

– Ultrasound motion imaging –

Simulating ultrasound images

a very brief introduction





by

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Disclaimer: The views expressed in this course are those of the author and do not necessarily reflect the multiple positions of the ultrasound community. The examples may contain errors and can carry an implied judgement due to author's preference for one side of an issue over another.
Be critical and take a step back while reading this document!

TOC

- **why using simulations?**
- **MUST**: Matlab UltraSound Toolbox
- **SIMUS**: what's inside?

WHY USING *simulations?*

why doing simulations?

The “optimal” methodology (if possible): *in silico*, *in vitro* & *in vivo*

Before *in vitro* and *in vivo*, use computational ultrasound imaging to:

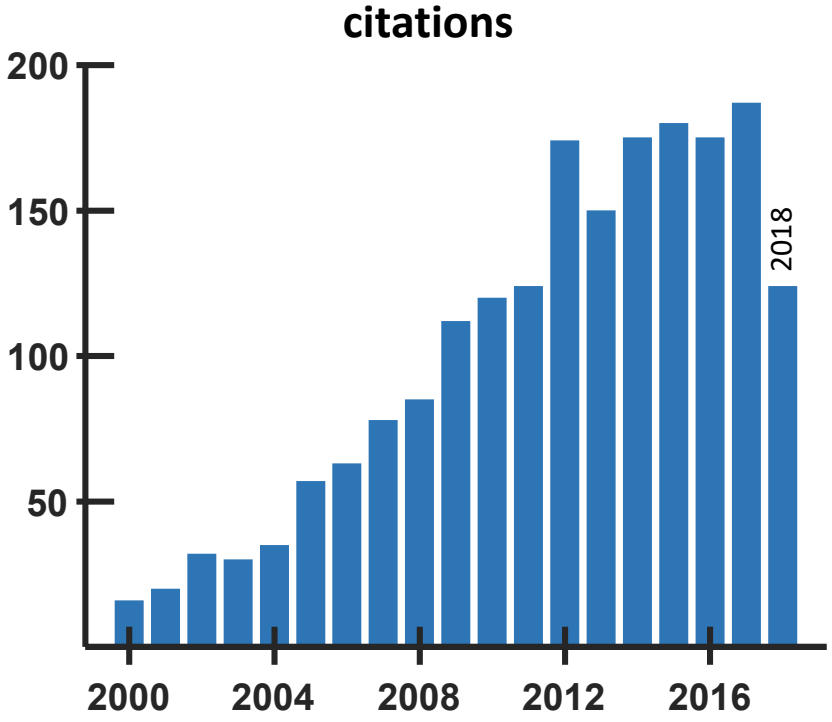
1. test your ultrasound sequences (PW, DW, MLT…)
2. optimize your algorithms
3. explore multiple configurations
4. compare with others (e.g. challenges)

Computational ultrasound imaging must ideally be:

1. easy to program
2. realistic
3. easy to parallelize in the 3-D era

computational ultrasound imaging

- Computational ultrasound imaging is increasingly used
- Jørgen Jensen, "***Field**: A program for simulating ultrasound systems*." 1996

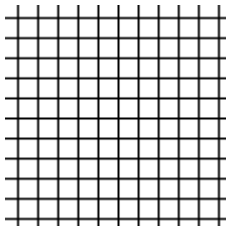


Field II Simulation Program

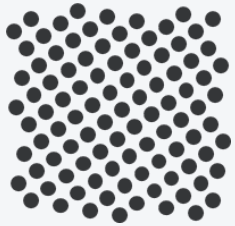
source: *Field II Simulation Program* (http://field-ii.dk)

mesh-based *vs.* mesh-free

EULERIAN



LAGRANGIAN

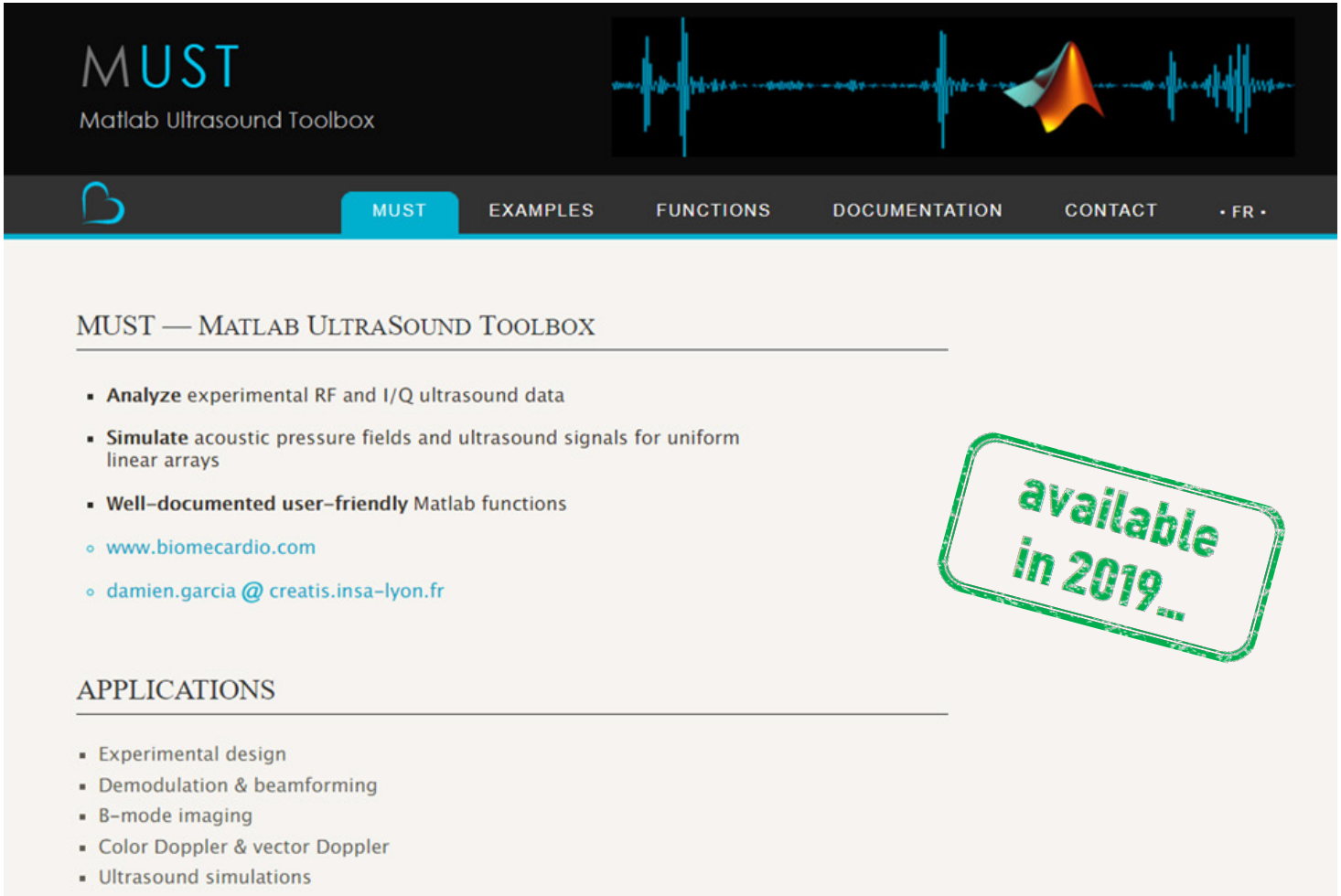


Grid-based	Mesh-free
k-Wave (www.k-wave.org)	***Field II*** (field-ii.dk)
Finite difference method	Weakly backscattering particles

Each particle possesses and transports its physical properties

MUST: MATLAB ultrasound toolbox

MUST: Matlab UltraSound Toolbox



MUST & SIMUS

During the hands-on sessions, you will use **SIMUS** from the **MUST**

- **MUST** = **M**atlab **U**ltra**S**ound **Toolbox**
- **SIMUS** = **SIM**ulations for **U**ltra**S**ound

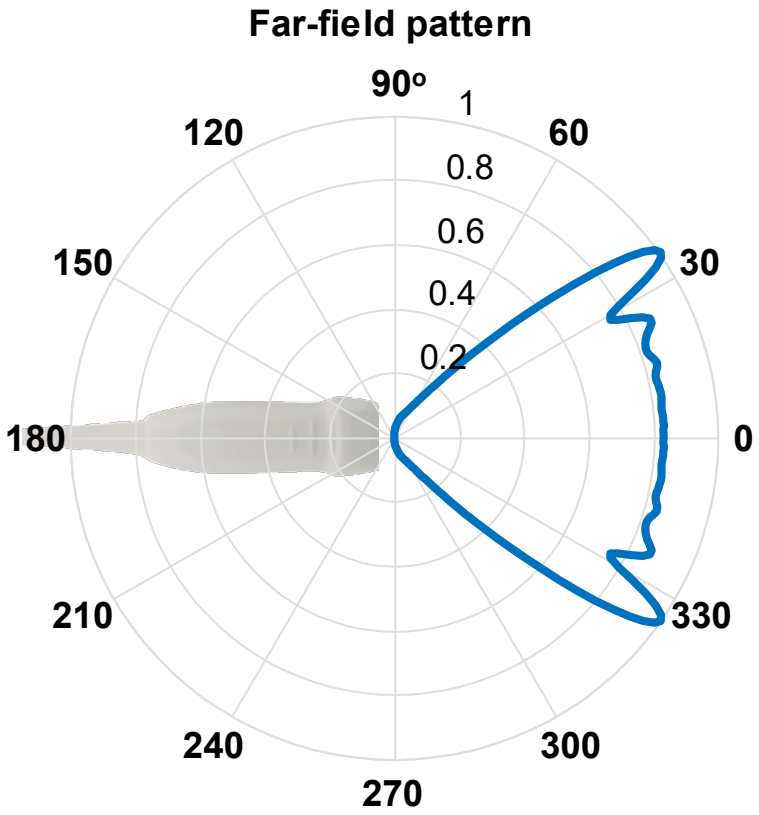
Matlab **U**ltra**S**ound **Toolbox**

1. a Matlab toolbox for ultrasound
2. demodulation, beamforming
3. color Doppler, vector Doppler
4. contains **PFIELD** and **SIMUS**

SIMulations for **U**ltra**S**ound

1. PFIELD: simulate acoustic pressure fields
2. SIMUS: simulate transmit and receive in ultrasound imaging
3. parallelizable

acoustic far-field pattern



pressure fields with PFIELD



Focused

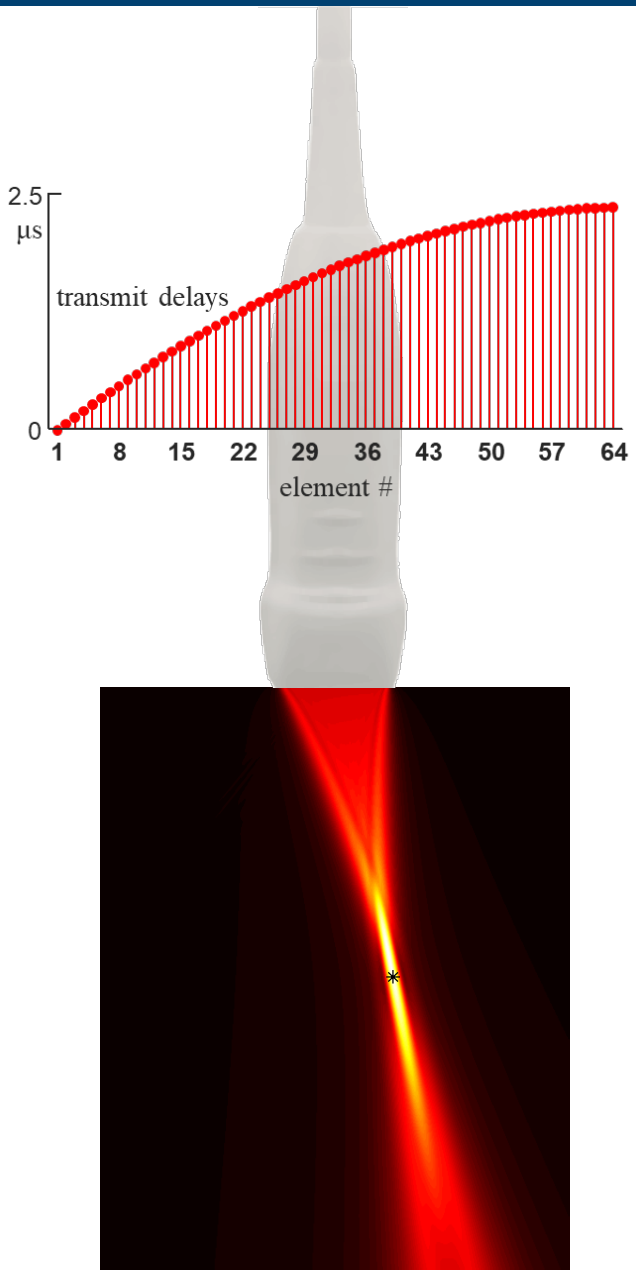


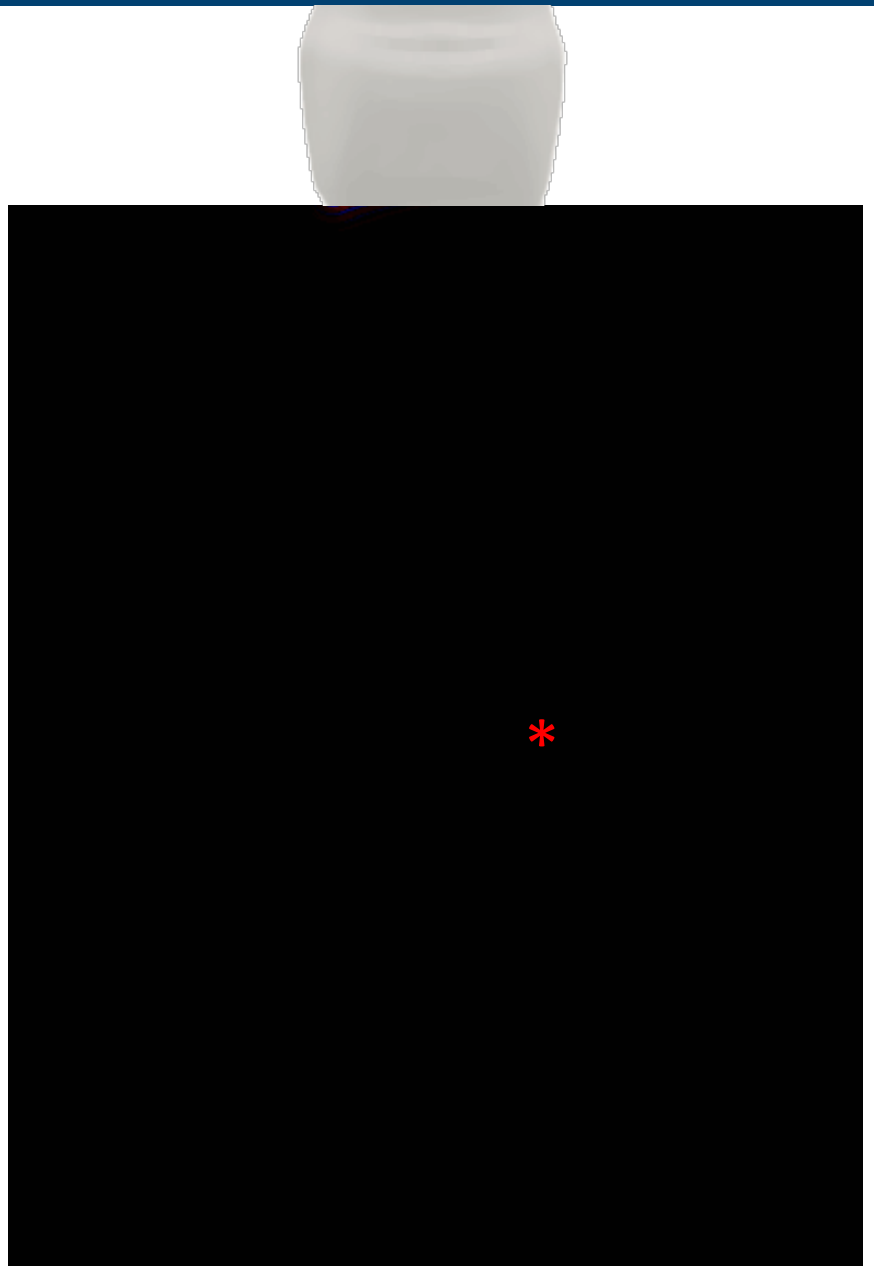
Divergent



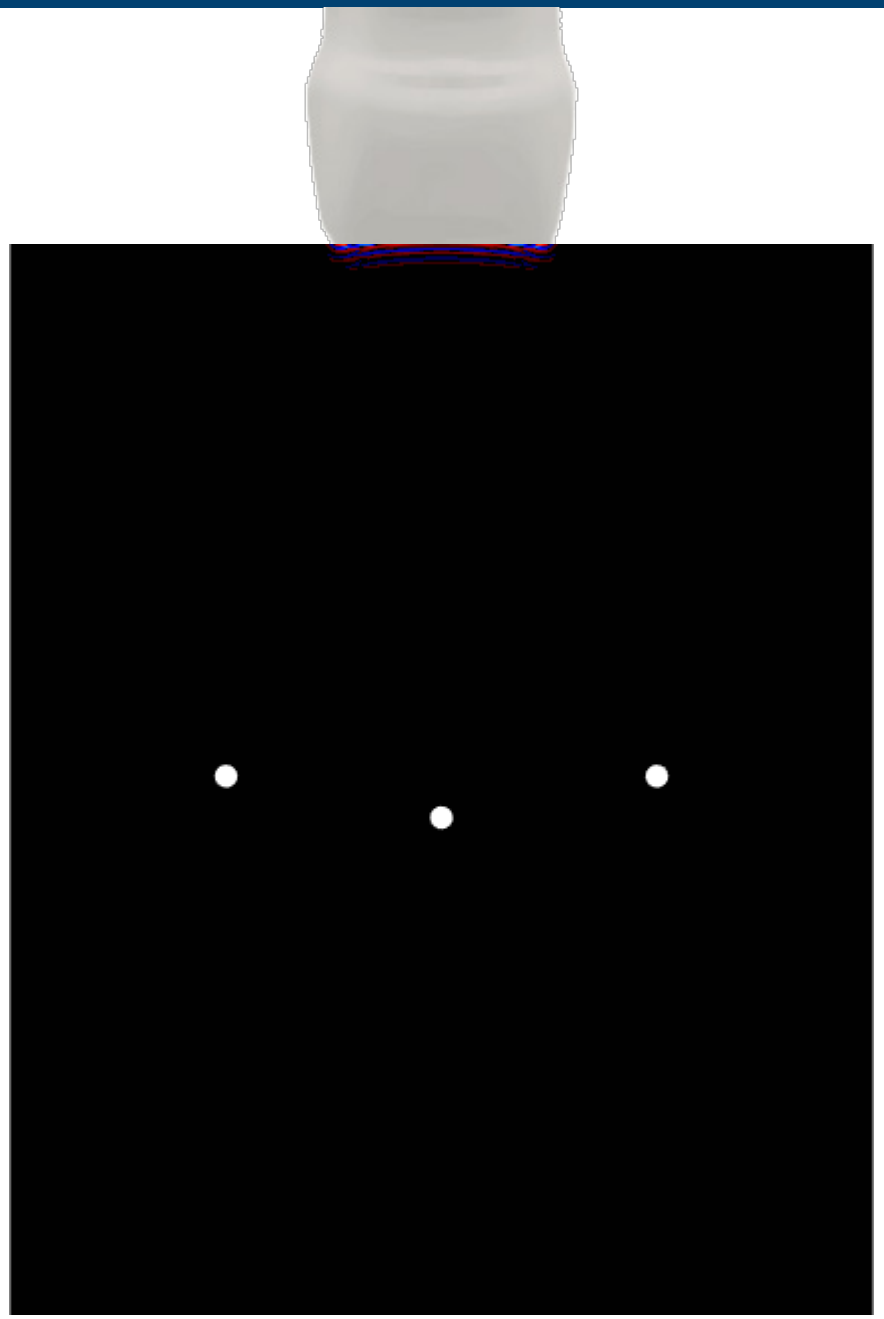
MLT (“multi-line transmit”)

