

# Strain and deformation estimation in cardiac imaging



Current and emerging frameworks

Andrew Gilbert

Trial Lecture

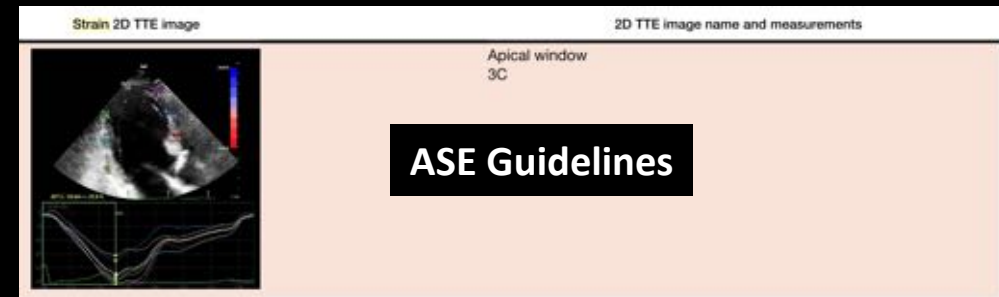
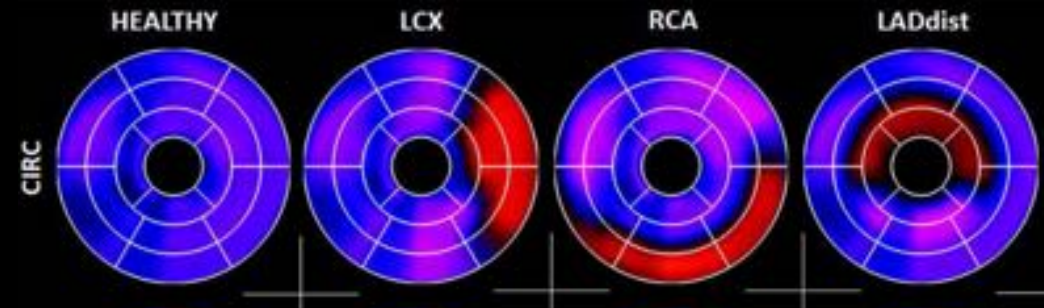
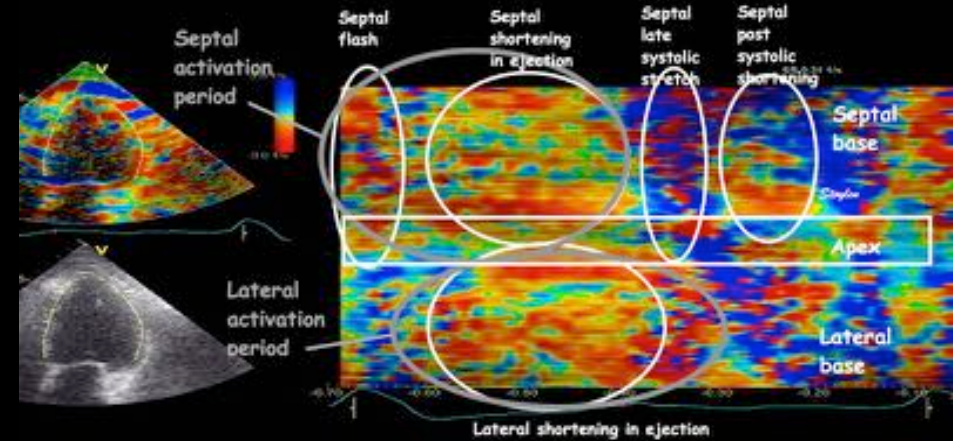
02.07.2021

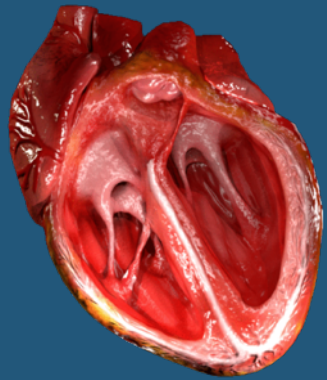
# Why perform strain estimation?

Strain imaging provides a detailed analysis of regional and global deformation patterns of cardiac chambers.

Strain measurements help better differentiate between pathologies, leading to better diagnoses and earlier treatments. Strain can also track progress during treatment.

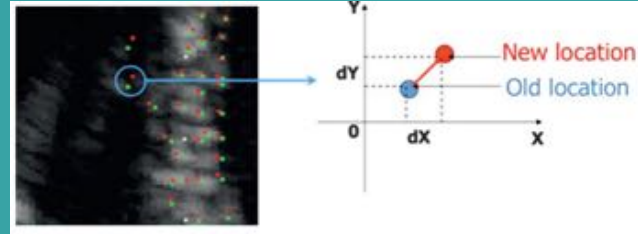
An area where research has led to a powerful and easy-to-use clinical tool.





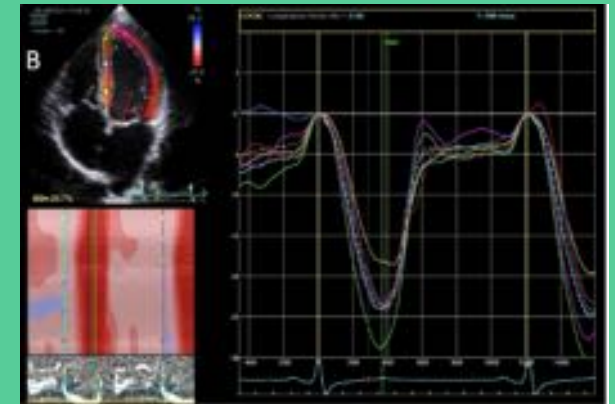
# Physics and basis of cardiac strain

[Wikimedia Foundation]



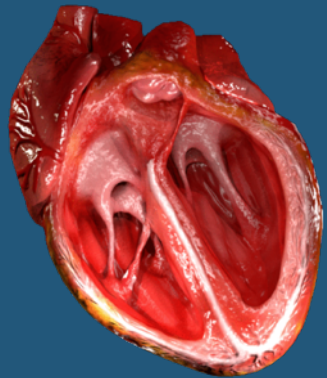
# Methods of strain estimation

[folk.ntnu.no/stoylen]



# Clinical workflow and examples

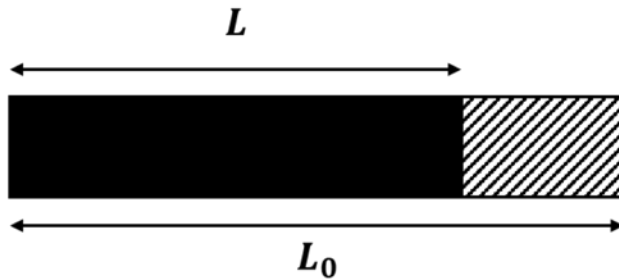
[Loncaric et al. *Global Cardiology*, 2018]



# Physics and basis of cardiac strain

Strain/deformation is the mechanical transformation of a body from a *reference* configuration to a *current* configuration.

1D



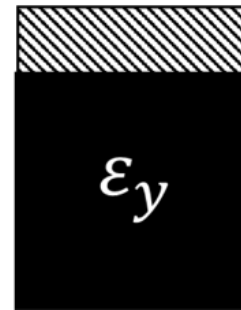
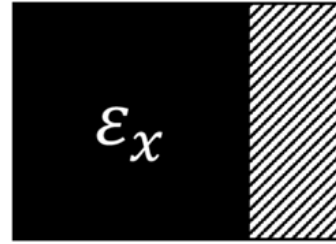
$$\varepsilon = \frac{L - L_0}{L_0}$$

$$\varepsilon(t) = \frac{L(t) - L_0}{L_0}$$

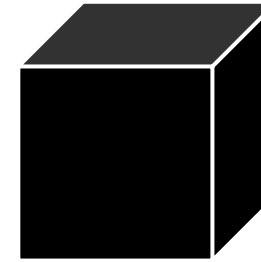
Eulerian strain is sometimes used:

$$\varepsilon_E(t) = \int_{t=0}^t \frac{dL}{L} \partial t = \ln(1 + \varepsilon(t))$$

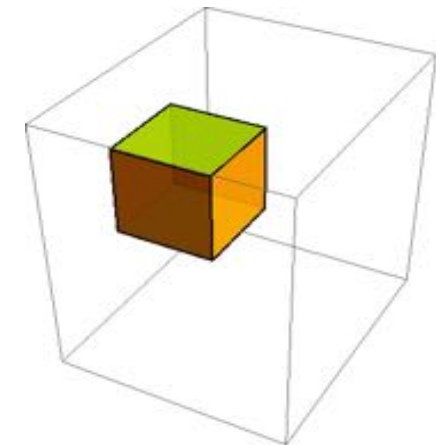
2D



3D



$$\varepsilon = \begin{bmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z \end{bmatrix}$$

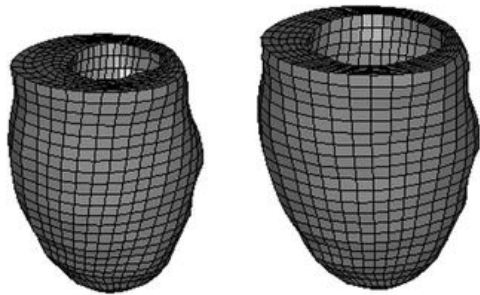


# The heart muscle contracts (systole) and relaxes (diastole) to pump blood through the vasculatory systems

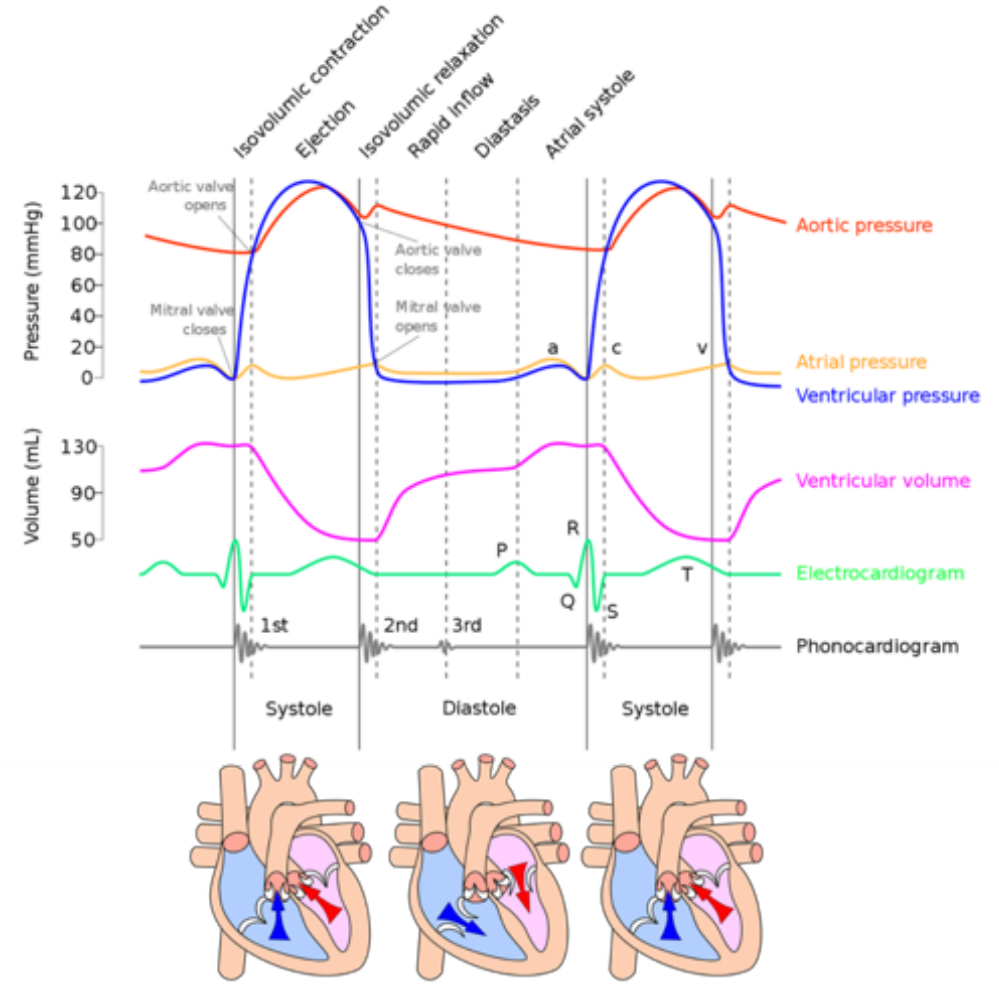
Physics and basis of cardiac strain



Our analysis here is focused on the left ventricle



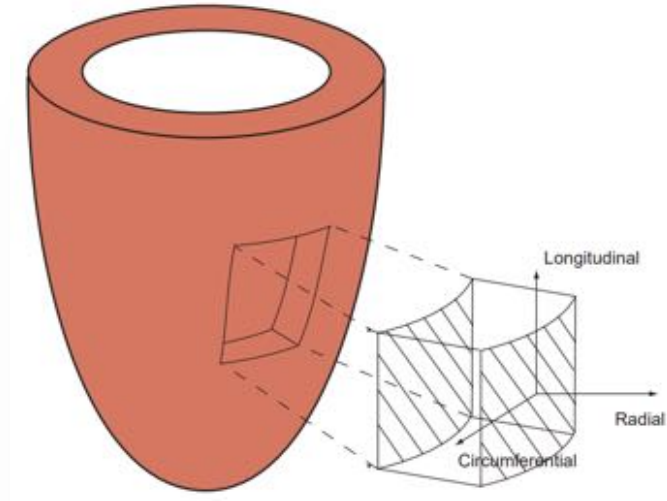
Pumping causes a deformation of the ventricle from systole (left) to diastole (right)



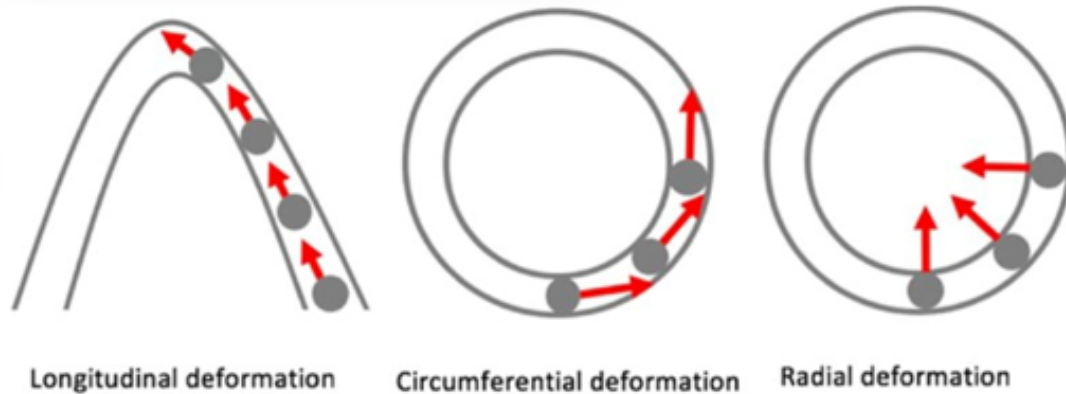
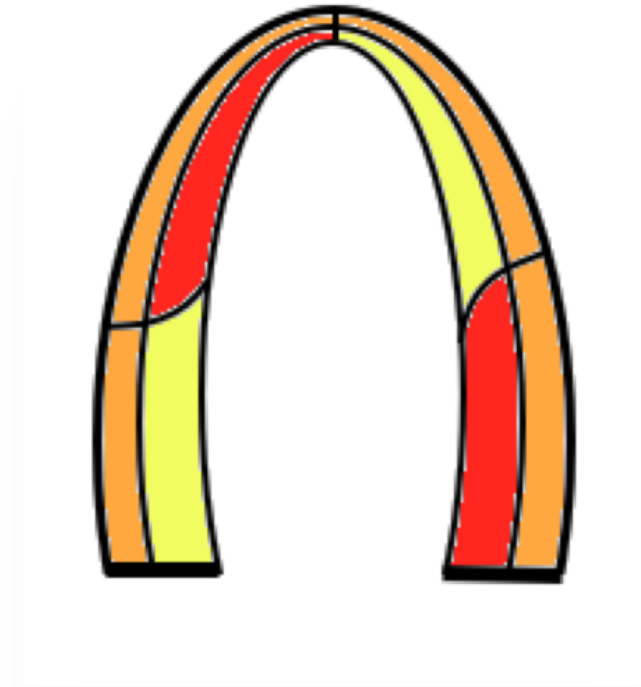
Motion occurs through a combination of electrical activation and pressure gradients

For cardiac imaging, the axes of deformation are redefined in terms of the anatomy of cardiac structure.

Physics and basis of cardiac strain



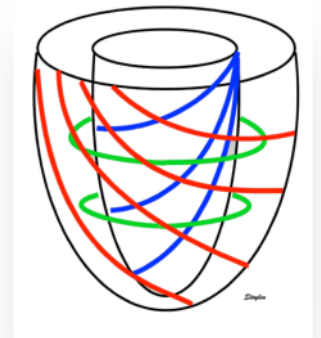
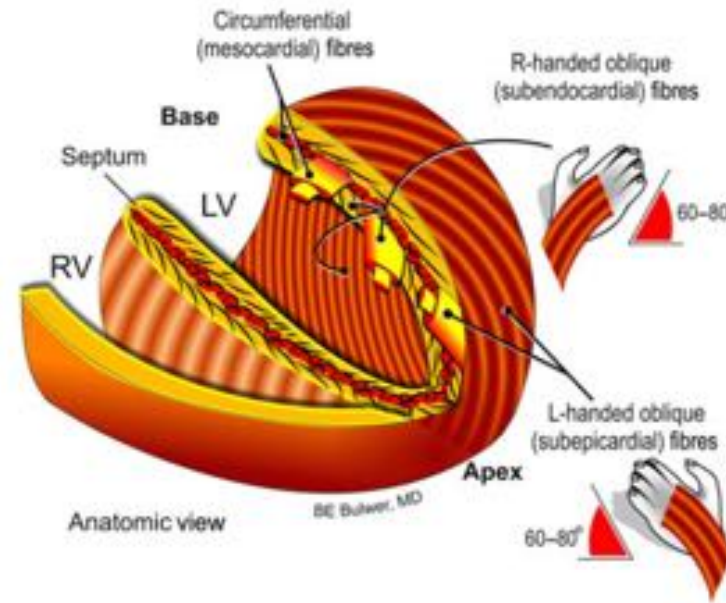
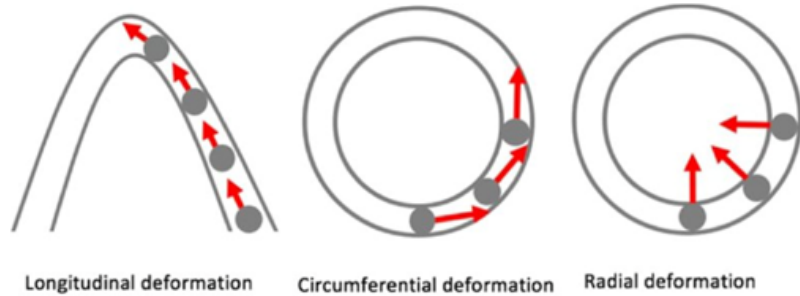
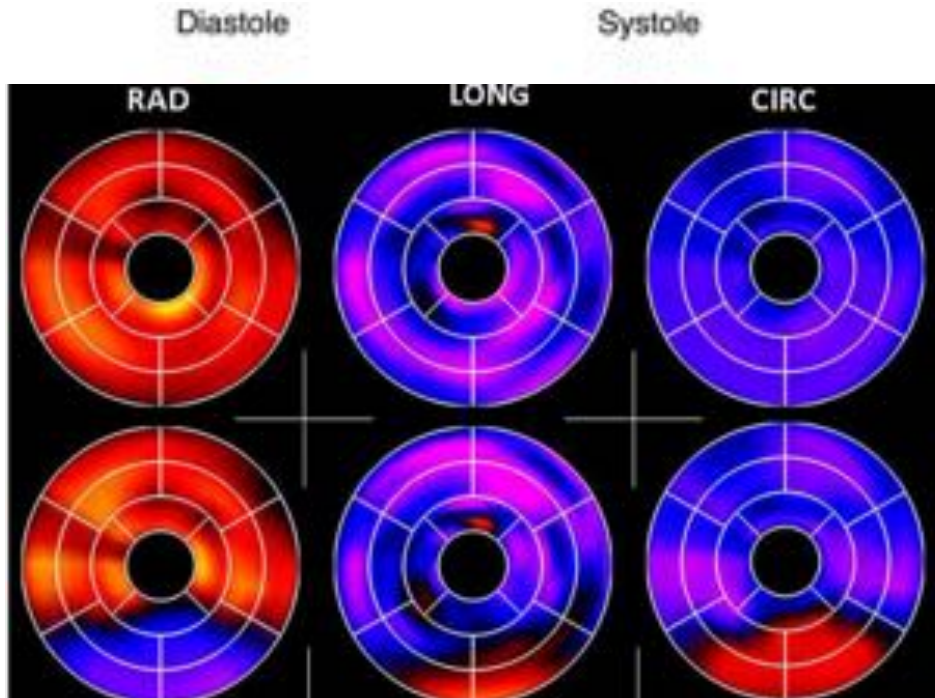
$$\epsilon = \begin{bmatrix} \epsilon_L & \epsilon_{LC} & \epsilon_{LR} \\ \epsilon_{CL} & \epsilon_C & \epsilon_{CR} \\ \epsilon_{RL} & \epsilon_{CL} & \epsilon_R \end{bmatrix}$$



