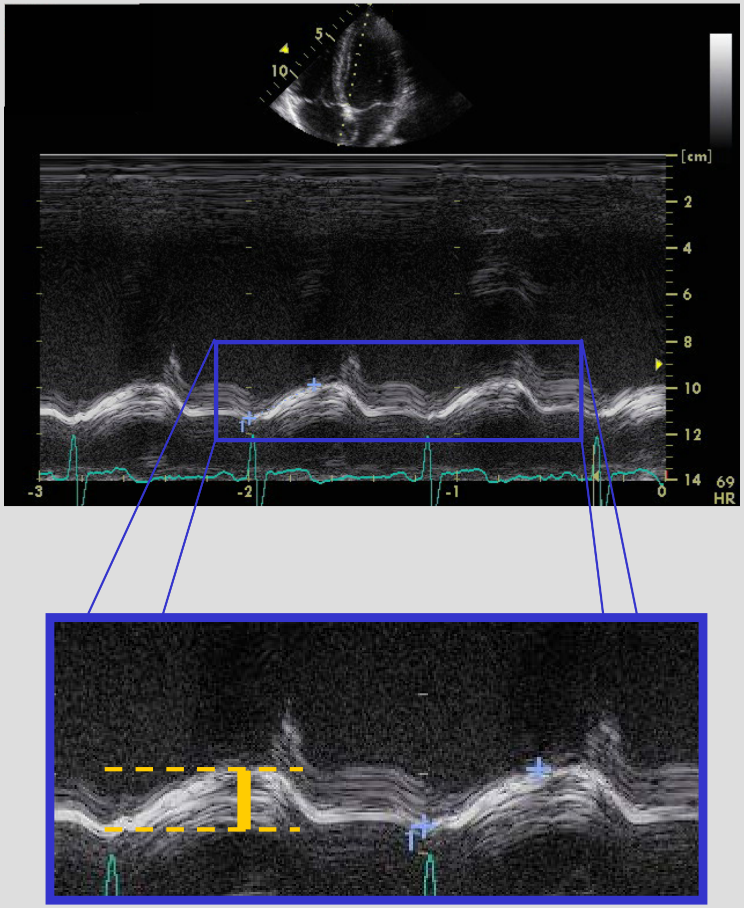
Courtesy: S.I.Rabben, Univ. of Oslo, Norway



→ Measure local deformation to study the local contribution to ejection/filling (i.e. local myocardial function)

M-mode measurements





$$WT = \frac{ESWT - EDWT}{EDWT}$$

$$FS = \frac{ESD - EDD}{EDD}$$

$$D = EDL - ESL$$

Disadvantages of the M mode approach

- Dependent on endo- and epicardial border definition
  - ✓ Image quality dependent (cf. endocardial border)
  - ✓ Often difficult
  - ✓ User dependent and time consuming

- Relatively low spatial resolution
  - ✓ Use of envelope data (rather than RF)
  - ✓ Especially true for anatomic M-mode images

- Only *global* deformation characteristics can be measured
  - ✓ Global longitudinal shortening
  - ✓ Transmural (radial) wall thickening

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Regional myocardial function

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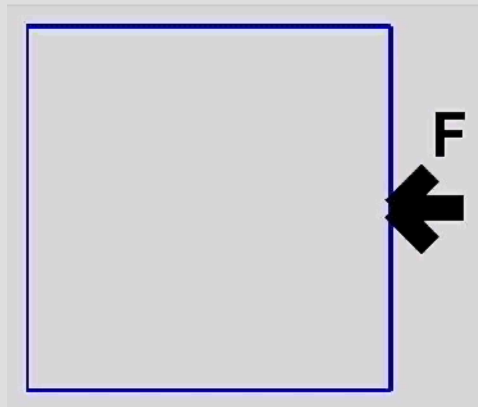
Passive elastic body



$$\sigma_{load}(t) \quad = \quad E \quad \times \quad \varepsilon(t)$$

Wall stress
(total force on a segment)

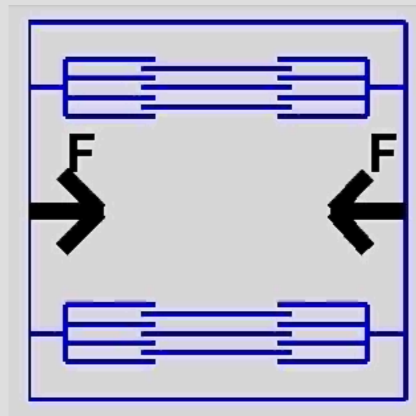
segmental elasticity

resulting deformation

cf. elastography ⇨ Strain imaging ≈ elasticity imaging
⇨ Strain image = elastogram

Regional myocardial function

Active elastic body



Active contractile stress

$$C(t) \quad + \quad \sigma_{load}(t) \quad = \quad E \quad \times \quad \varepsilon(t)$$

Regional myocardial function
(contractility)

Wall stress
(total force on a segment)
cavity pressure,
geometry,
neighbouring segment interaction

segmental elasticity

resulting deformation

⇨ *If the assumption is made that <u>external stresses (loading) can be neglected</u>, local strain directly relates to local contractile stress*

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Velocity Gradient ~ Strain

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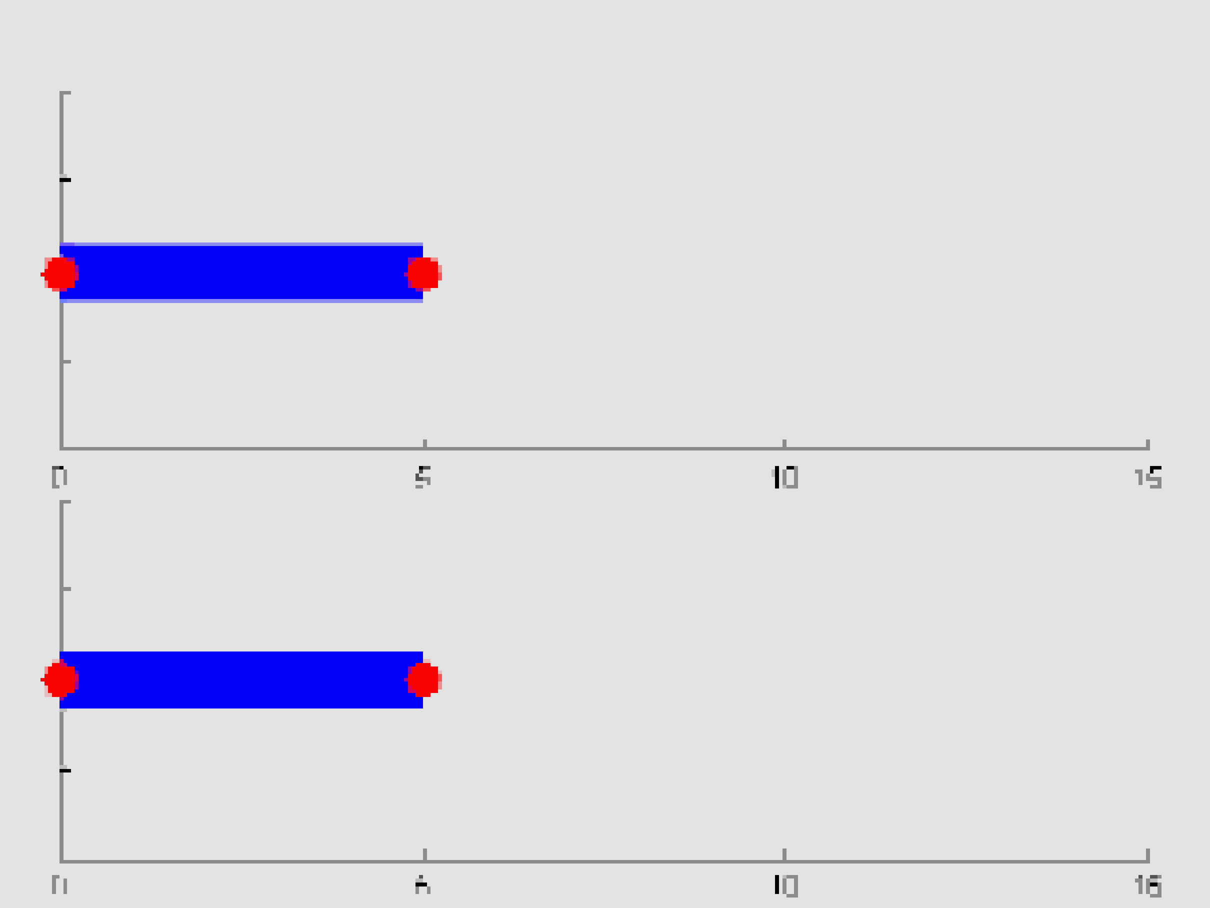
Global motion
v1 = v2

Lengthening
v1 ≠ v2



The spatial gradient in velocities (instantaneous motion) = strain rate (instantaneous strain)

$$\longrightarrow \quad \frac{v_2 - v_1}{\Delta x} = \dot{\varepsilon}$$

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Cardiac Deformation Imaging

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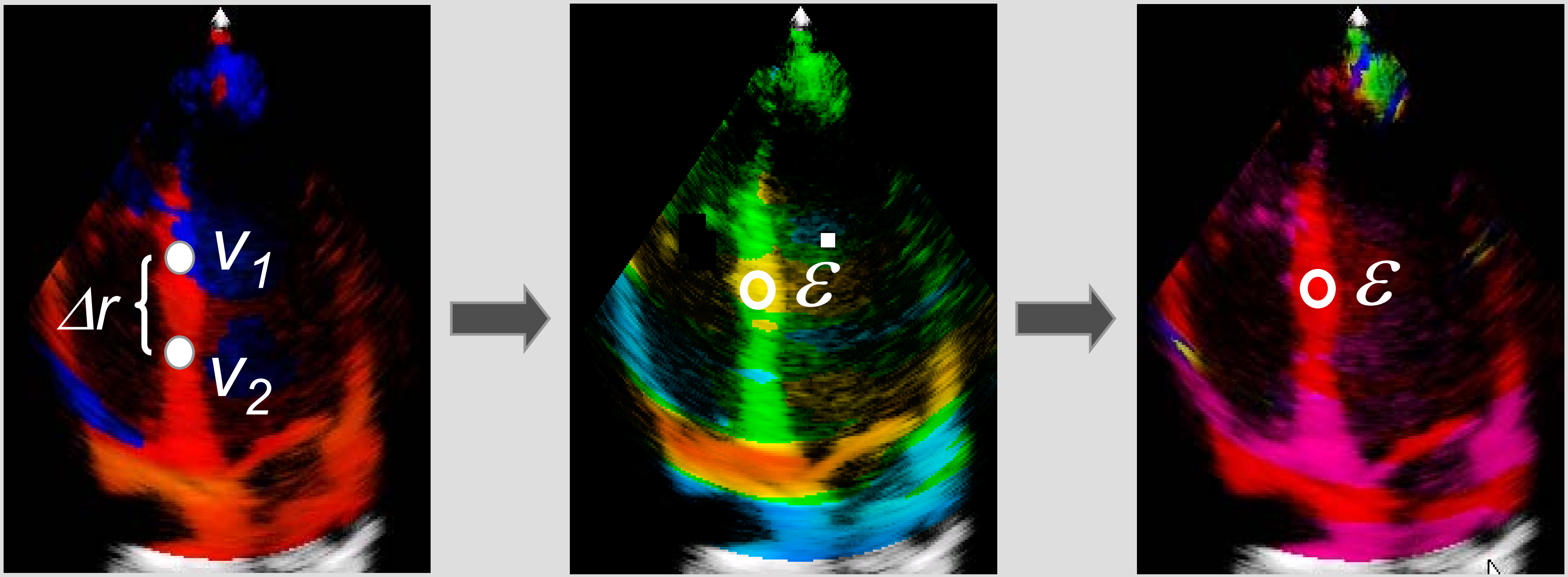
Velocities | Natural strain rate | Natural strain



Calculate spatial gradient

Integrate temporally

⇨ Strain and strain rate estimation = motion/velocity estimation + post-processing

Note:

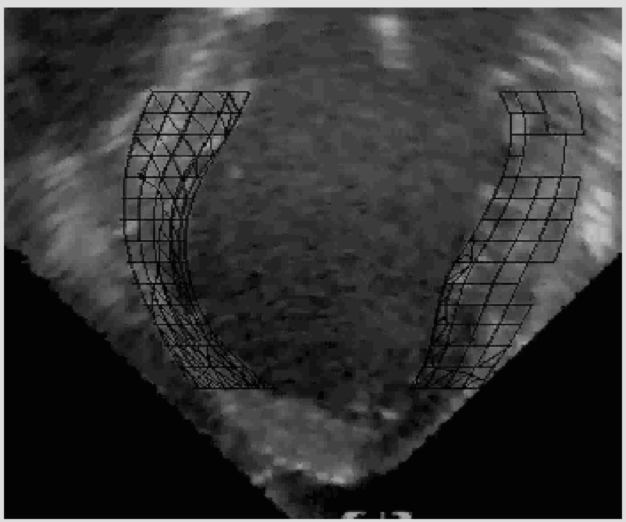
Elastography: motion $\xrightarrow{\text{grad}}$ (instantaneous) strain $\xrightarrow{\text{int}}$ cumulative strain

SRI: velocity $\xrightarrow{\text{grad}}$ strain rate $\xrightarrow{\text{int}}$ strain

Measuring myocardial motion and deformation I

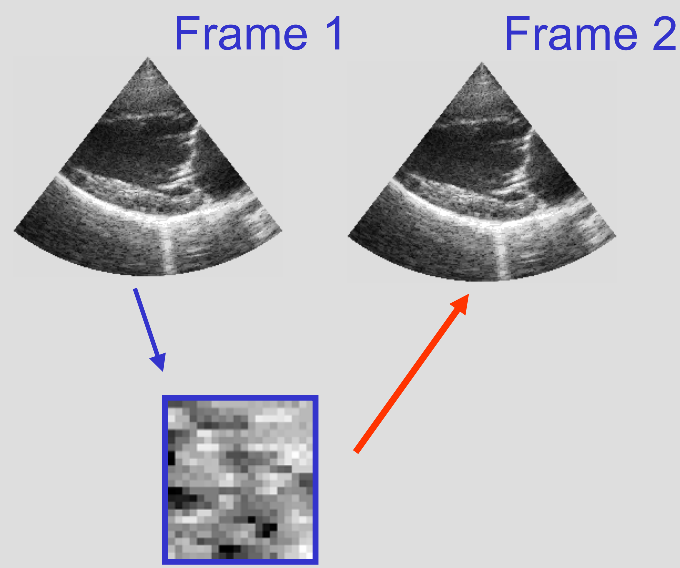
B-mode (envelope) data

Segmentation – mechanical model based



Papademetris *et al.*,
Medical Image Analysis 5(1):17-28, 2001
IEEE-TMI 21(7):786-800, 2002

Speckle tracking



Optical flow ($E_x u+E_y v = -E_t$)
J. Meunier *et al.*, 1984
C. Jansen *et al.*, EuroEcho, 2002

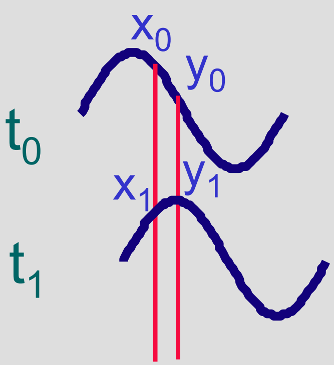
Cross correlation based (block-matching)
G. Trahey *et al.*, IEEE-TBME, 34:965-967
E. Konofagou *et al.*, IEEE Symposium 2002