transmit focusing



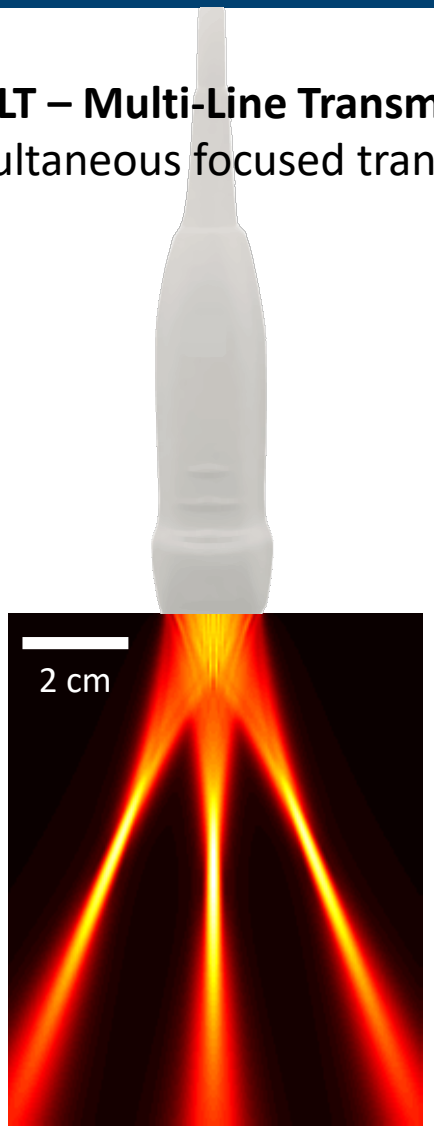


pressure fields with PFIELD



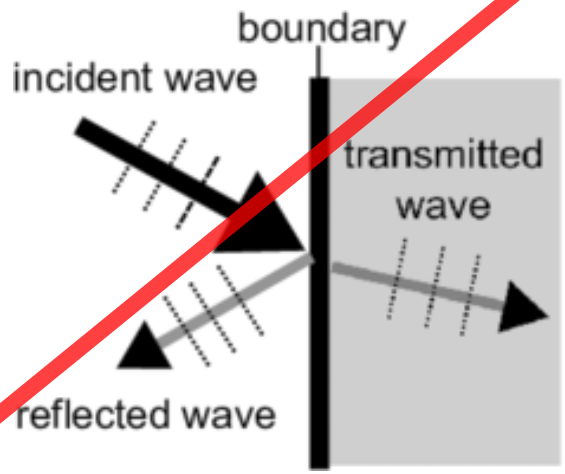
MLT – Multi-Line Transmit

3 simultaneous focused transmits

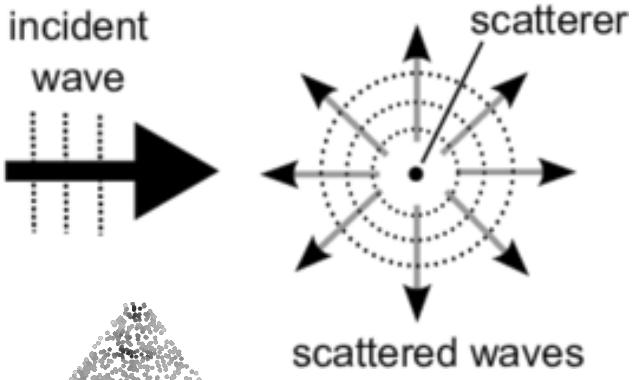


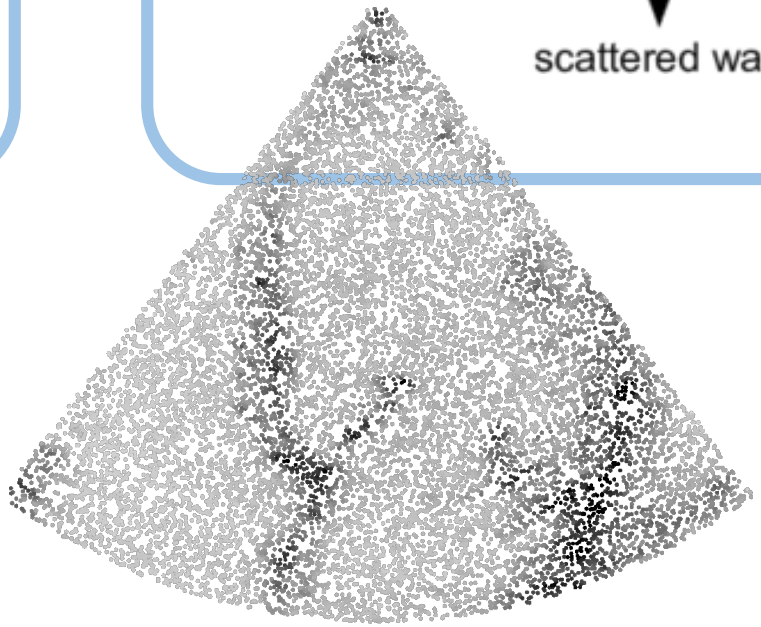
ONLY the diffuse scattering is considered in SIMUS! (as in FieldII)