Shear strains do exist in cardiac deformation, but we will focus on the 3 main components

# The composition of the myocardium means the 3 components of cardiac strain are closely related.

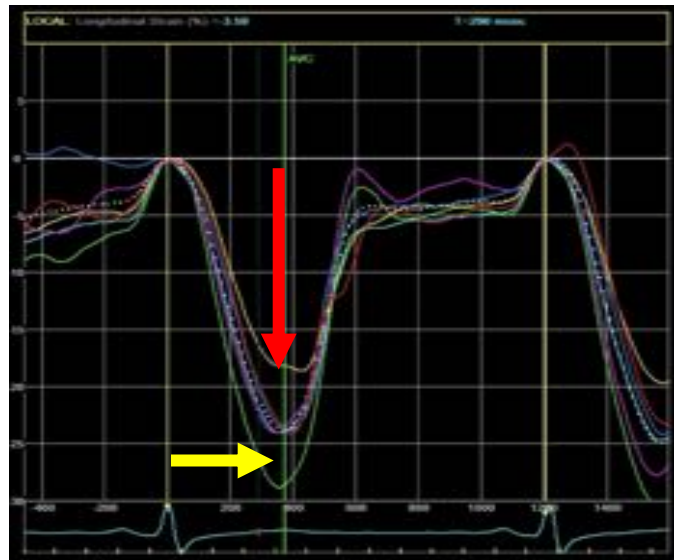
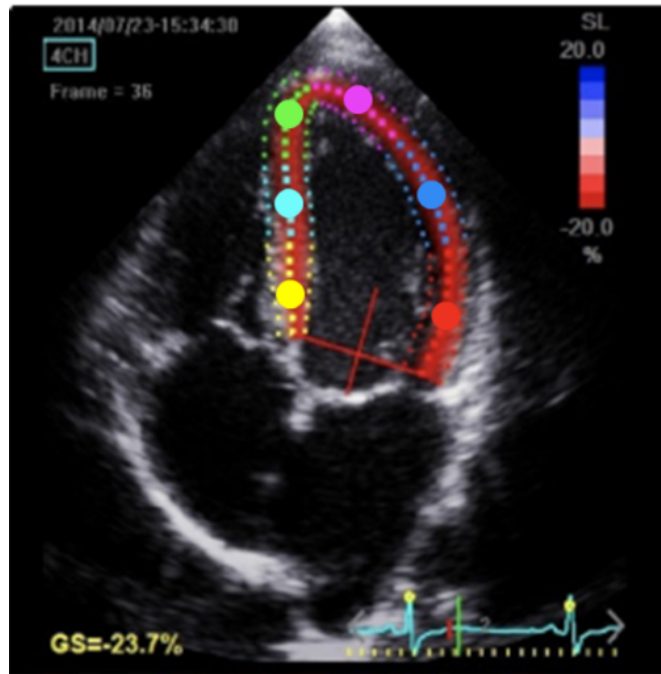
Physics and basis of cardiac strain



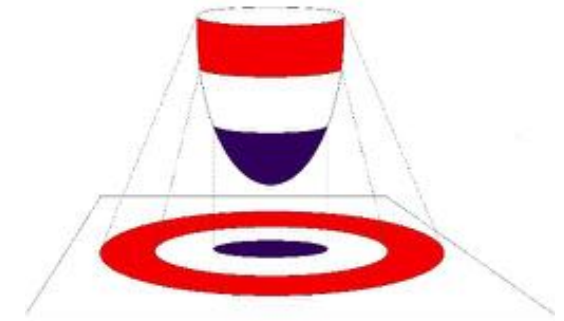
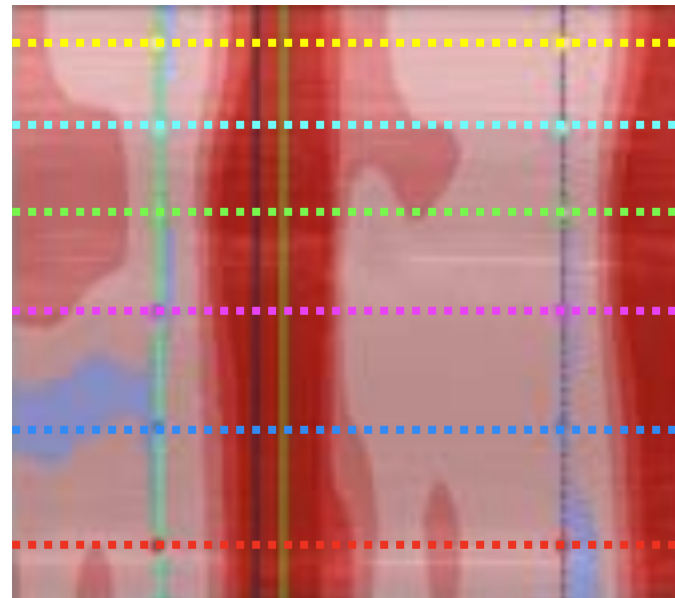
# Visualizing spatial and temporal myocardial strain patterns

Physics and basis of cardiac strain

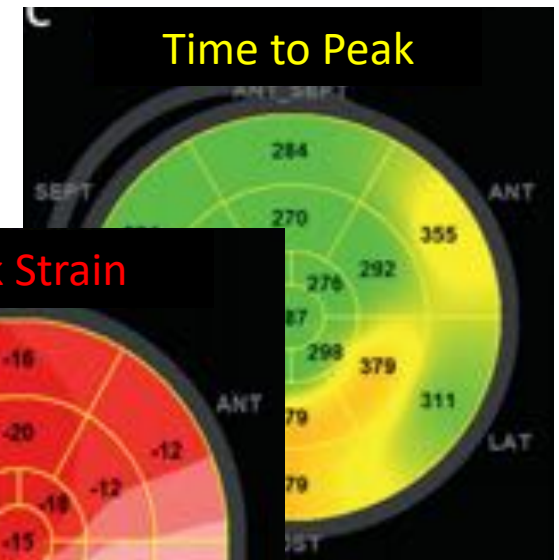
## 2D spatial patterns



## Temporal patterns

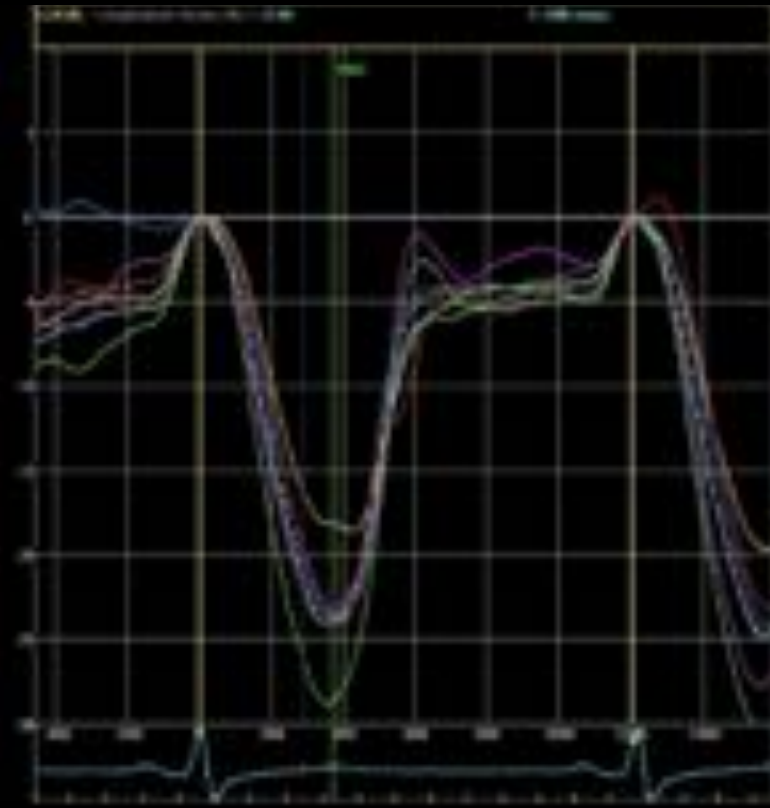
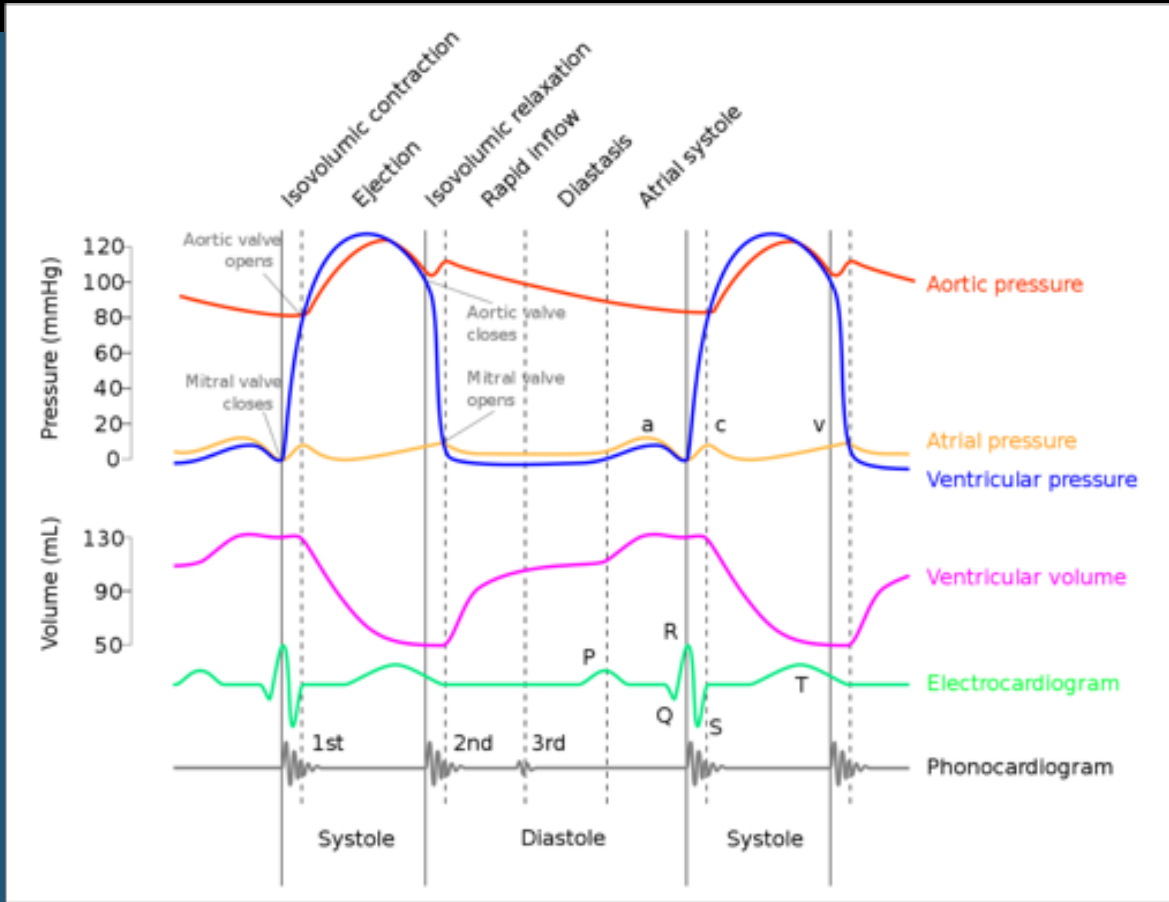


## 3D spatial patterns



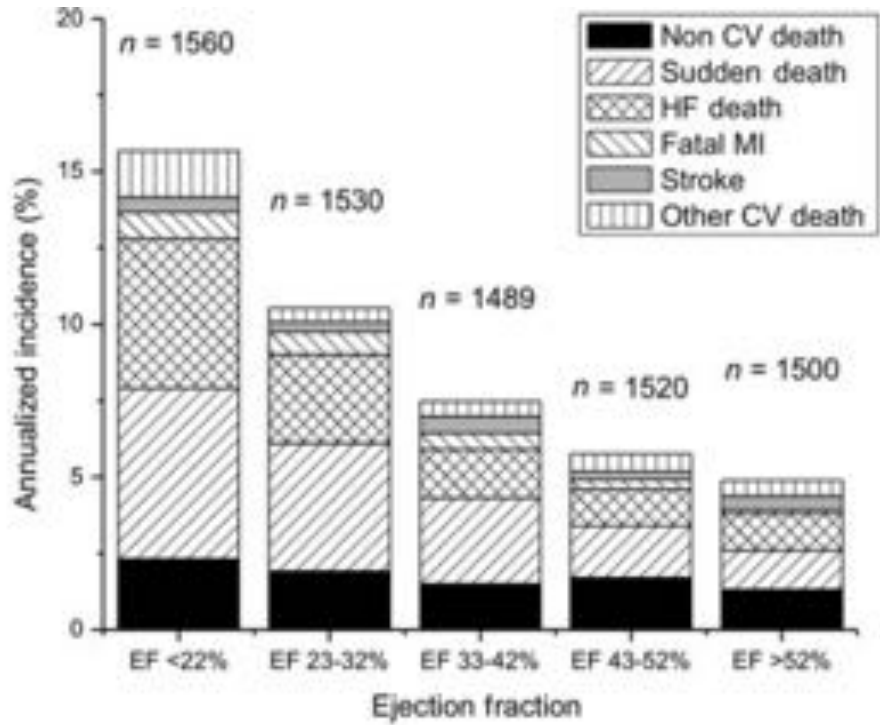
# Why do we measure this? Strain is directly correlated to measurements of volume.

## Physics and basis of cardiac strain

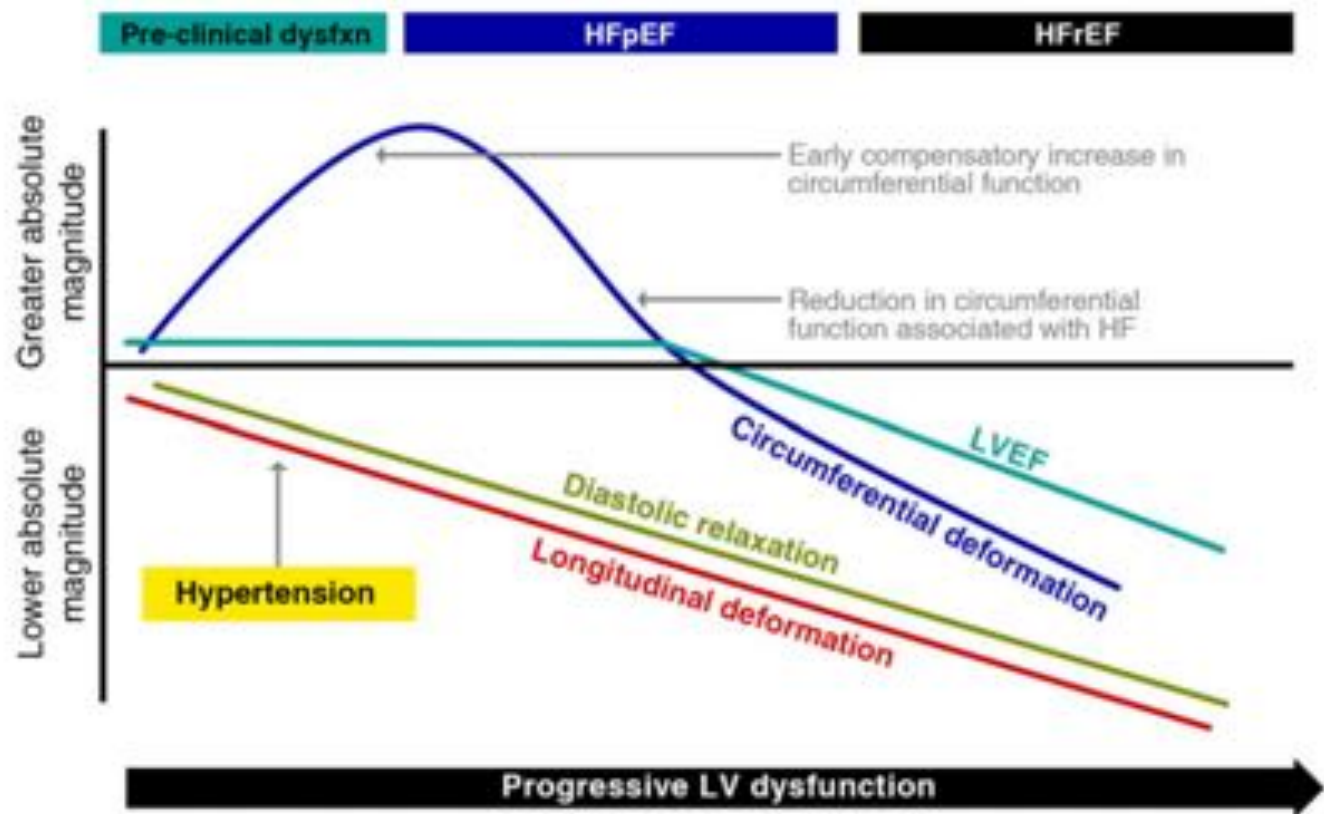


# Deformation metrics add early diagnostic value compared to other metrics.

Physics and basis of cardiac strain

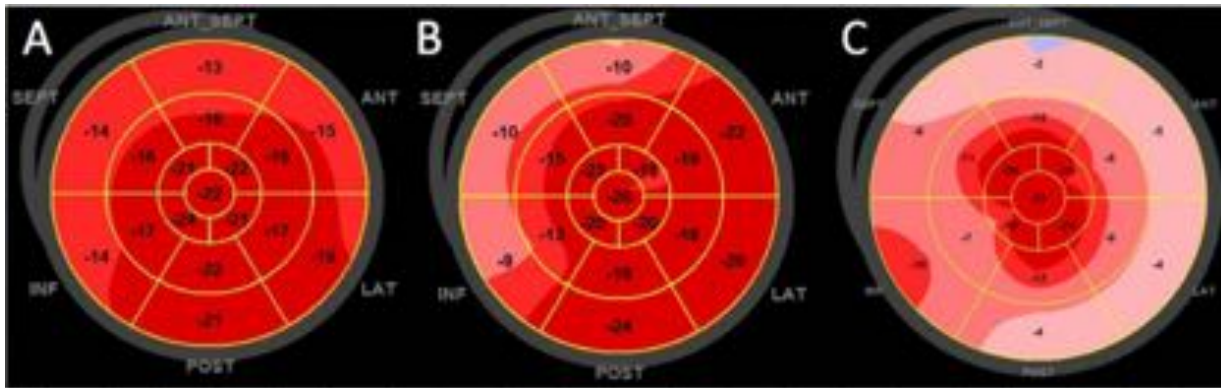
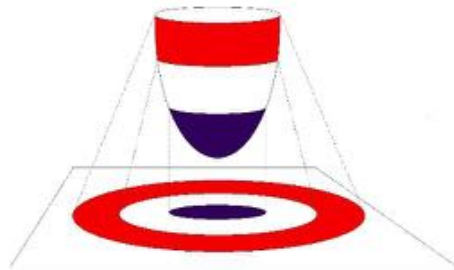


Ejection fraction is a good global measure of heart health

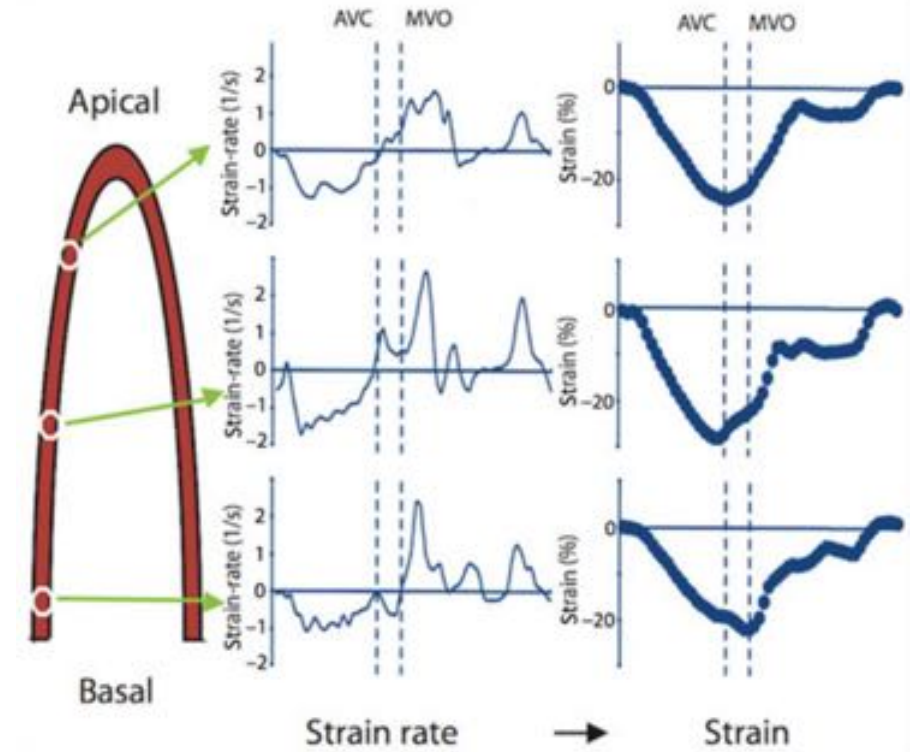


But deformation imaging can provide earlier information to allow for better pre-emptive treatment planning.