Behar *et al.*,
Ultrasonics,
43:57-65, 2004

Measuring myocardial motion and deformation II

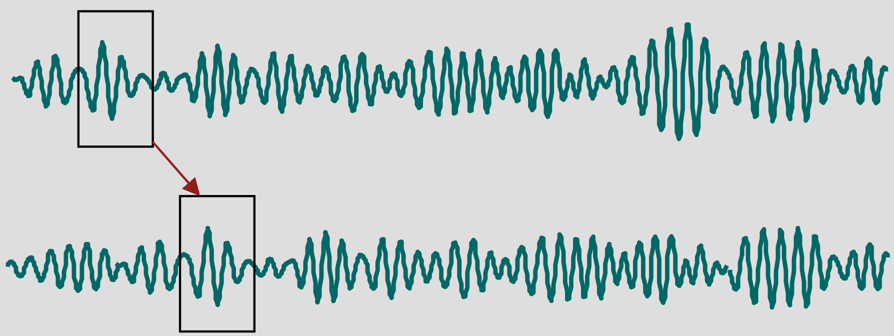
RF data

Auto-correlation



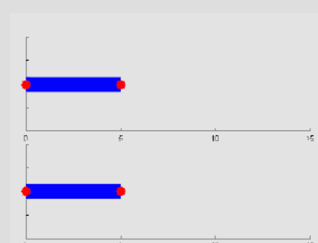
M-mode / B-mode + Off-line / Real-time

Cross-correlation



Motion → Velocity

Spatial gradient



Instantaneous strain → Strain rate

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Auto- vs. cross-correlation

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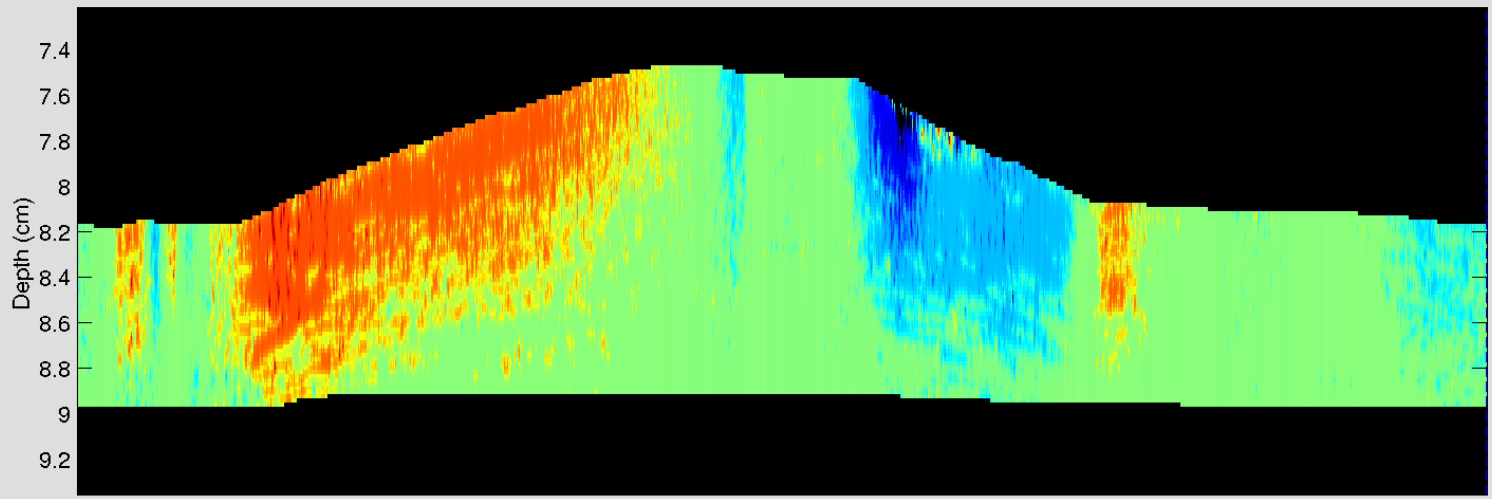
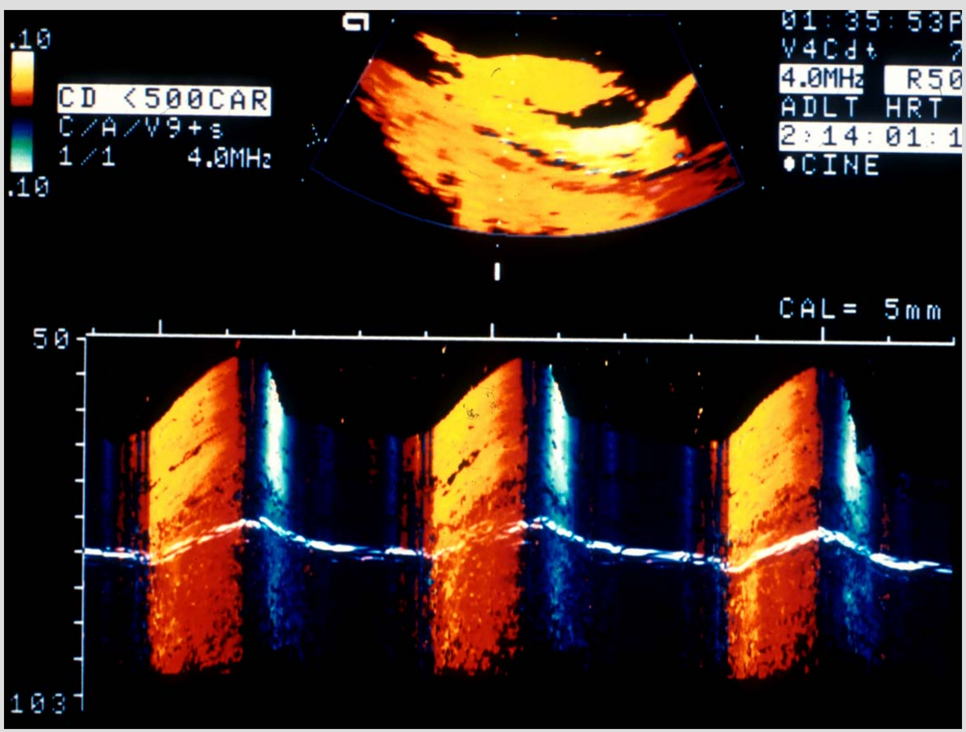
Cross-correlation

Broad bandwidth data





Auto-correlation

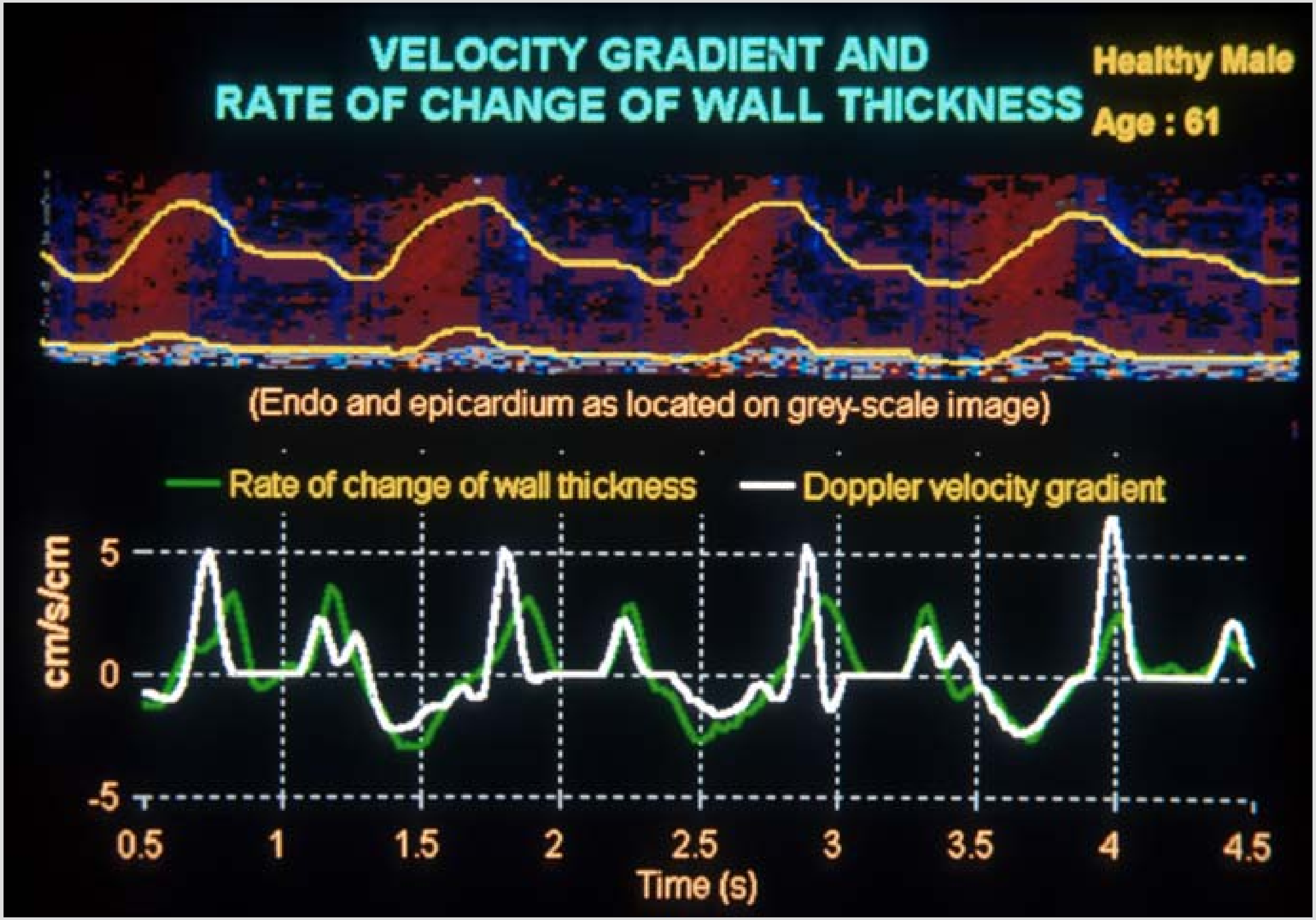
"Classic" velocity (gradient) method

Similar but narrow band

Spatial resolution intrinsically worse but *real-time*

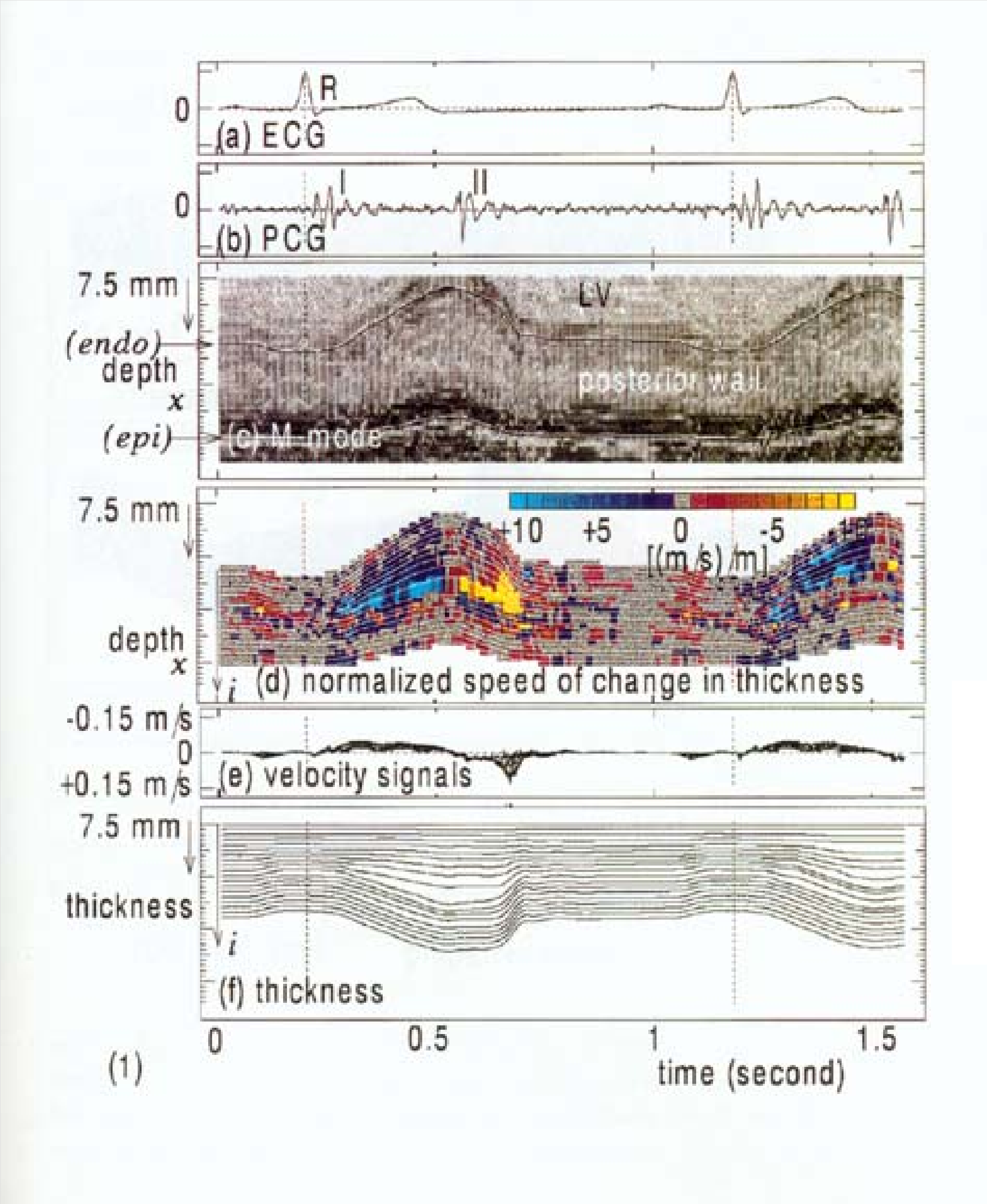
Auto correlation strain (rate) imaging

Conventional DMI imaging + offline post processing



Courtesy: George Sutherland '92

X correlation strain (rate) imaging



- Indicate initial position endo- and epicardium
- Automatic:
  - —Transmural division
  - —RF-tracking
  - —Strain rate estimation
- Real-time system ('99)