Specular scattering



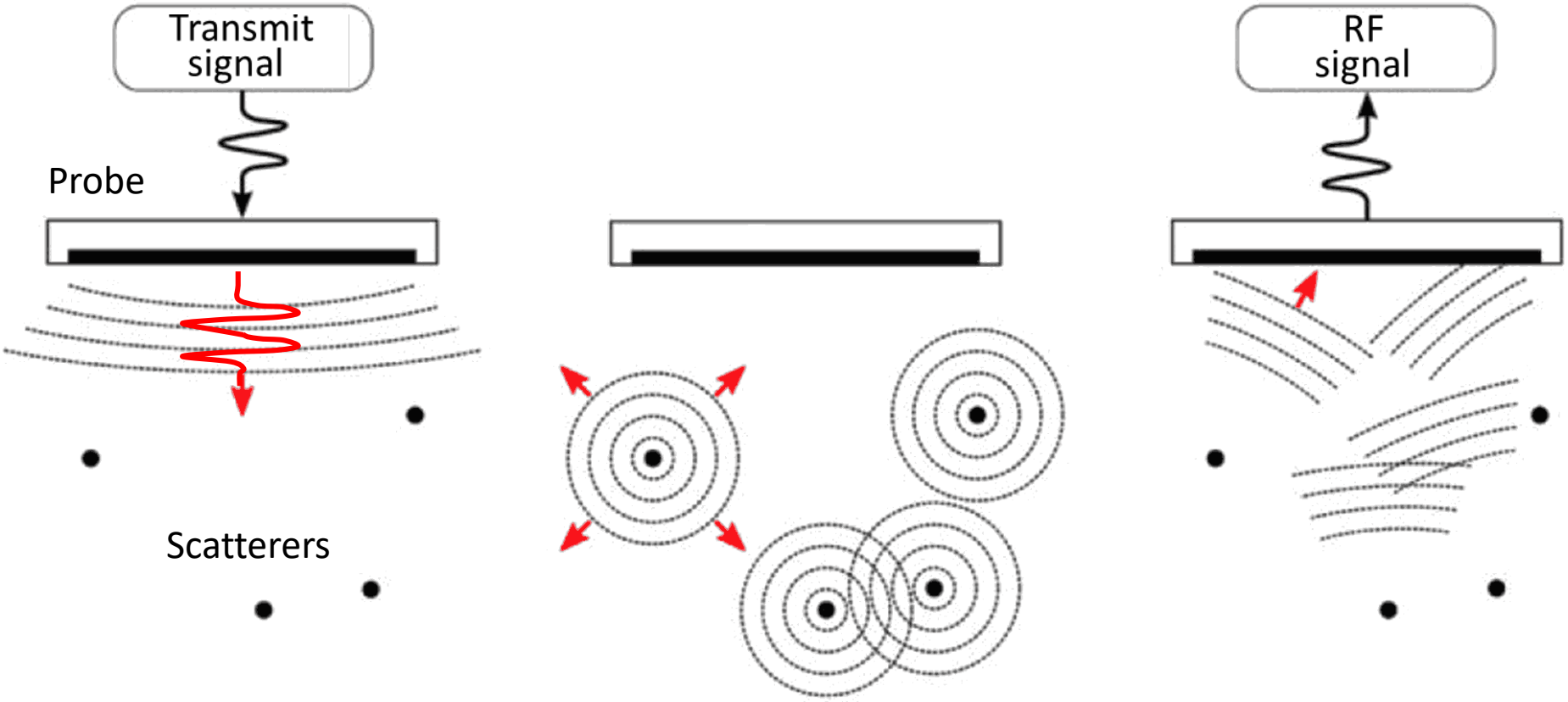
Diffuse (Rayleigh) scattering



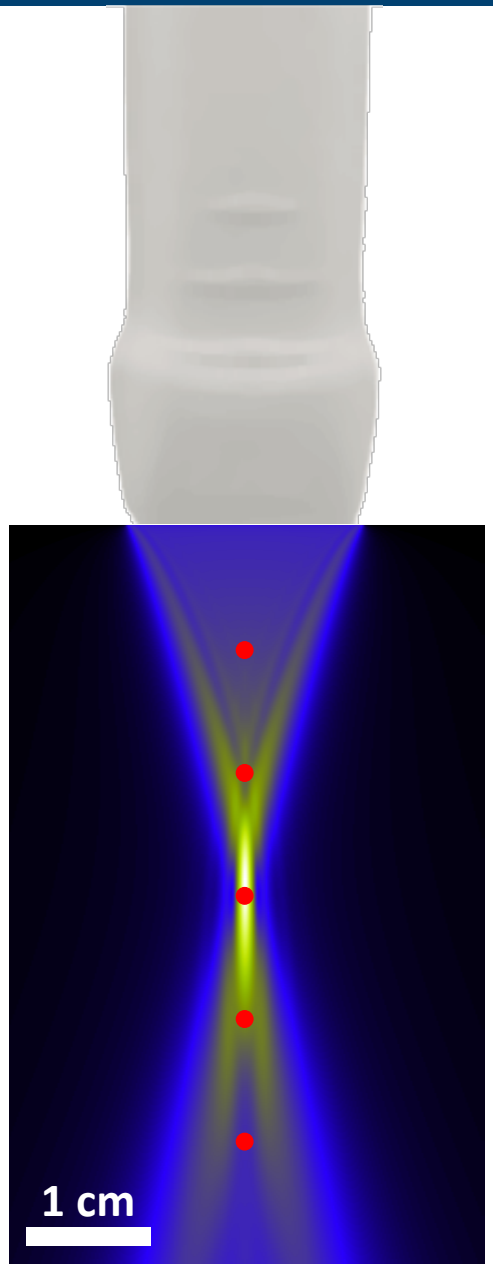


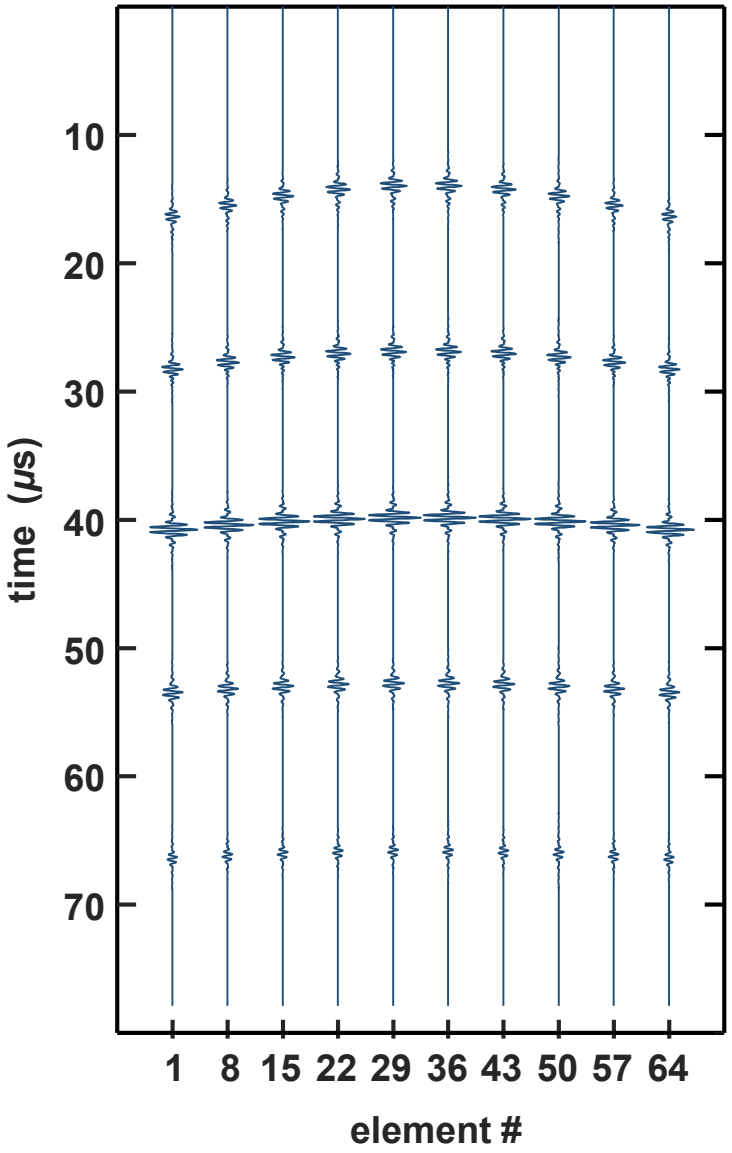
source: doi:10.13140/RG.2.1.3563.2486

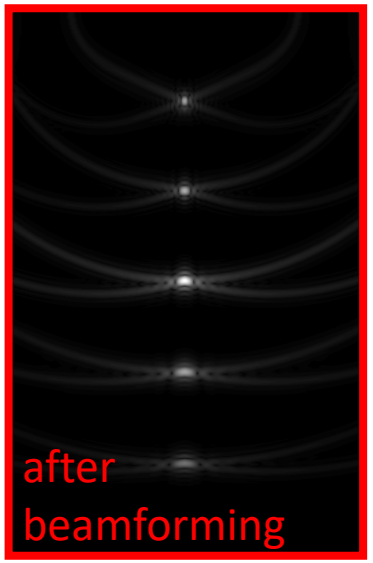
basic principle in SIMUS



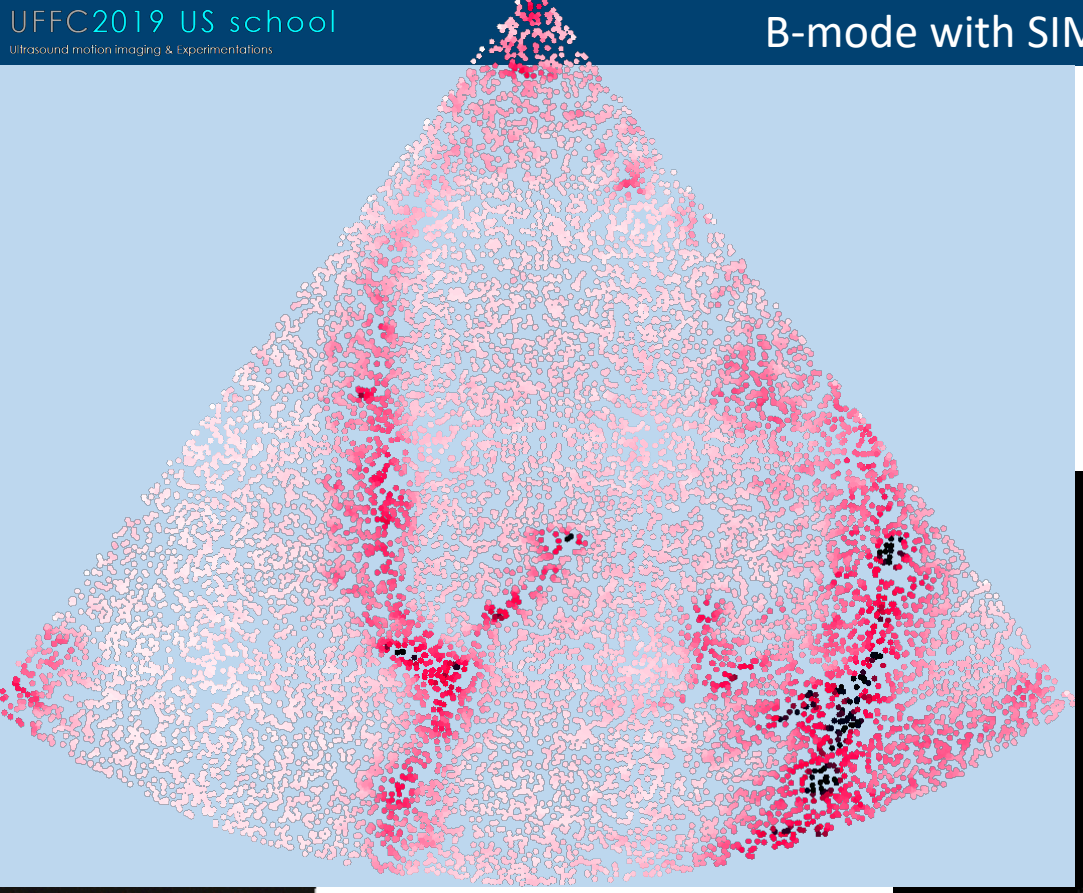
RF signals with SIMUS

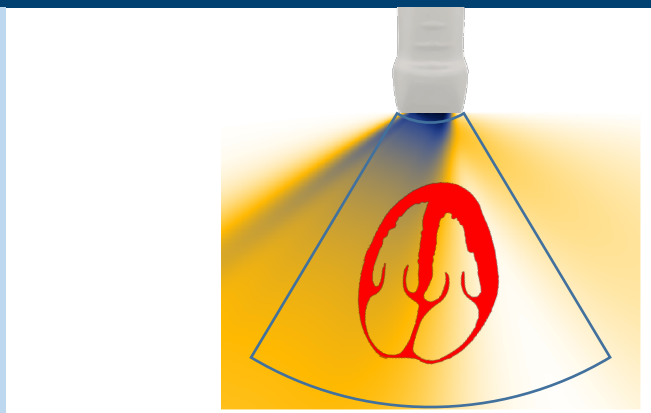


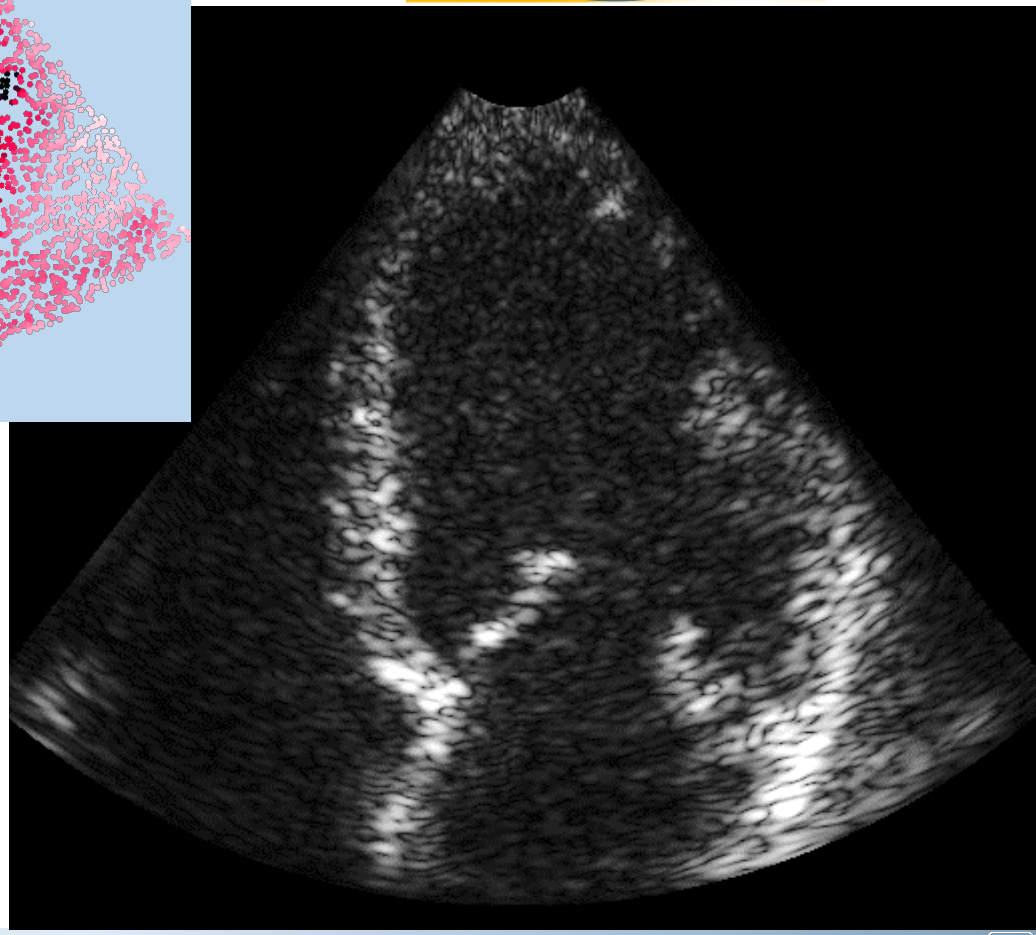


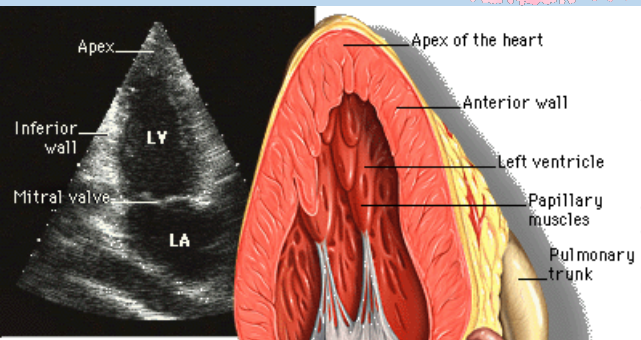


B-mode with SIMUS



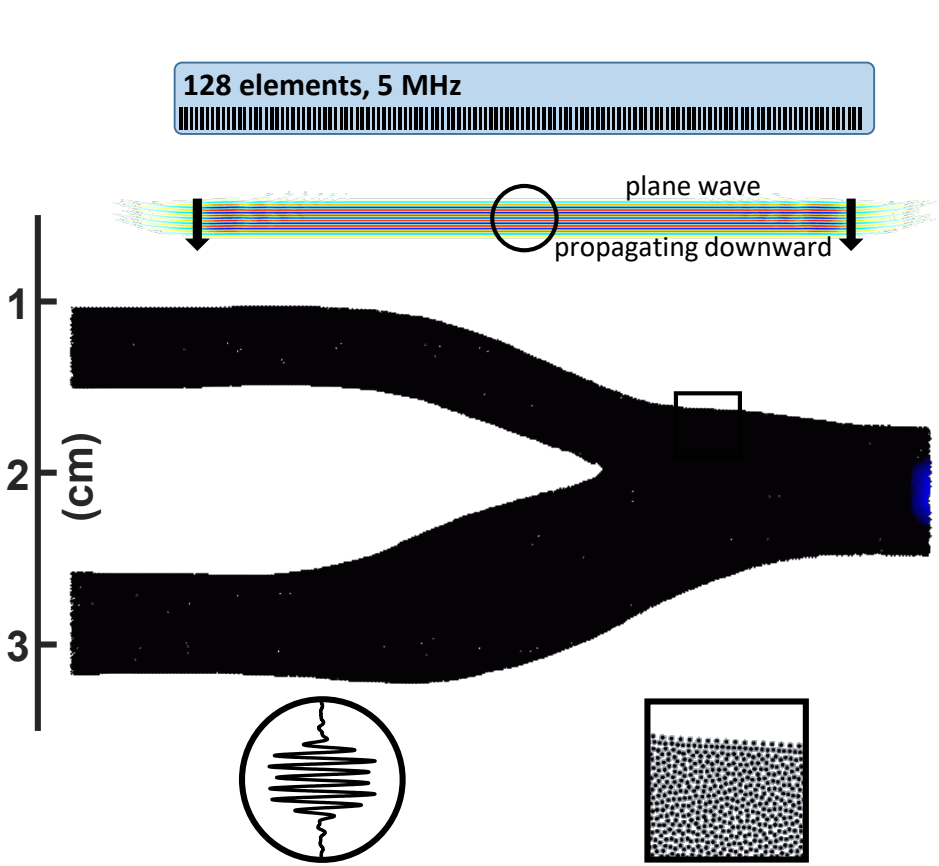


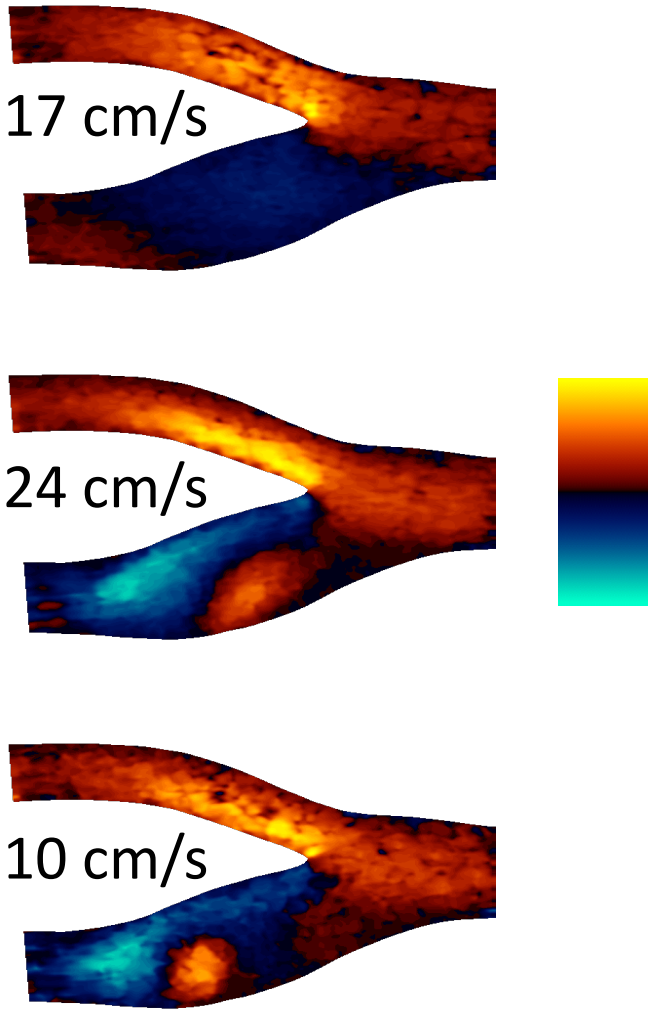




www.yale.edu/imaging/echo_atlas/views/apical_2c.html

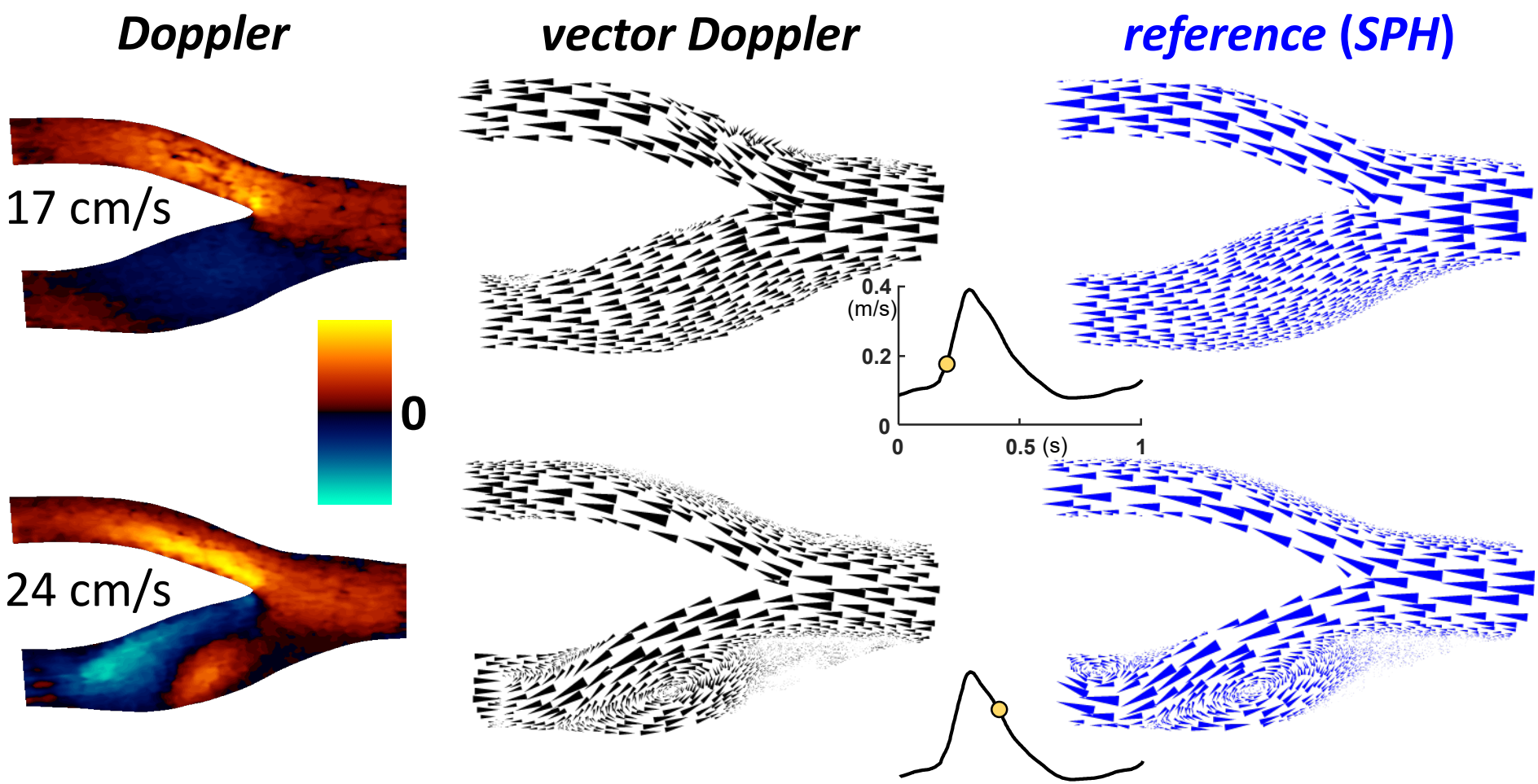
color Doppler with SIMUS





source: Shahriari and Garcia.
Phys Med Biol, 2018;63:205011.

color Doppler with SIMUS



source: Shahriari and Garcia.
Phys Med Biol, 2018;63:205011.

what's inside

SIMUS

Assumptions

1. no dissipative effects (no viscosity, no heat conduction)
2. homogeneous, isotropic, elastic medium
3. low-amplitude perturbations (small particle velocities, small fluctuations of pressure and density)
4. $\Rightarrow$ **linearization**

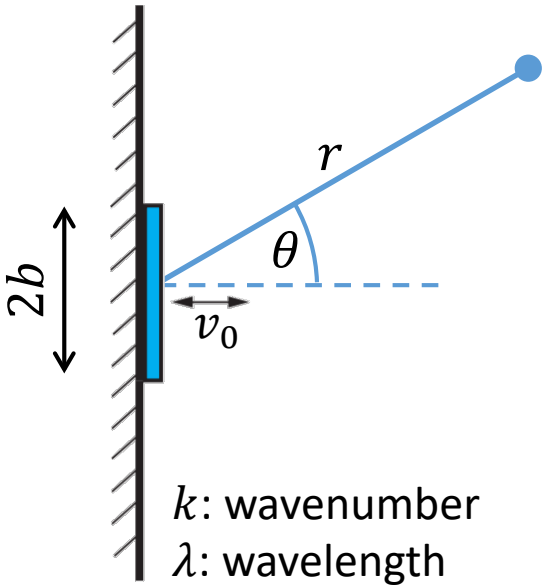
2D acoustic wave equation:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

$$\hat{P} = \mathcal{F}(p) \quad \Rightarrow \quad \frac{\partial^2 \hat{P}}{\partial x^2} + \frac{\partial^2 \hat{P}}{\partial z^2} + \frac{\omega^2}{c^2}\hat{P} = 0$$

1-D element model

1. linear piston in a rigid baffle
2. piston vibrating with a uniform normal velocity
3. high frequency; far field
4. $\Rightarrow kr \gg 1; r \gg \pi b^2/\lambda$



k: wavenumber
λ: wavelength

directivity of the element:

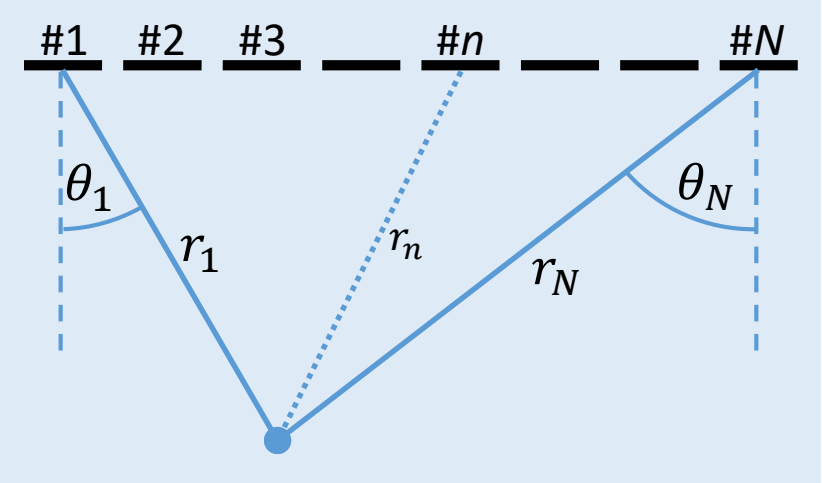
$$D_b(\theta, k) = \mathrm{sinc}(kb \sin\theta)$$

$$\boldsymbol{p(x, z, \omega, t)} = \boldsymbol{\rho c v_0(\omega)} \sqrt{\frac{2}{i\pi}} \boldsymbol{kb\, D_b(\theta, k)} \frac{\boldsymbol{e^{ikr}}}{\sqrt{\boldsymbol{kr}}} \boldsymbol{e^{-i\omega t}}$$