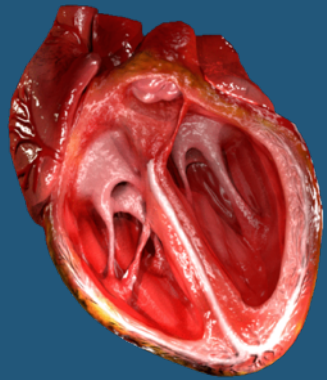
Deformation imaging also provides regional and temporal information, better isolating regions of concern.



Bulls eye plots show the peak deformation in every segment.

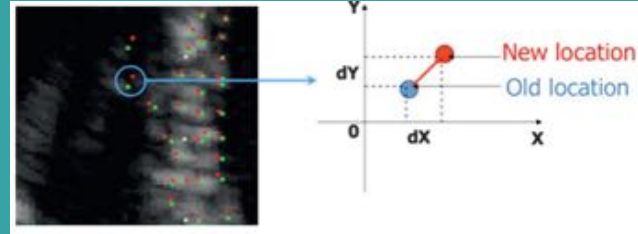


Strain (rate) curves show deformation (rate) across time.



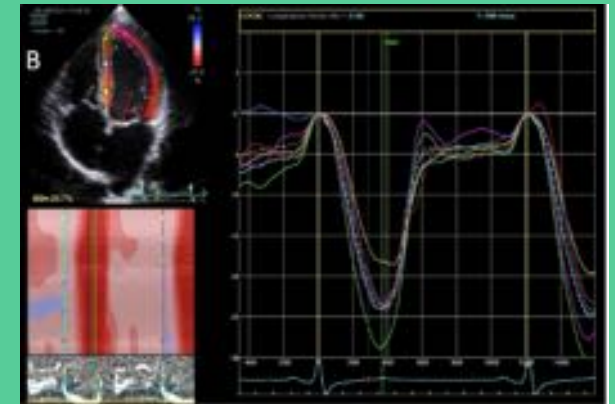
# Physics and basis of cardiac strain

[Wikimedia Foundation]



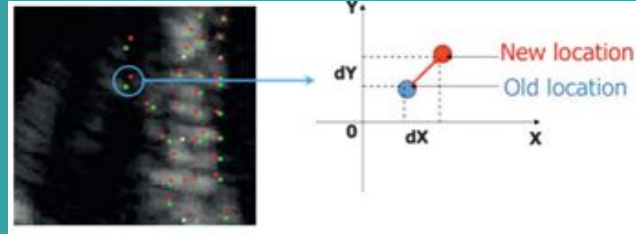
# Methods of strain estimation

[folk.ntnu.no/stoylen]



# Clinical workflow and examples

[Loncaric et al. *Global Cardiology*, 2018]



# Methods of strain estimation

# Strain and strain rate are derived from displacement and velocity

Methods of strain estimation

Temporal derivative

Spatial derivative

Displacement

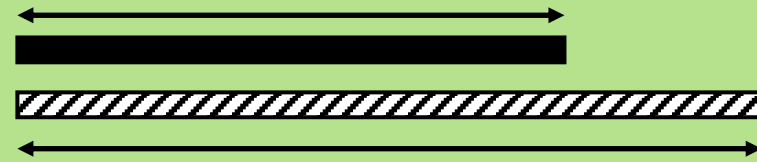
$x_0$        $x_1$



$$d = x_1 - x_0$$

Strain

$L_0$



$$\varepsilon = \frac{L_1 - L_0}{L_0}$$

Velocity



$$V = \dot{d} = \frac{x_1 - x_0}{\Delta t}$$

Strain rate

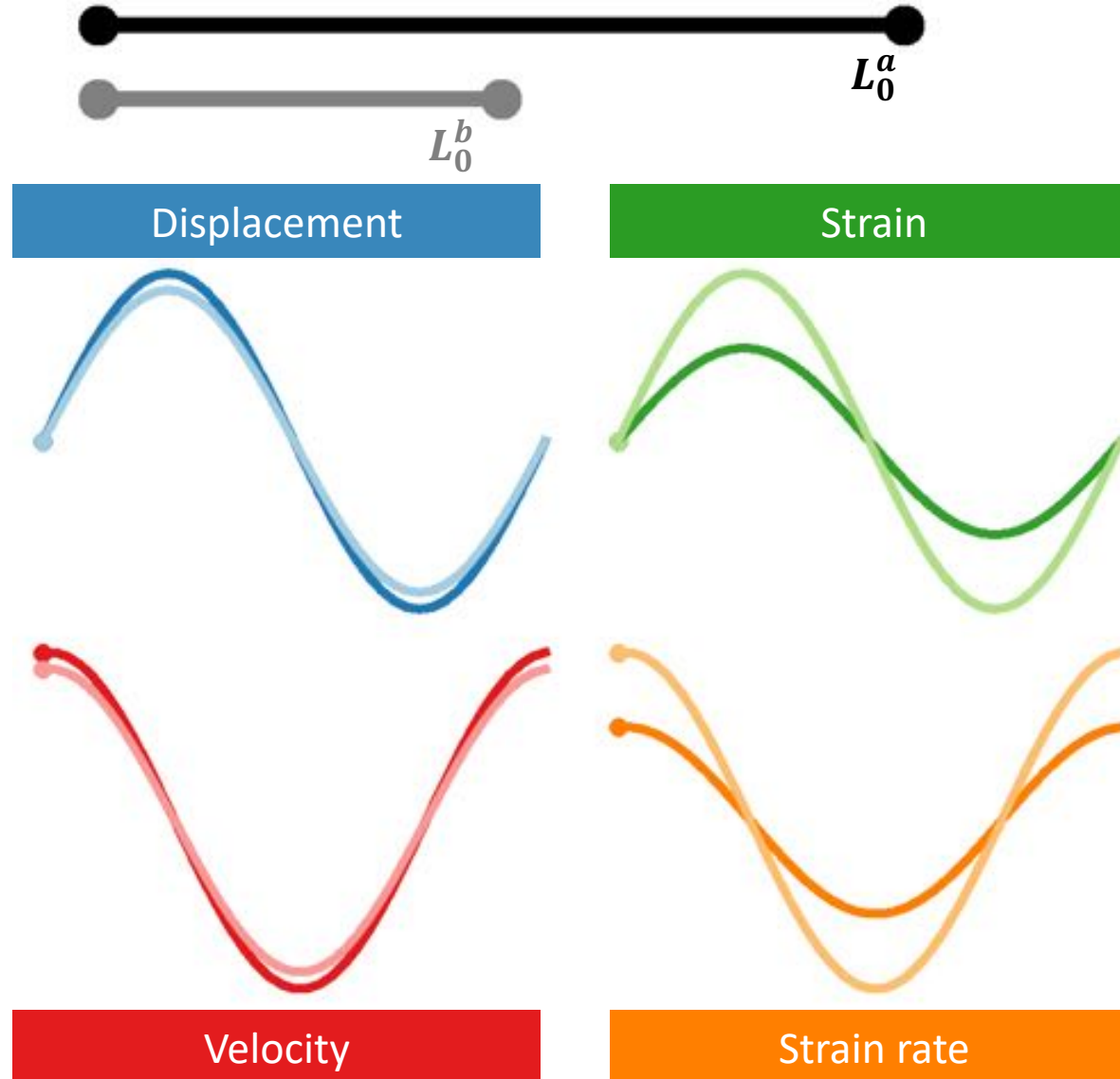
$L_0$



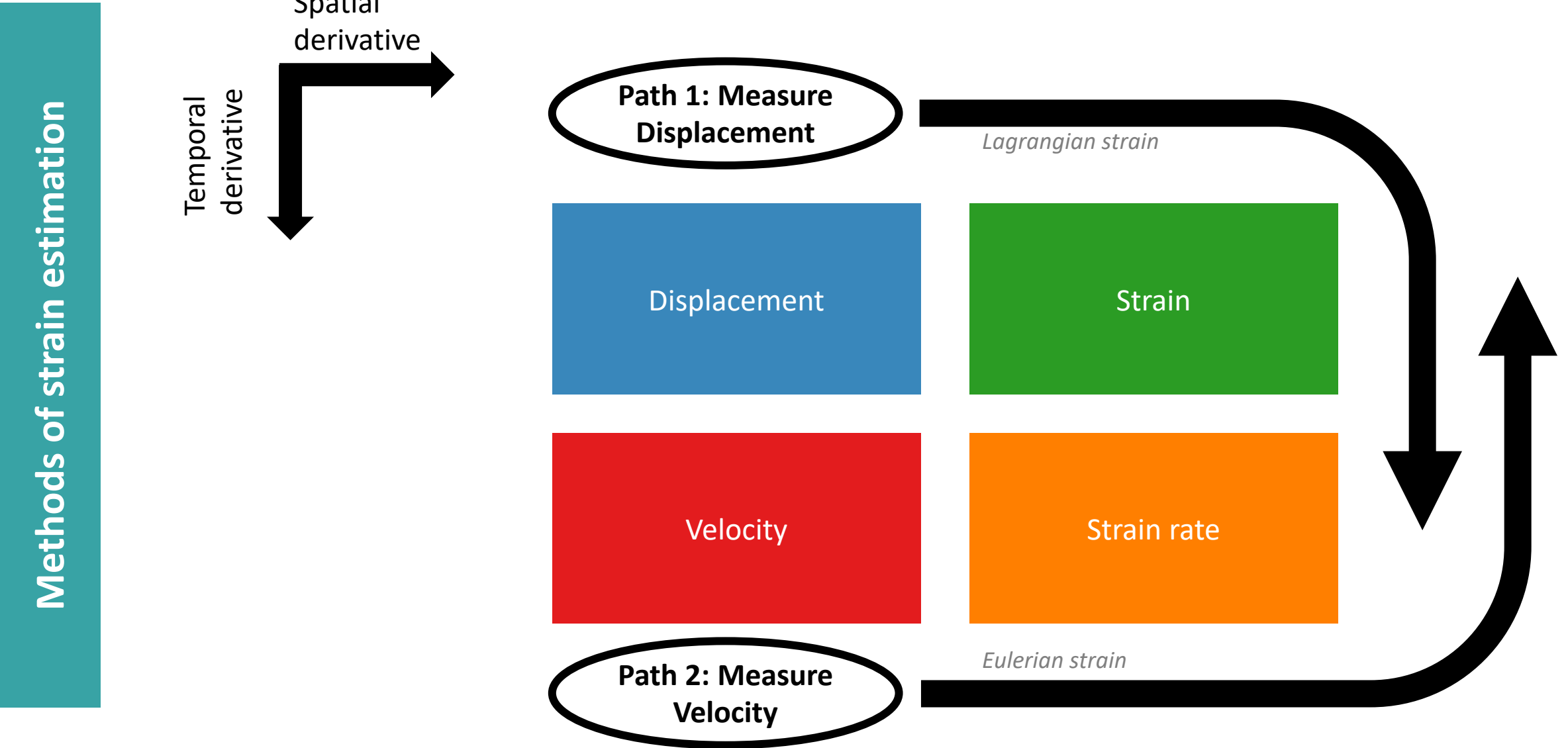
$$\dot{\varepsilon} = \frac{\varepsilon}{\Delta t} = \frac{v_1 - v_0}{L_0}$$

# Strain and strain rate describe relative rather than absolute lengthening and shortening

Methods of strain estimation

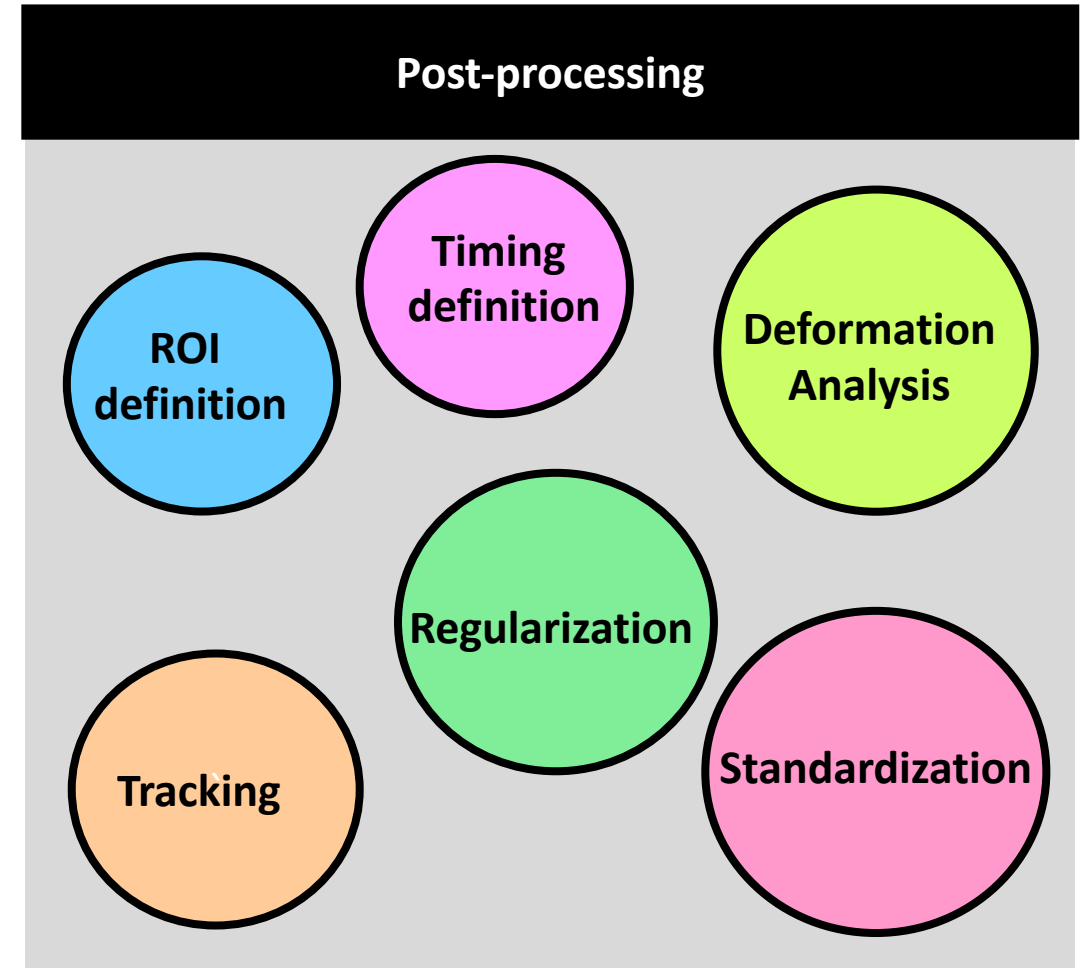
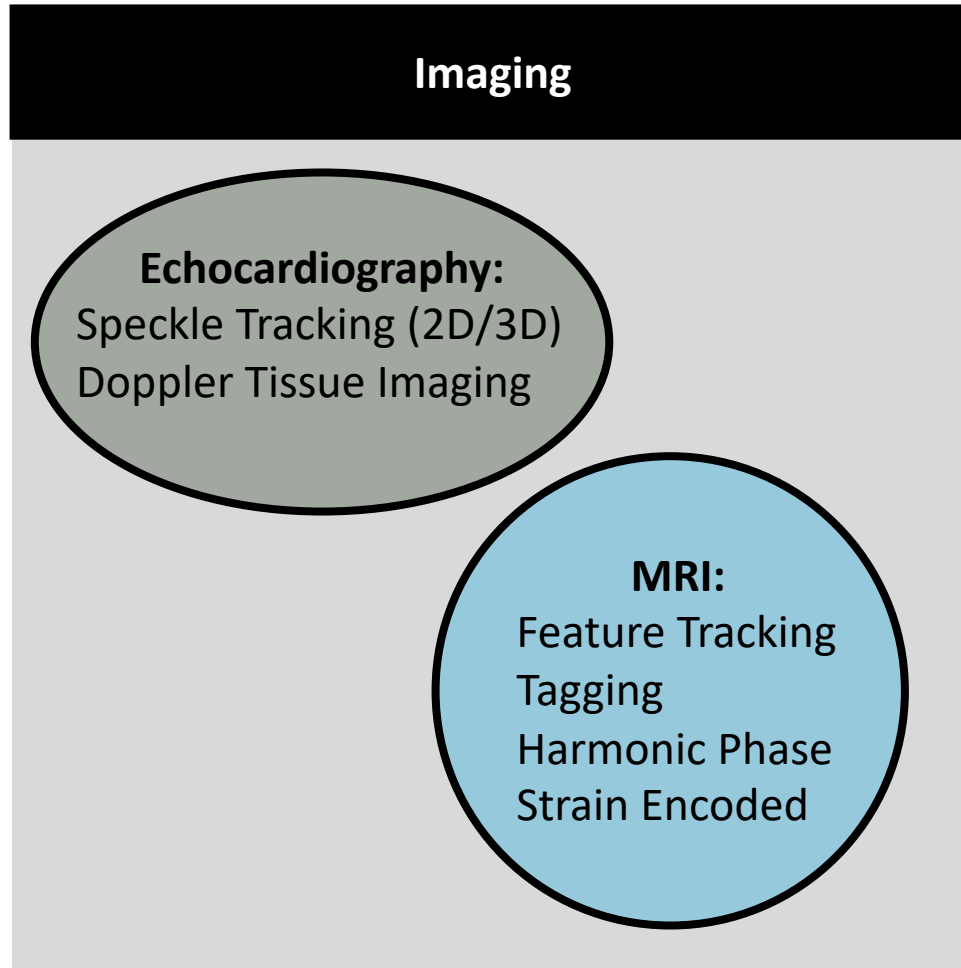


# Strain and strain rate can be derived from displacement or velocity measurements.



# Strain estimation varies by the imaging method and post-processing functions.

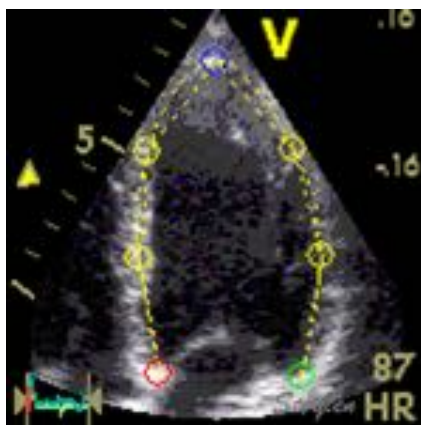
## Methods of strain estimation



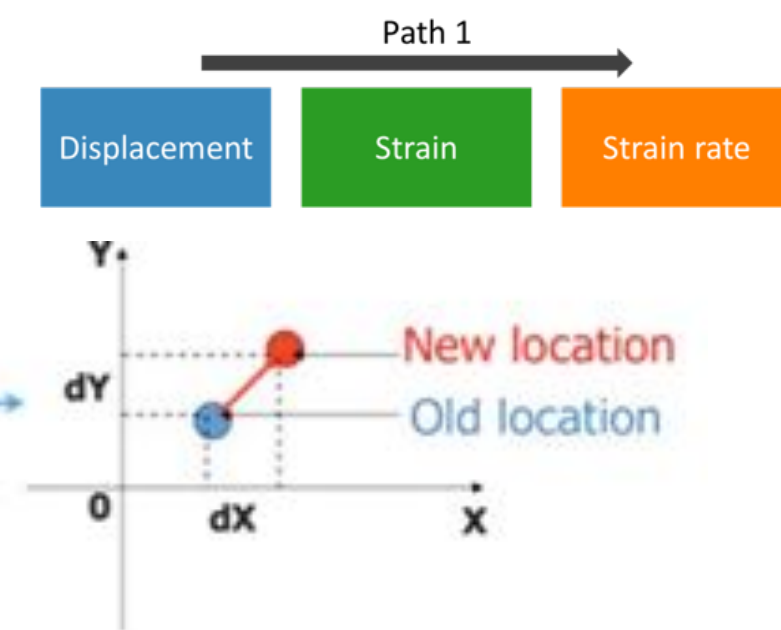
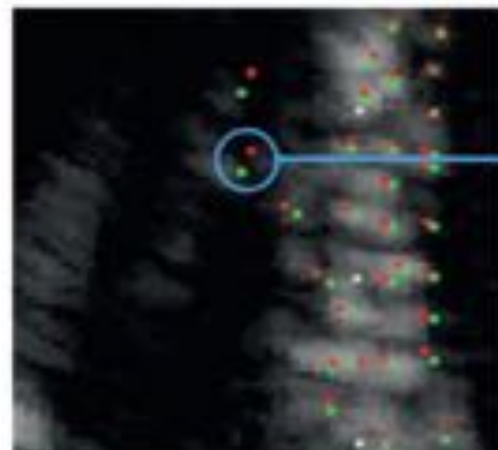
# Displacement measurements in echo: speckle tracking

Speckles are patterns of interference and reflections created by the interactions of sound waves hitting the tissue.