Courtesy: IEEE-UFFC '97
H.Kanai
Sendai University, Japan

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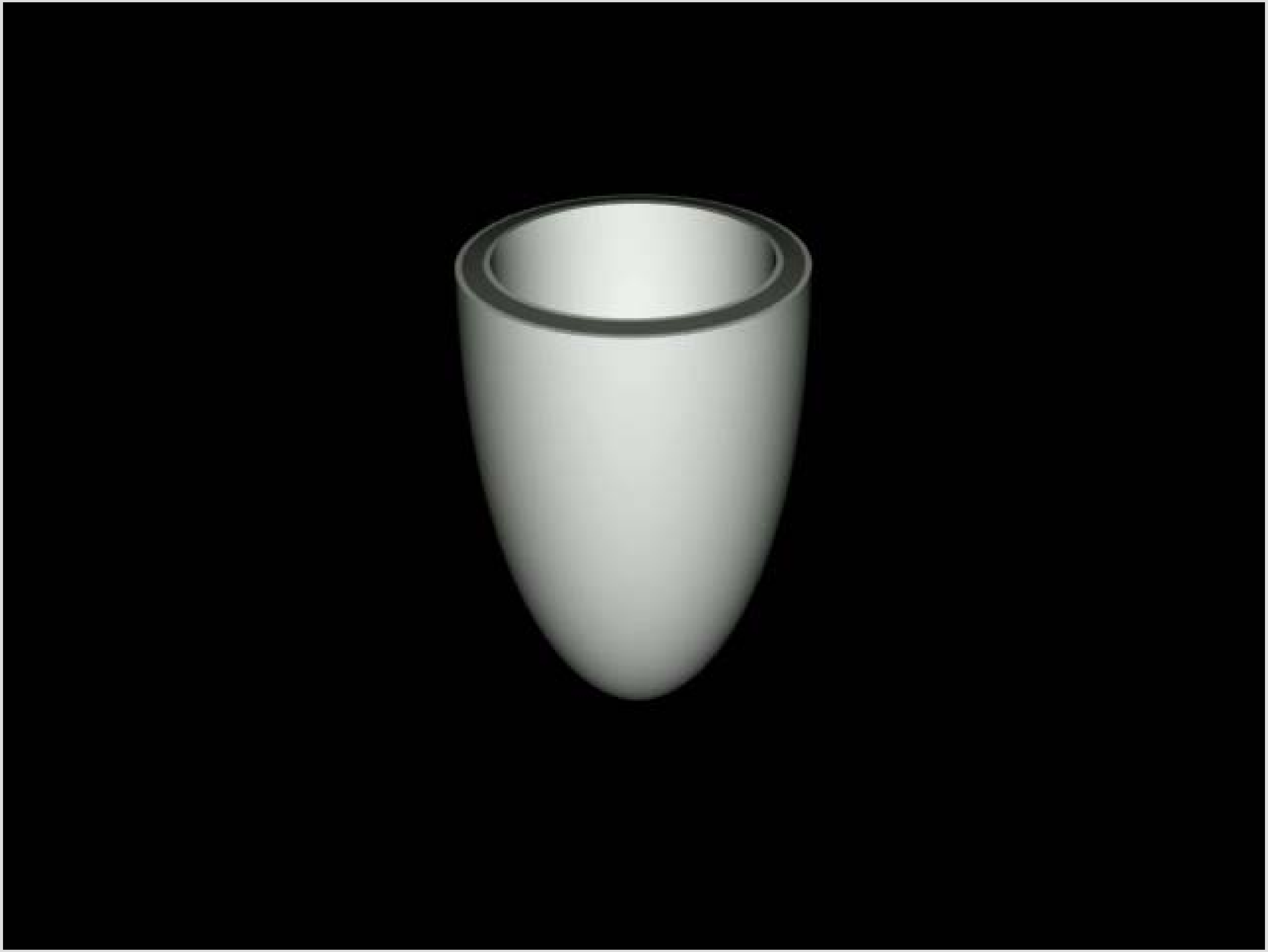
Principle of deformation imaging

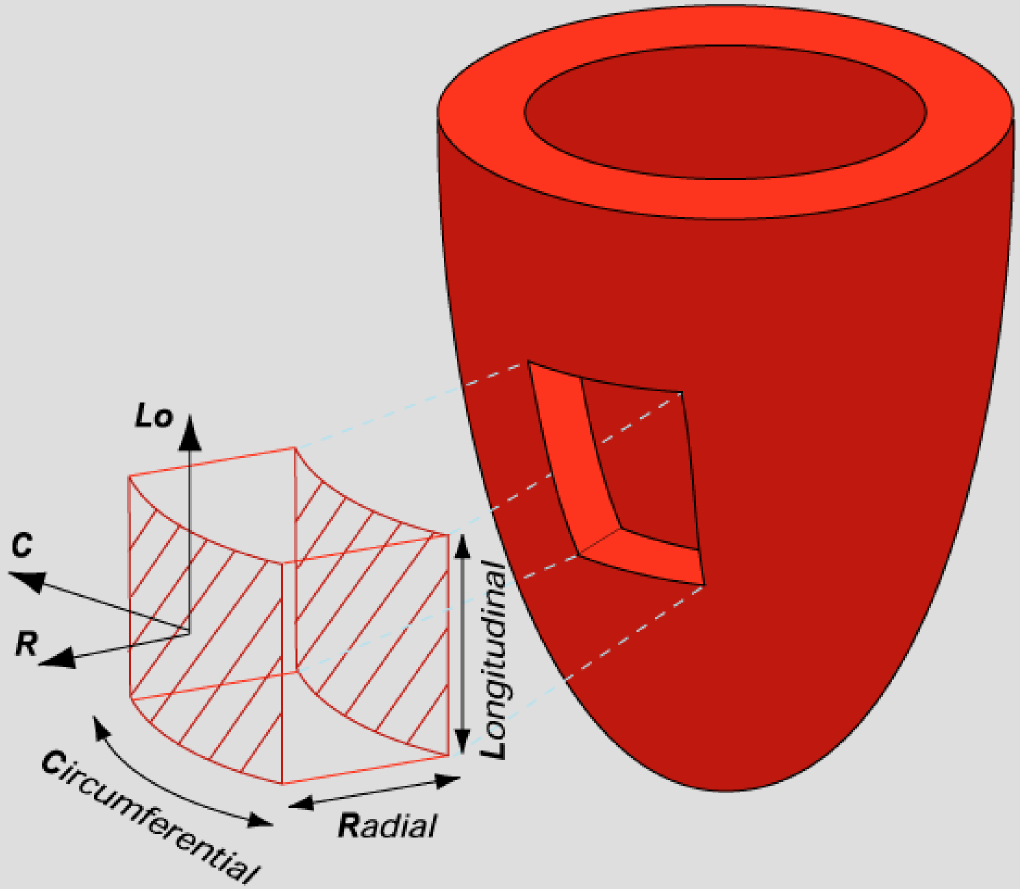


Local cardiac coordinates

- Radial
- Longitudinal
- Circumferential

⇩

$$\varepsilon = \begin{bmatrix} \varepsilon_{RR} & \varepsilon_{RC} & \varepsilon_{RL} \\ \varepsilon_{CR} & \varepsilon_{CC} & \varepsilon_{CL} \\ \varepsilon_{LR} & \varepsilon_{LC} & \varepsilon_{LL} \end{bmatrix}$$



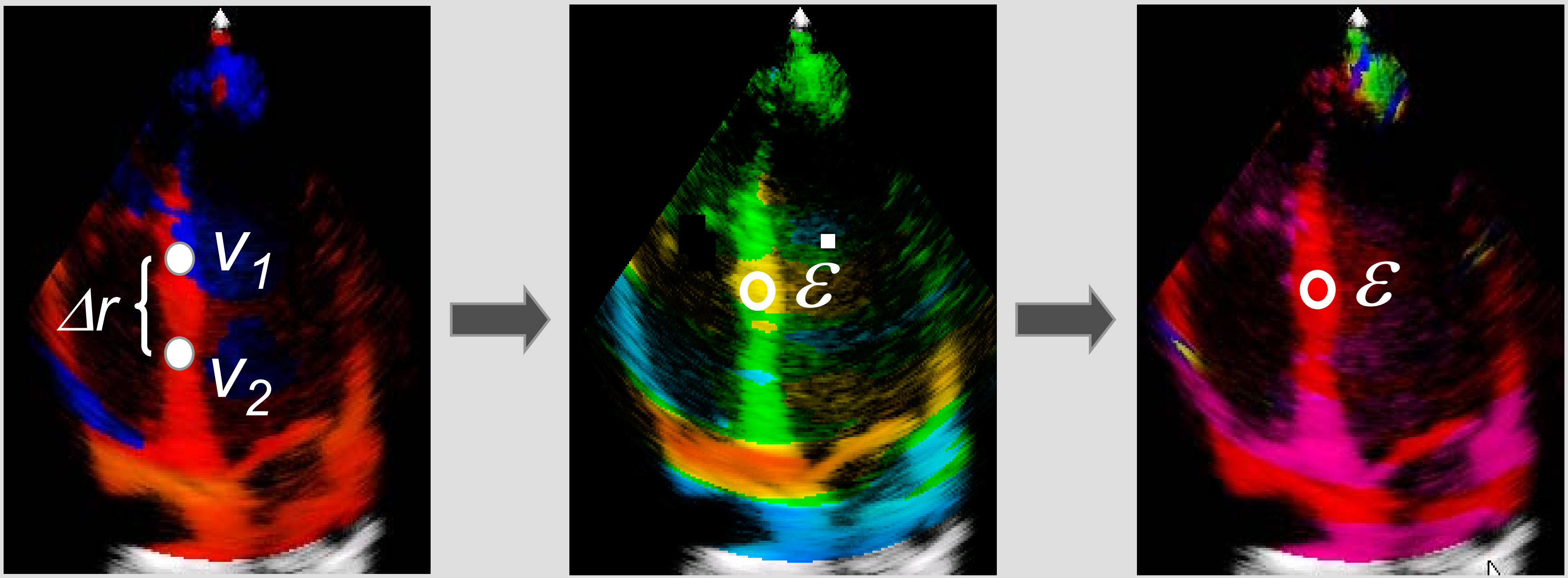
Facilitates physical interpretation and mathematics of the strain values

(e.g. RR = wall thickening; CC/LL = circumferential/longitudinal shortening)

Strain and strain rate imaging

Most *animal and clinical* studies have been based on MVI (myocardial velocity imaging) data based on the auto-correlation methodology

Velocities | Natural strain rate | Natural strain



Calculate spatial gradient

Integrate temporally

⇨ Strain and strain rate estimation = motion/velocity estimation + post-processing

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Validation in-vitro I

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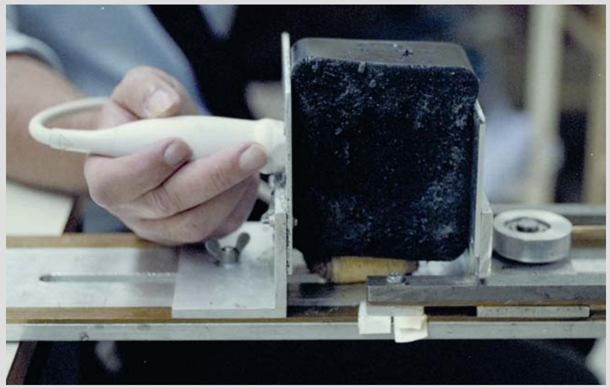
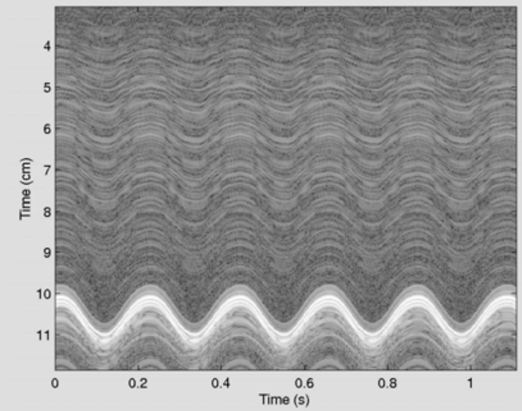
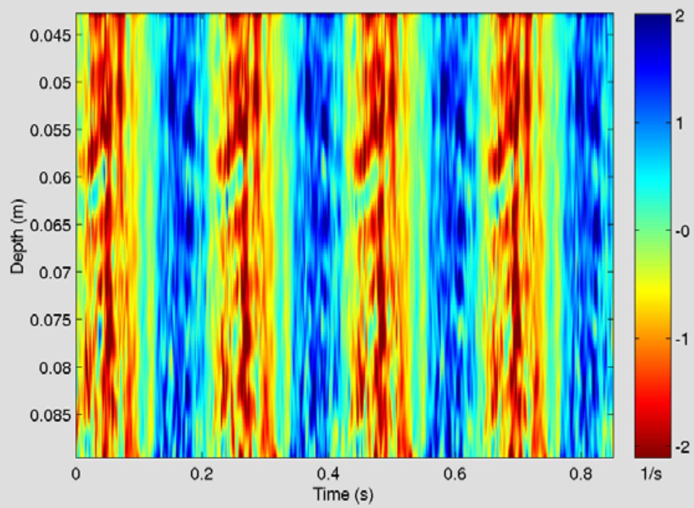
Cyclic compression of approx. 10% at 5Hz