1-D array

The acoustic field of a 1-D array is the sum of the acoustic fields generated by the single elements

(linear acoustics)

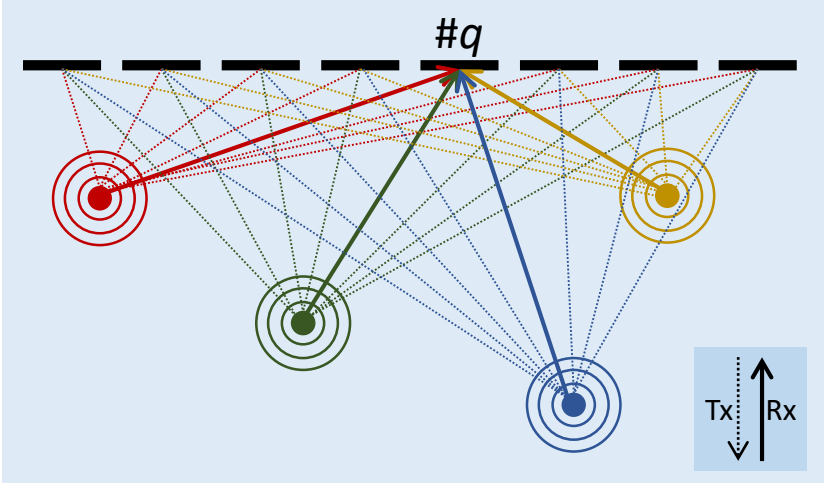


$$p(x, z, \omega, t) = \rho c v_0(\omega) \sum_{n=1}^{N} W_n e^{i\omega\Delta\tau_n} \left[\sqrt{\frac{2}{i\pi}} kb\, D_b(\theta_n, k) \frac{e^{ikr_n}}{\sqrt{kr_n}} \right] e^{-i\omega t}$$

W: apodization
$\Delta\tau$: delay

echo signals

1. The acoustic scatterers become individual monopole point sources when the incident wave reaches them (**cylindrical waves in 2-D**; **spherical waves in 3-D**)
2. The scatterers do not acoustically interact with each other (**single scattering**)



BSC: backscattering coefficient

$$p_q(\omega,t) = \left(\rho c\sqrt{kb}\,v_0(\omega)\right)\sum_{m=1}^{\#\text{ of particles}}\left[\mathrm{BSC}_m\left(\sum_{n=1}^{N} W_n e^{i\omega\Delta\tau_n}\left[D_b(\theta_{nm},k)\frac{e^{ikr_{nm}}}{\sqrt{r_{nm}/b}}\right]\right)D_b(\theta_{qm},k)\frac{e^{ikr_{qm}}}{\sqrt{r_{qm}/b}}\right]e^{-i\omega t}$$

Field II *vs.* SIMUS

Field II



SIMUS



Time-based	frequency-based
Matlab m + mex files	*Matlab* fully open codes
	included in MUST

presently, only in 2-D

GENERATION OF REALISTIC SYNTHETIC ULTRASOUND IMAGES

A synthetic approach based on physical simulators

Olivier Bernard

CREATIS

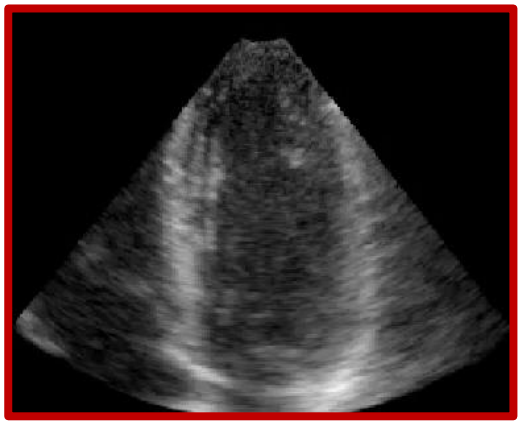
University of Lyon, France

Cardiovascular diseases

▶ Cardiac imaging

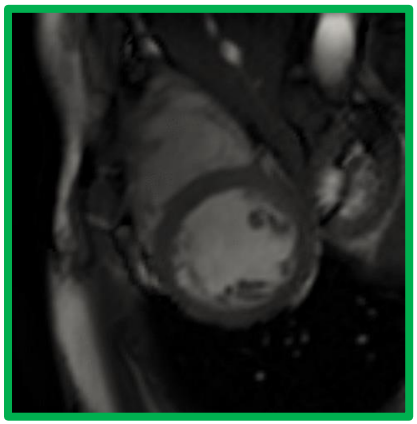
- Assessment of cardiac function (diagnosis / patient follow-up)
- Different modalities for different needs

US



Most common modality (safe, cheap, portable)

Cine MR



More advanced examination (better image contrast)

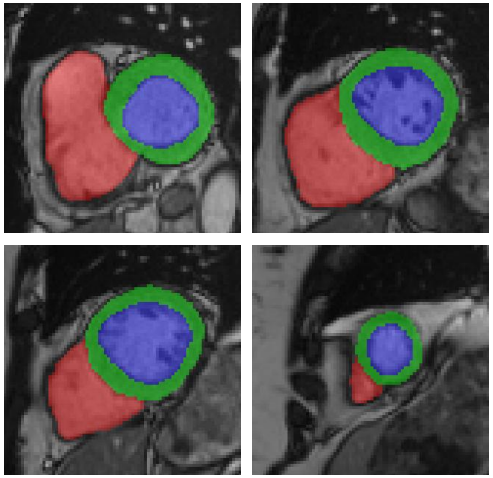
Tagged MR



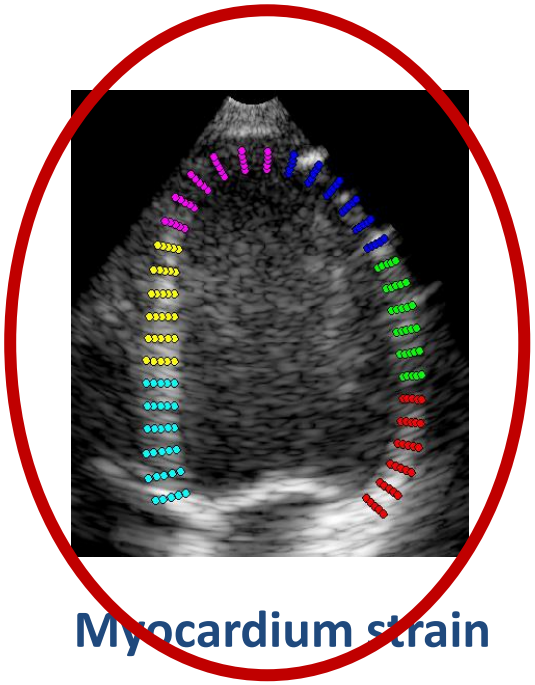
Gold standard for motion quantification

Cardiovascular diseases

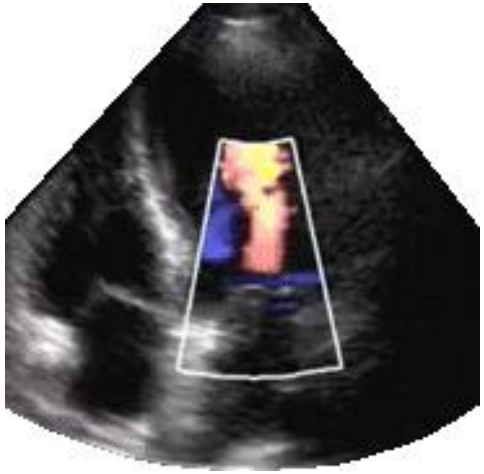
- **Cardiac function analysis through**
  - **Anatomical measurements** — **Volumes / Ejection fraction**
  - **Dynamic measurements** — **Strain / Flow / Doppler**