For a small enough  $\Delta t$  the reflection patterns will be constant



The result is a region of interest tracked through the cardiac cycle



## Speckle tracking:

1. Define kernel  $K_t$  from speckles in first frame
2. Advance to next frame
3. Find position of  $K_t$  in the new frame  
*The change in position describes the deformation.*
4. Update the kernel for the new frame ( $K_{t+1}$ ) and repeat 2-4



# Velocity measurements in echo: tissue Doppler imaging

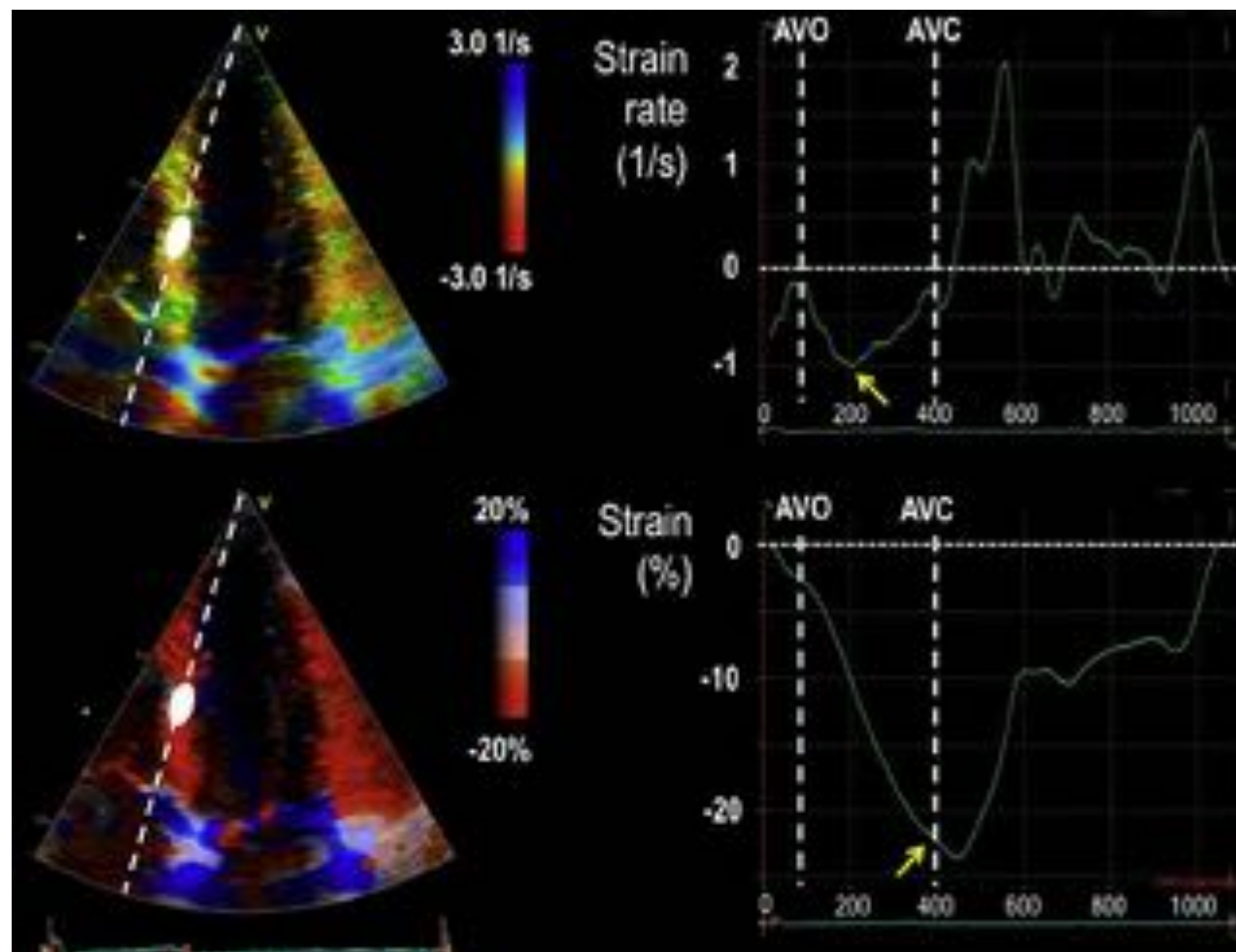
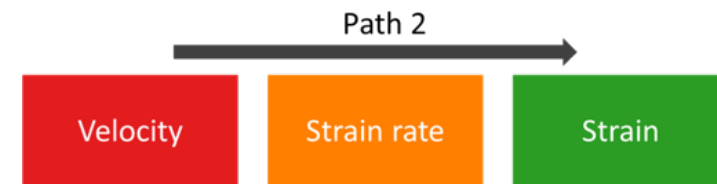
**The Doppler effect:** sound waves will change in frequency due to the relative difference in velocity between an object emitting the waves (the heart) and an observer (the probe)

We can use the Doppler effect to record velocities for every point in the image

$$V = \frac{c * (F_R - F_T)}{2 * F_T * \cos(\theta)}$$

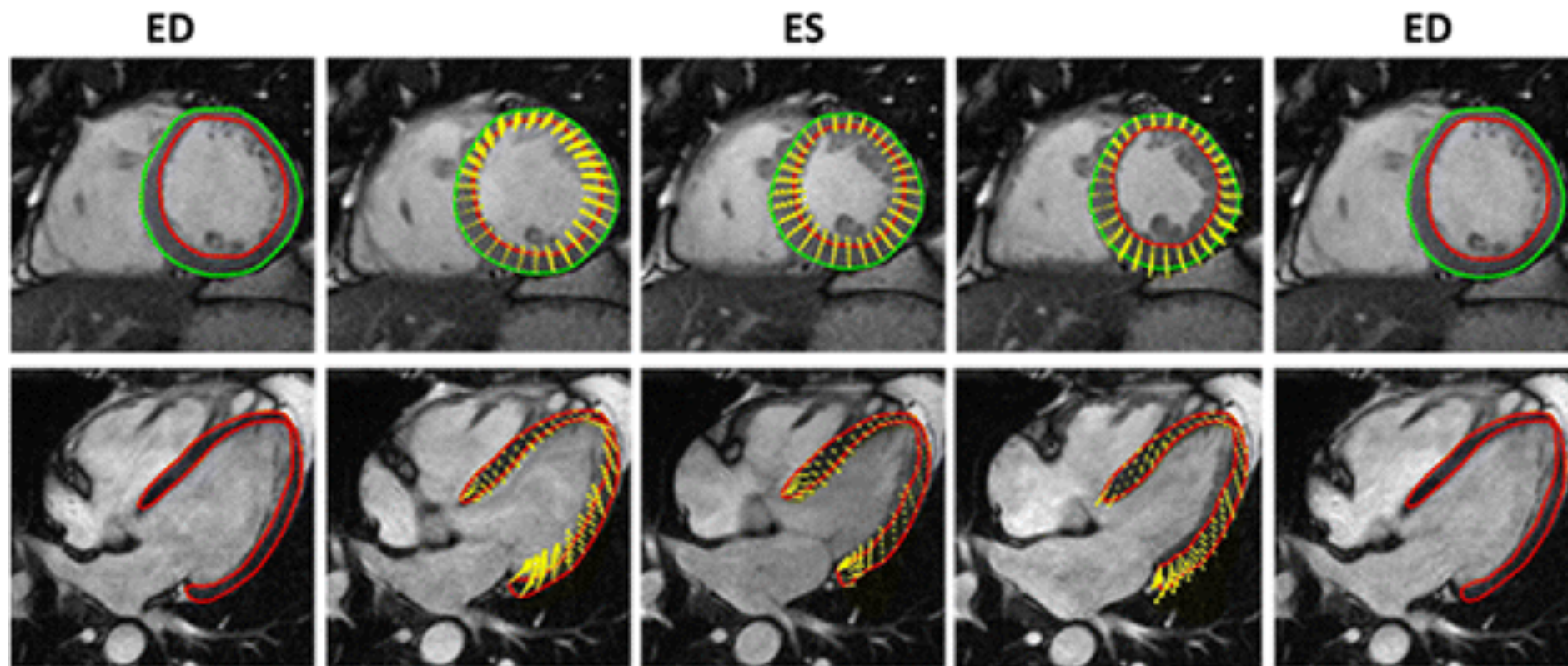
*In TDI, calculated using autocorrelation*

Velocities are only measured in the direction parallel to the beam ( $\cos(\theta)$ )



# Feature tracking can also be applied to cardiac magnetic resonance imaging

## Methods of strain estimation



There are no consistent speckles, the endo/epicardial borders are tracked instead.

These borders are much easier to see (and track) in CMR.

Path 1



Displacement

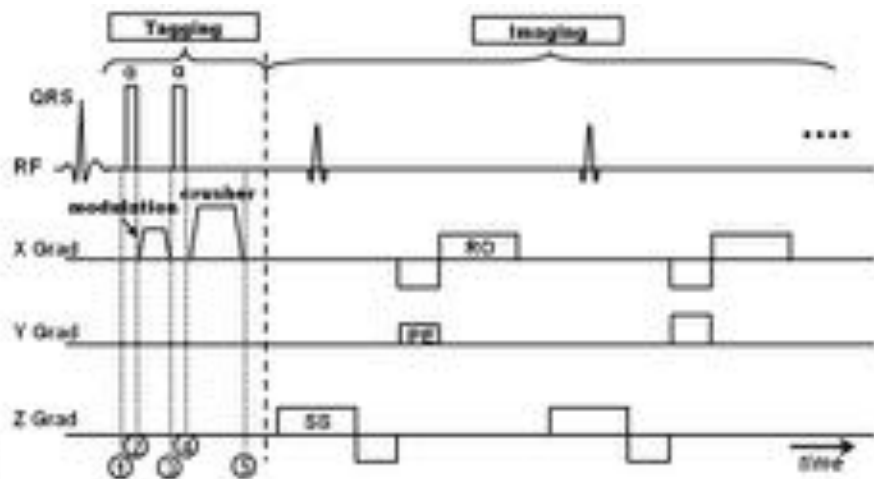
Strain

Strain rate

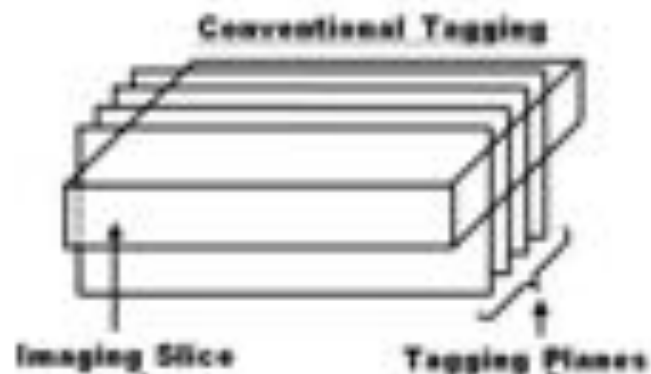
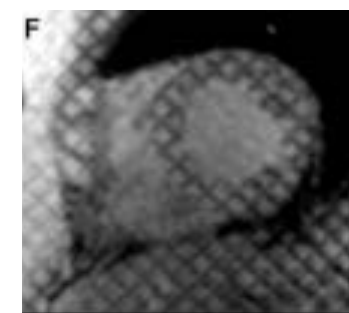
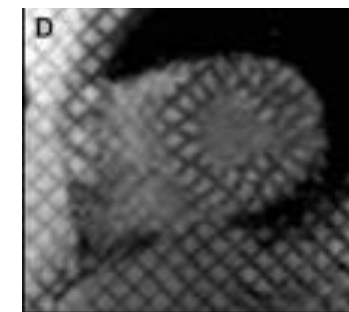
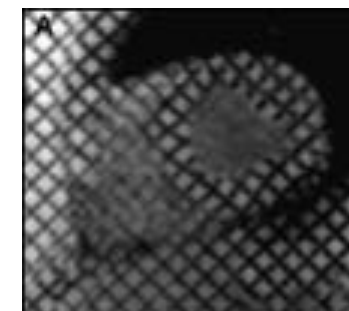
[Morais, *J of Cardio Magn Resonance*, 2010]

# Tagging can be used to add a distinctive pattern to the tissue to allow for easier tracking

## Methods of strain estimation



Tagging pulses are added to polarize the particles in the myocardium before the imaging pulses.



Tagging fades over time



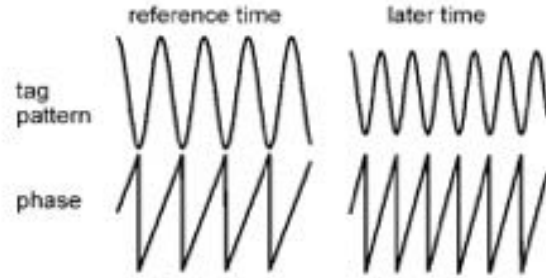
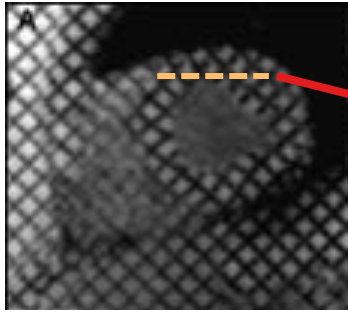
Displacement

Strain

Strain rate

# Harmonic phase (HARP) imaging is used to directly decode the velocity from a tagged image.

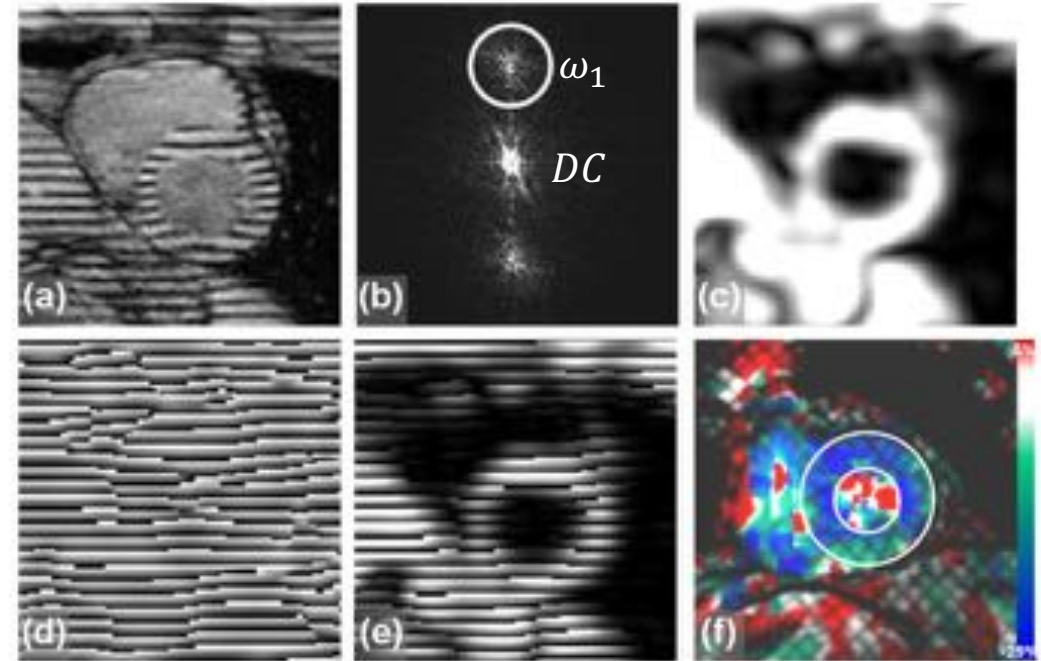
## Methods of strain estimation



At the *later time*, the signal **reduces** in amplitude (fading) and **increases** in frequency (tissue compression). The frequency change is reflected in the phase

$$I(p, t) = \mathbf{D}(p, t)e^{j\phi(p, t)}$$

- Tagged short-axis MR image ( $I$ )
- K-space (frequency space) of tagged image
- Magnitude image ( $D_{\omega_1}$ )
- Phase image ( $\phi_{\omega_1}$ )
- Magnitude image \* phase image
- Tissue velocities calculated from change in phase



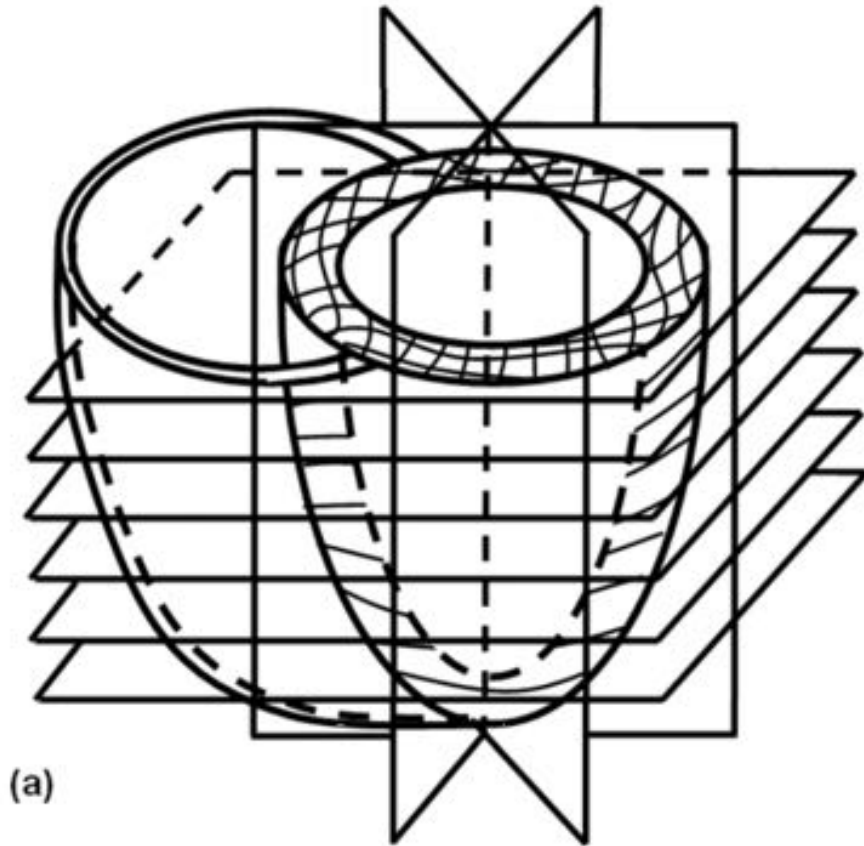
Path 2

Velocity

Strain rate

Strain

# Tagging can also be extended to 3D.

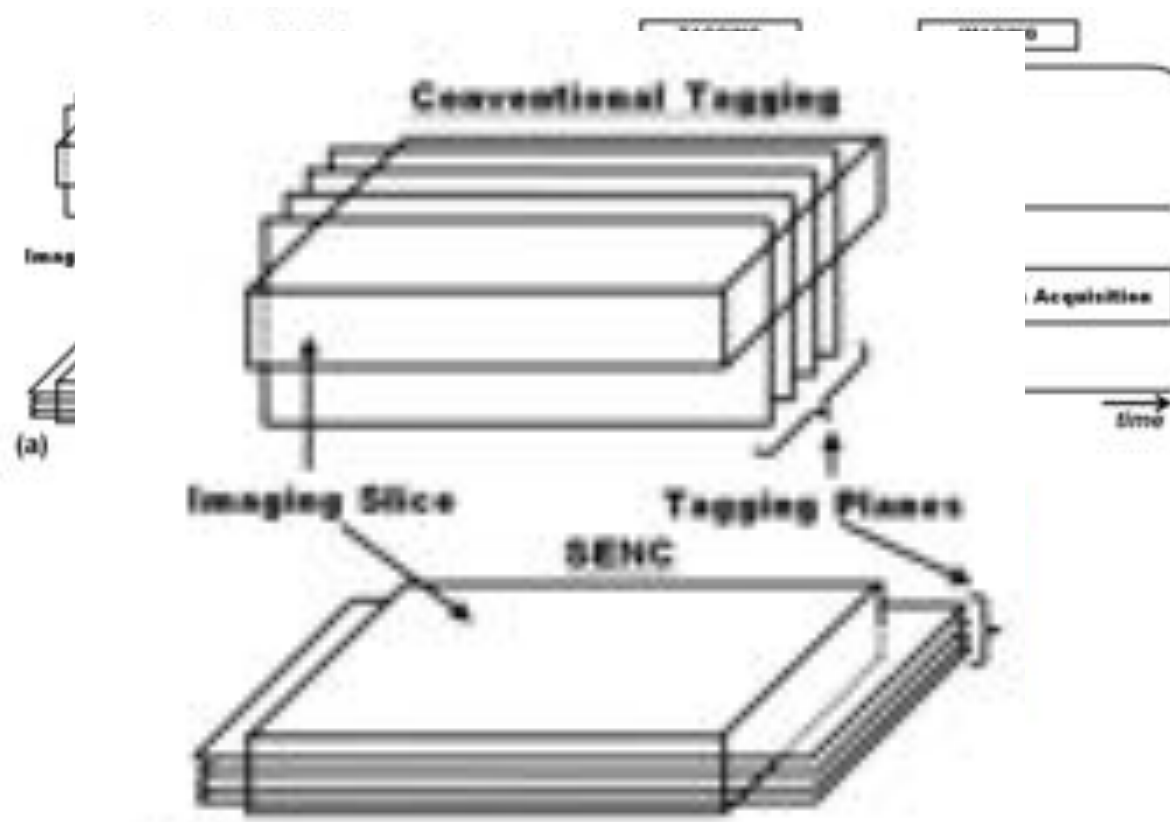


Long and short axis images are collected and combined.