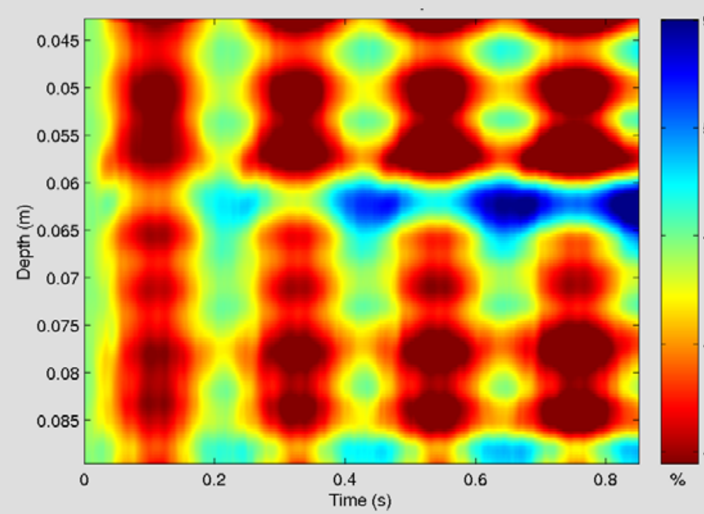


M-mode





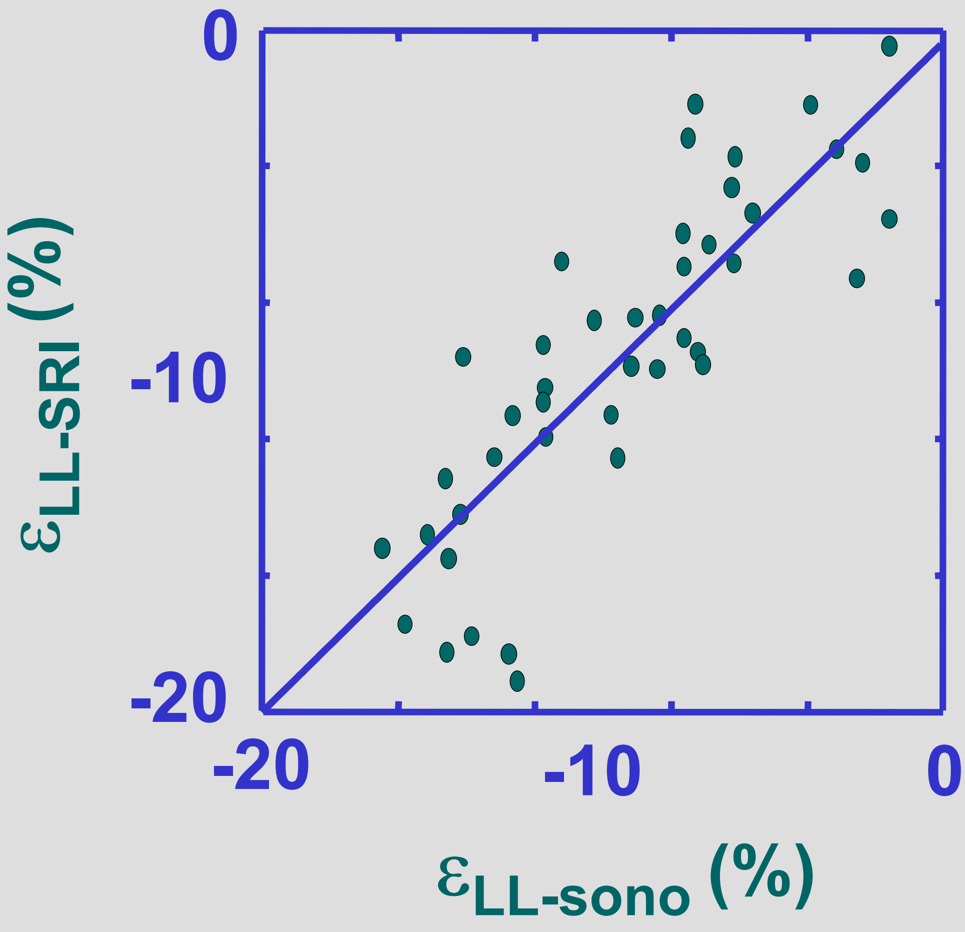
Strain rate



Strain

A. Heimdal *et al.*, *Echocardiography* 1998; M. Belohlavek *et al.*, *Echocardiography* 2001

Validation in vivo I: SRI vs sonomicrometry



Linear correlation

$\varepsilon_{SRI}=0.98\bullet\varepsilon_{sono} - 0.44$

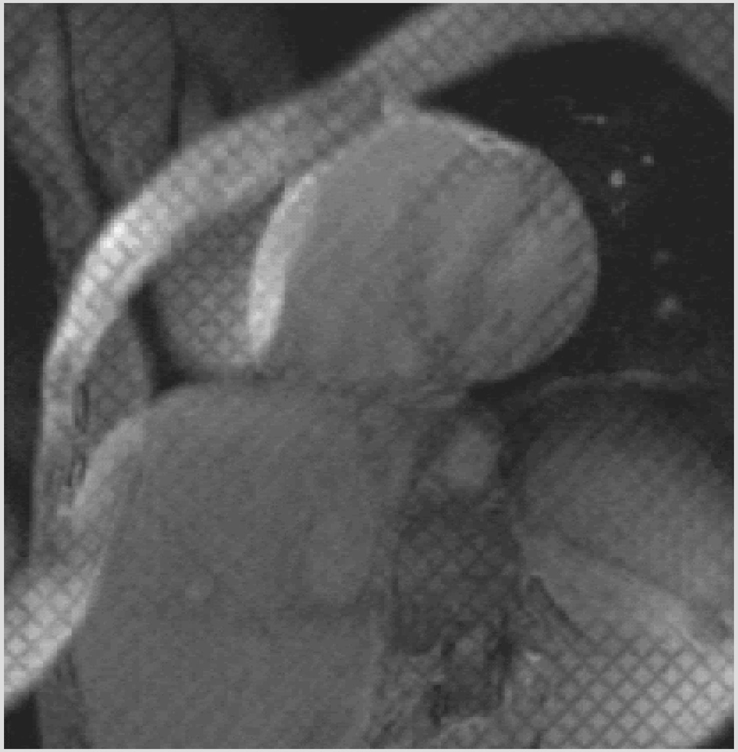
$R=0.84$ - $N=43$

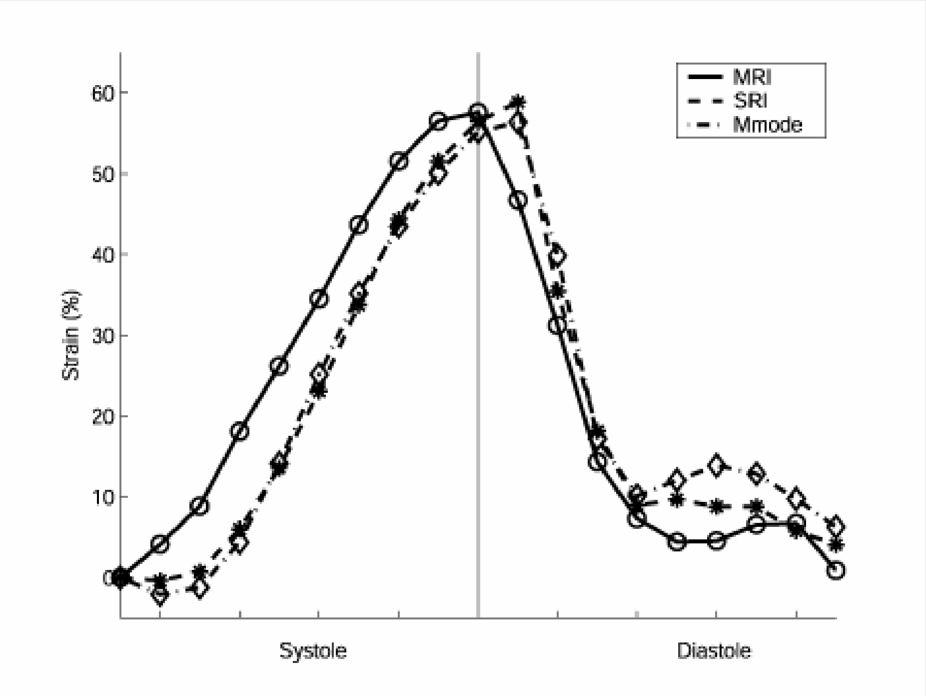
$p<0.0001$

Courtesy: Fadi Jamal 2001
Lyon, France

S.Urheim *et al.*, *Circulation* 2000; F. Jamal *et al.*, *Am. J. Physiol.*, 2003

Validation in vivo II: SRI vs MRI (tagging) / Mmode





Intra-class Correlation Coefficient: 0.69

T. Edvardsen *et al.*, *Circulation* 2002; E. Konofagou *et al.*, *IEEE Ultrasonics Symp.,* 2003
L. Herbots *et al.*, *UMB* 2003

Normal Strain Rate

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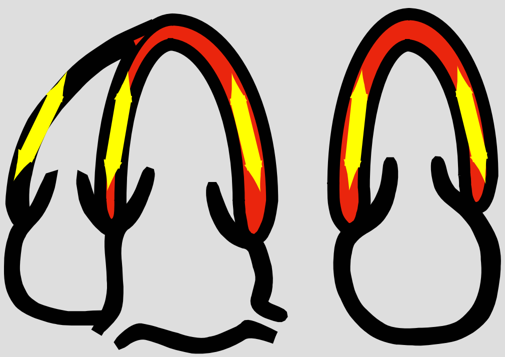
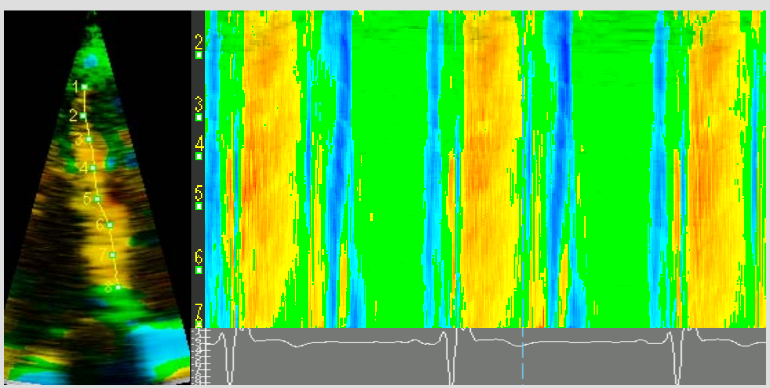
Longitudinal

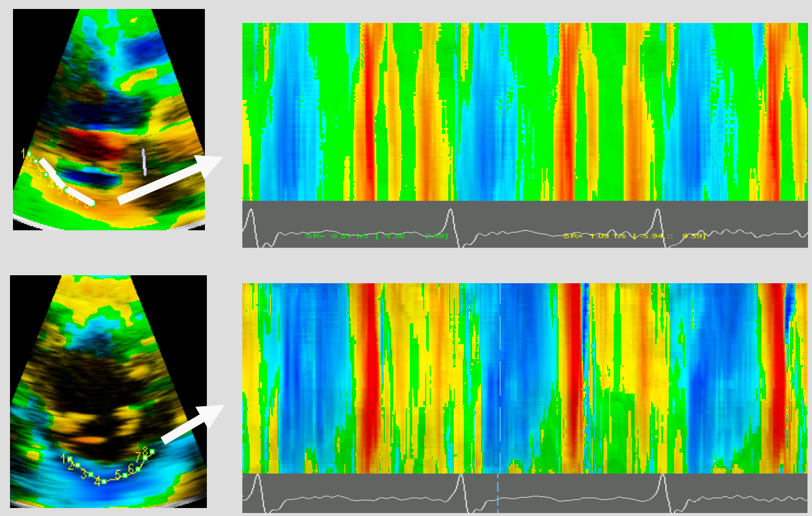




Systolic shortening → **compression**

Diastolic lengthening → **expansion**

Radial



Systolic thickening → **expansion**

Diastolic thinning → **compression**

M. Kowalski *et al.*, *Eur. J. Echocardiogr.* 2001; J. Sun *et al*., J. Am. Soc. Echocardiogr., 2004 *(normal values in adults)*
F. Weidemann *et al.*, *J. Am. Soc. Echocardiogr.*, 2002 *(normal values in children)*

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In-vivo normal examples

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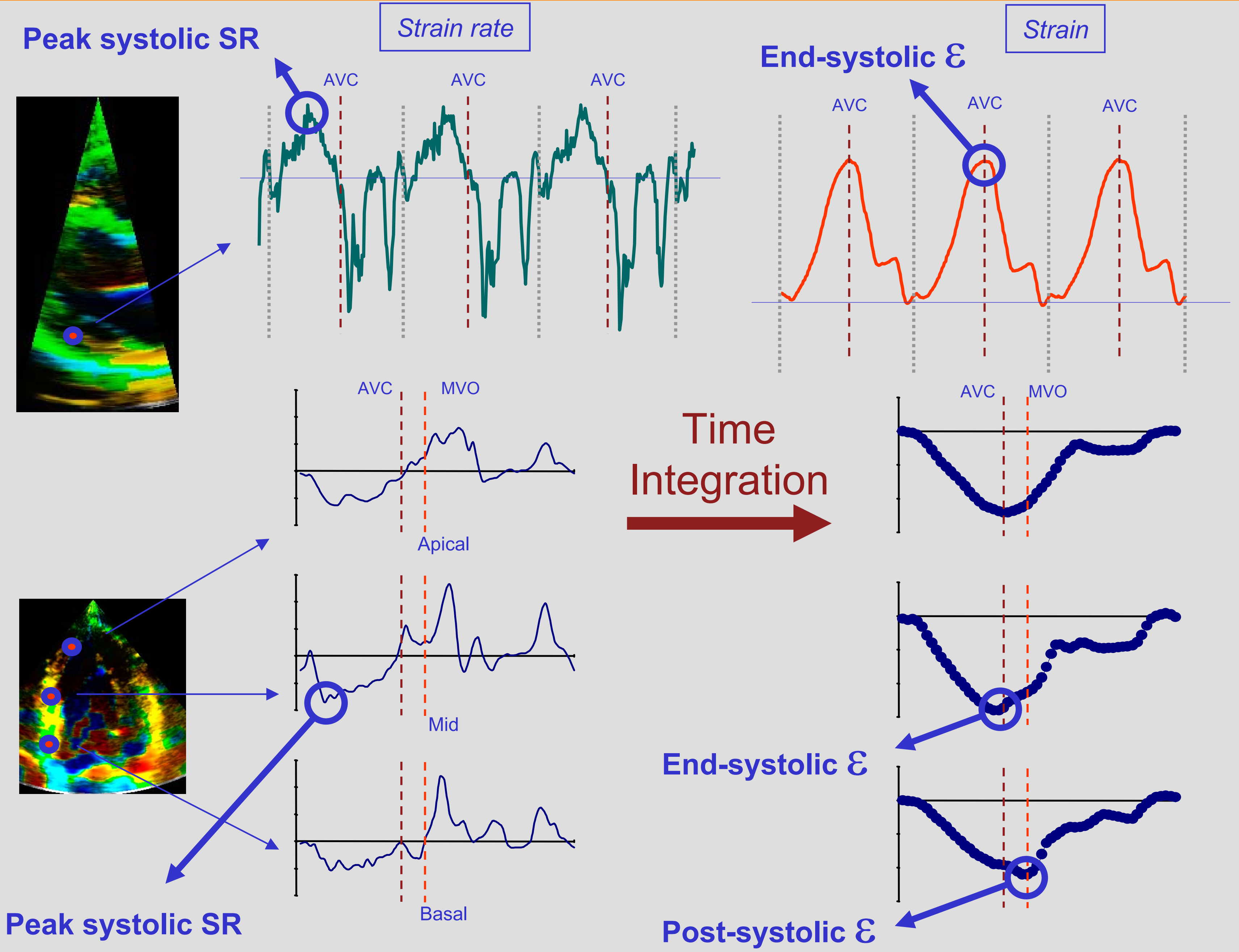
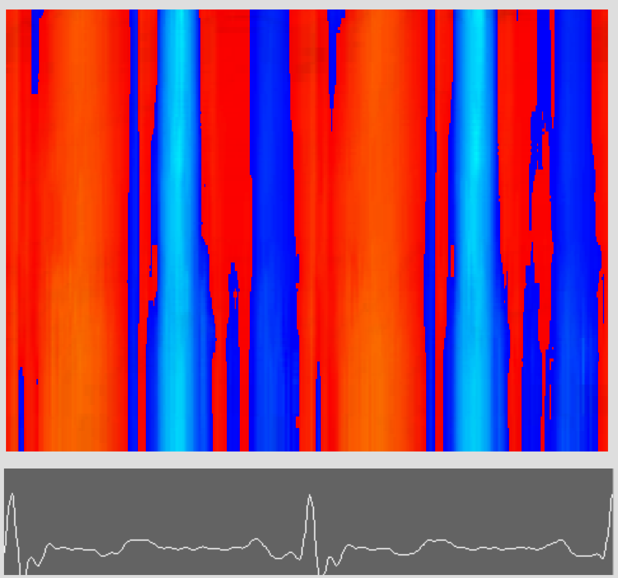
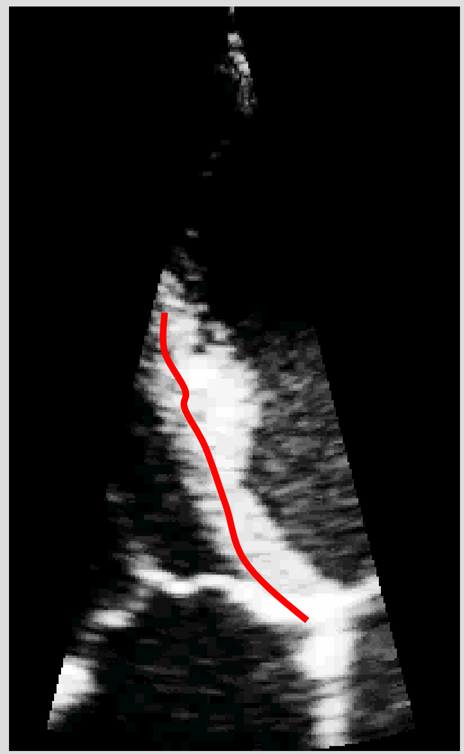


In-vivo abnormal example

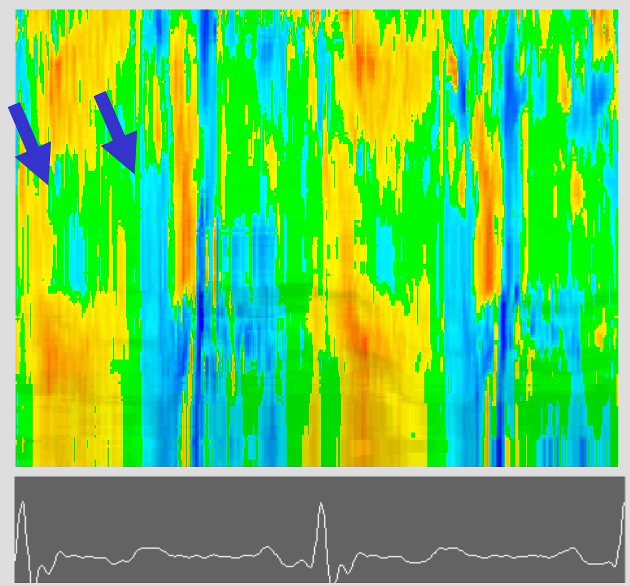
Hypertrophic non-obstructive cardiomyopathy

Velocity





Strain Rate



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Assessing myocardial function?