Ejection Fraction



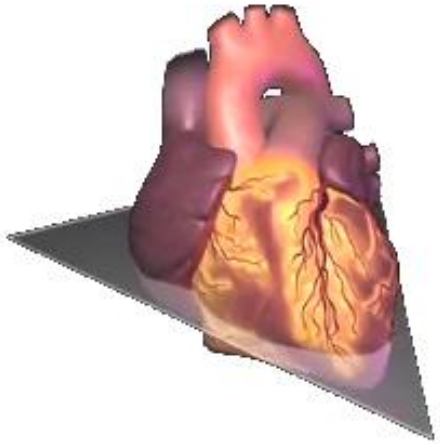
Myocardium strain

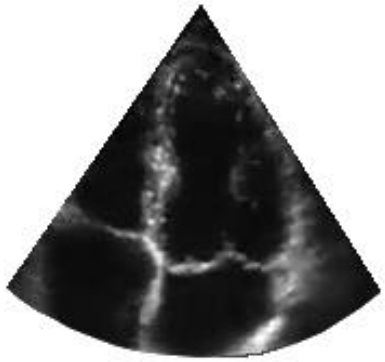


Color Doppler

Strain imaging – echocardiography illustration

Apical 4 chambers view







Short axis view

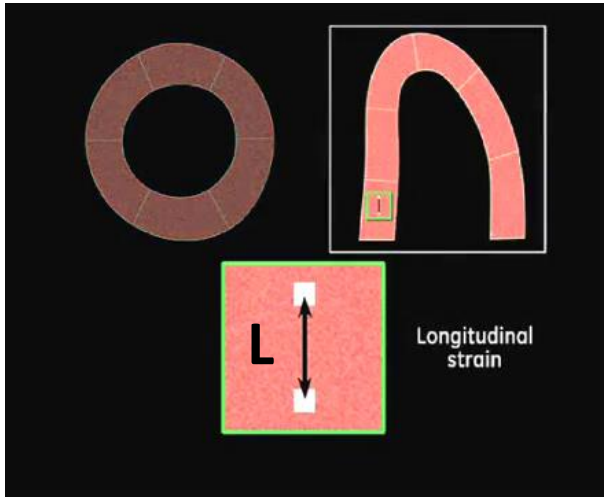




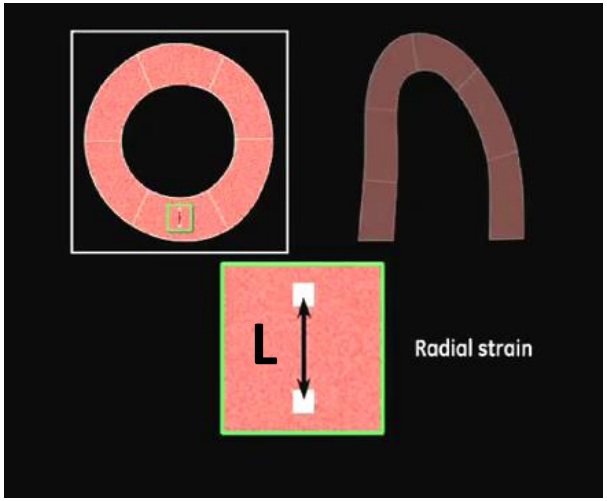


Strain imaging – echocardiography illustration

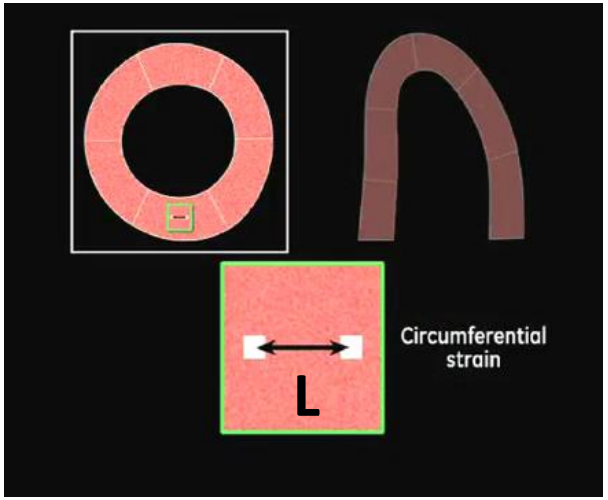
Longitudinal



Radial



Circumferential

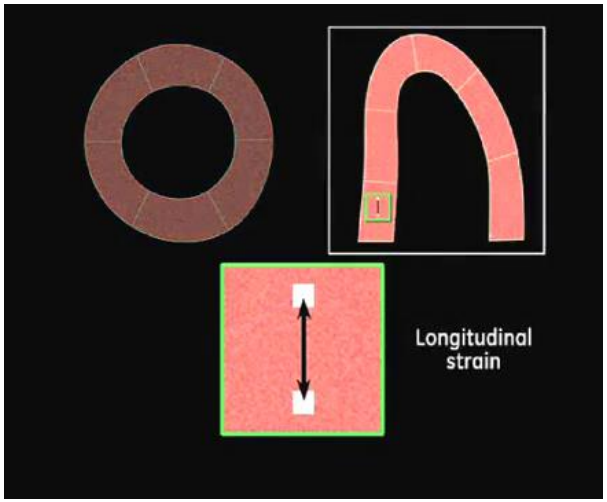


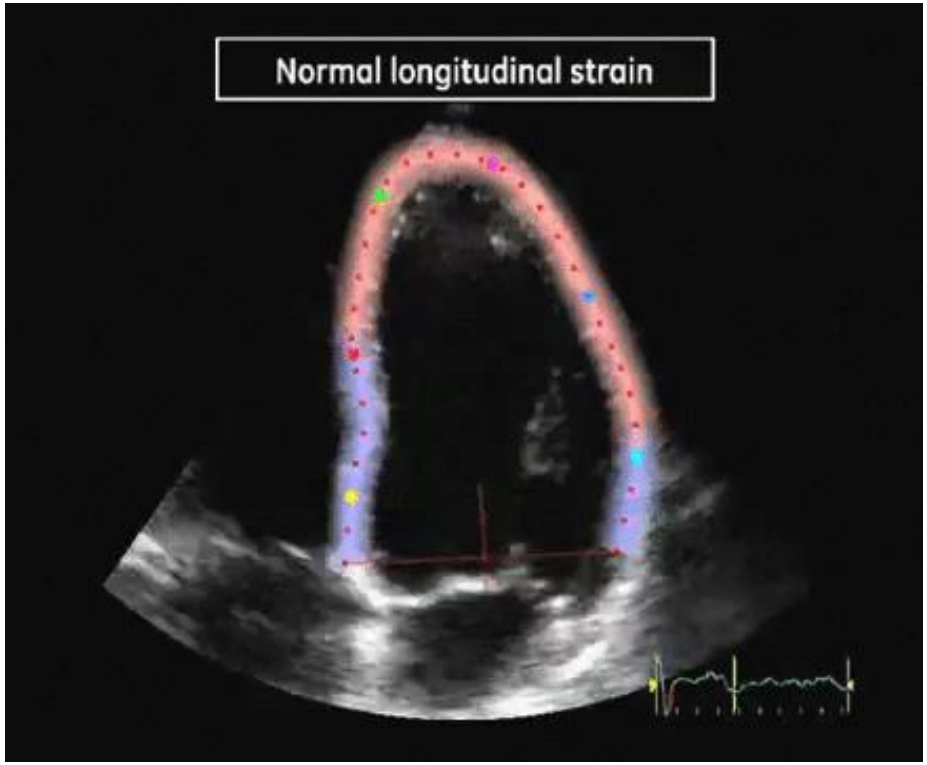
Normalized deformation

$$e = \frac{\Delta L}{L}$$

Echocardiography illustration

Longitudinal strain

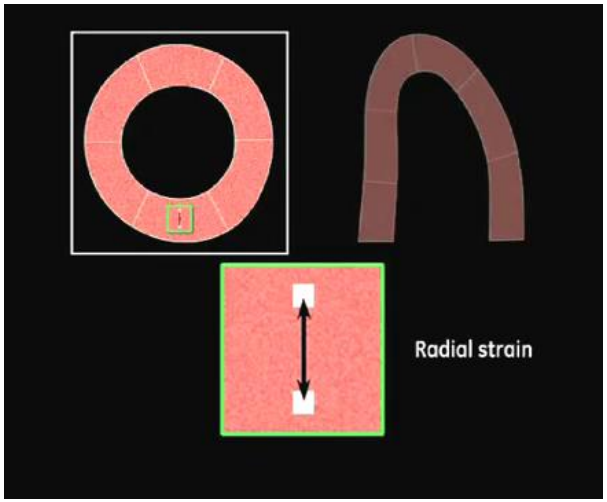


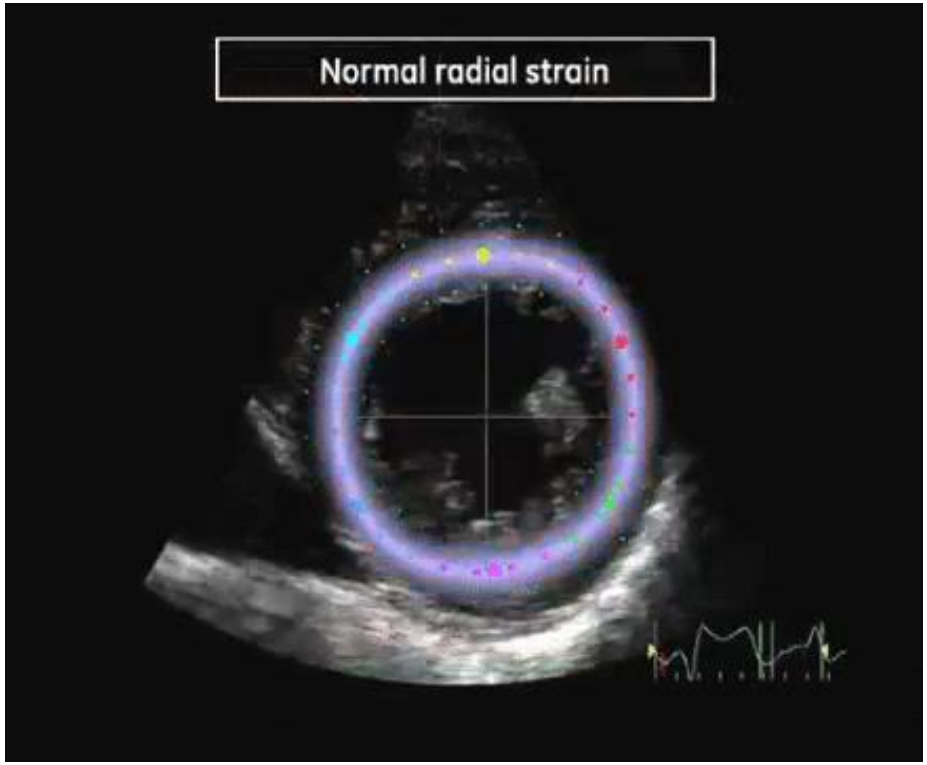


Source: GE Healthcare web site

Echocardiography illustration

Radial strain

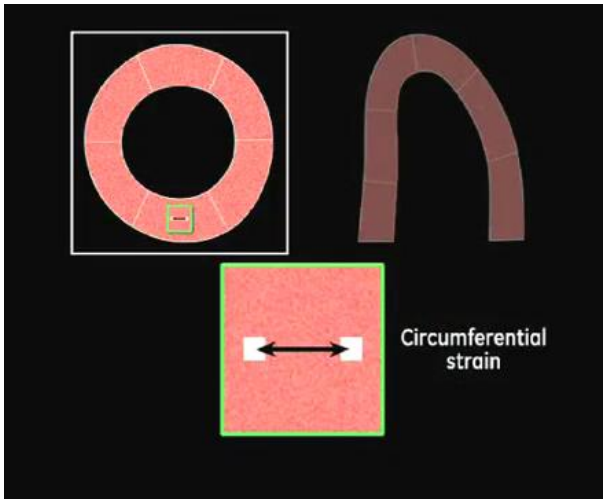


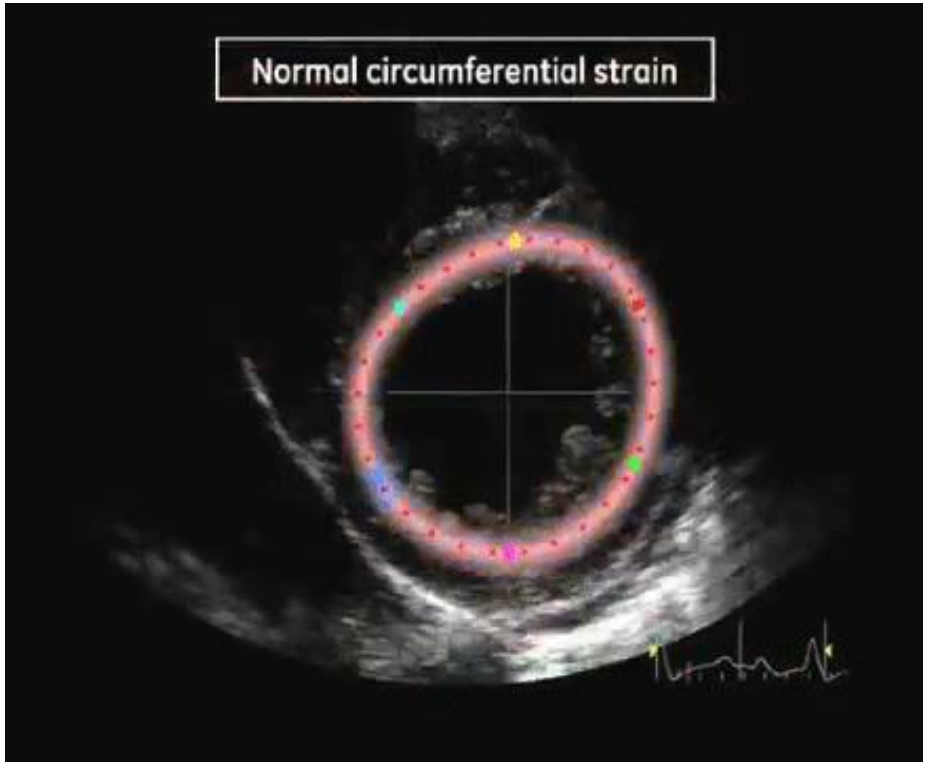


Source: GE Healthcare web site

Echocardiography illustration

Circumferential strain

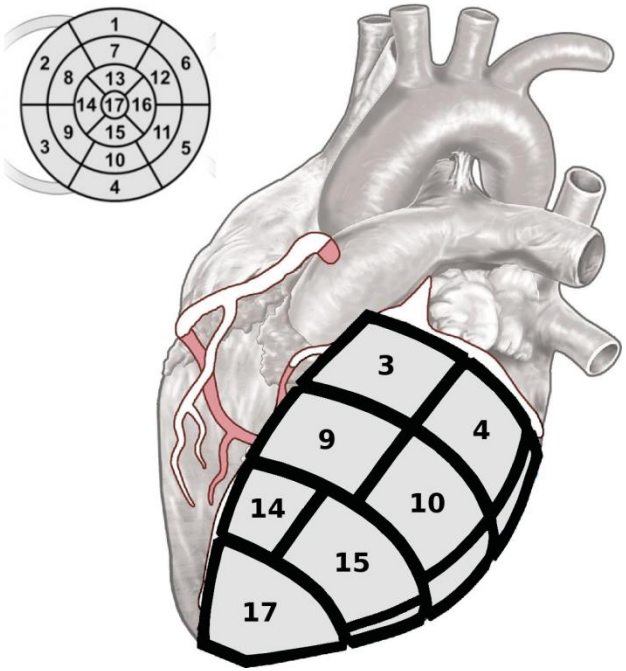


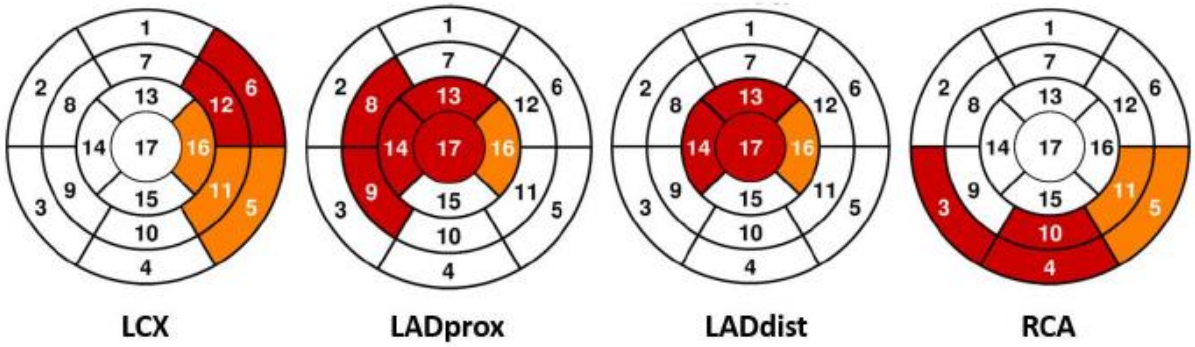


Source: GE Healthcare web site

Myocardial strain

- Sensitive to change of systolic function
  - Strong potential for detecting heart diseases at early stage
- Ischemic case: reduced motion of specific segments

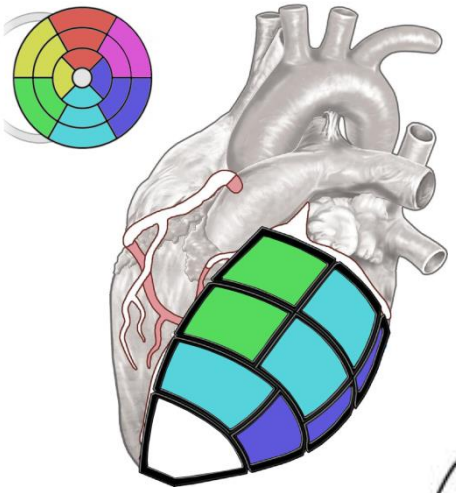




LCX:	Occlusion of Left Circumflex
RCA:	Occlusion of Right Coronary Artery
LADdist:	Distal occlusion of the Left Anterior Descending Artery
LADprox:	Proximal occlusion of the Left Anterior Descending Artery

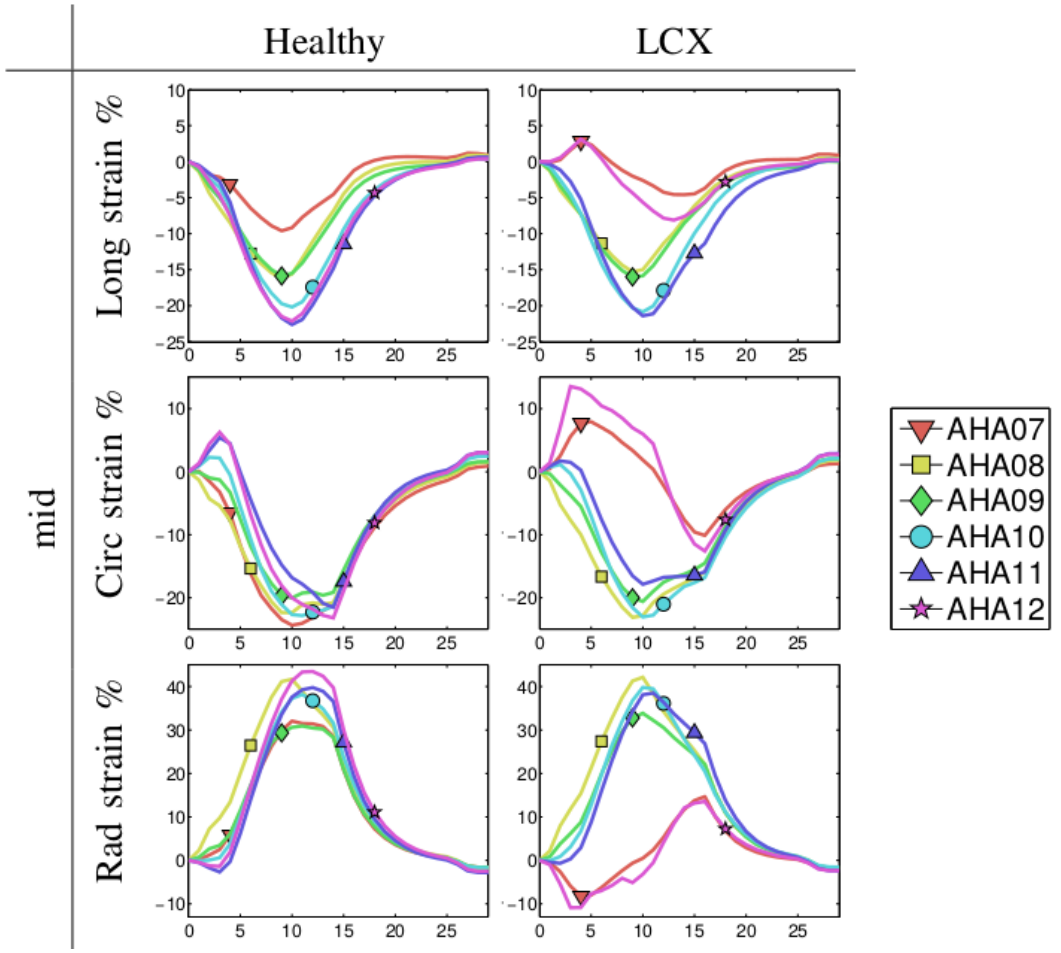
Myocardial strain

- **LCX example**





LCX



Myocardial strain

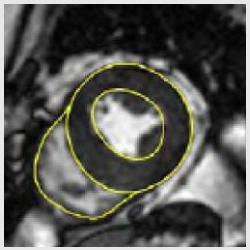
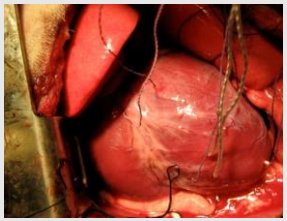
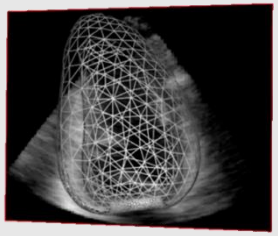
- So everything is beautiful in a wonderful word ?
  - Not really…

➔ Strain measurements are not reproducible enough
➔ Needs for automatic and reproducible measurements

- Only global longitudinal strain (GLS) is used (in ultrasound)
- Regional strain NOT used (despite the clinical interests)

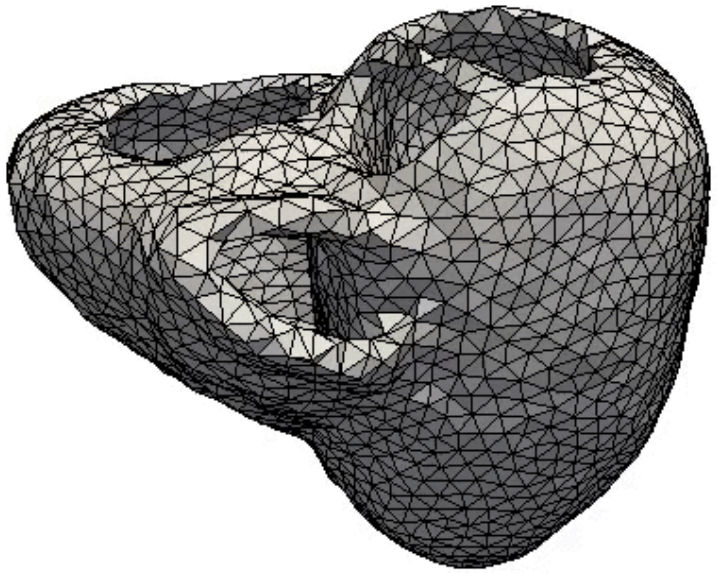
Solid quantitative validations are required

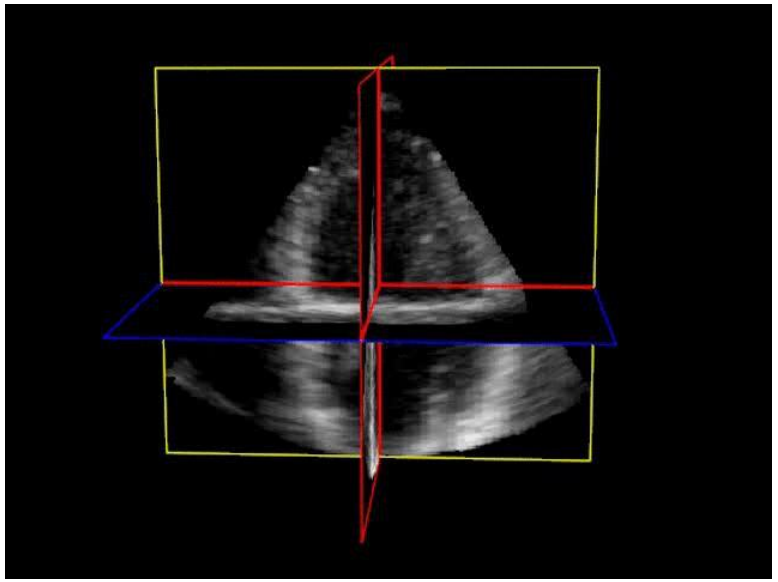
Validation of cardiac strain quantification

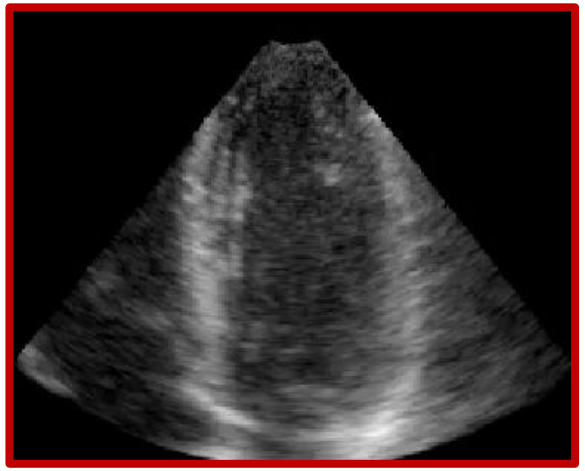
Manual tracking	Physical phantom	Animal experiments	Realistic synthetic images
			
Straightforward	**Real acquisitions**	**Measure strain directly**	**Dense strain Ground-truth**
• **Tedious** • **Inter and intra-expert variability**	• **Realism (image quality/involved structures) not yet sufficient**	• **Image quality is too good** • **Ethical question**	• **Let's see what's going on**