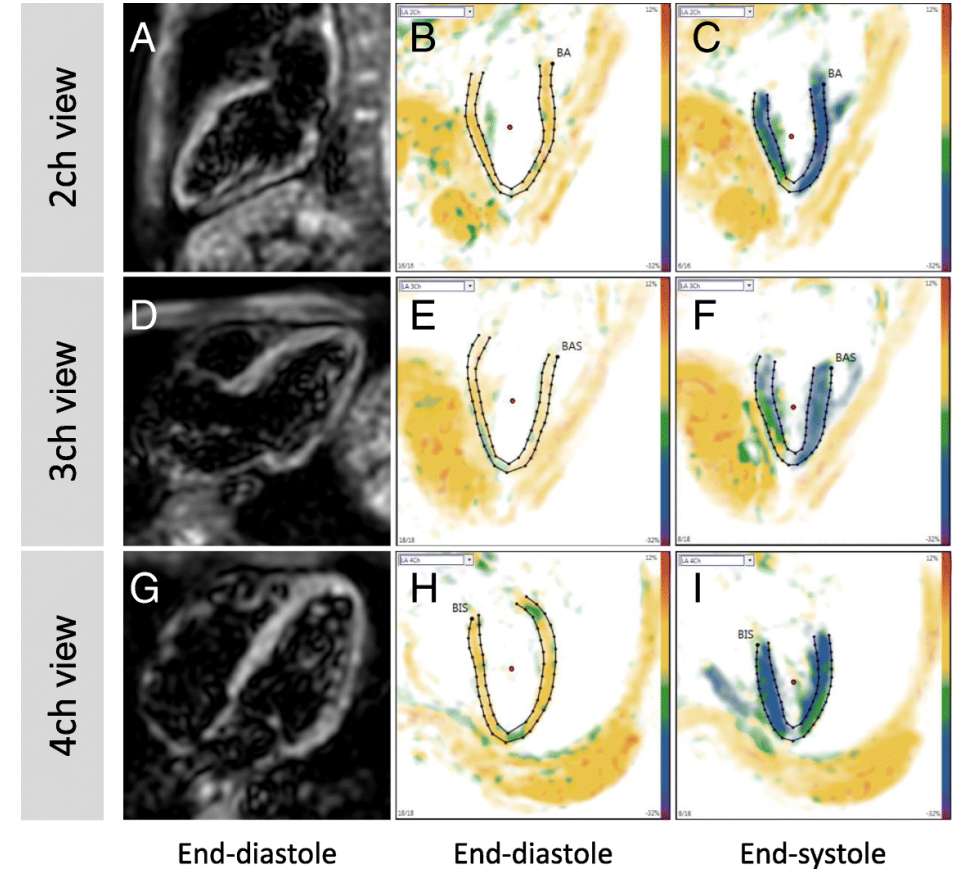
Tagging is reverse for each direction of imaging.

# Finally, strain-encoded images are acquired by tagging in the through-plane direction

## Methods of strain estimation



Setting the demodulation **tuning frequency** low (LT) or high (HT) will correspond to capturing regions of low or high motion.



Velocity

Strain rate

Strain

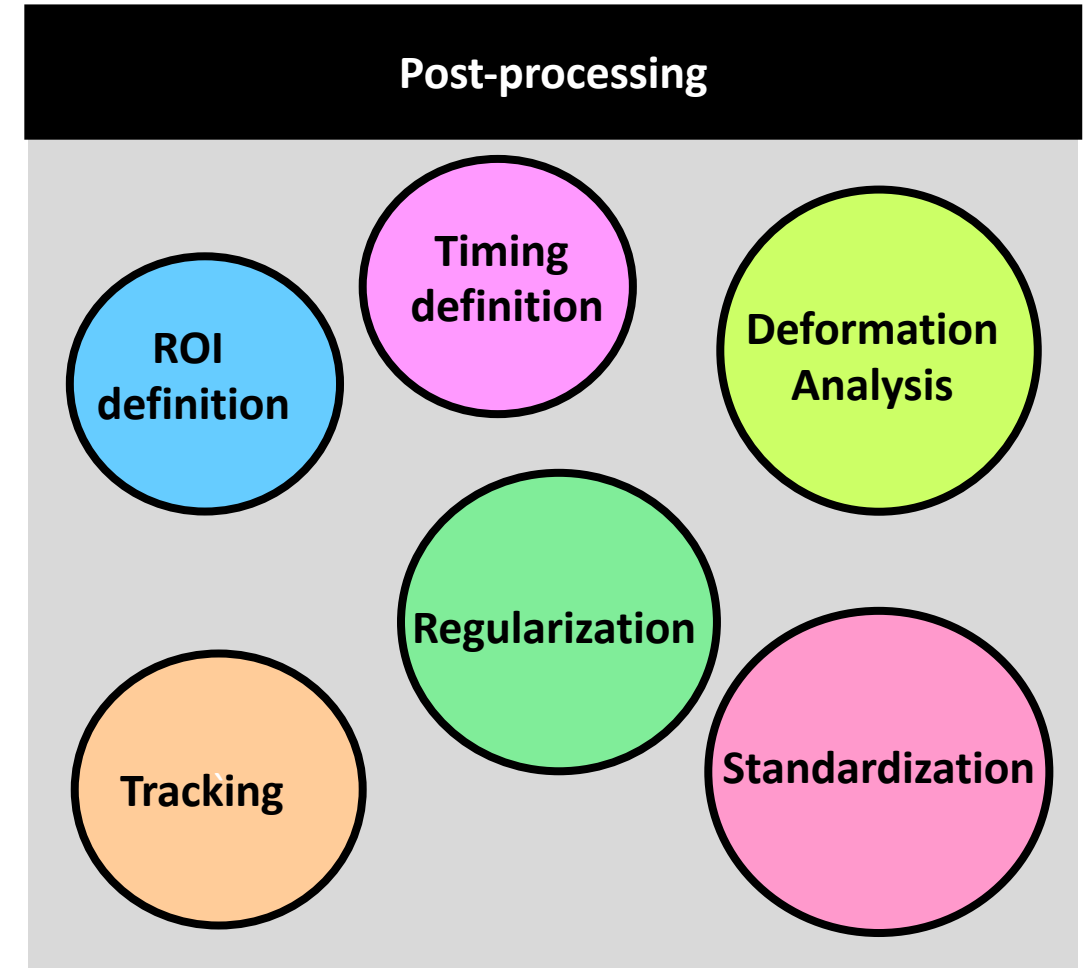
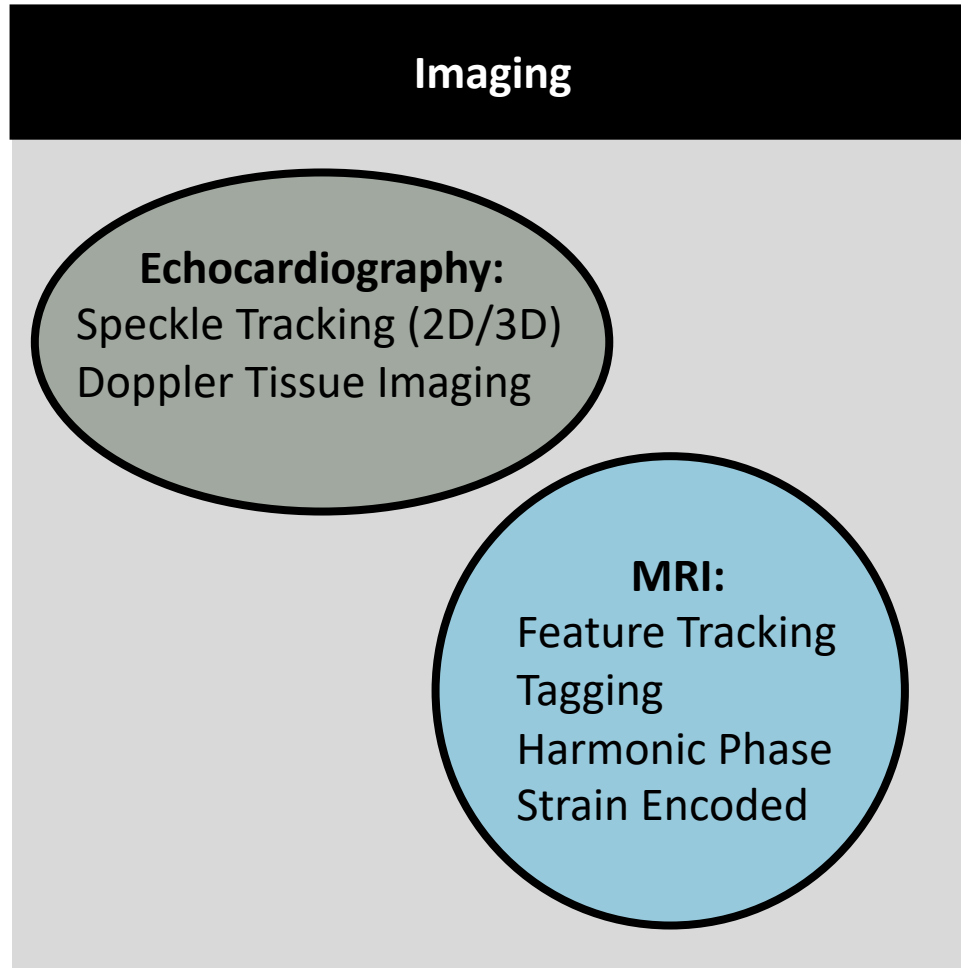
# Advantages and disadvantages of different imaging methods.

## Methods of strain estimation

	Method	Pros	Cons
Echo	Tissue Doppler	<ul style="list-style-type: none"> <li>- High temporal resolution</li> <li>- Live visualization</li> <li>- Good regional assessment</li> </ul>	<ul style="list-style-type: none"> <li>- Specialized acquisition</li> <li>- Angle dependent</li> <li>- Noisy</li> <li>- More difficult global assessment</li> </ul>
	2D Speckle Tracking	<ul style="list-style-type: none"> <li>- No specialized acquisition</li> <li>- Better temporal resolution than MRI</li> <li>- Semi/fully automated tracking</li> <li>- Fast processing</li> </ul>	<ul style="list-style-type: none"> <li>- Inter-vendor differences</li> <li>- Dependent on image quality</li> <li>- Out of plane motion (for all 2D methods)</li> </ul>
	3D Speckle Tracking	<ul style="list-style-type: none"> <li>- Only single acquisition needed</li> <li>- No out of plane motion</li> </ul>	<ul style="list-style-type: none"> <li>- Low spatial and temporal resolution</li> <li>- Limited standardization/clinical impact</li> </ul>
MRI	Feature Tracking	<ul style="list-style-type: none"> <li>- No specialized acquisition</li> </ul>	<ul style="list-style-type: none"> <li>- Lower temporal resolution than echo</li> <li>- Variability in regional measurements</li> <li>- Inter-vendor differences</li> </ul>
	Tagging & Harmonic Phase	<ul style="list-style-type: none"> <li>- More accurate regional strain measurements</li> </ul>	<ul style="list-style-type: none"> <li>- Specialized acquisition</li> <li>- Heavy post-processing</li> <li>- Fading tags</li> </ul>
	Strain Encoded	<ul style="list-style-type: none"> <li>- Good global and regional strain measurements</li> </ul>	<ul style="list-style-type: none"> <li>- Low signal-to-noise ratio</li> <li>- No standardization</li> <li>- Specialized acquisition</li> </ul>

# Improvements to imaging methods are slower, most advancements are happening in the post-processing.

## Methods of strain estimation



# Deep learning can be used to locate the ROI automatically, accurately, and quickly.

ROI definition

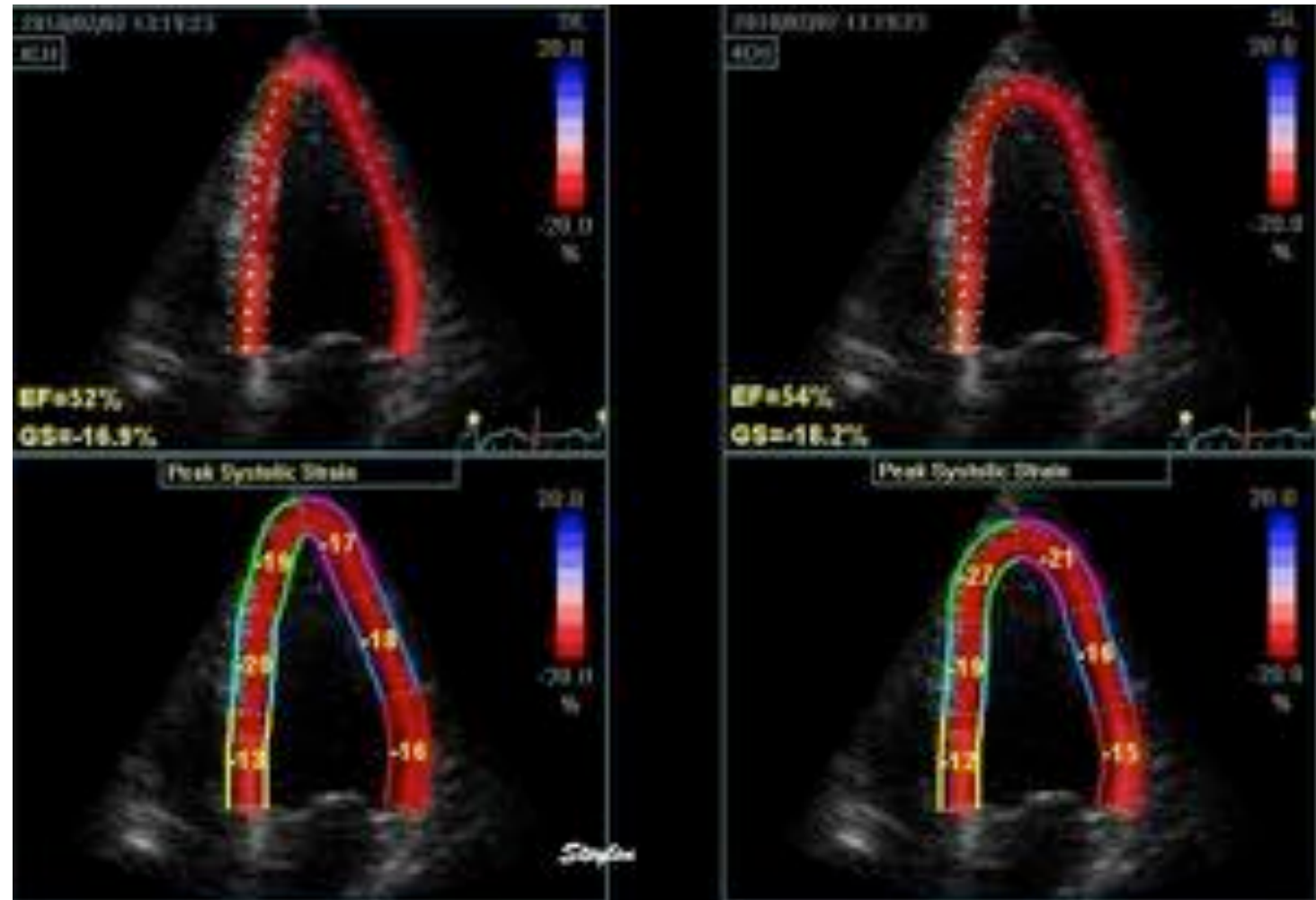
Tracking

Analysis

Standardization

Methods of strain estimation

The ROI definition significantly affects strain calculations



# Deep learning can be used to locate the ROI using segmentation.

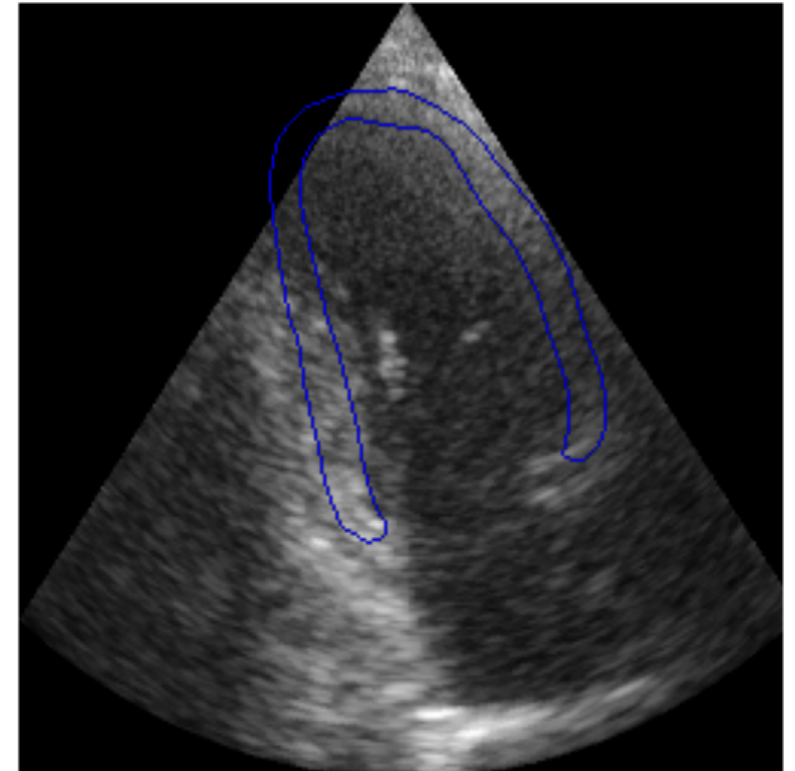
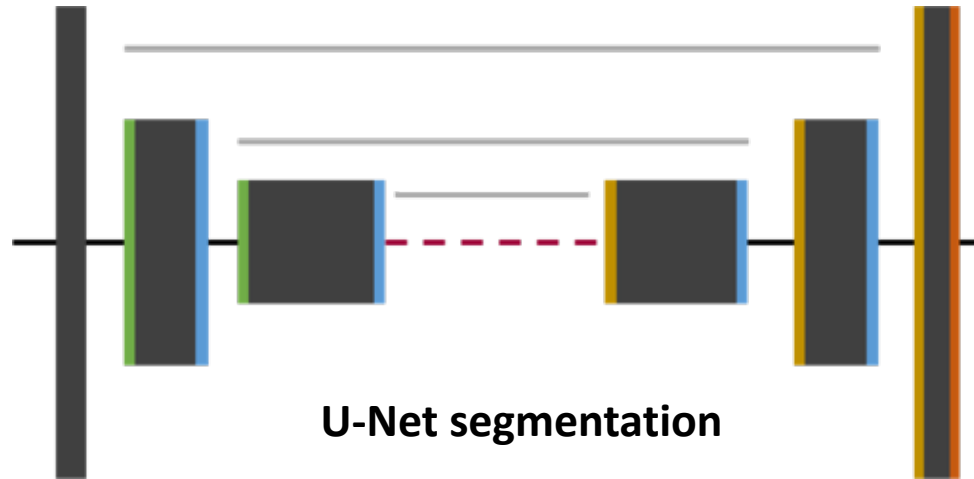
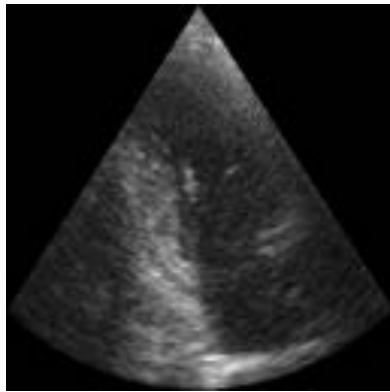
ROI definition

Tracking

Analysis

Standardization

Methods of strain estimation



Faster performance  
Reduced variability  
Increased repeatability

# Deep learning can be used to speed up optical flow tracking.

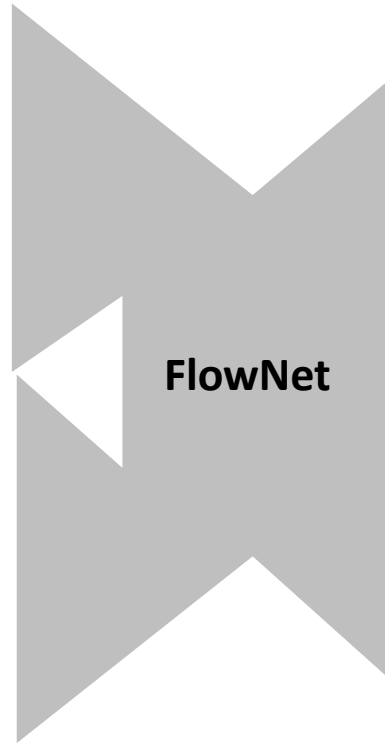
ROI definition

Tracking

Analysis

Standardization

Methods of strain estimation



Color encodes motion direction

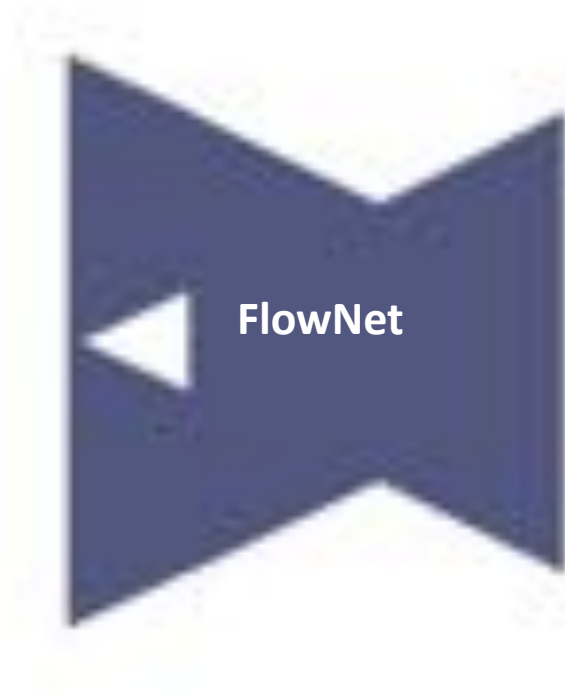
# Deep learning can be used to speed up optical flow tracking.