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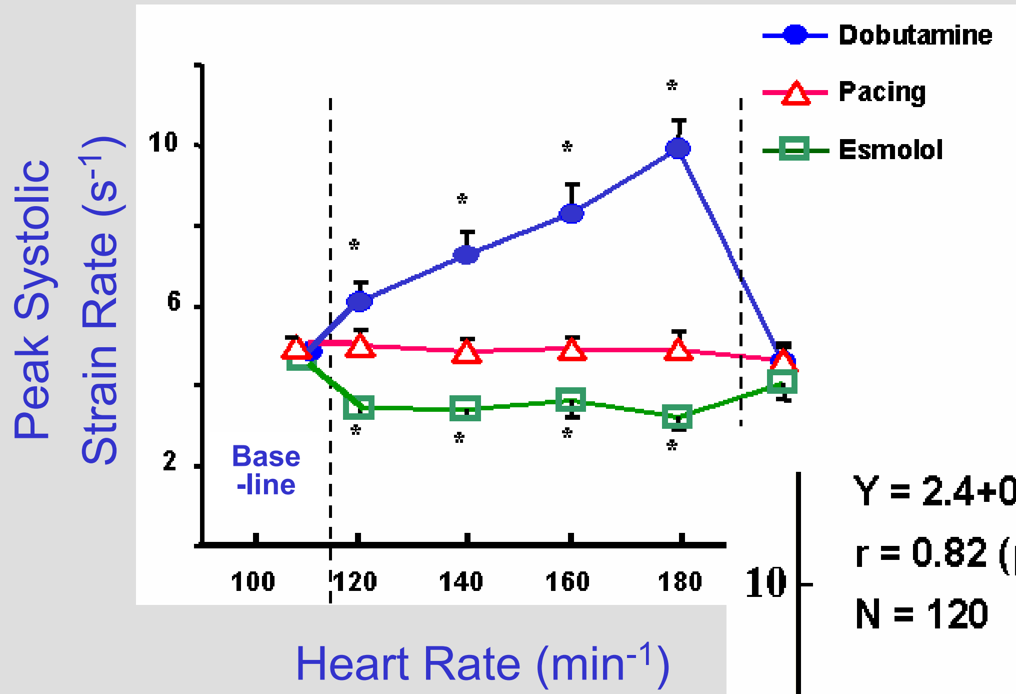
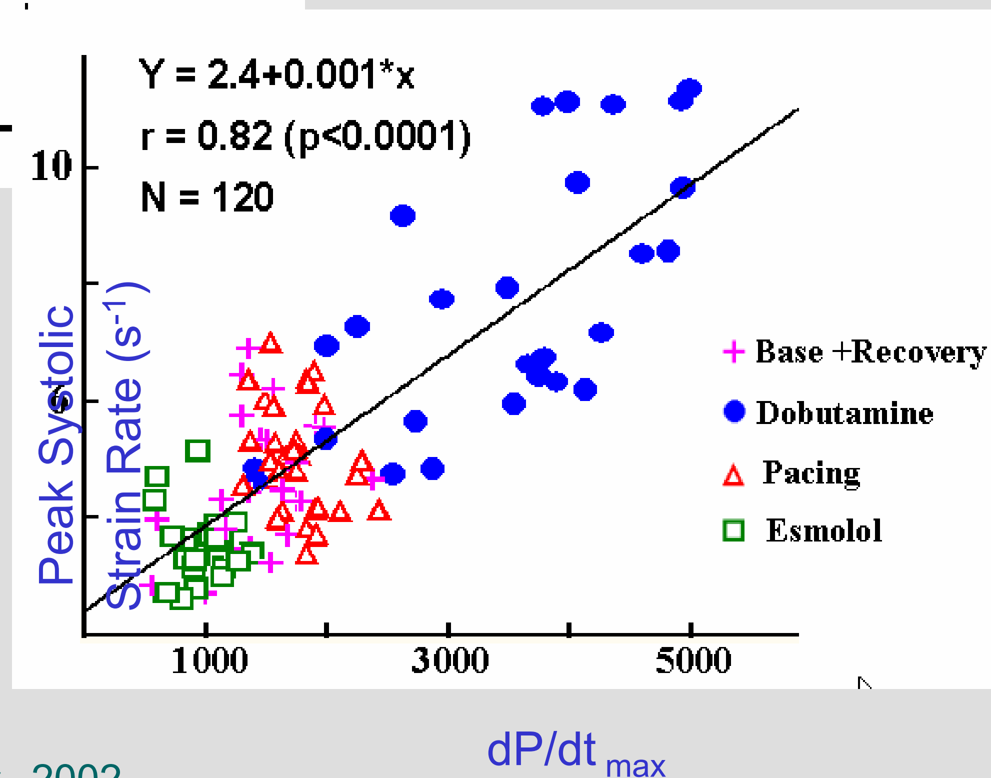




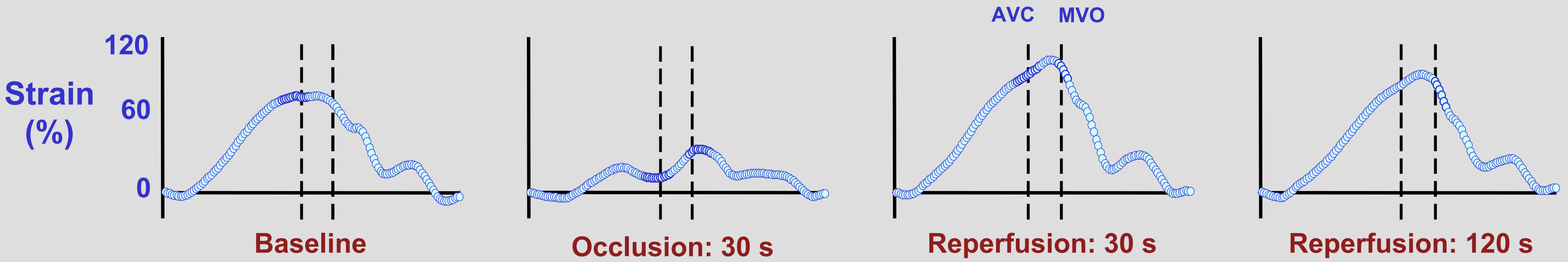
F. Weidemann *et al.*, *J. Am. Soc. Echocardiogr.*, 2002

F. Weidemann *et al.*, *Am. J. Physiology – Heart and Circ.*, 2002

Experimental ischemia

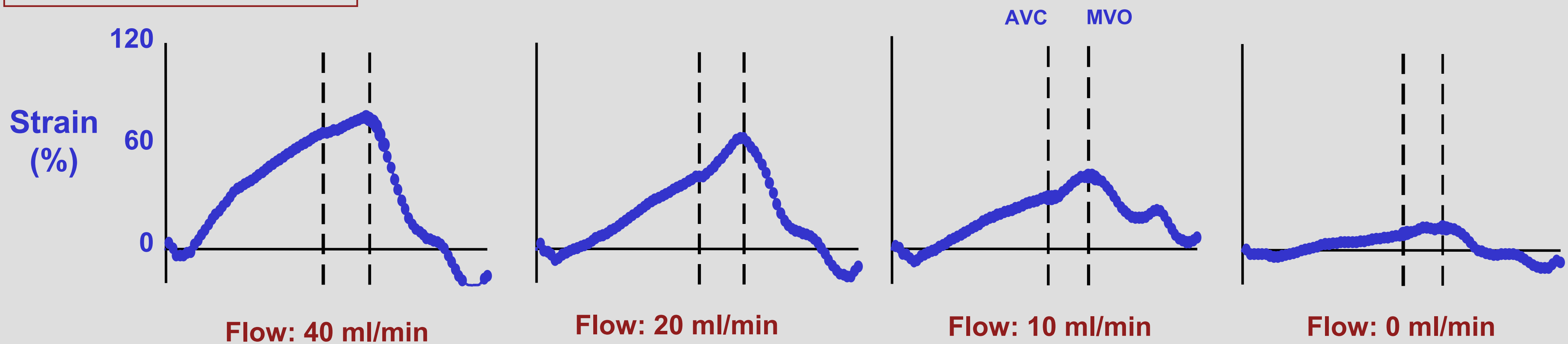
Acute total Ischemia

F. Jamal *et al.*, *J.Am.Soc.Echocardiogr.*, 2001; C. Pislaru *et al.*, *JACC*, 2001
M. Belohlavek *et al.*, *JASE*, 2001, Pislaru *et al.*, *JACC*, 2002



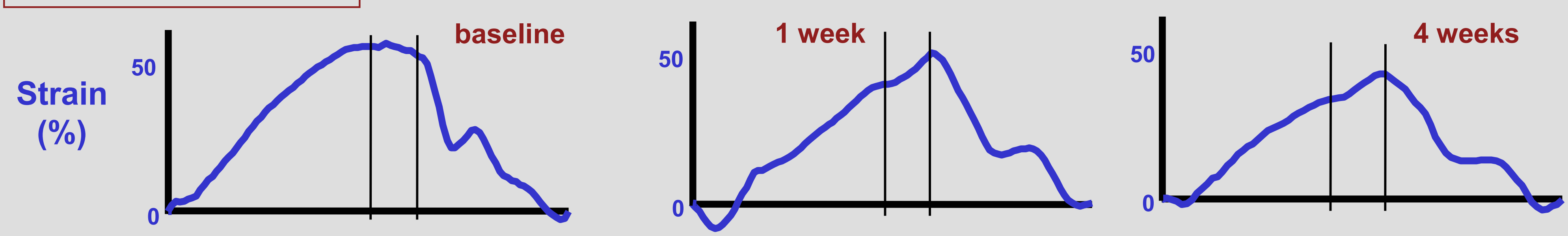
Graded Ischemia

Jamal *et al.*, *J.Am.Soc.Echocardiogr.*, 2001; Weidemann *et al.*, *Clin.Science*, 2003



Chronic Ischemia

F. Weidemann *et al.*, *Circulation*, 2003



Dobutamine Response

	REST			DOBUTAMINE STRESS		
	SR_{SYS}	ε_{SYS}	PSI	SR_{SYS}	ε_{SYS}	PSI
Normal	5 /s	60 %	2 %	↗	↗↘	→
Stunning	↓	↓	↑	↗	↗	↘
Acute Ischemia	↓	↓	↑	↘	↘	↗
Nontransmural MI	↓	↓	↑	↗↘	→	↗
Transmural MI	↓	↓	↑	→	→	→

SRI can differentiate stunned from ischemic myocardium
F.Jamal *et al.*, *Circulation*, 2001

SRI can differentiate transmural from non-transmural MI
F.Weidemann *et al.*, *Circulation*, 2003

SRI + dobutamine stress can differentiate the different ischemic substrates
⇨ *Quantitative stress echo!*

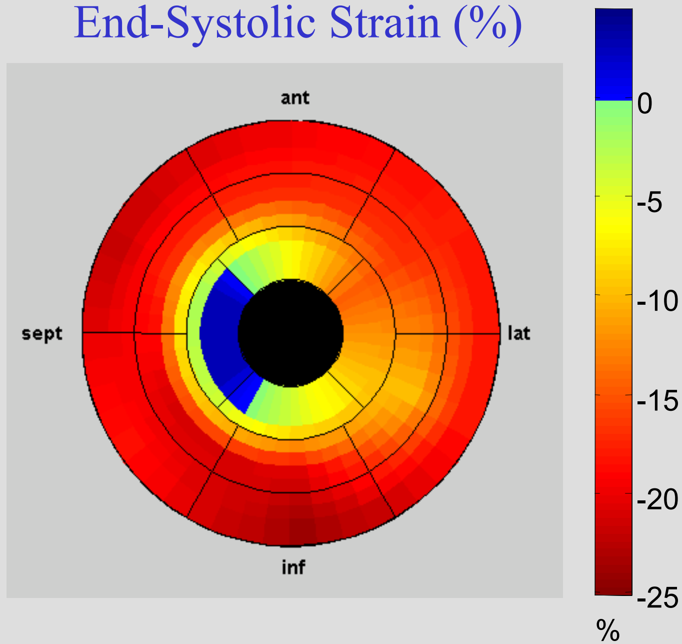
M.Kowalski *et al.*, *Eur. J. Echocardiography*, 2003; J.Voigt *et al.*, *Circulation*, 2003

Bulls eye representation of ε_{LL} ?

15 patients with acute ischemia (stem-cell study)

- Baseline end-systolic ε_{LL} analyzed and represented as a 17 segment bulls eye
- Blinded *(non-medical!)* reader identified area at risk (per segment)
- Compared to angiographic data

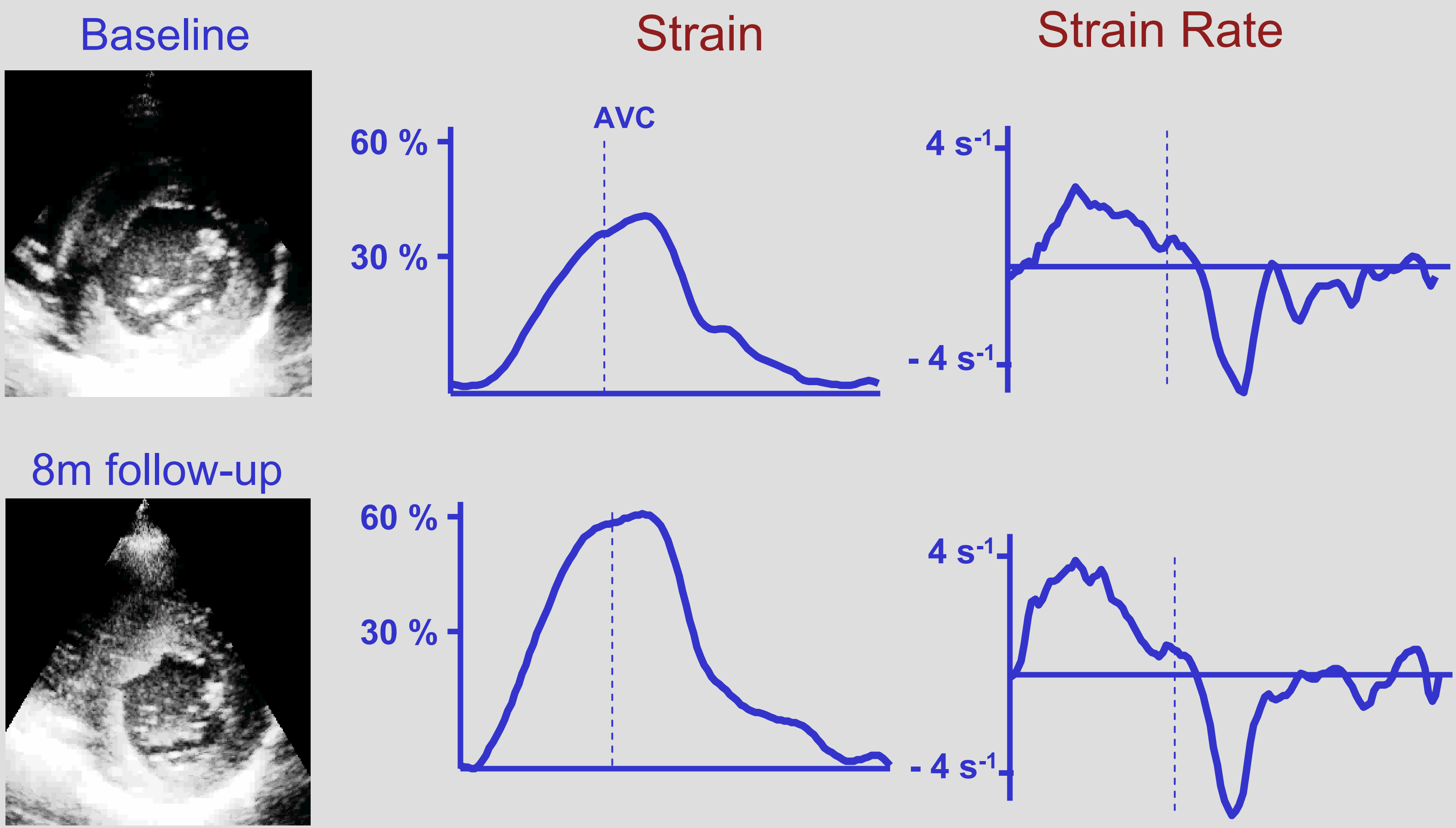
End-Systolic Strain (%)