Generation of realistic synthetic images

Motivations





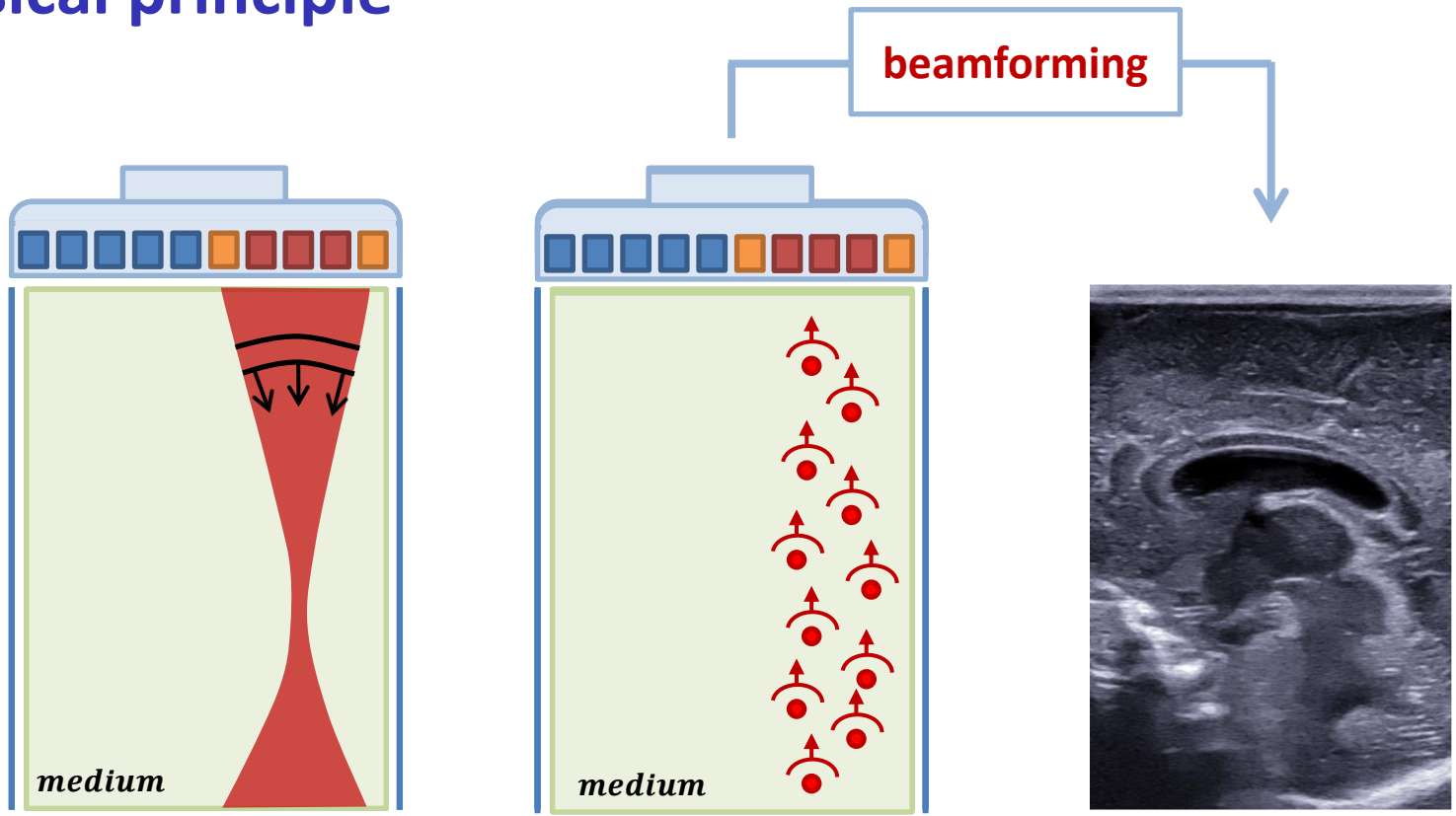


Generation of realistic synthetic images

Ultrasound modality

- **Physical principle**
- Physical simulator
- Proposed pipeline

Physical principle

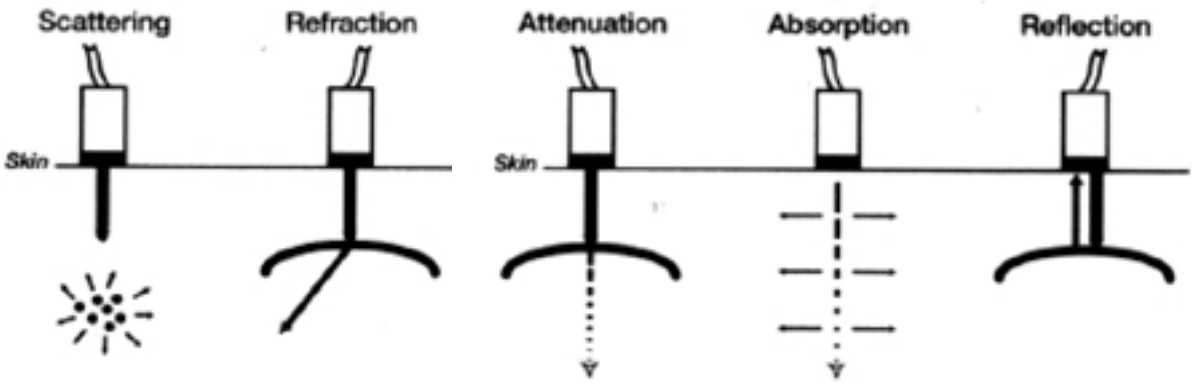


Typical frame rate: from 50 to 100 images / second

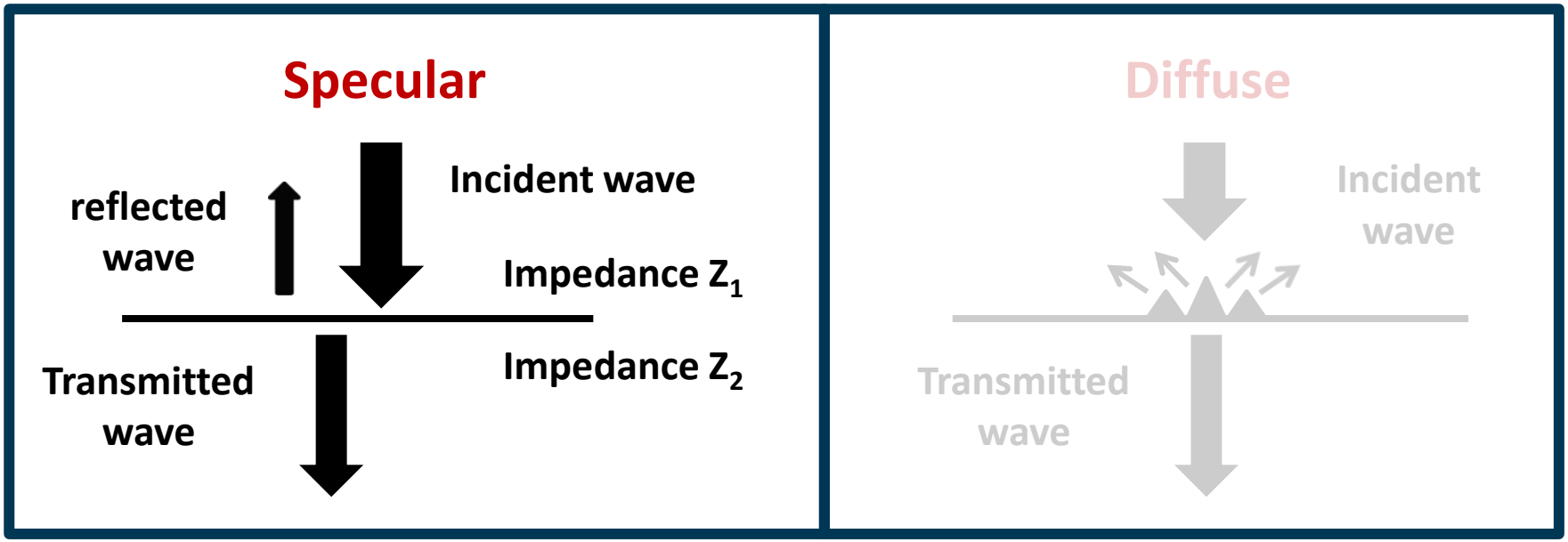
Interaction between wave and medium

- When propagating, acoustic waves
  - create expansion and contraction of the insonified medium
  - interact with the medium in many different ways

→ Reflection
→ Refraction
→ Scattering
→ Attenuation

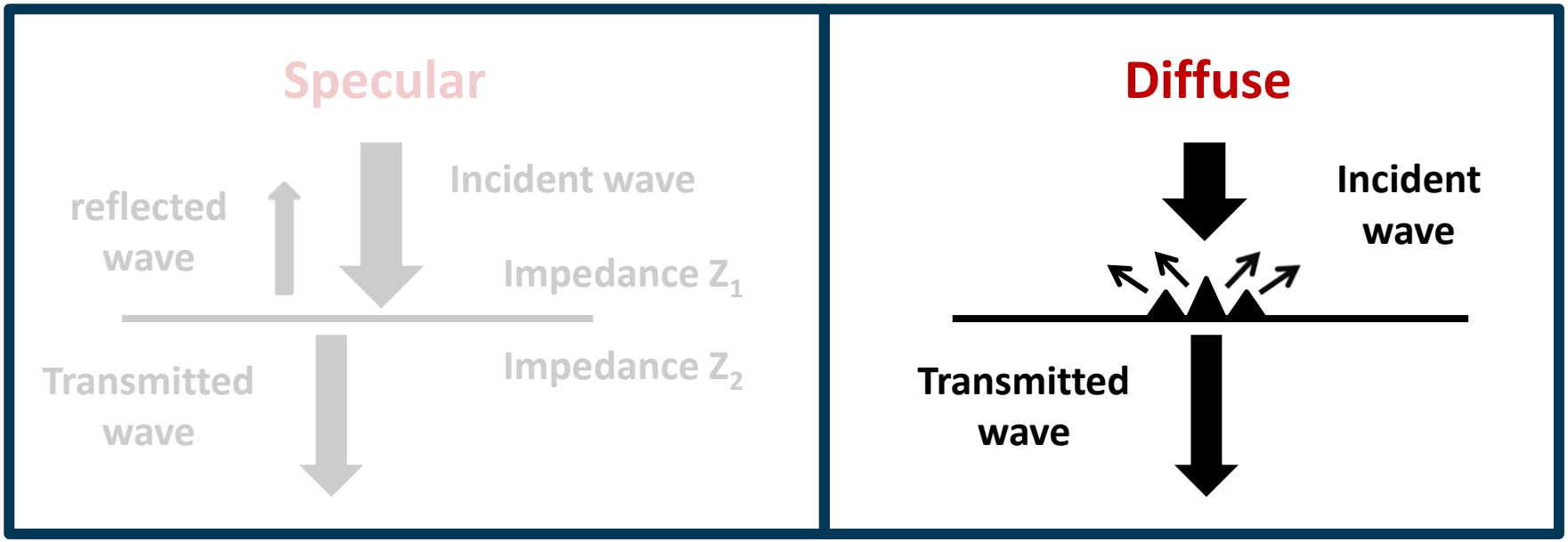


Interaction between wave and medium



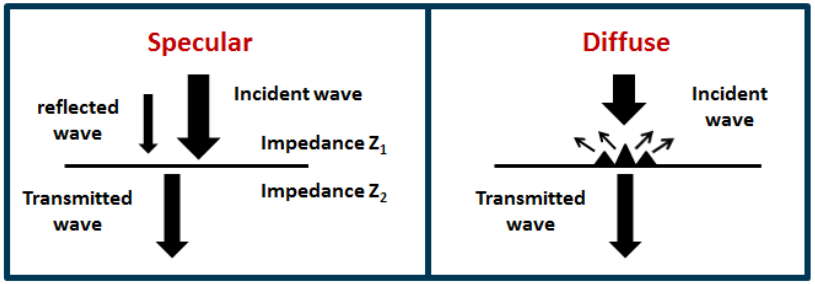
- **Specular**
  - Large reflector (dimensions $> \lambda$)
  - Smooth surface (*e.g.* bone)

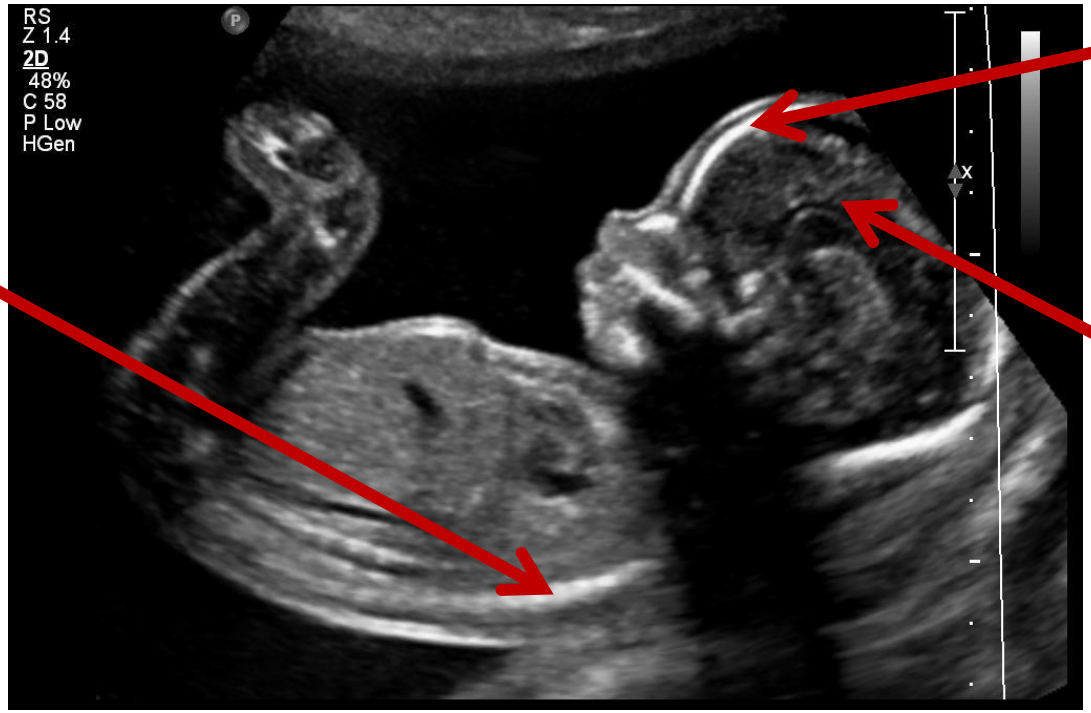
Interaction between wave and medium



- **Diffuse**
  - Rough surface (*e.g.* smooth tissue)
  - Wave is reflected in several directions

Interaction between wave and medium





Specular (skull)

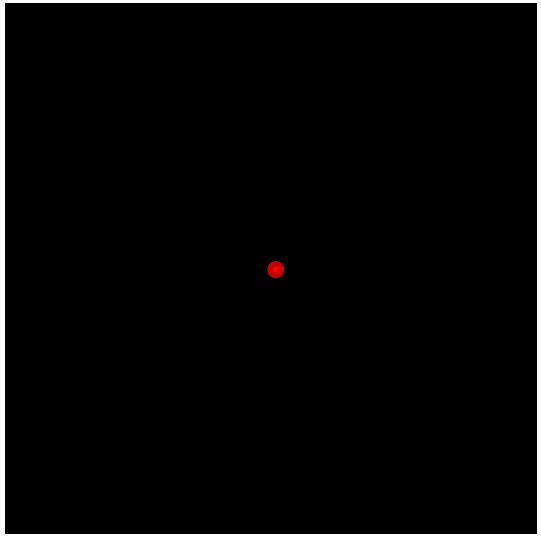
Specular (spine)

Diffuse (brain)

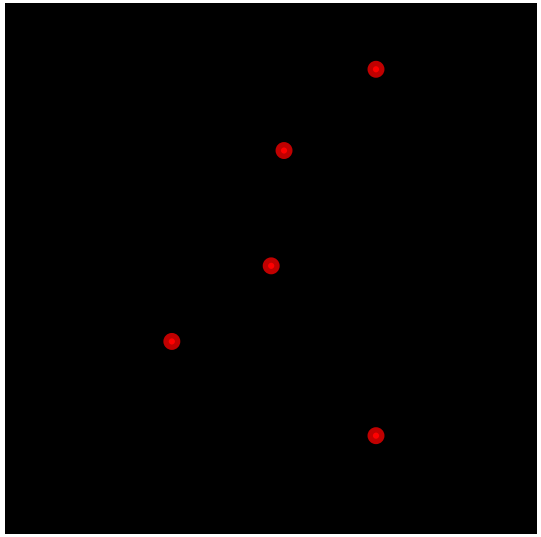
Interaction between wave and medium

▶ Scattering

- Structures with dimensions $< \lambda$
- Particularly true with blood (red cell dim ~8µm, λ>0.1mm)



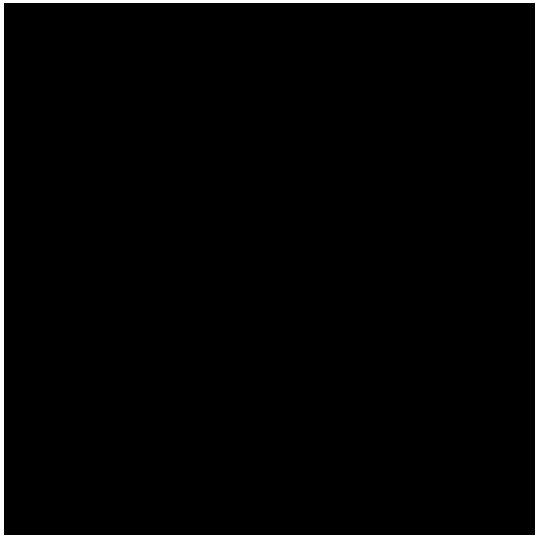
one scatterer



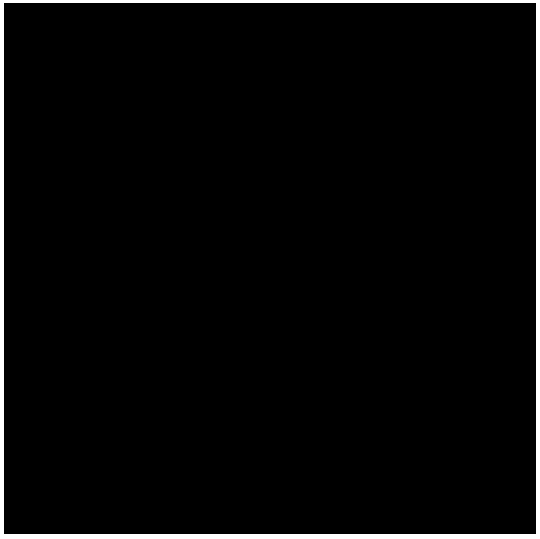
few scatterers

Interaction between wave and medium

- **Scattering**
  - Many scatterers => speckle phenomenon !