ROI definition

Tracking

Analysis

Standardization



Methods of strain estimation

Faster performance

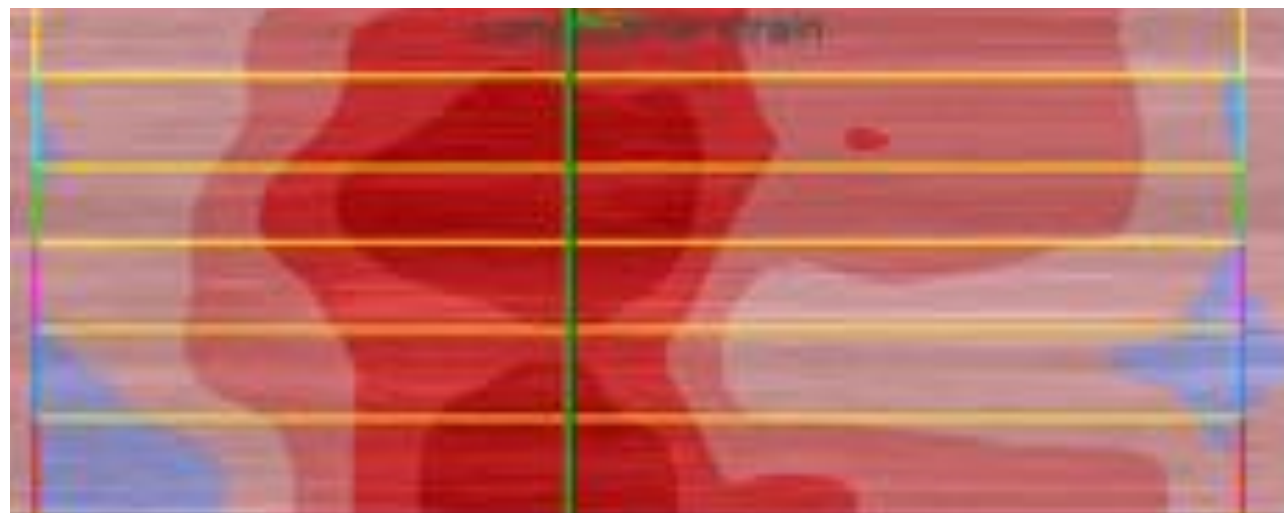
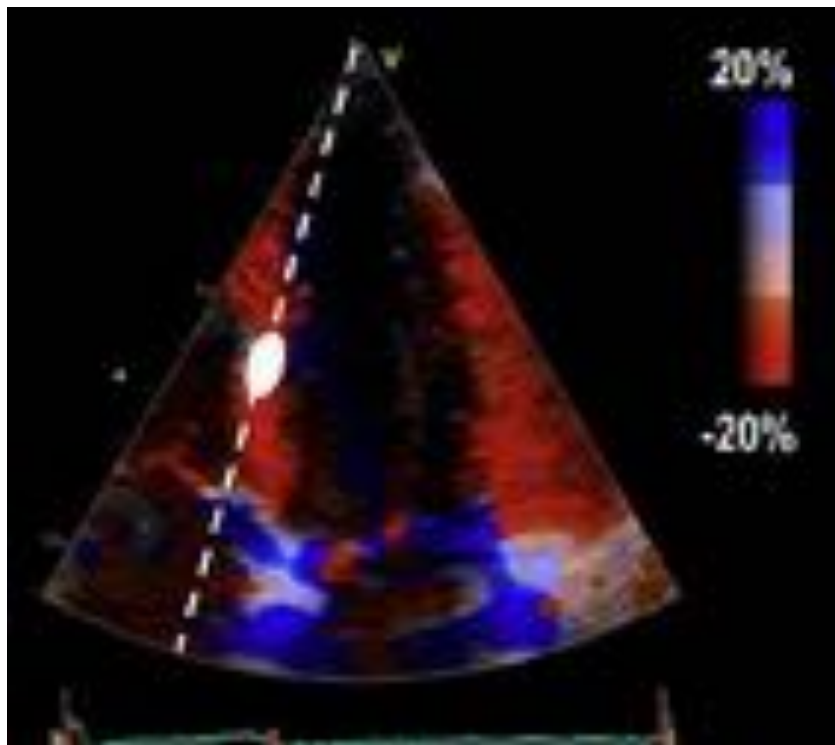
# Advanced shape analysis can be used to better quantify variations in deformation.

ROI definition

Tracking

Analysis

Standardization



Strain gives a pixel-wise map of displacement across the myocardium

Methods of strain estimation

# Advanced shape analysis can be used to better quantify variations in deformation.

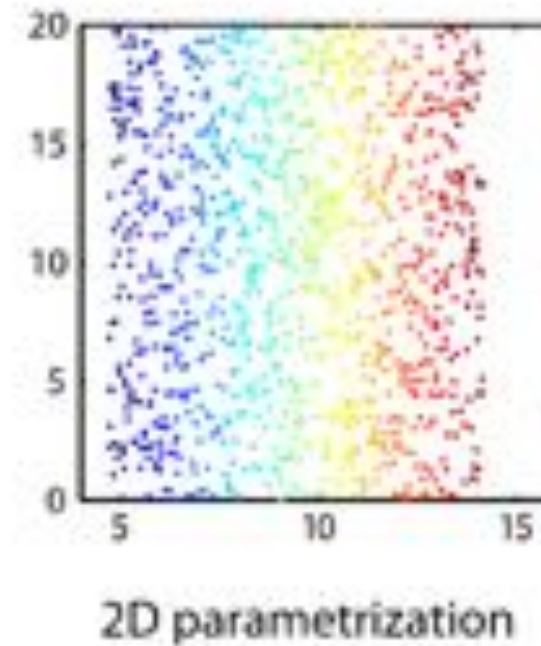
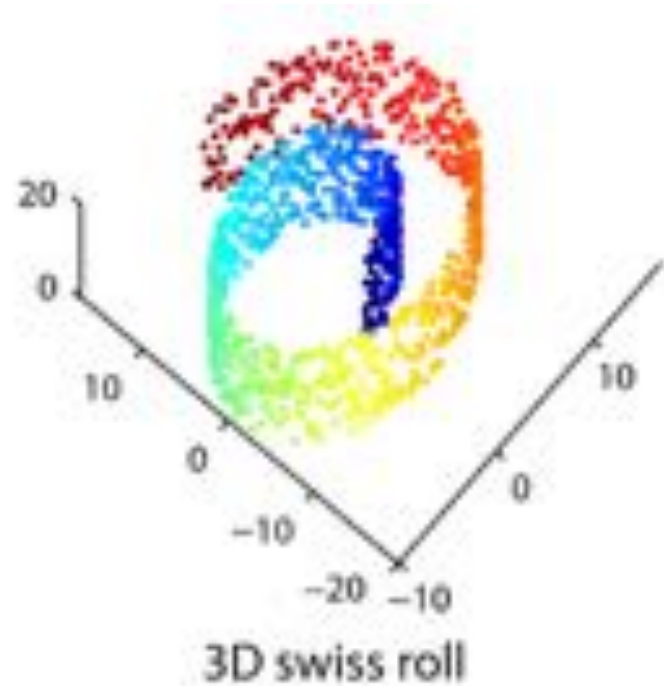
ROI definition

Tracking

Analysis

Standardization

Methods of strain estimation



Motion is strongly correlated, and the dimensionality can be reduced to a manifold.

# Advanced shape analysis can be used to better quantify variations in deformation.

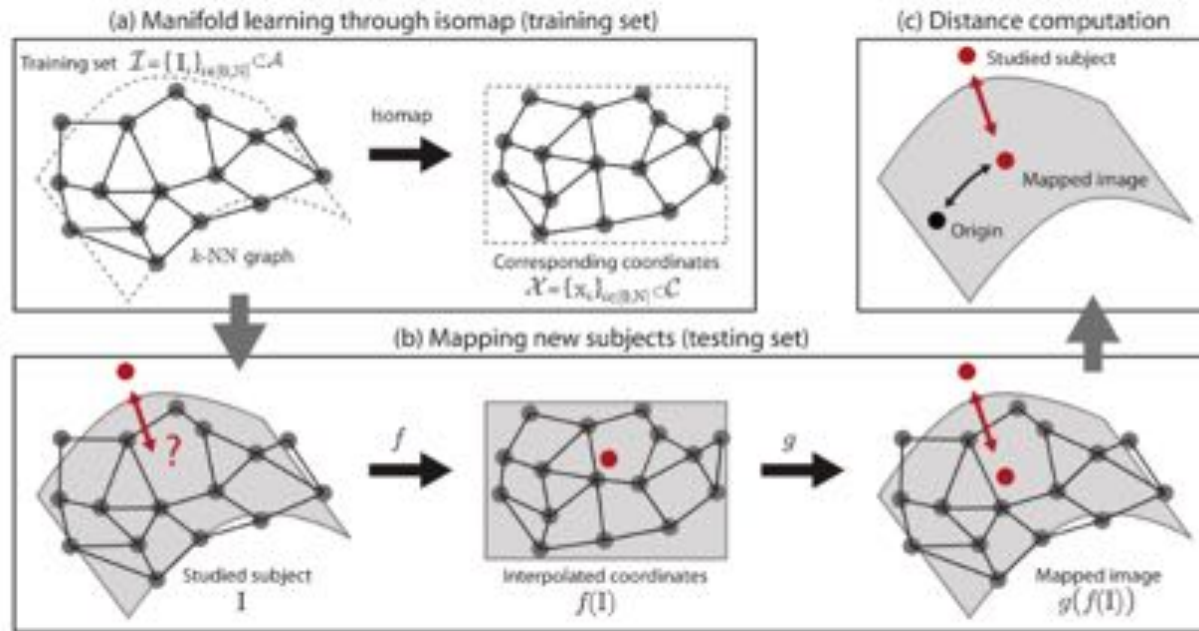
ROI definition

Tracking

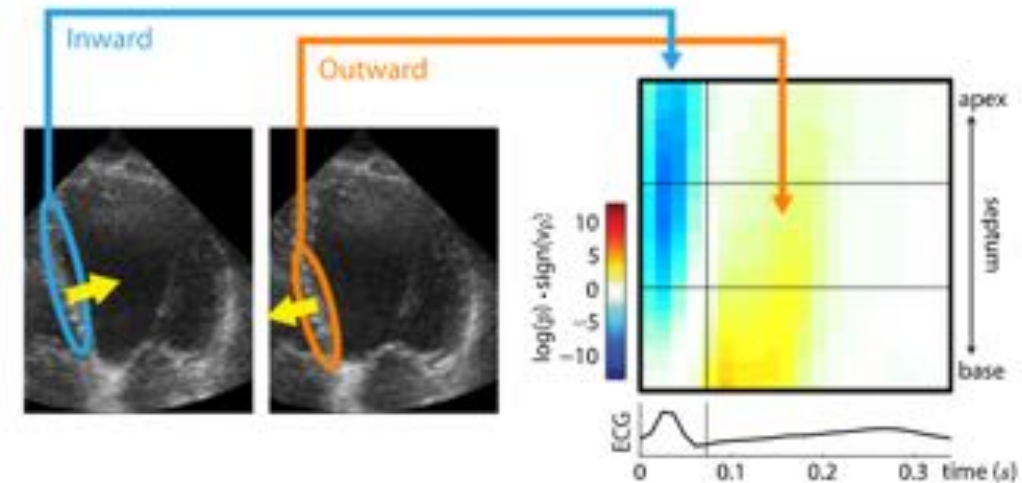
Analysis

Standardization

Methods of strain estimation



Abnormal motion patterns can then be identified based on an atlas of normal



Motion is strongly correlated, and the dimensionality can be reduced to a manifold.

# Advanced shape analysis can be used to better quantify variations in deformation.

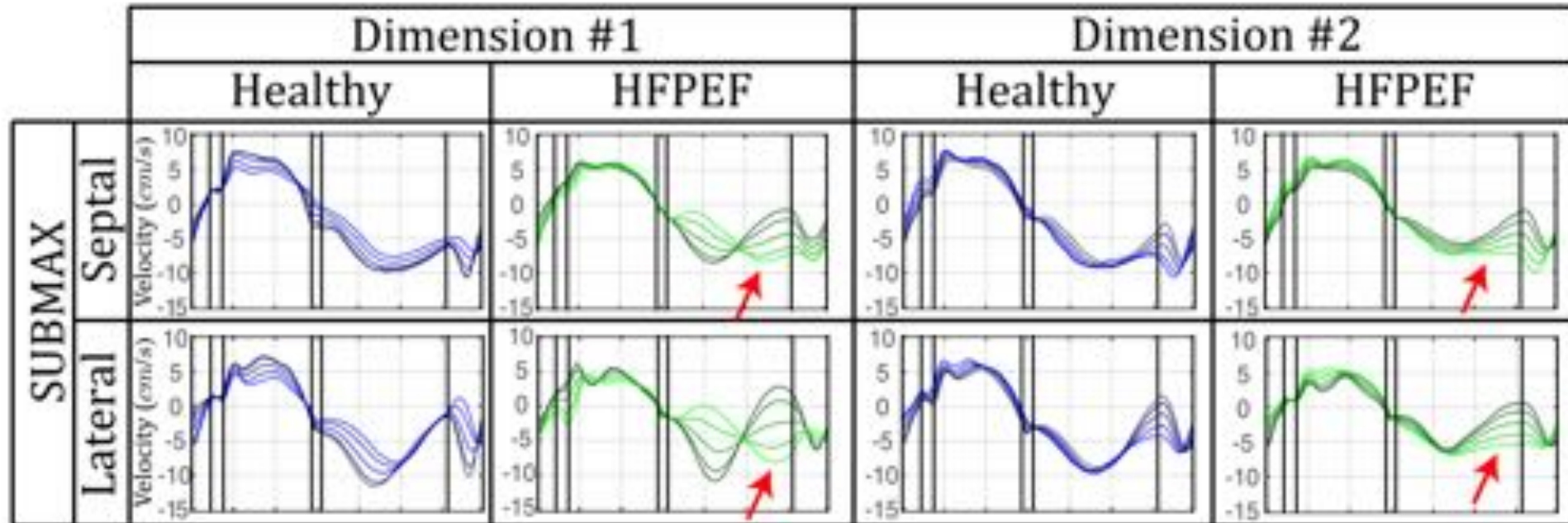
ROI definition

Tracking

Analysis

Standardization

Motion patterns can be correlated with disease



Automated abnormal motion detection  
Personalized diagnoses

Methods of strain estimation

# Advanced shape analysis can be used to better quantify variations in deformation.

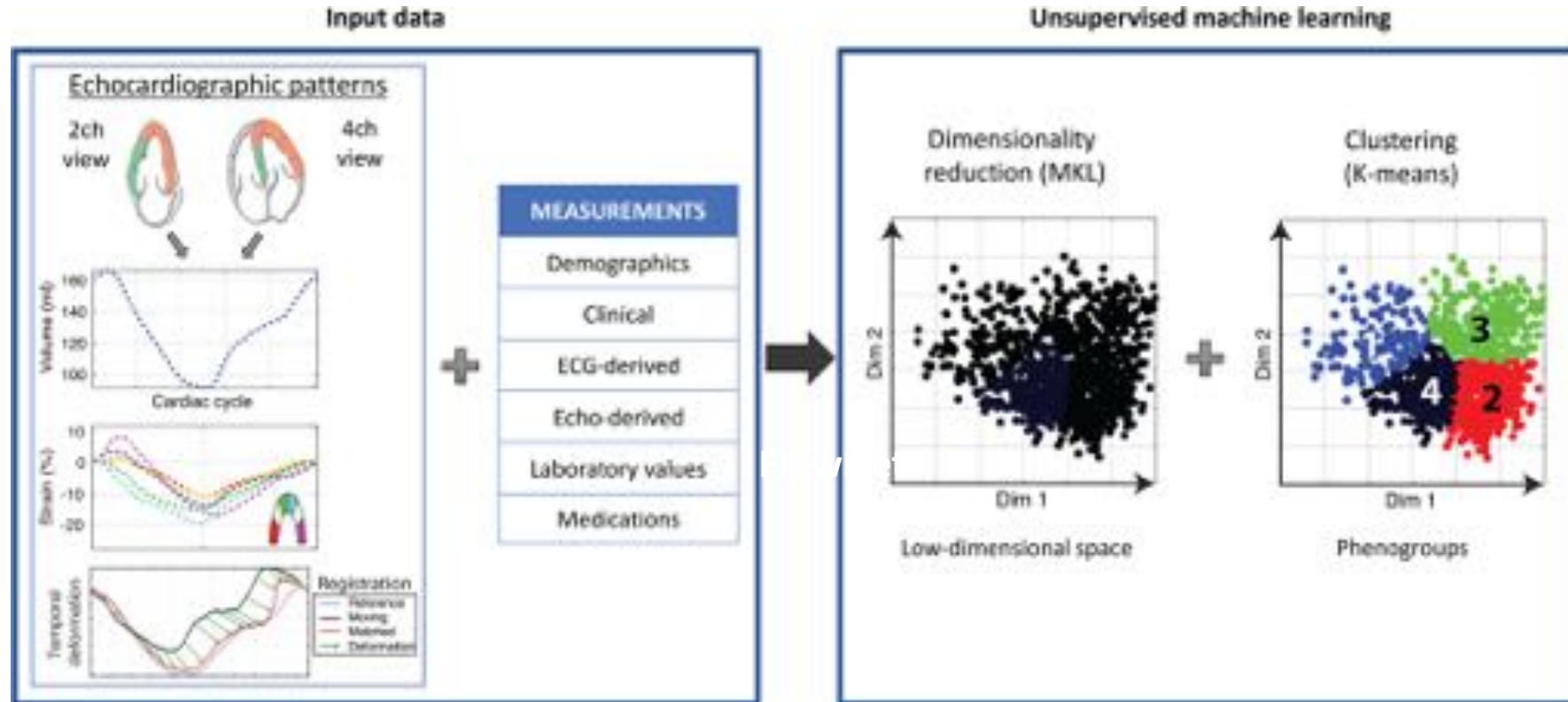
ROI definition

Tracking

Analysis

Standardization

Methods of strain estimation



Unsupervised learning can also be used to integrate other clinical factors and measurements into a common analysis framework.

# Anatomical models can be used to create synthetic gold-standard ground truth data.

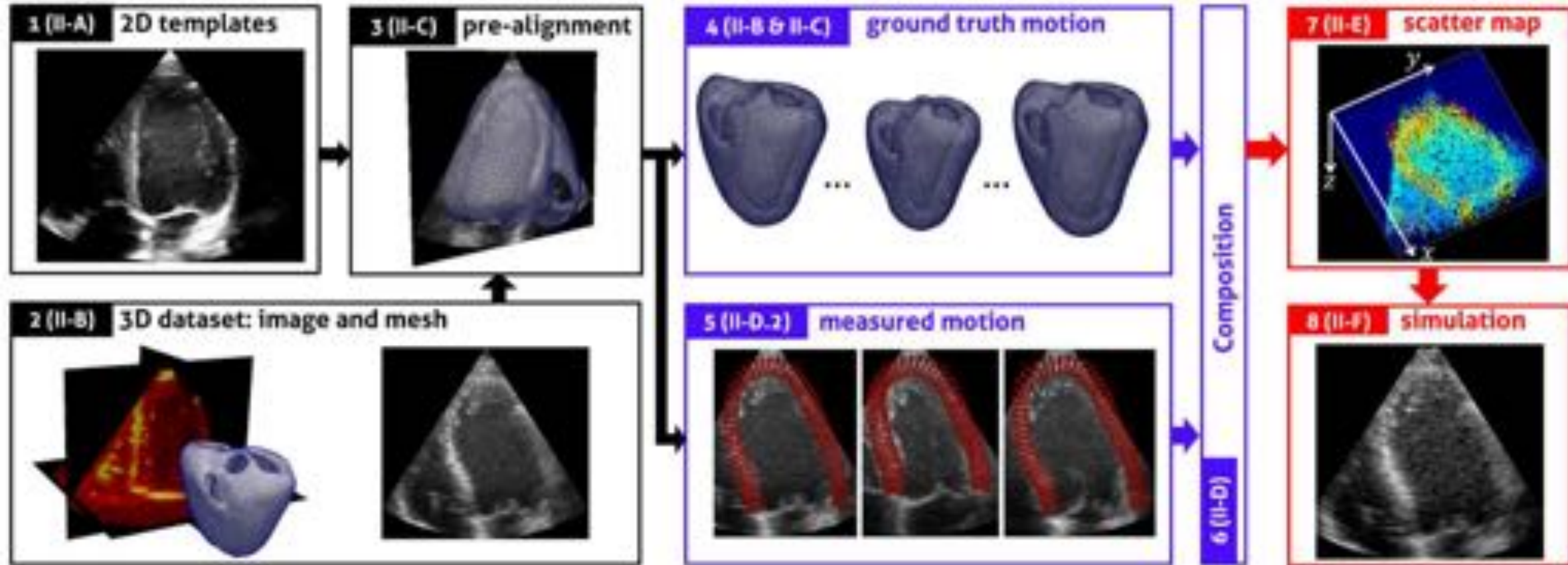
ROI definition

Tracking

Analysis

Standardization

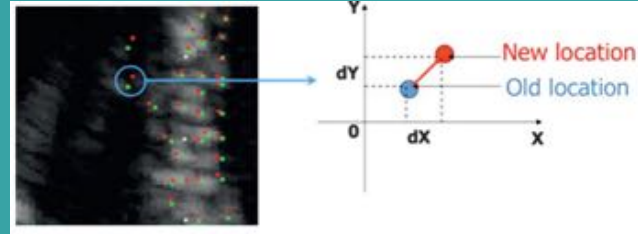
Methods of strain estimation





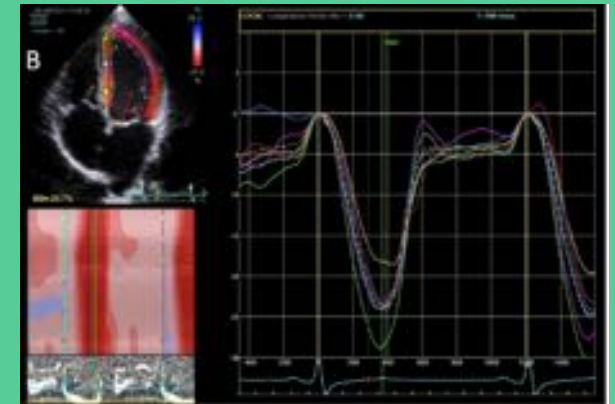
# Physics and basis of cardiac strain

[Wikimedia Foundation]