⇨ Sensitivity = 81%; Specificity = 79%

L. Herbots *et al.*, Eur. J. Echocardiograph. 2004 (In press)

SRI for therapy follow-up



Study in patients with Friedreich's Ataxia using "Idebenone" as therapy

SRI could show early functional improvement

G. Buyse *et al.*, *Neurology,* 2003; G. Di Salvo *et al.*, *AJC*, 2003

F. Weidemann *et al.*, *Circulation,* 2003; F. Weidemann *et al.*, *Eur. Heart Journal*, 2004 (In press) (Fabry disease)

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SRI for therapy: CRT

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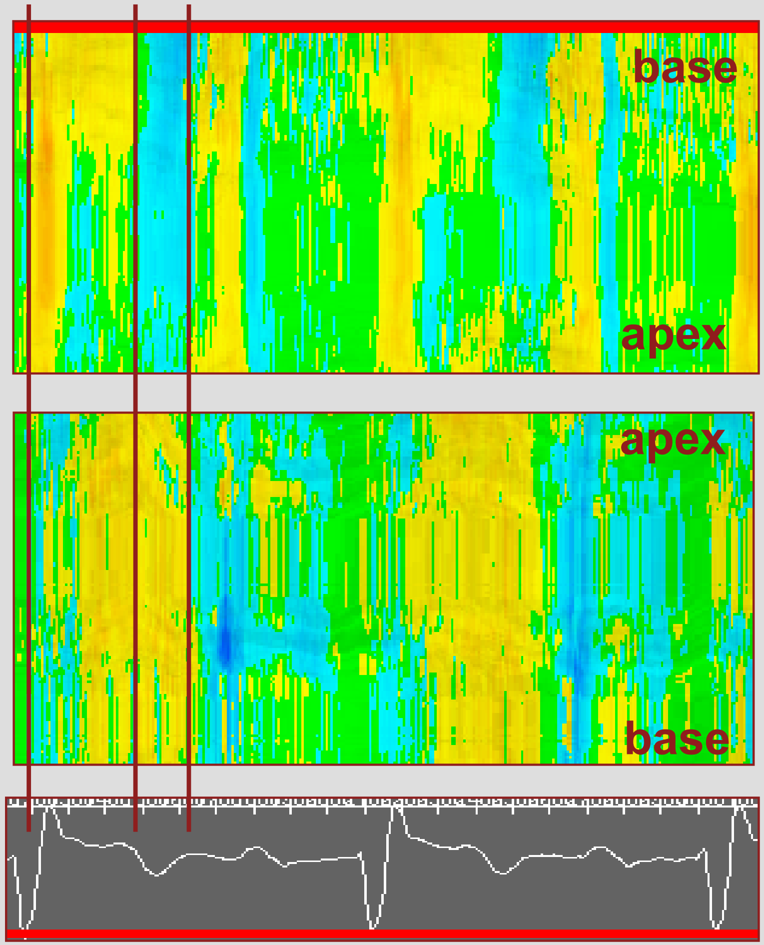
Strain Rate

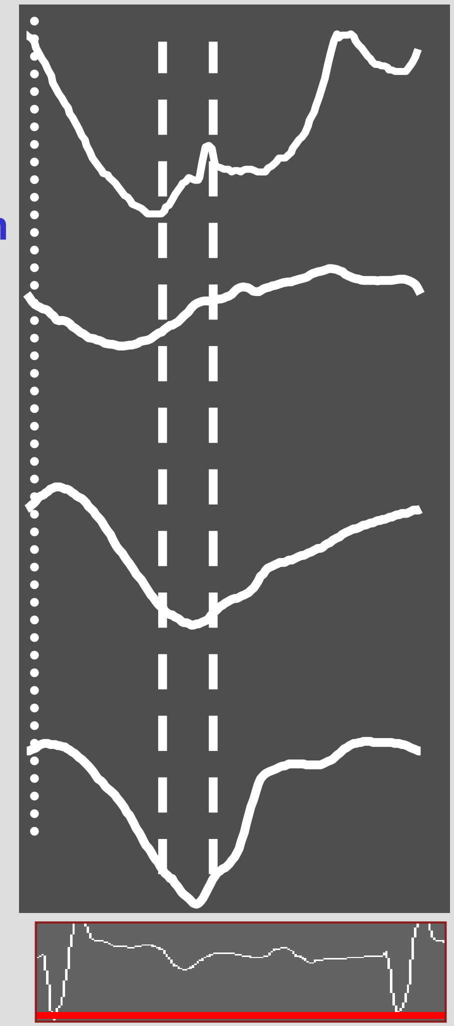
Strain

LBBB



Septum

Lateral wall



O. Breithardt *et al.*, *JACC,* 2003

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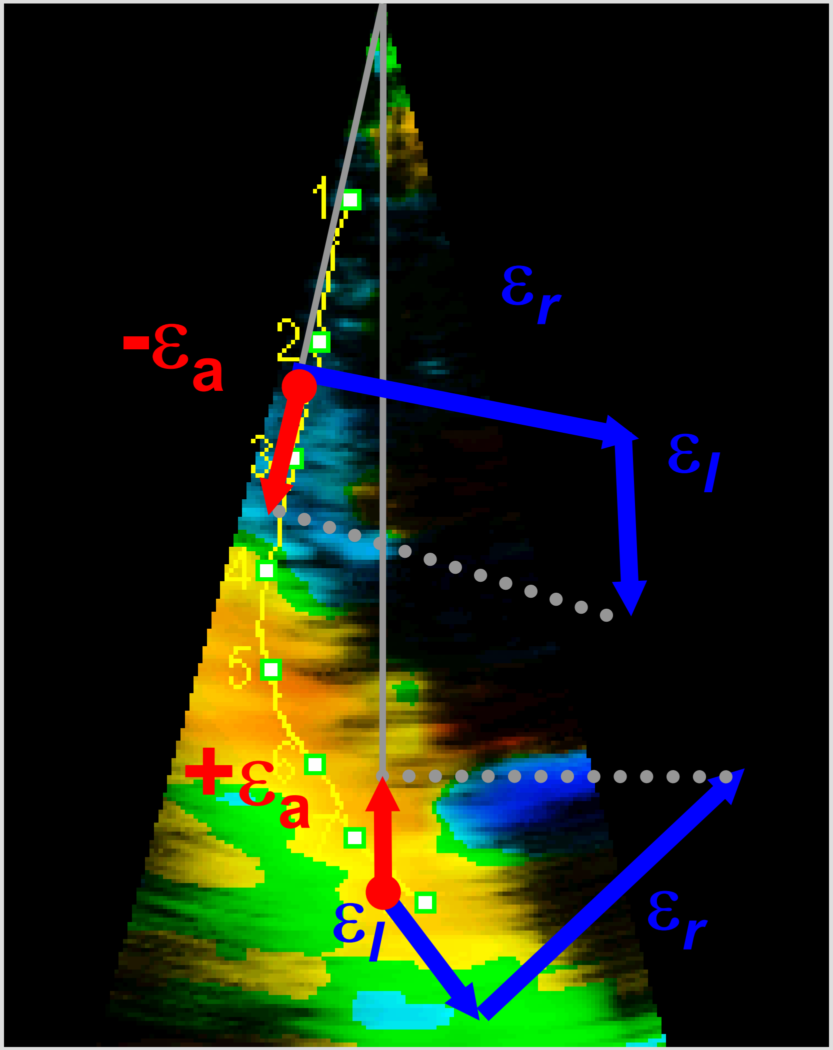
SRI pitfall: angle dependency

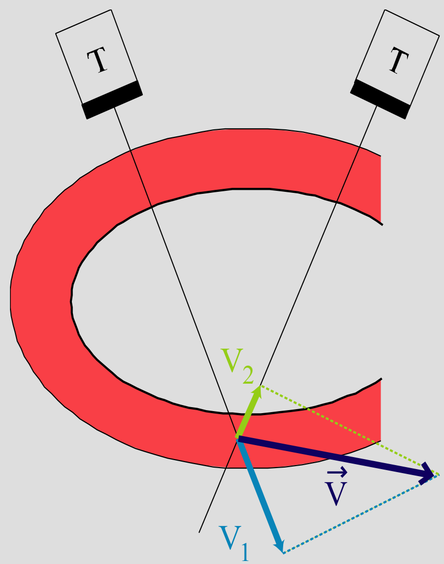


Courtesy: Jens-Uwe Voigt, University of Erlangen, Germany

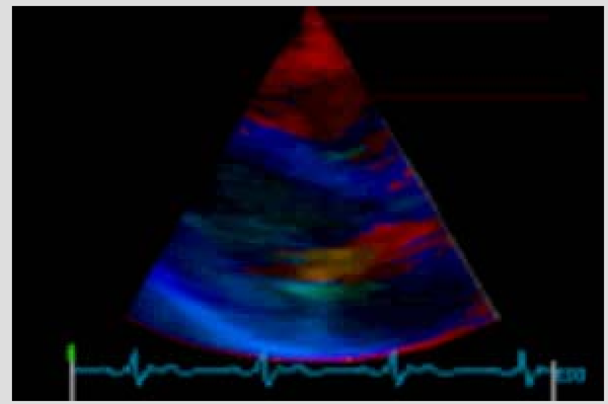
P.L. Castro *et al.*, *Biomed. Sci. Instrum.*, 2000
S.I. Rabben *et al.*, *IEEE Ultrasonics Symp.*, 2003 (Effect of angle on SRI values)

Possible solution

Origin problem: 1D velocities → 1D strain rate

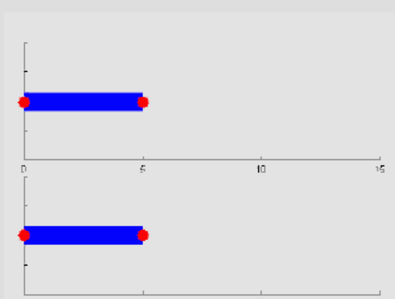


MVI data set



Contains only velocity info
ALONG THE IMAGE LINE

Assume: 2D velocities → 2D strain (rate) tensor

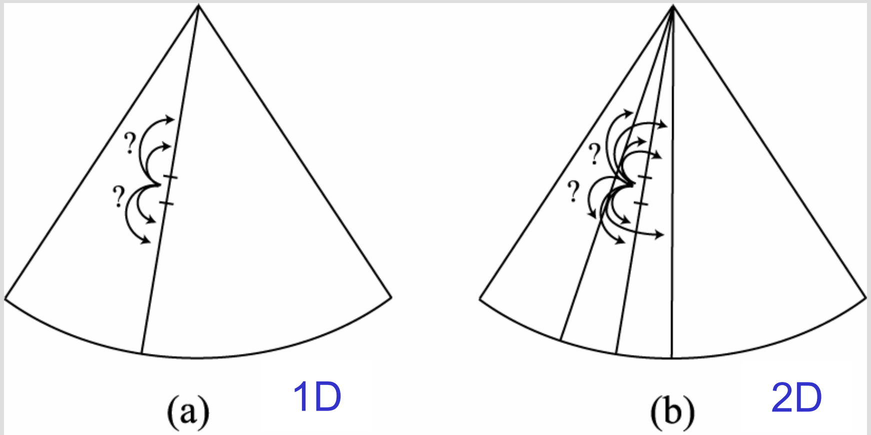


$$\begin{pmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} \end{pmatrix} = \begin{pmatrix} \dot{\varepsilon}_{xx} & \dot{\varepsilon}_{xy} \\ \dot{\varepsilon}_{yx} & \dot{\varepsilon}_{yy} \end{pmatrix} = \dot{\varepsilon}$$

For elastography: E. Konofagou *et al.*, *UMB*, 1998

RF based 2D motion/velocity

Generalized RF
time-shift estimator
(displacement estimator)



1D RF kernel

Optimal distance measure between RF patterns for cardiac SRI?

Viola *et al.* IEEE-UFFC, 2003
S. Langeland *et al.*, *UMB*, 2003

Cross Correlation (XC)
Normalized Cross Correlation (NXC)
Sum of Absolute Differences (SAD)
Sum of Squared Differences (SSD)

2D RF kernel

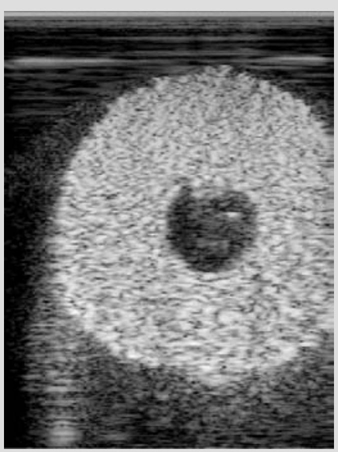
K. Kaluzynski *et al.* IEEE-UFFC, 2001
X. Chen *et al.* IEEE Symposium, 2002
X. Chen *et al.* IEEE Symposium, 2003

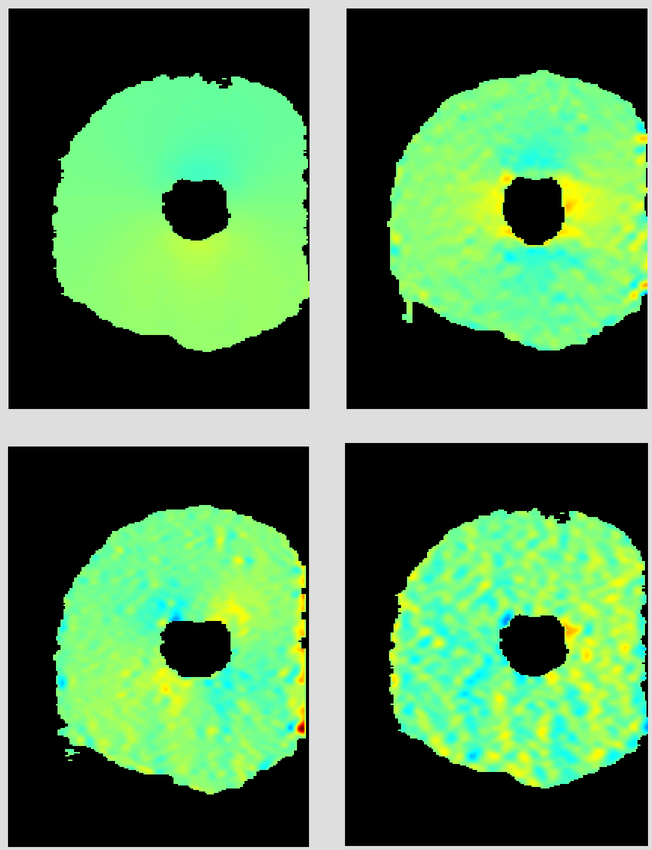
In vitro feasibility

2D kernel

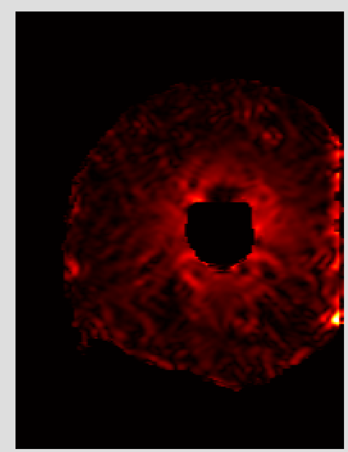
$$\begin{pmatrix} \frac{v_x}{x} & \frac{v_x}{y} \\ \frac{v_y}{y} & \frac{v_y}{x} \end{pmatrix} = \begin{pmatrix} \dot{\varepsilon}_{xx} & \dot{\varepsilon}_{xy} \\ \dot{\varepsilon}_{yx} & \dot{\varepsilon}_{yy} \end{pmatrix} = \dot{\varepsilon}$$