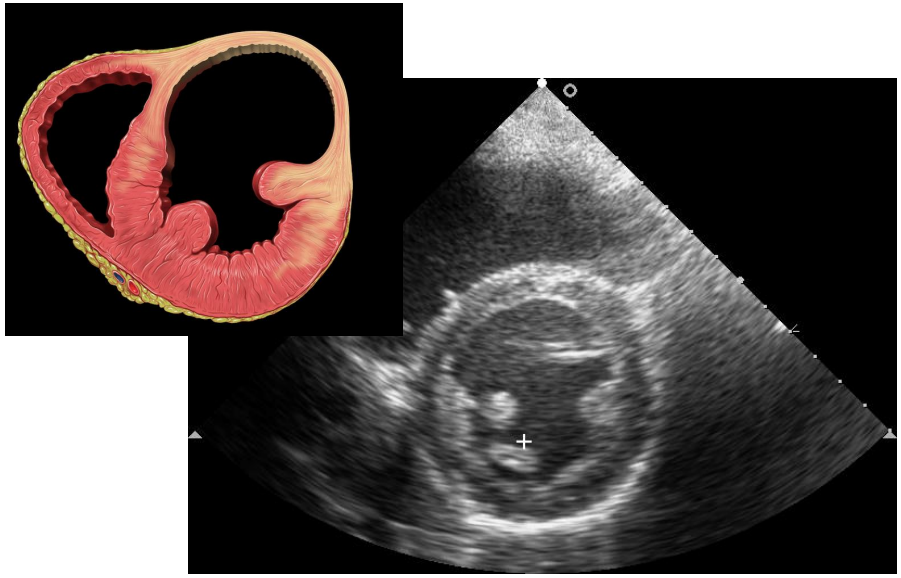
Plane wave



Focus wave

Interaction between wave and medium

- **Scattering**
  - Soft tissue behaves as a set of scattering points
  - Ultrasound image is mainly an interference imaging technique
  - Intrinsic speckle properties (local signature of the tissue)



Generation of realistic synthetic images

Ultrasound modality

- Physical principle
- **Physical simulator**
- Proposed pipeline

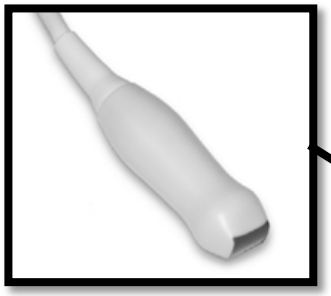
Physical simulator

- Several existing physical simulators in the literature
  - Field II (Cole) *https://field-ii.dk*
  - Creanuis *https://creatis.insa-lyon.fr/site7/fr/CREANUIS*
  - Simus *http://www.biomecardio.com*
  - …

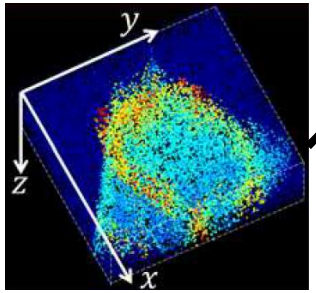
- Based on the same strategy
  - Modeling of the emitted field (linear / non-linear propagation)
  - Modeling of the insonified medium through points scatterers

Physical simulator

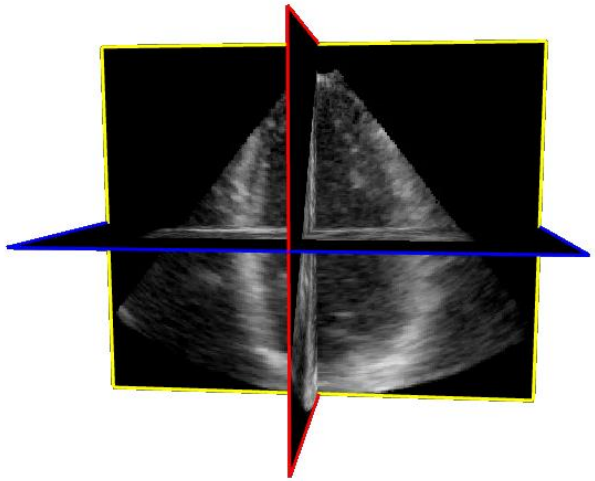
Probe settings



Medium definition

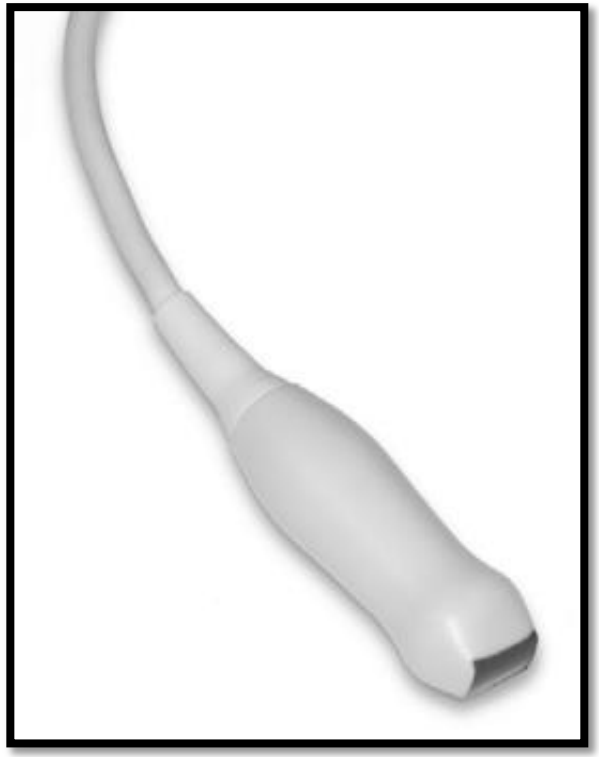


Physical simulator



Physical simulator – modeling of the emitted field

Ultrasound Probe design



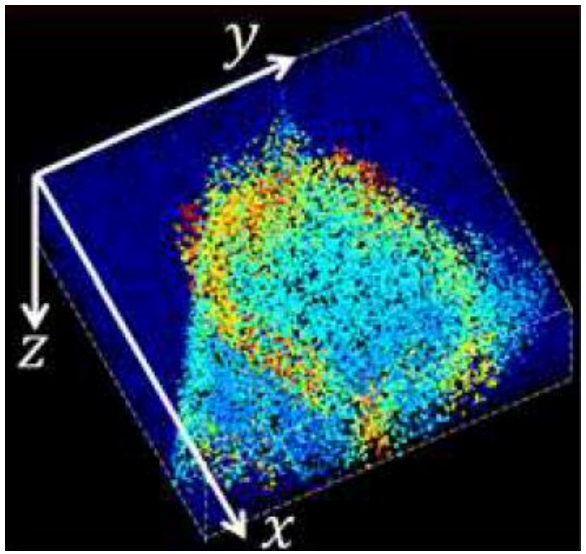
Cardiac probe

Linear phased-array

Properties	Value
Nb. of elements	64
Pitch	0,28 mm
Height	13 mm
Elevation focus	60 mm
Center Frequency	2.7 MHz
Bandwidth	60 %

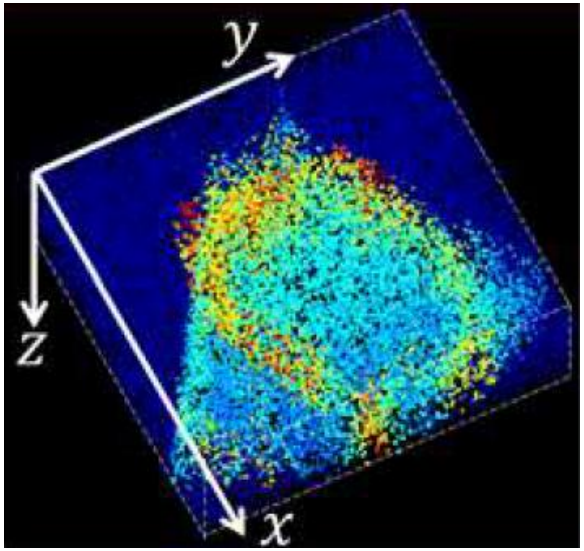
Physical simulator – modeling of insonified medium

- **Scattering map**
  $\{(x_i, y_i, z_i), a_i\}_{i \in [1,N]}$
  - positions (x_i, y_i, z_i)
  - amplitude a_i
  - number of scatterers ***N***
- **Specular reflection**
  - Strong amplitudes a_i
- **Scattering**
  - Many scatterers per resolution cell

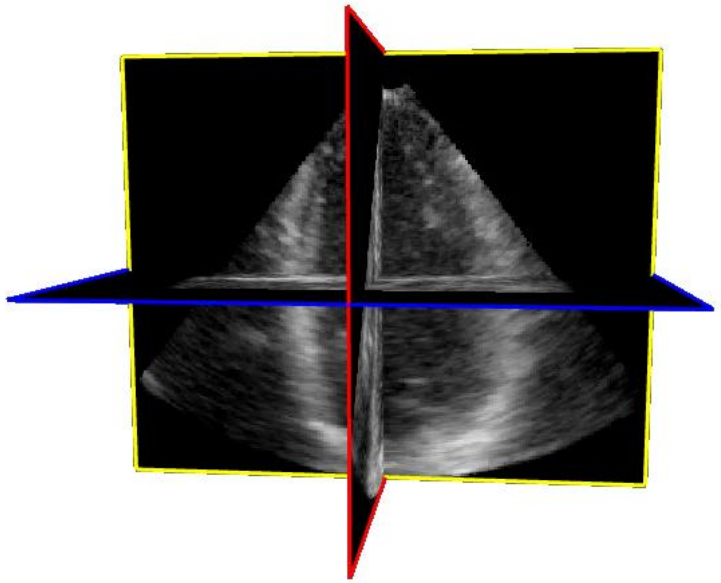


Physical simulator – modeling of insonified medium

- How to choose *N*, (x_i, y_i, z_i) and a_i ?



Physical simulator



Realistic synthetic image

Physical simulator – modeling of insonified medium

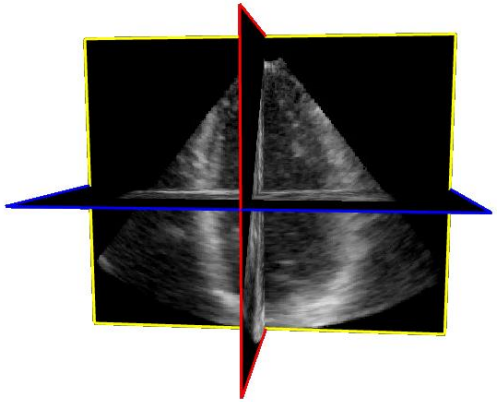
- **Scatterers position and number**
  - From the chosen probe settings
    - ➔ Compute the corresponding resolution cell ($\approx 0,5mm^3$)
  - From the dimensions of the image to simulate
    - ➔ Choose 20 scatterers per resolution cell (fully developed speckle)
    - ➔ Compute the corresponding total number of scatterers *N*

The *N* scatterers are then uniformly distributed over the image dimensions to fill the image space

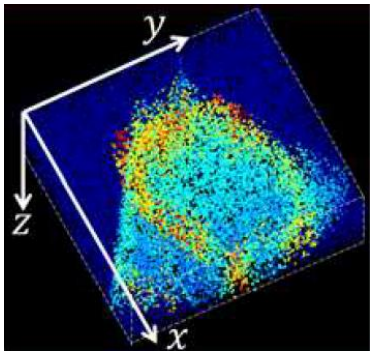
Scatterers amplitude

- Synthetic image-based approach

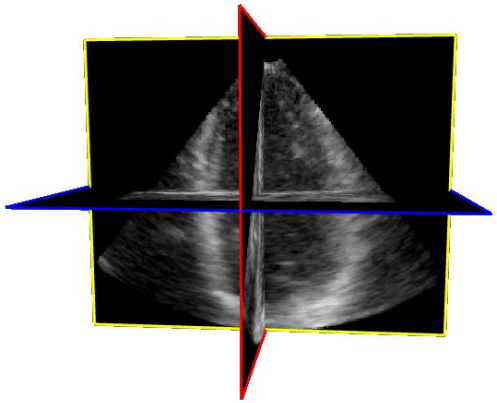
  ➔Compute the corresponding backscattered amplitude from a real image (template)