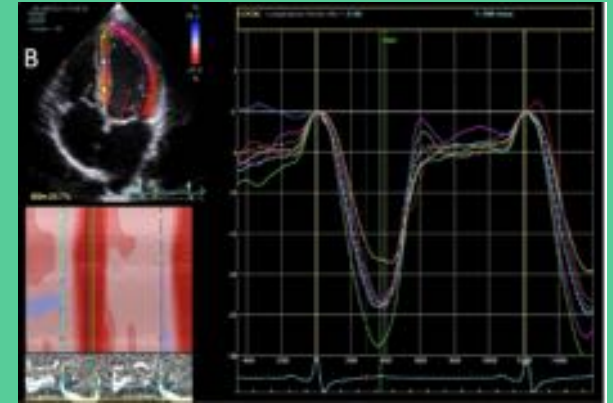
# Methods of strain estimation

[folk.ntnu.no/stoylen]



# Clinical workflow and examples

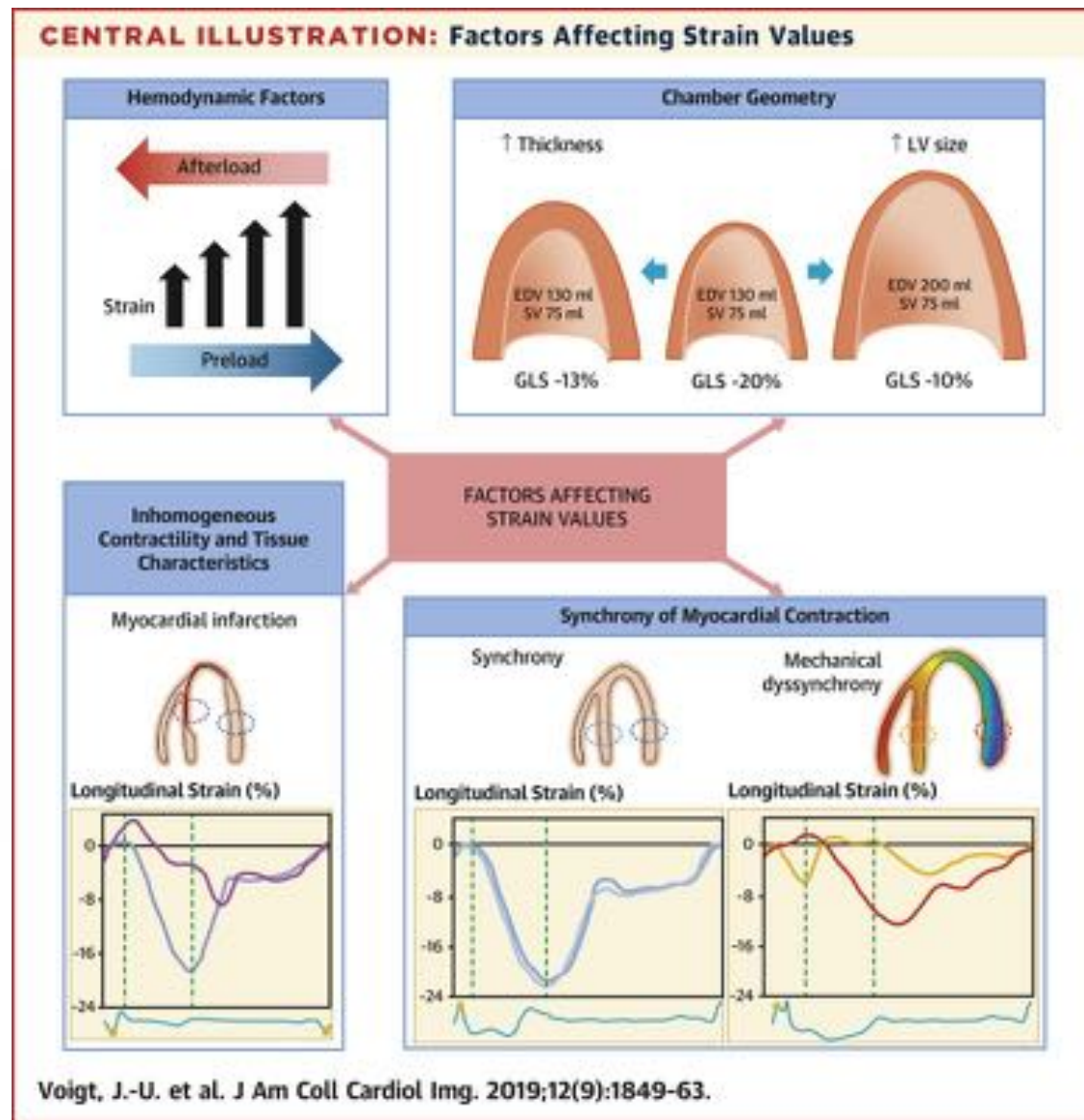
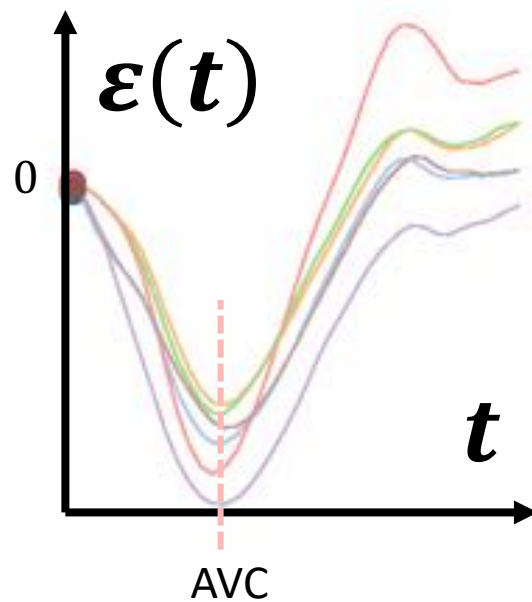
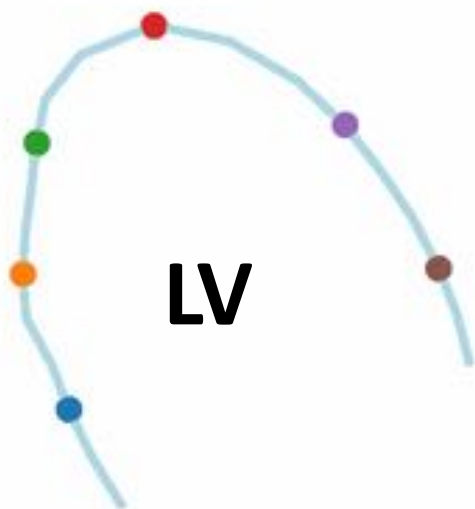
[Loncaric et al. *Global Cardiology*, 2018]



# Clinical workflow and examples

# Function and strain are closely related: functional changes can be seen in regional deformation patterns

Clinical workflow and examples



For speckle tracking echocardiography, the first step is selecting the region of interest.

Clinical workflow and examples

4CH  
FR: 61 fps  
HR: 54 bpm

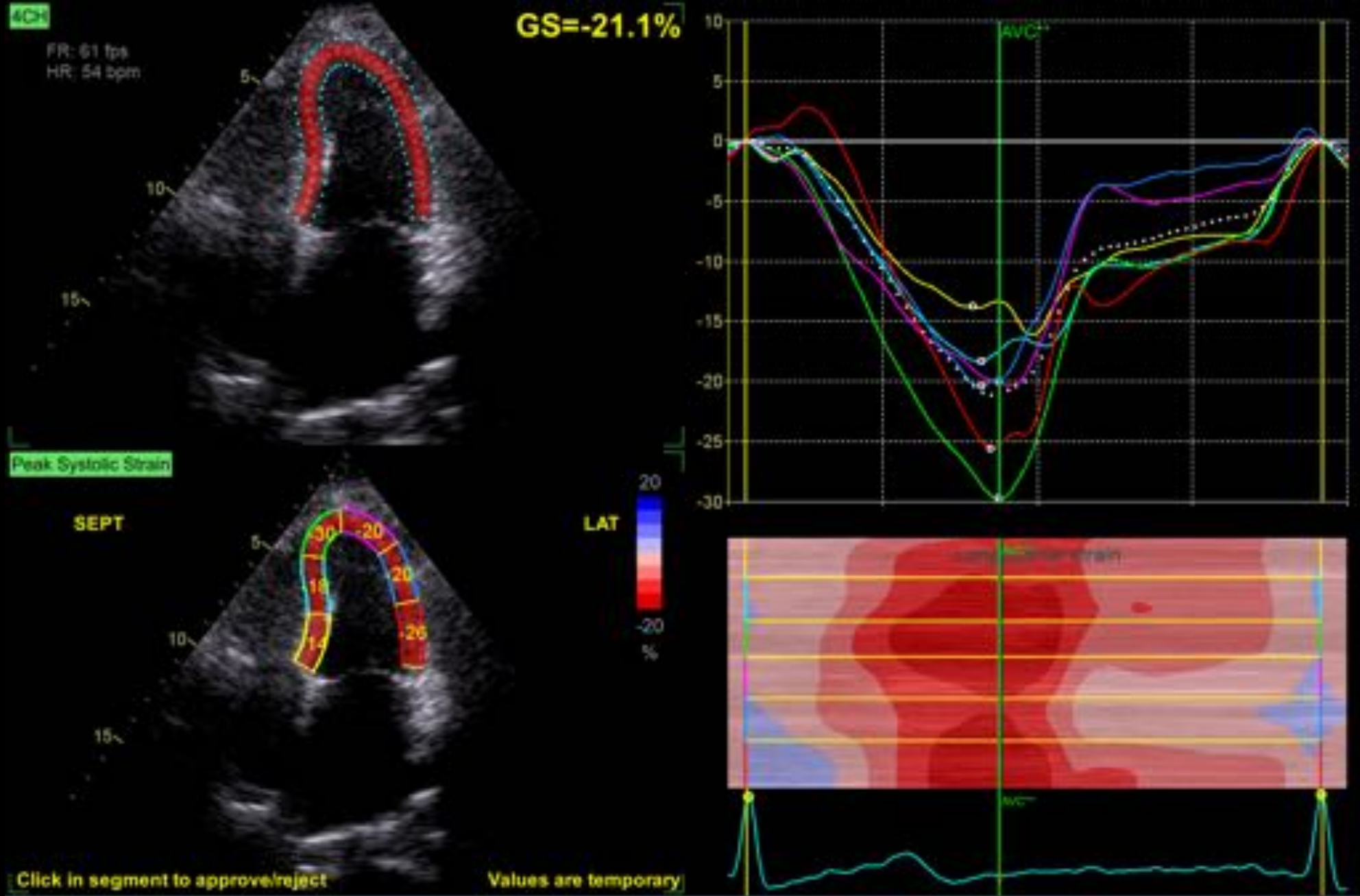
SEPT

LAT

Stop  
Speed  
Zoom  
Gain  
Select view (M-Mode)  
Define ROI  
After adjusting ROI, select one view or wall to track.  
None 3-Days  
ROI Width  
Process  
Results  
Add new wall (select track)  
Add new 3-wall  
Cancel

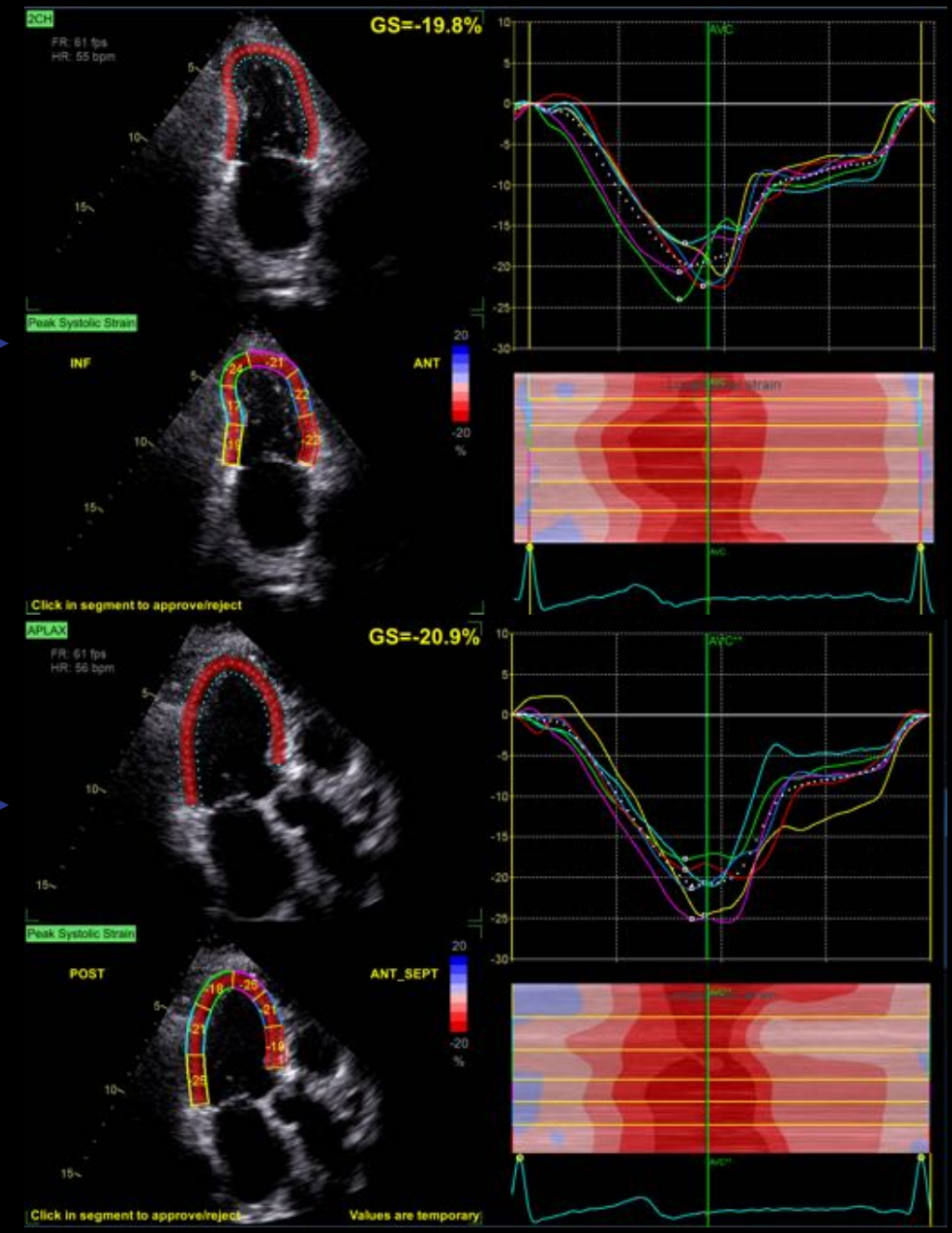
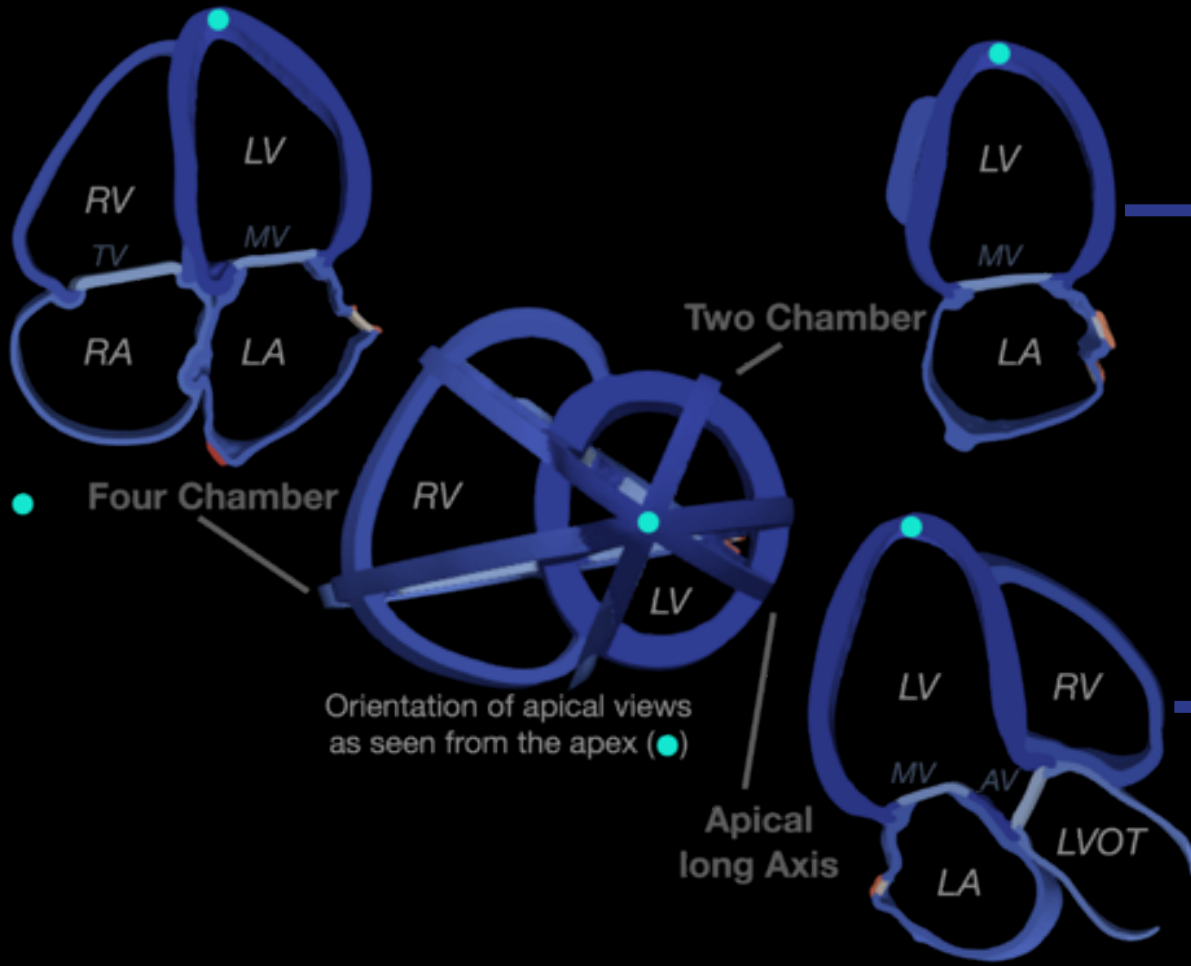
# The ROI is tracked through the cardiac cycle to give deformation results