B-mode image





ε intensity



K. Kaluzynski et al.
IEEE-UFFC, 2001

In vitro validation

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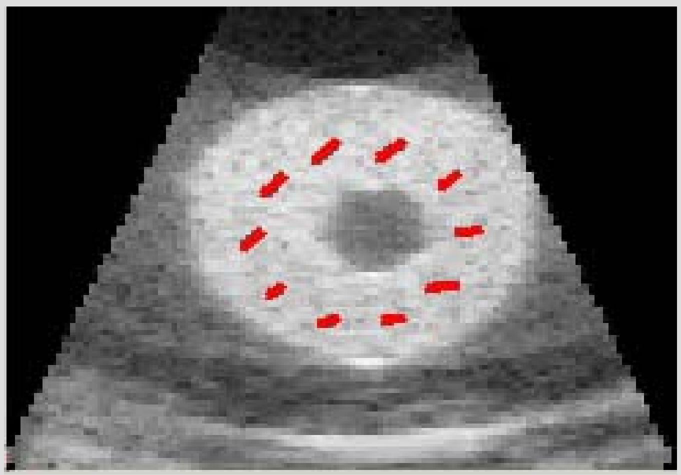
1D kernel

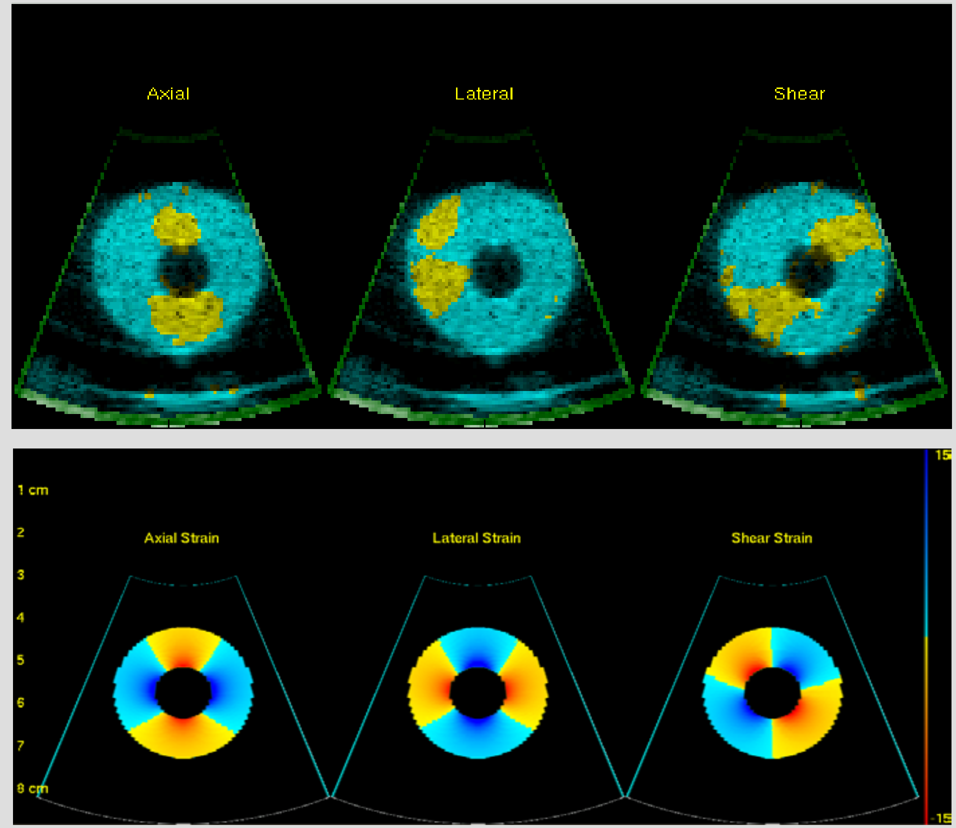
2D velocity vector



2D strain

Experiment

Theory



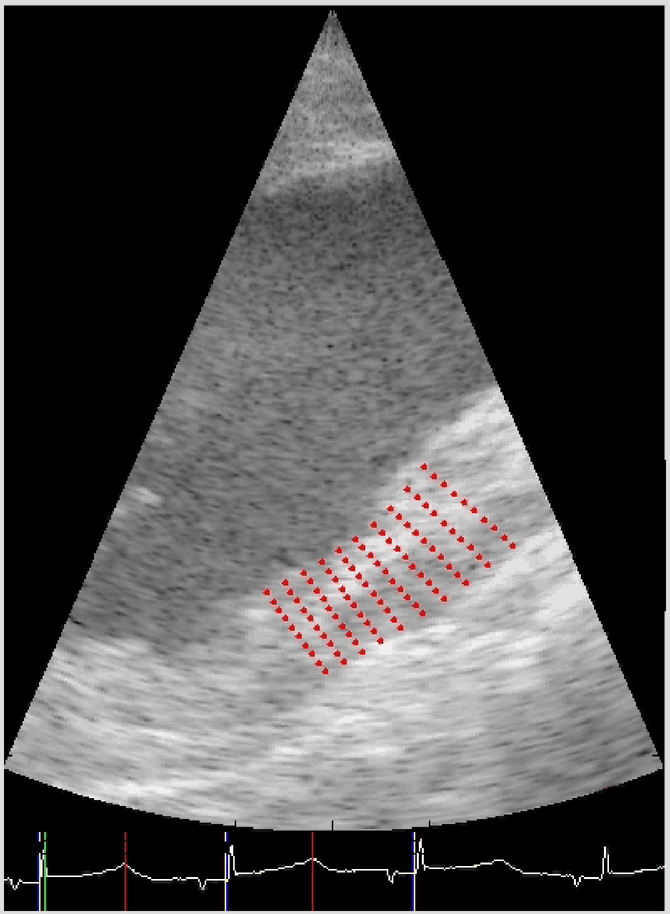
Axial Lateral Shear

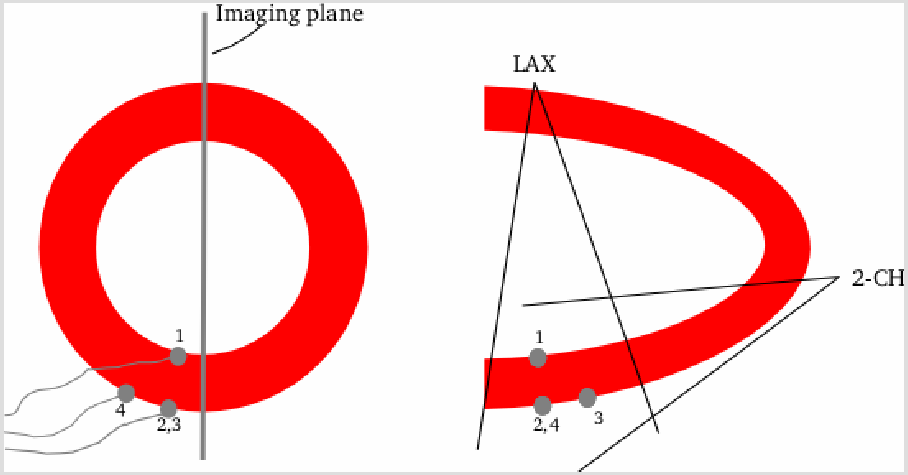
Good correlation of both axial and lateral strain values against micro-crystal data (r ≈ .90)

S.Langeland *et al.*, *IEEE UFFC.*, 2004 (In press)

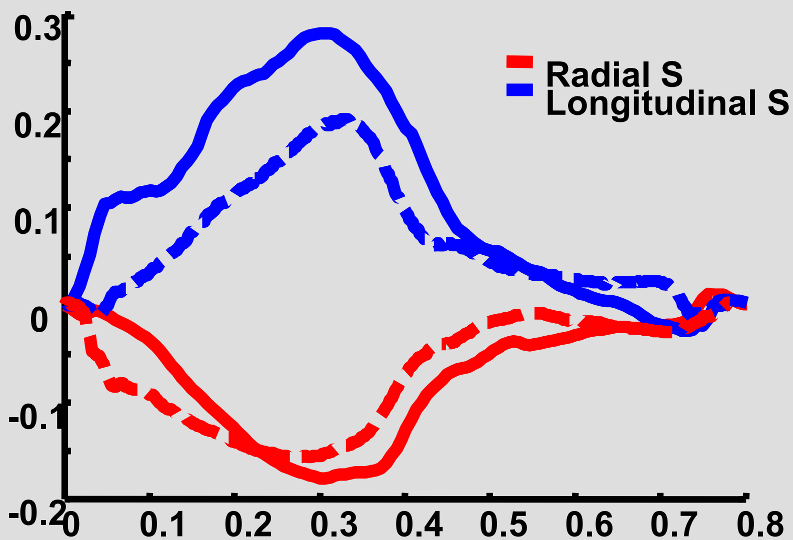
Results in-vivo validation

2D strain in-vivo





Solid = ultrasound
Dashed = micro-crystals



S.Langeland *et al.*, *IEEE Ultrasonics Symposium*, 2004

Envelope based 2D motion/velocity

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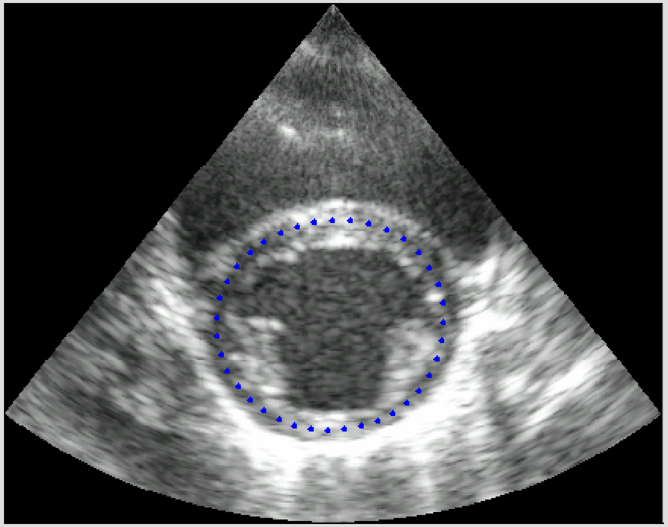
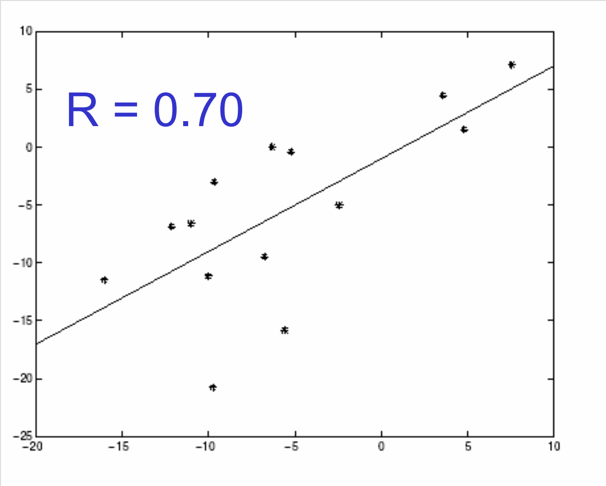
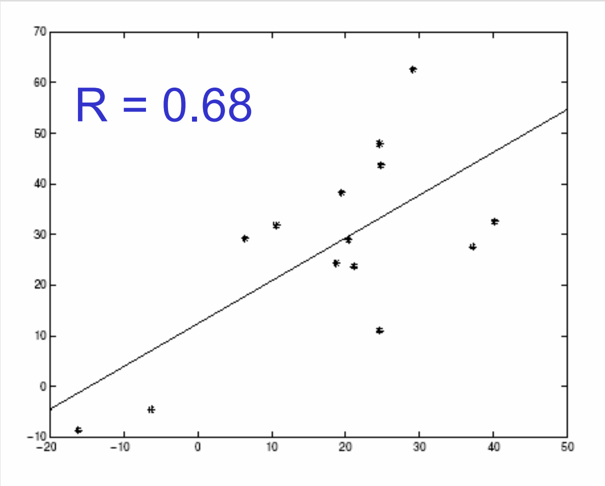
Optical Flow

C. Jansen *et al.* Eur. J. Echocardiogr., 2002 (abstract)
Behar *et al*. Ultrasonics, 2004





Longitudinal



Radial

Initial clinical results: M. Leitman *et al*., *J. Am. Soc. Echocardiogr*. 17(10):1021-1030, 2004

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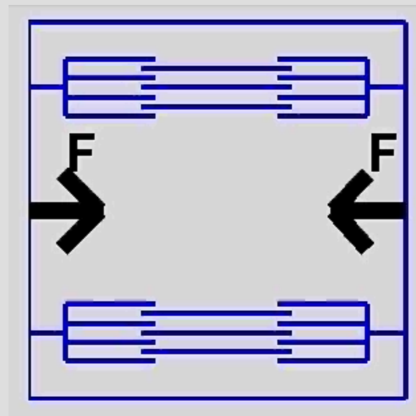
Regional myocardial function

Active elastic body



Active contractile stress

$$C(t) + \sigma_{load}(t) = E \times \varepsilon(t)$$

Regional myocardial function *(contractility)*

Wall stress
(total force on a segment)
cavity pressure,
geometry,
neighbouring segment interaction

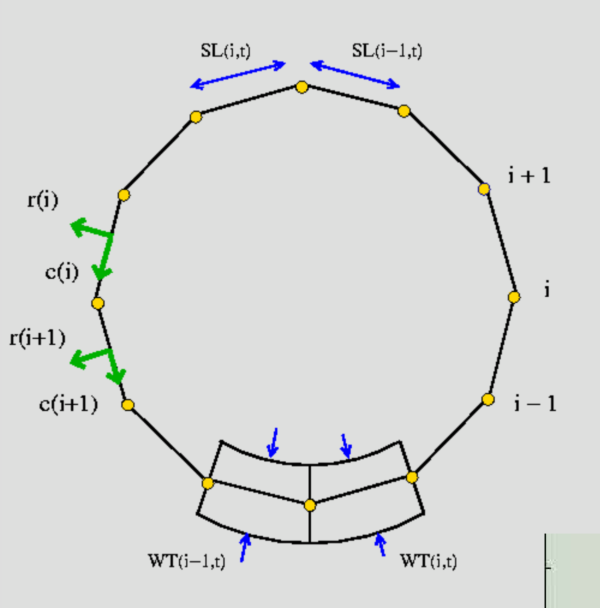
segmental elasticity

resulting deformation

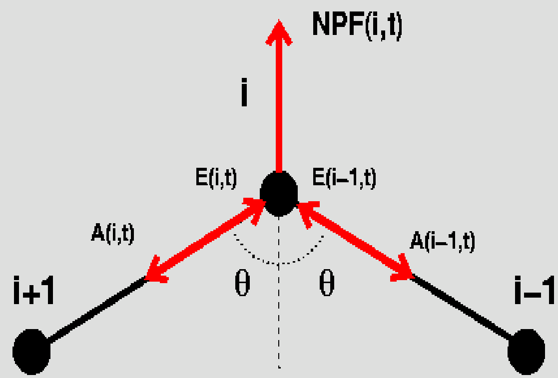
⇨ *If the assumption is made that* ***__external stresses (loading) can be neglected__****, local strain directly relates to local contractile stress*