Clinical workflow and examples



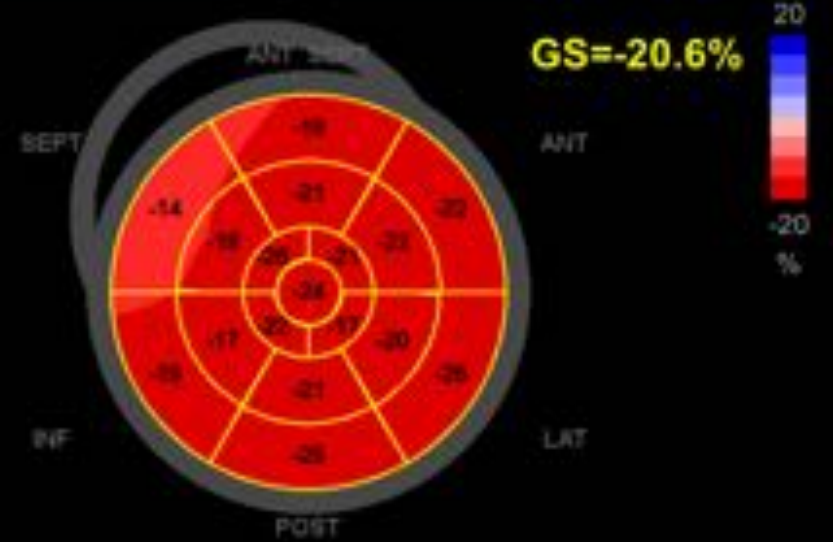
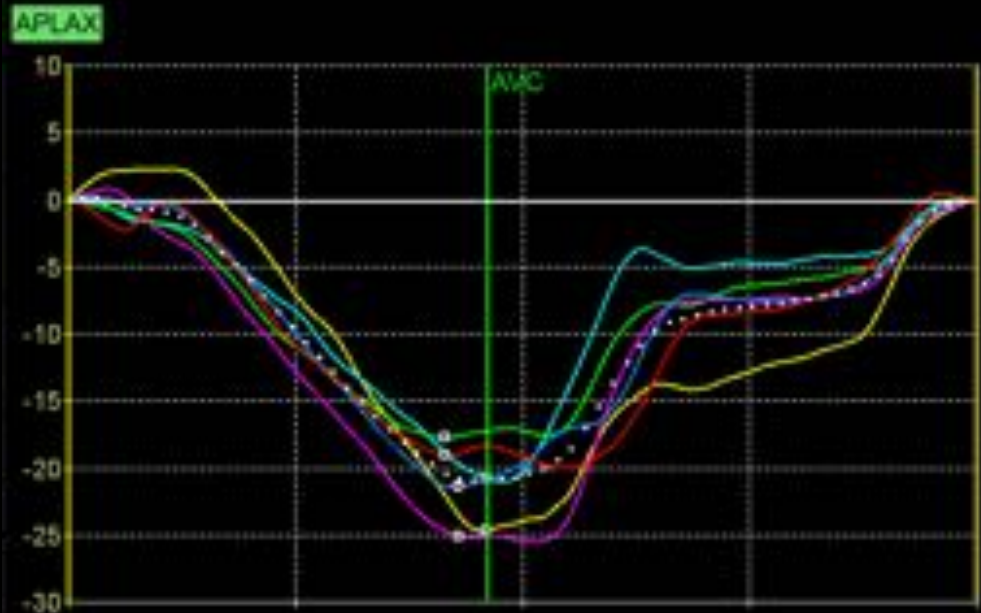
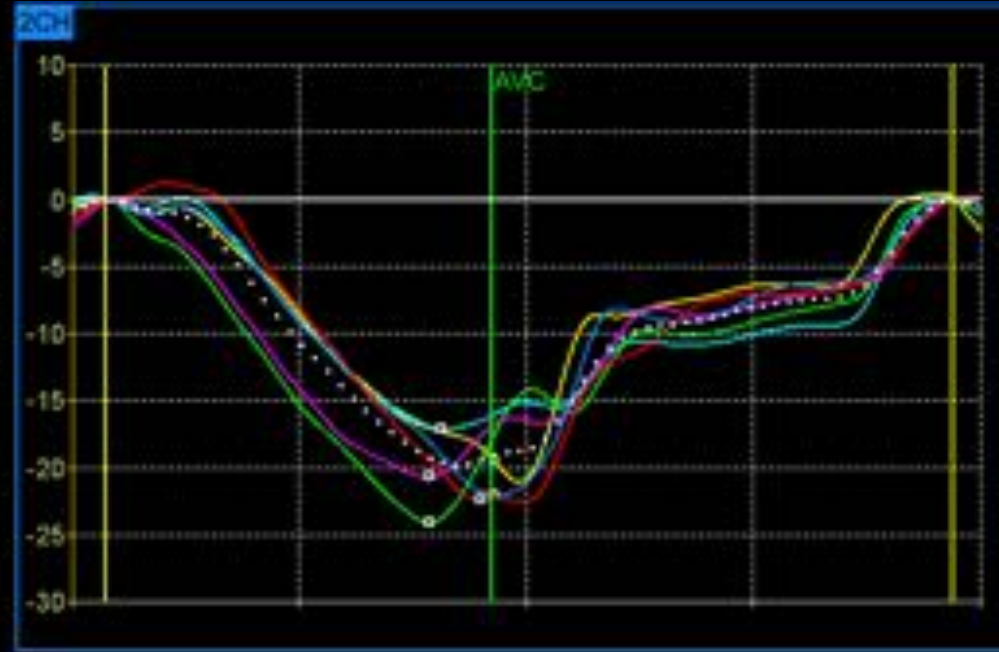
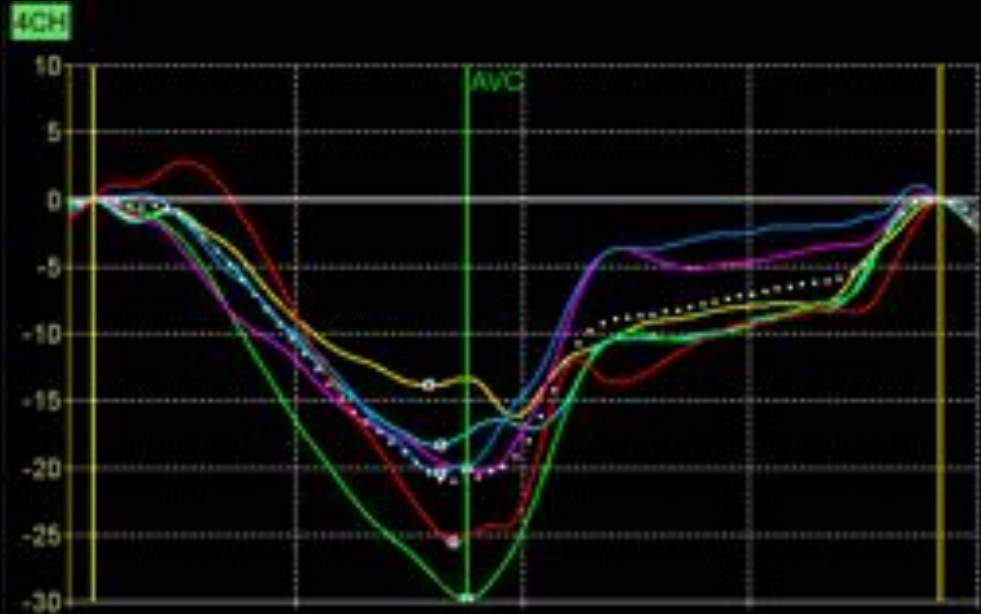
# Repeat for 2CH and APLAX images to give find the strain across the ventricle

Clinical workflow and examples



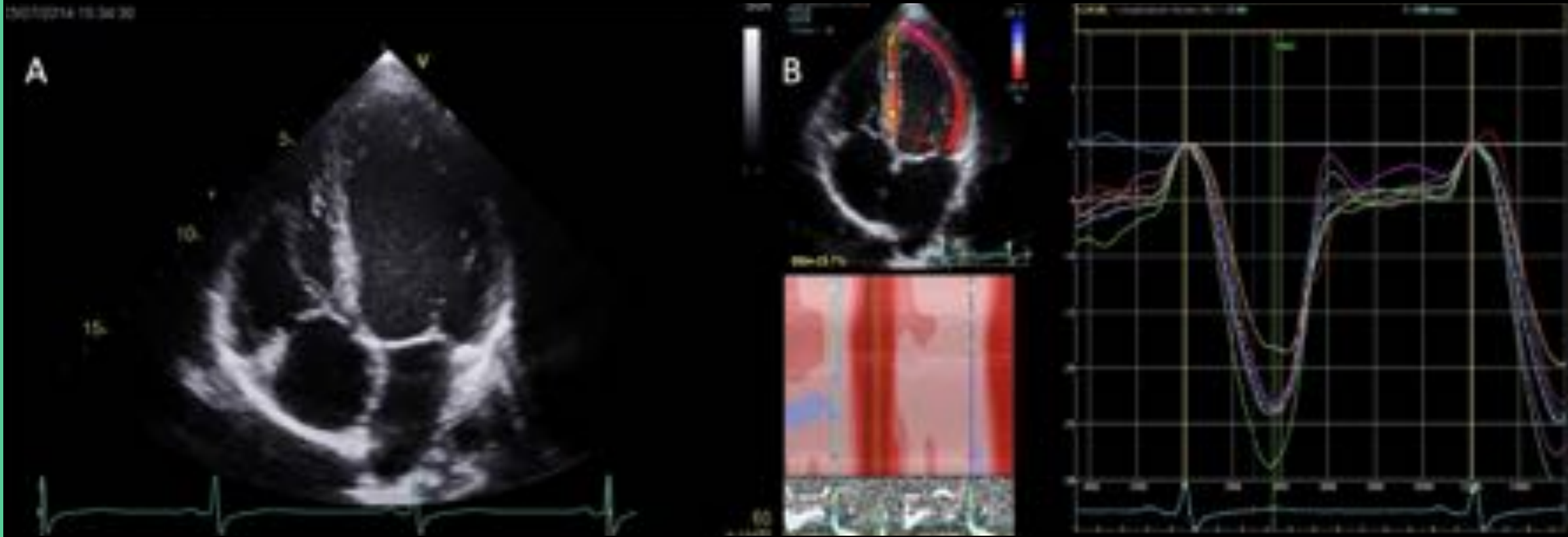
# Repeat for 2CH and APLAX images to give find the strain across the ventricle

Clinical workflow and examples



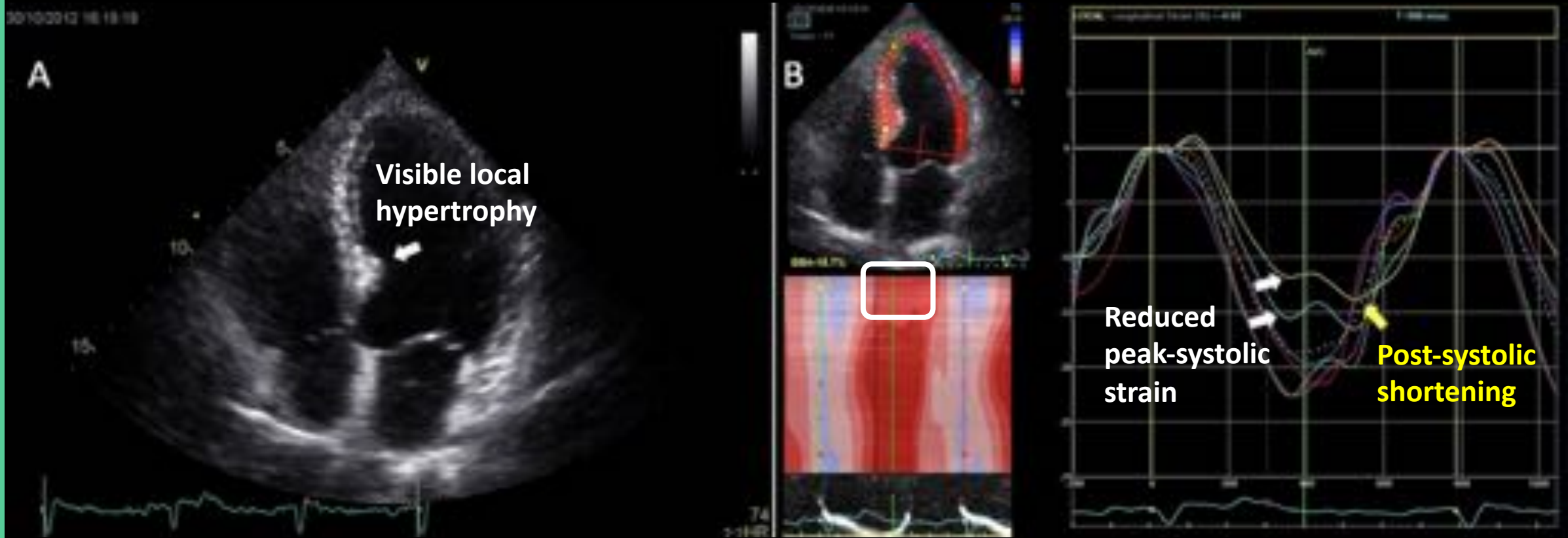
In normal cases, strain imaging shows consistent deformation across the ventricle.

Clinical workflow and examples



# Local hypertrophy causes a reduction in regional longitudinal strain

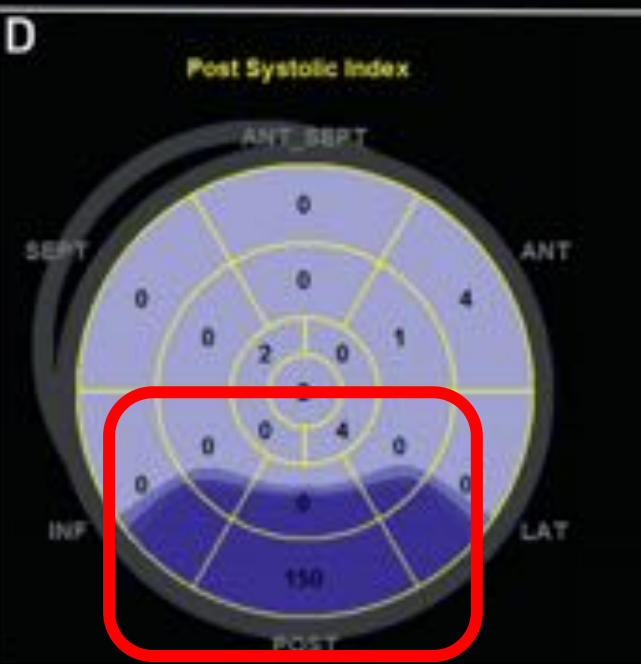
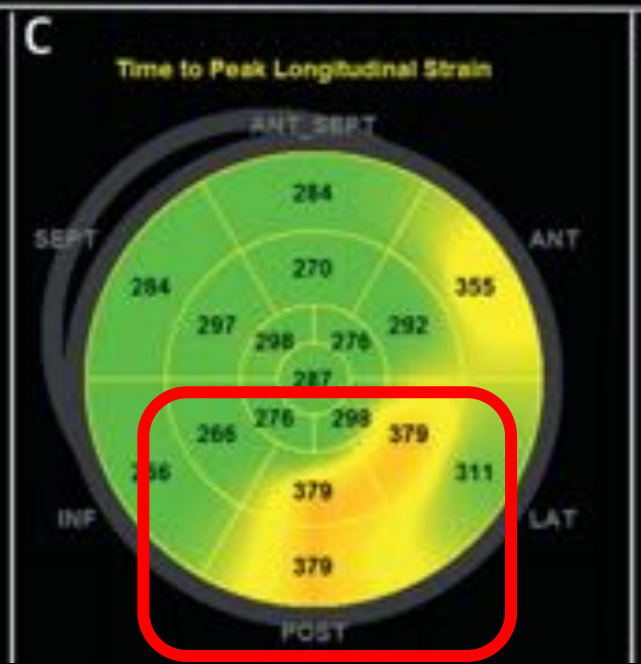
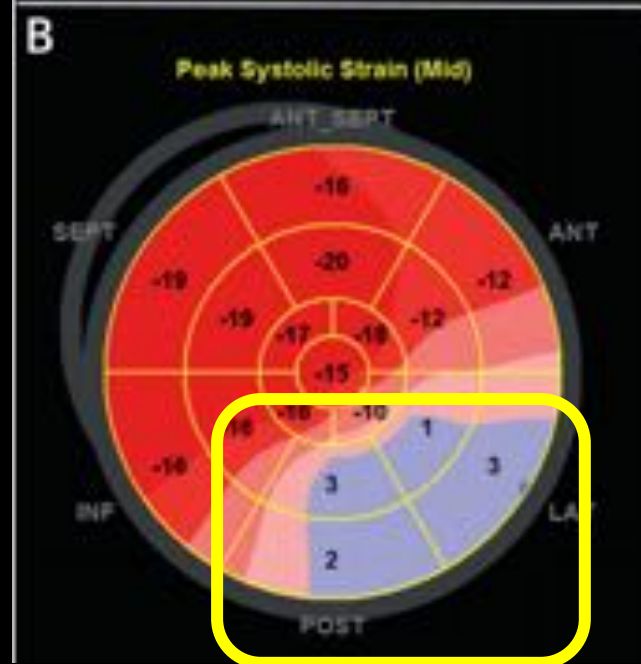
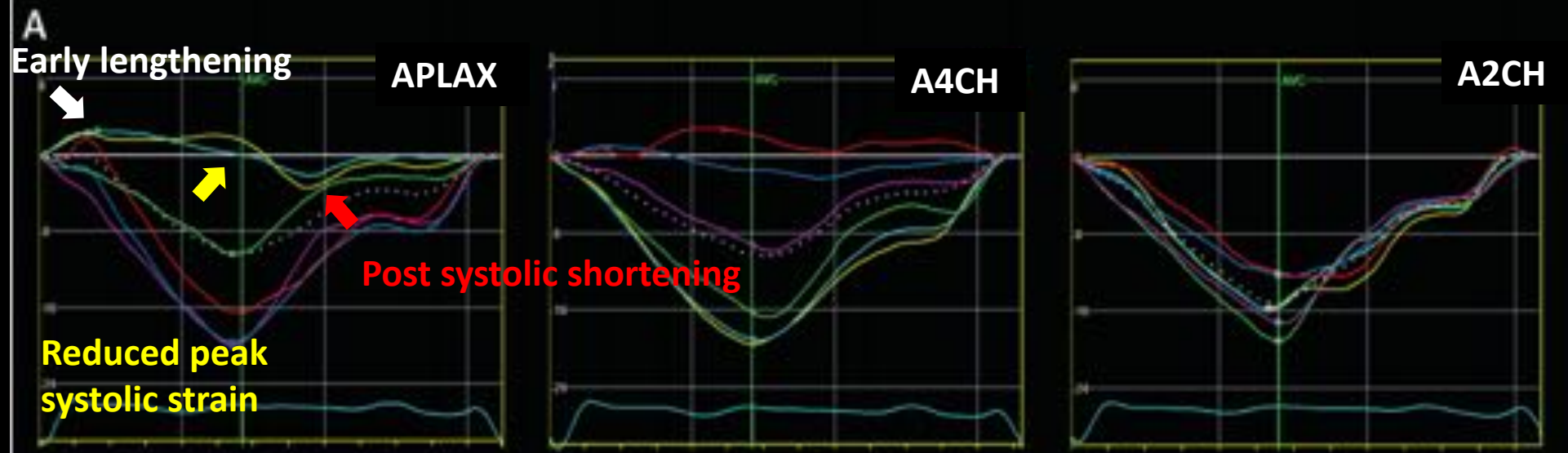
Clinical workflow and examples





# Ischemia will reduce myocardial function in the infarcted segment.

Clinical workflow and examples



# Strain and deformation estimation in cardiac imaging

Summary

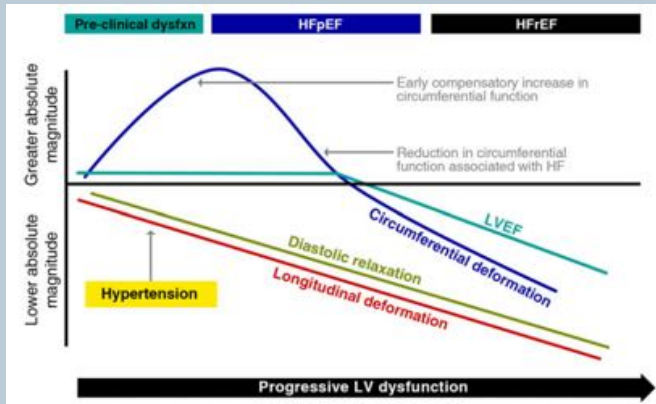
## Physics and basis of cardiac strain

### Definition

$$\varepsilon(t) = \frac{L(t) - L_0}{L_0}$$

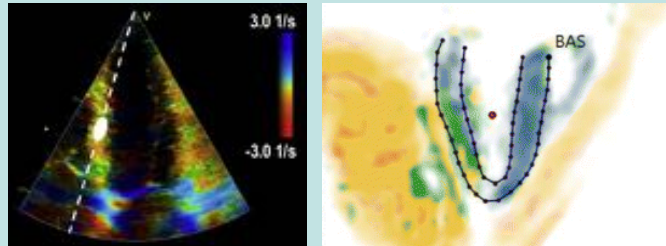


### Use case for strain

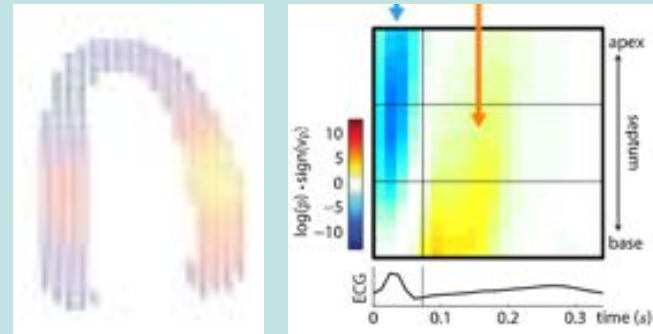


## Methods of strain estimation

### Echo and MRI

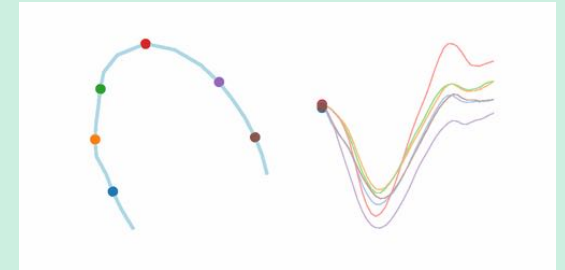


### Machine learning processing

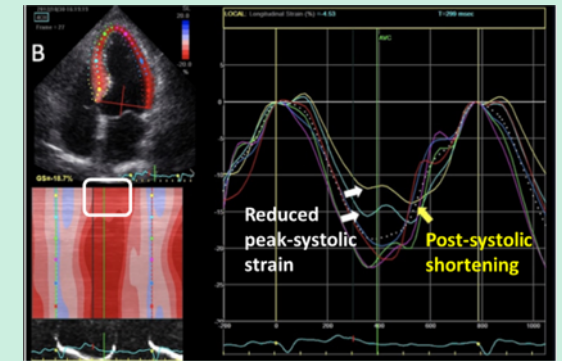


## Clinical workflow and examples

### Factors affecting strain



### Pathological cases



# (A few) acknowledgements/very useful resources

## Acknowledgements

### Strain/strain rate in echocardiography:

Asbjørn Støylen: [folk.ntnu.no/stoylen/strainrate/](http://folk.ntnu.no/stoylen/strainrate/)

### Strain in cardiac magnetic resonance imaging:

Ibrahim, El-Sayed H. "Myocardial tagging by cardiovascular magnetic resonance: evolution of techniques—pulse sequences, analysis algorithms, and applications." *Journal of Cardiovascular Magnetic Resonance* 13.1 (2011): 1-40

### Clinical cases:

Loncaric, Filip, Bart Bijmens, and Marta Sitges. "Added value of cardiac deformation imaging in differential diagnosis of left ventricular hypertrophy." *Global cardiology Science & Practice* 2018.3 (2018).



UiO : Universitetet i Oslo



Thank you



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