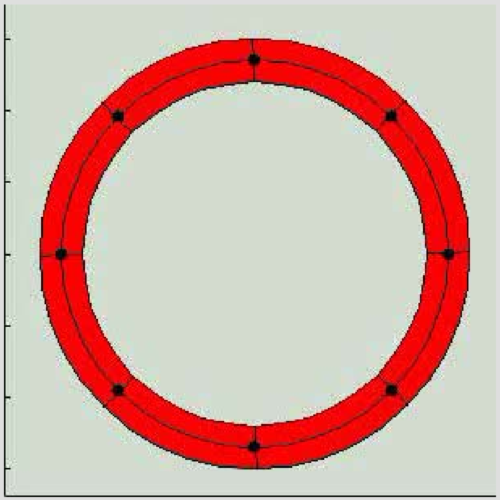
Towards active force development using SRI + mechanical models

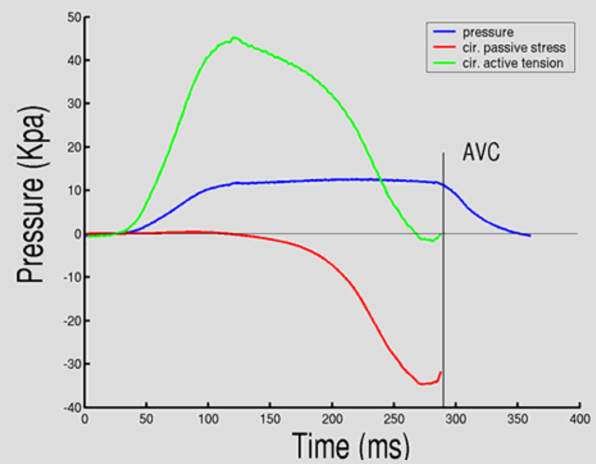
The left ventricle was modeled as a 2D circular array of 400 nodes



In each node → balance of forces



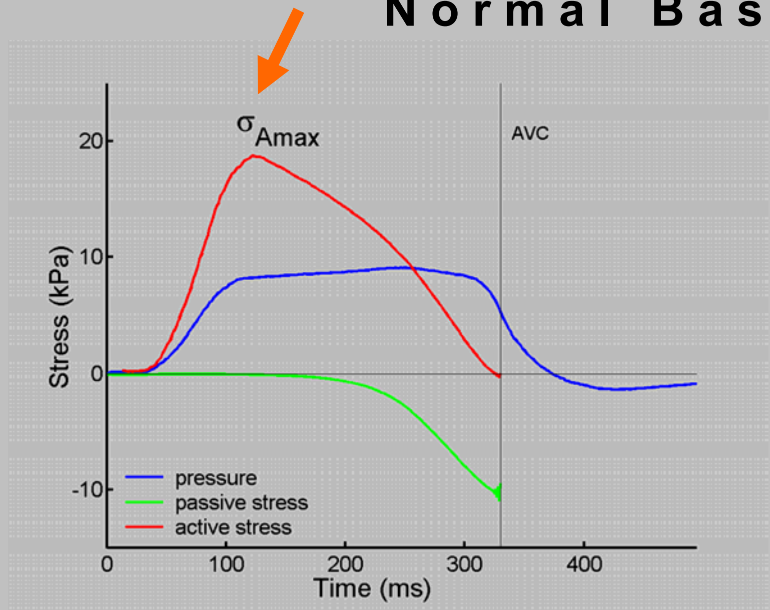




M. McLaughlin *et al.*,
IEEE EMBS Symposium, 2004

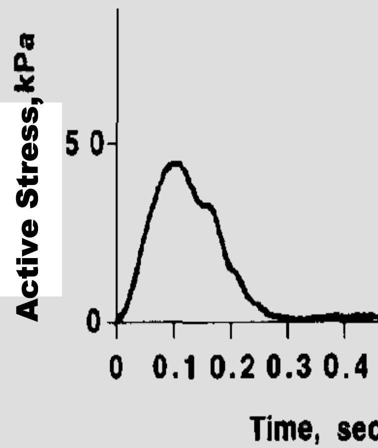
Results I

Normal Baseline Values



Parameter	Mean ± SE
σ_{Amax}	20.5 ± 1.3 kPa
T_σ_{Amax}	106 ± 5.7 ms
AVC	317 ± 9.8 ms
C_1	17 ± 23 kPa
C_2	281 ± 114

Active stress profiles measured
in isolated muscle strips



1. J.M. Guccione, et al. Measurements of active myocardial tension under a wide range of loading conditions. J. Biomechamics, 30(2): 189-192, 1997

M. McLaughlin *et al.*,
IEEE EMBS Symposium, 2004

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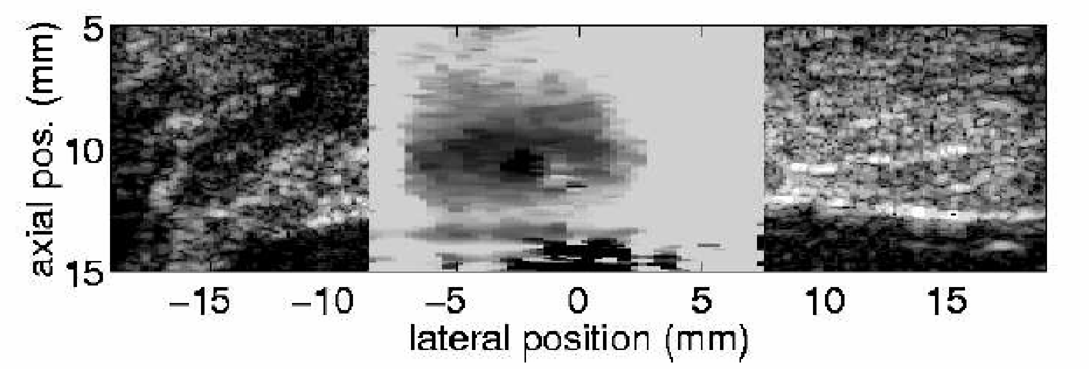
Non-invasive assessment of cardiac elasticity

Relative elastic properties

ARFI



B. Fahey *et al.*
IEEE Ultrasonics Symposium, 2003

Non-invasive assessment of cardiac elasticity

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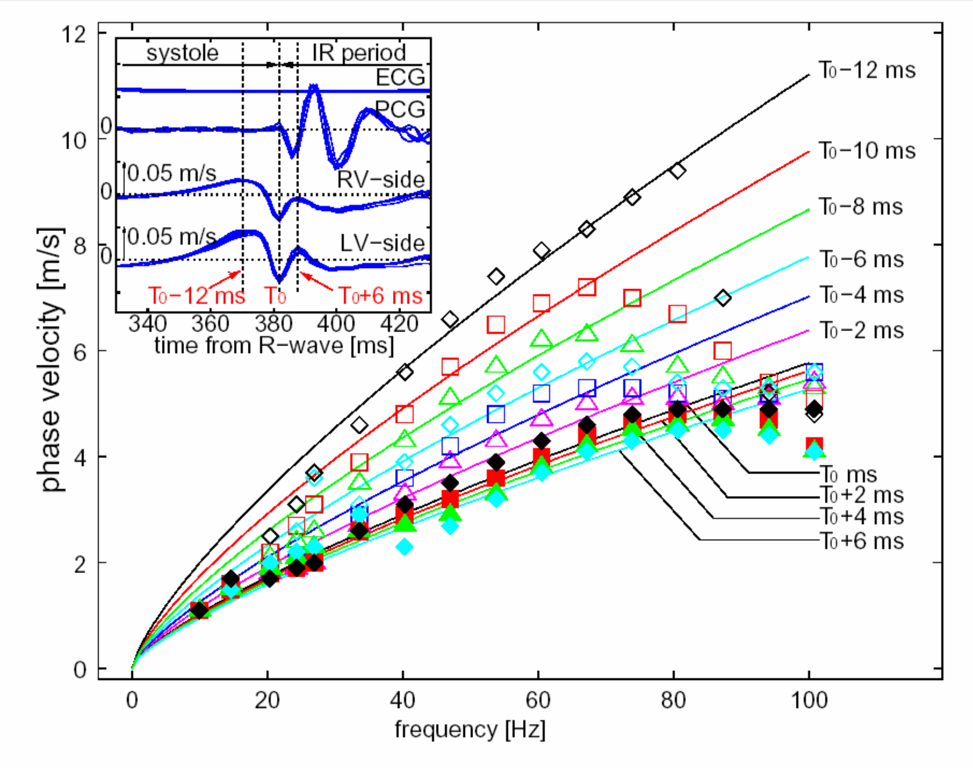
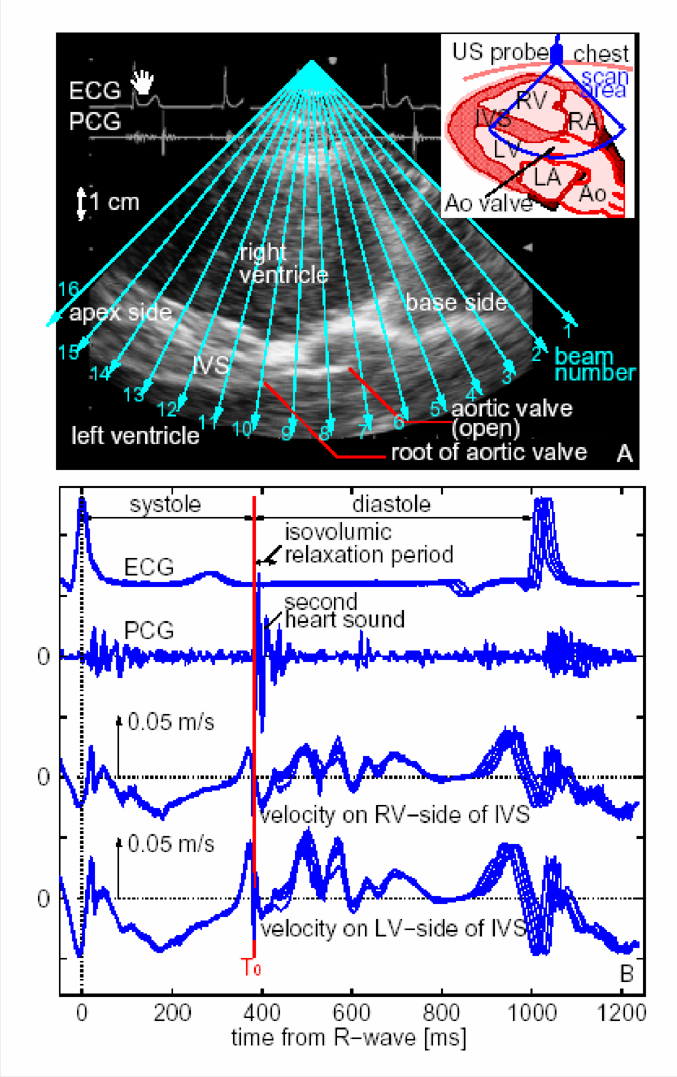
Elastic properties

→ Using Lamb wave propagation?





H. Kanai *et al.*
IEEE Ultrasonics Symposium, 2003

Conclusions I

- Strain and strain rate imaging are new echocardiographic tools for the assessment of regional myocardial function
- Different approaches towards cardiac deformation estimation have been proposed both based on the envelope and RF signals
- Important clinical applications will be:
  - Quantitative stress echocardiography
  - Therapy guidance and follow-up
- Further research is required to optimize the use of the current technique and to further test its clinical applicability

Conclusions II

- Multi-dimensional strain (rate) estimation is becoming possible (angle dependency will thus be solved)

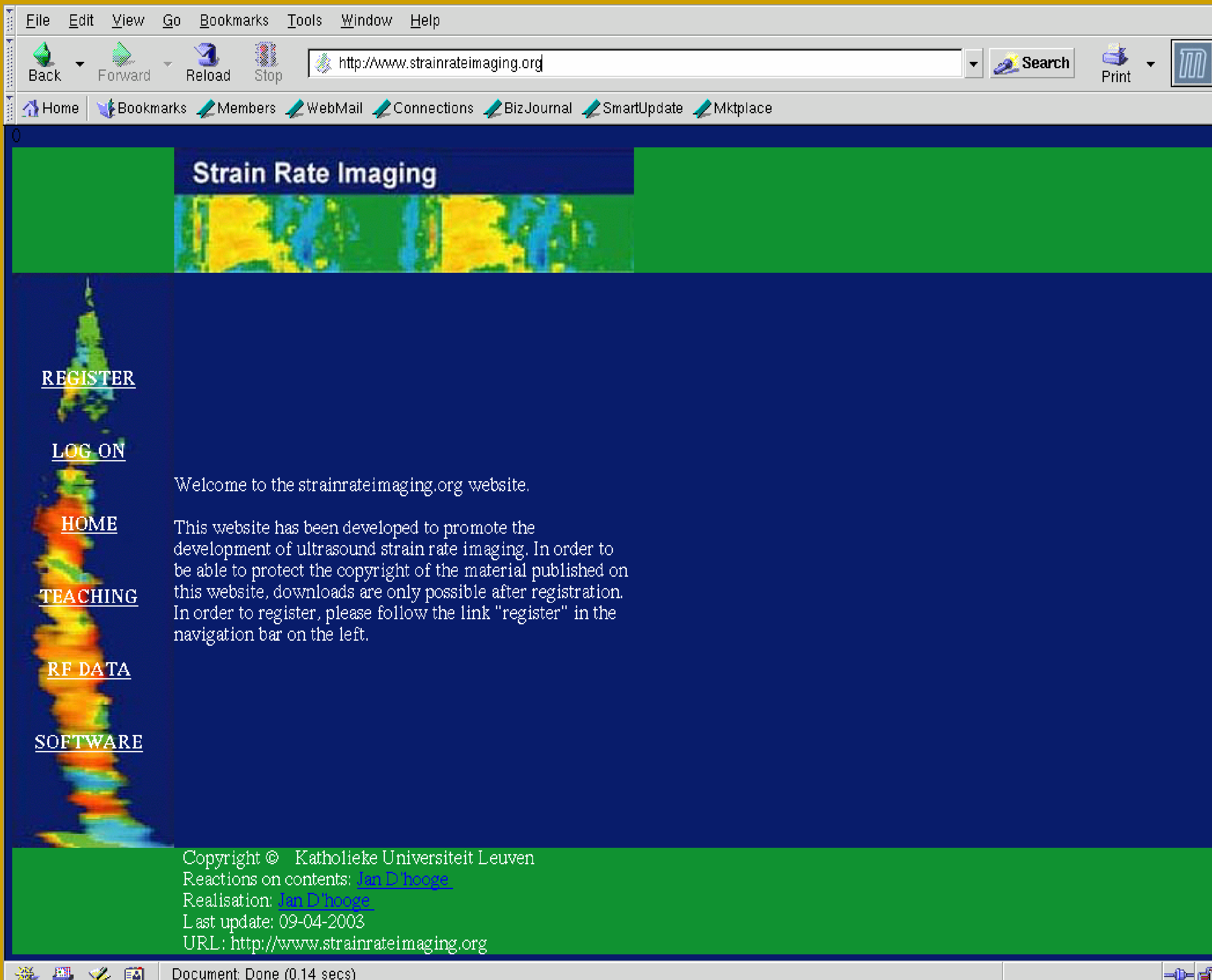
- Time-consuming analysis is being reduced through automated tracking of regions of interest

- Linking ultrasound deformation measurements to mathematical models of cardiac contraction can:

  1. Make the strain (rate) estimate more robust
  2. Estimate active stress development!

- New methods have been proposed for estimating myocardial relative and absolute elastic properties

www.strainrateimaging.org



- Teaching material
- Literature refs
- RF data sets
- SRI software

→ i.e. "Speqle"

- Latest developments

Stay tuned!