Real image



Scattering map

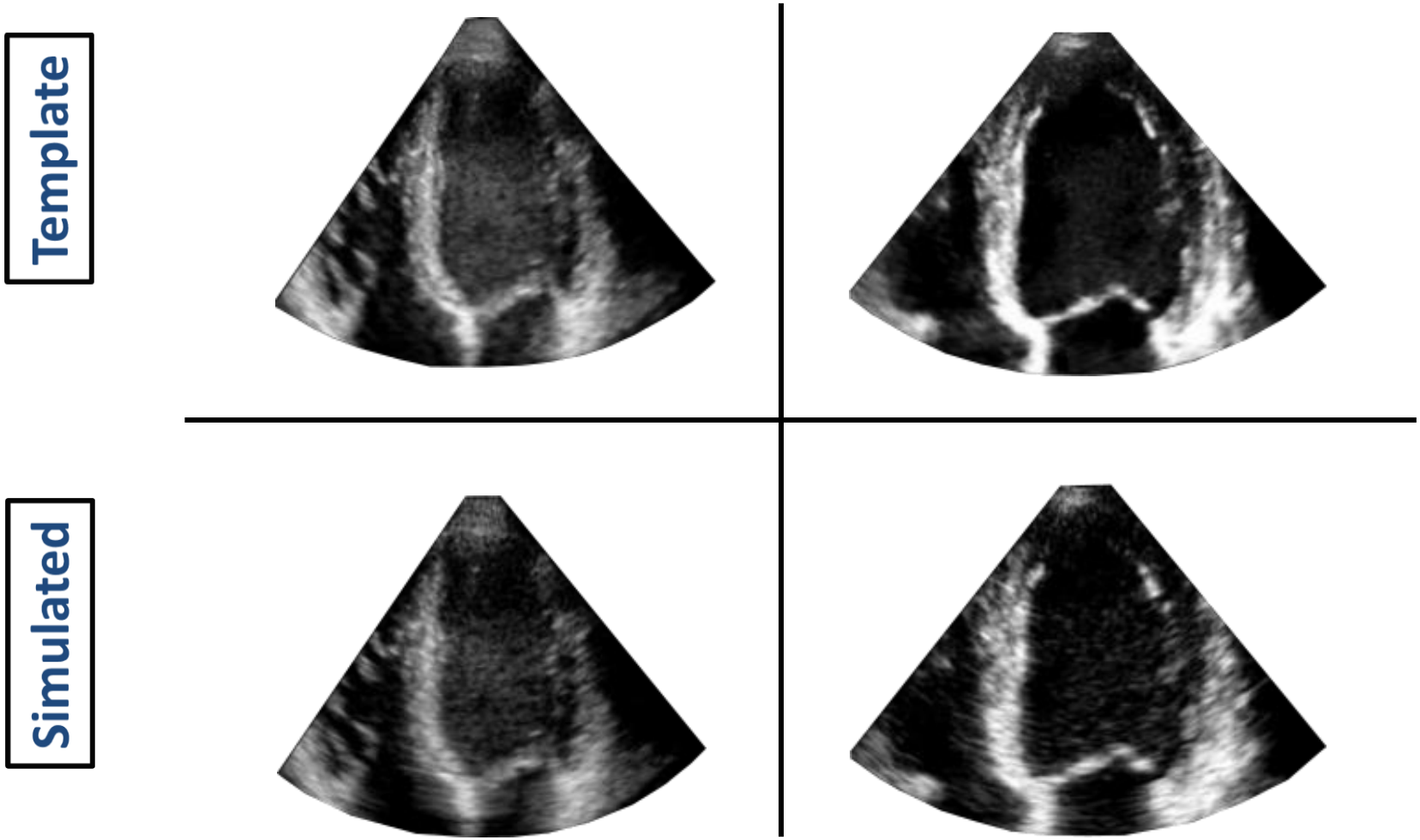


Synthetic image

$$a_i = 10^{\frac{dB_{range}}{20}\left(\frac{I}{I_{max}}-1\right)}$$

Cole

Static image simulation examples

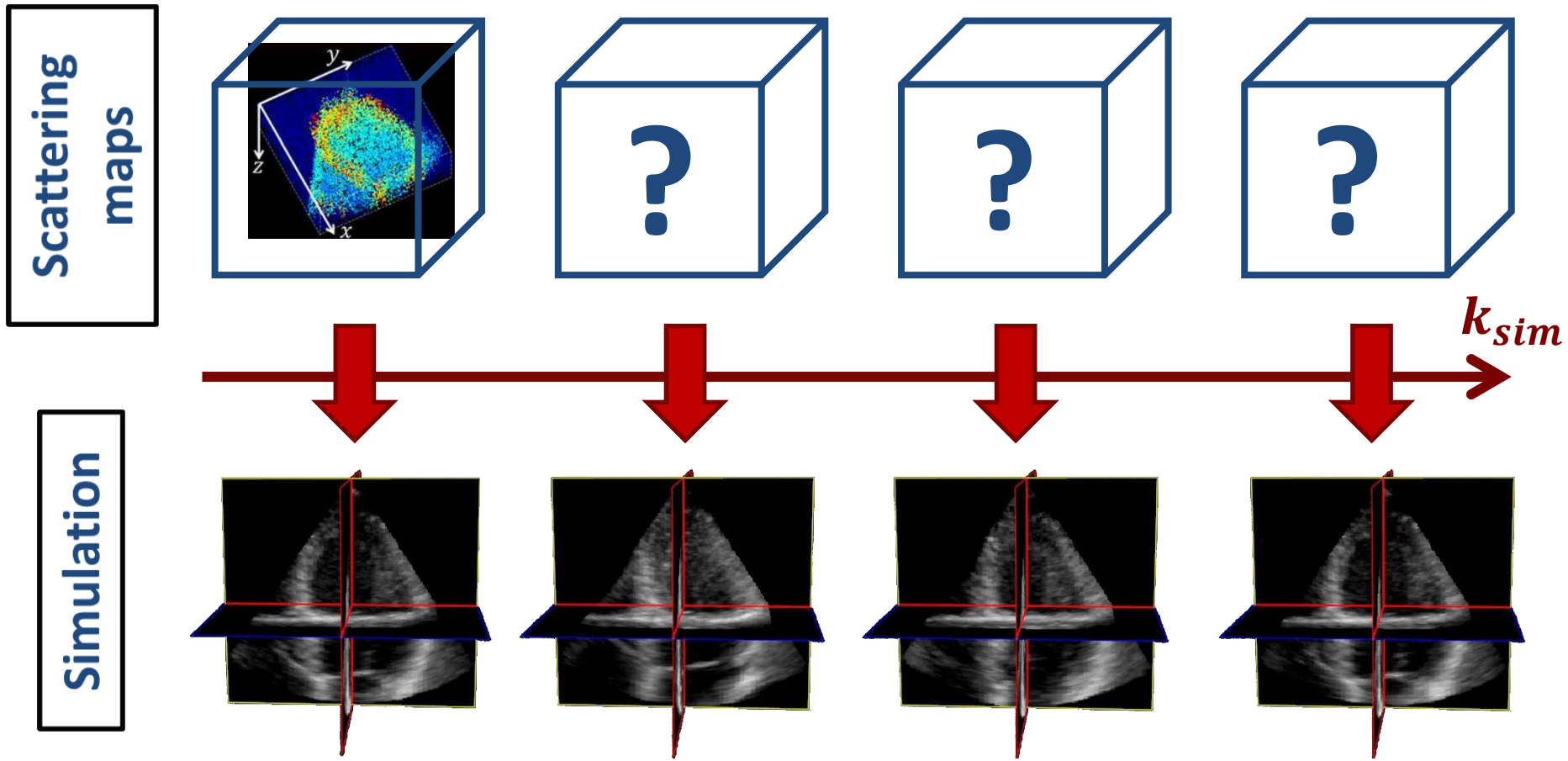


Generation of realistic synthetic images

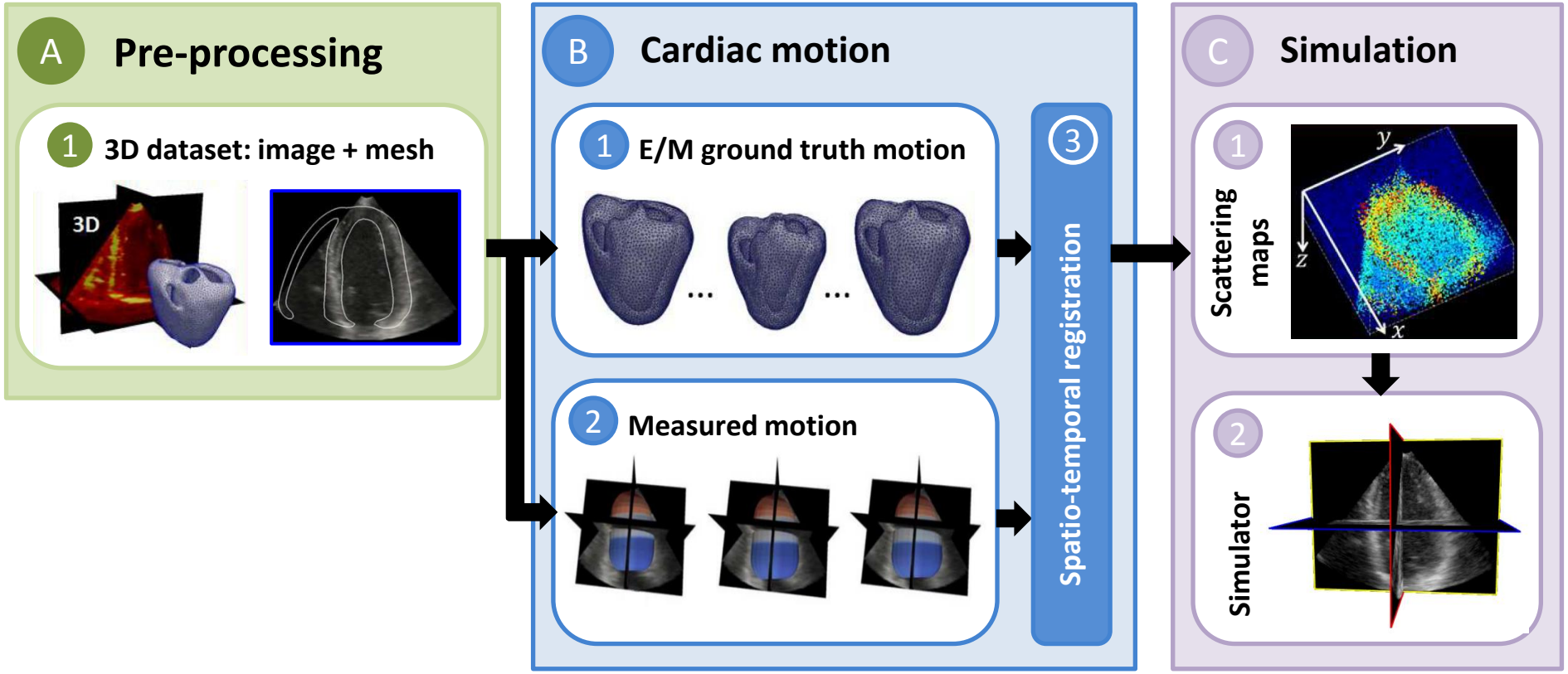
Ultrasound modality

- Physical principle
- Physical simulator
- **Proposed pipeline**

Temporal sequence simulation

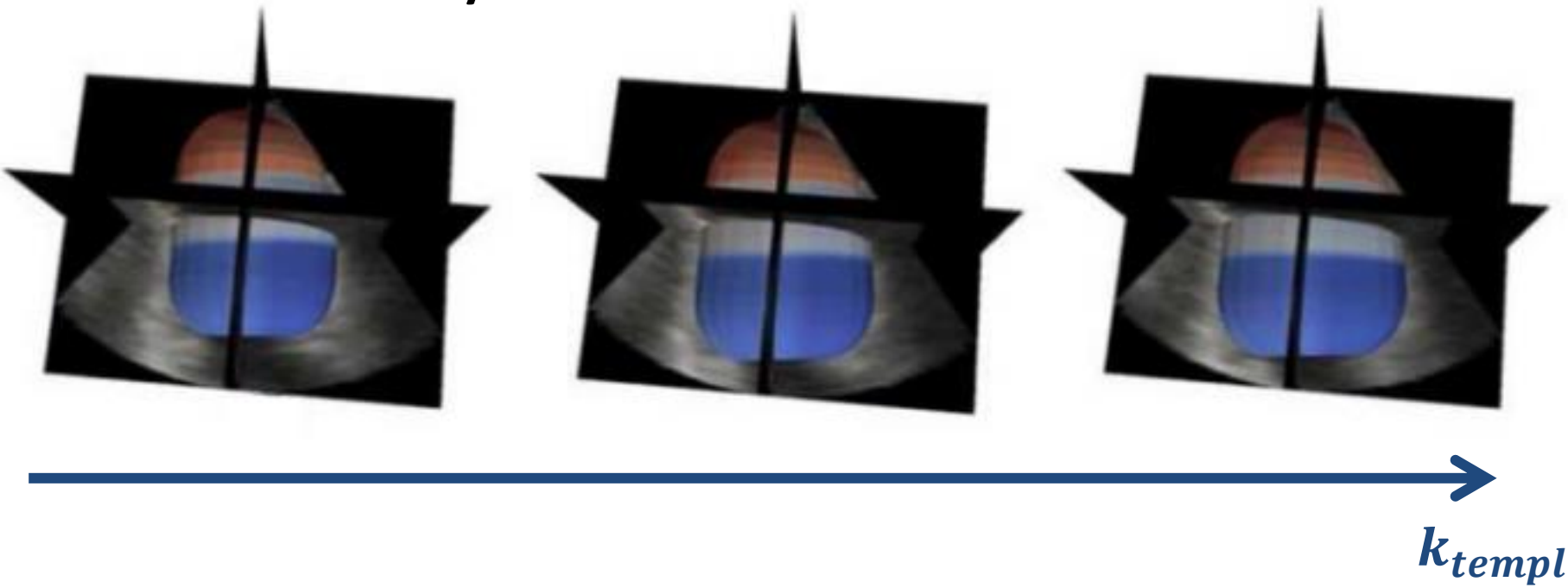


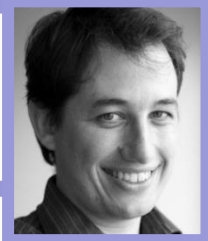
How to extend the simulation to a full sequence with the corresponding ground-truth ?



▶ Step A-1 ➔ Pre-processing

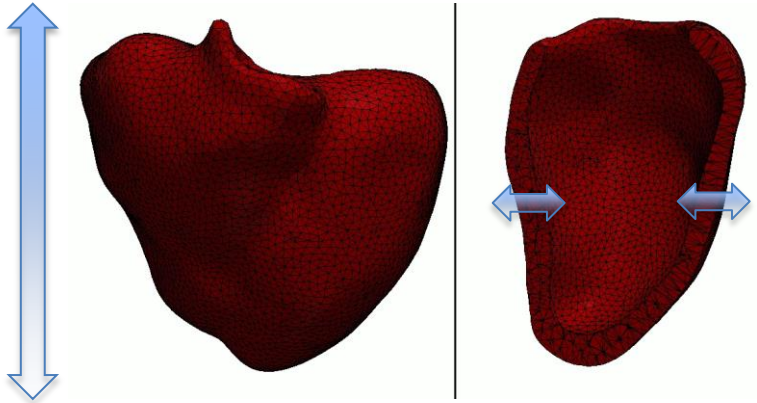
- Choose a given real sequence (template)
- Semi-automatic segmentation of the left-ventricle over the cardiac cycle



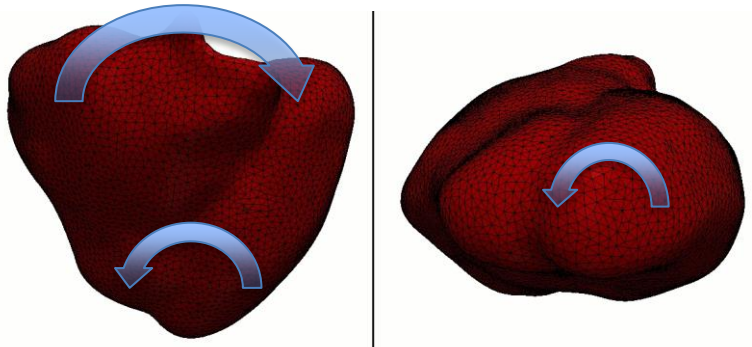


▶ Step B-1 ➔ Electromechanical ground-truth model

- **E/M model**
  - ***Electrical activation***
  - ***Mechanical contraction***
- **Biophysical parameters**
  - ***Myocardial contractility***
  - ***Stiffness***
  - ***Conduction***

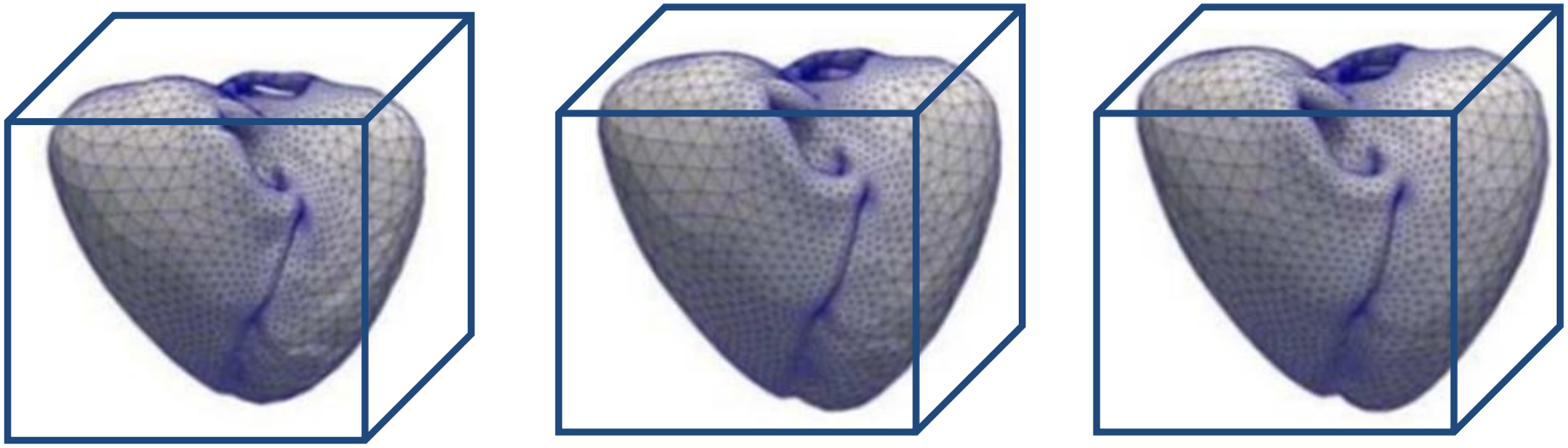


Long. motion Radial motion



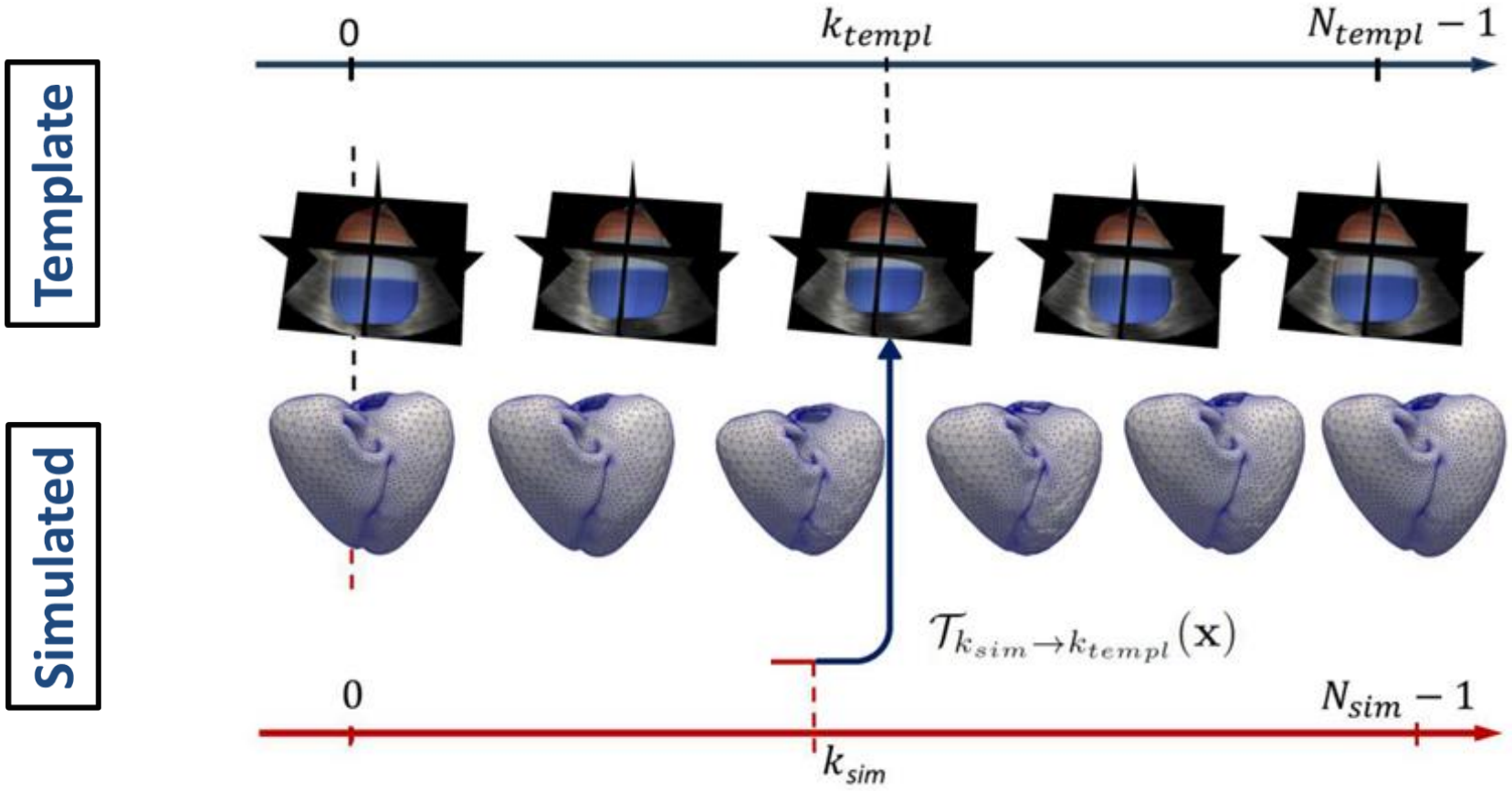
Inverse rotation torsion

▶ Step B-1 ➔ Electromechanical ground-truth model



k_{sim}

Step B-3 ➔ Spatio-temporal registration



▶ Step C-1 ➔ (Temporal) scattering maps

Myocardium scatterers

- **Backscattered amplitudes kept constant over the cardiac cycle**

  Speckle decorrelation is ensured thanks to the use of the physical simulator

- **Positions updated from the EM model**

  Motion reference

▶ Step C-1 ➔ (Temporal) scattering maps

Surrounding (non-myocardium) structure scatterers

- **Backscattered amplitudes re-estimated at each frame of the simulated cardiac cycle**

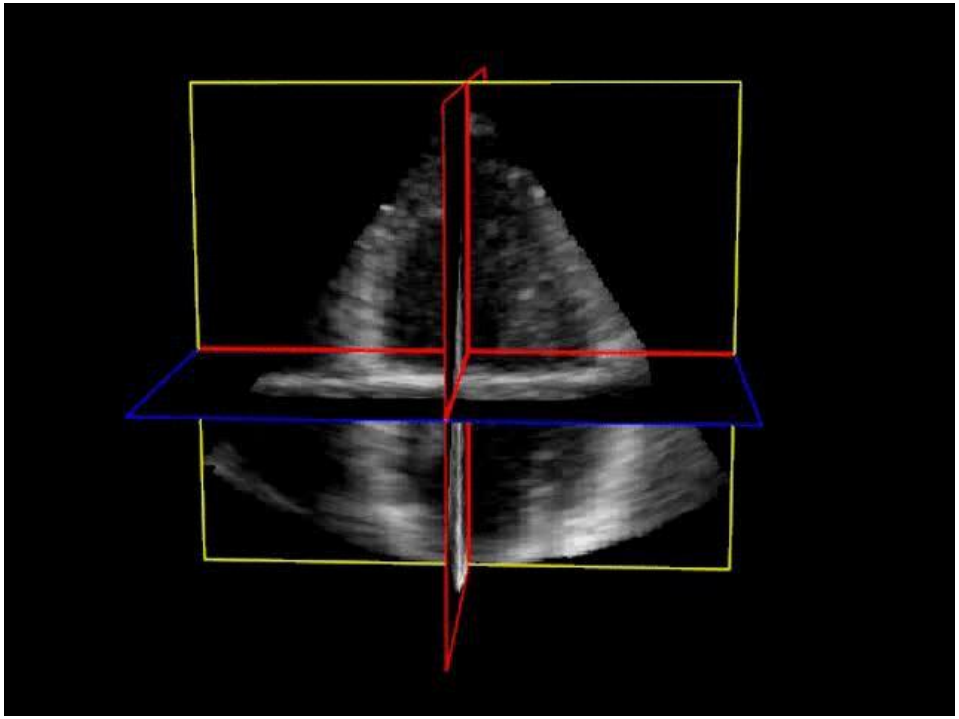
  Ensure the realistic nature of the simulation

- **Positions updated from the EM model**

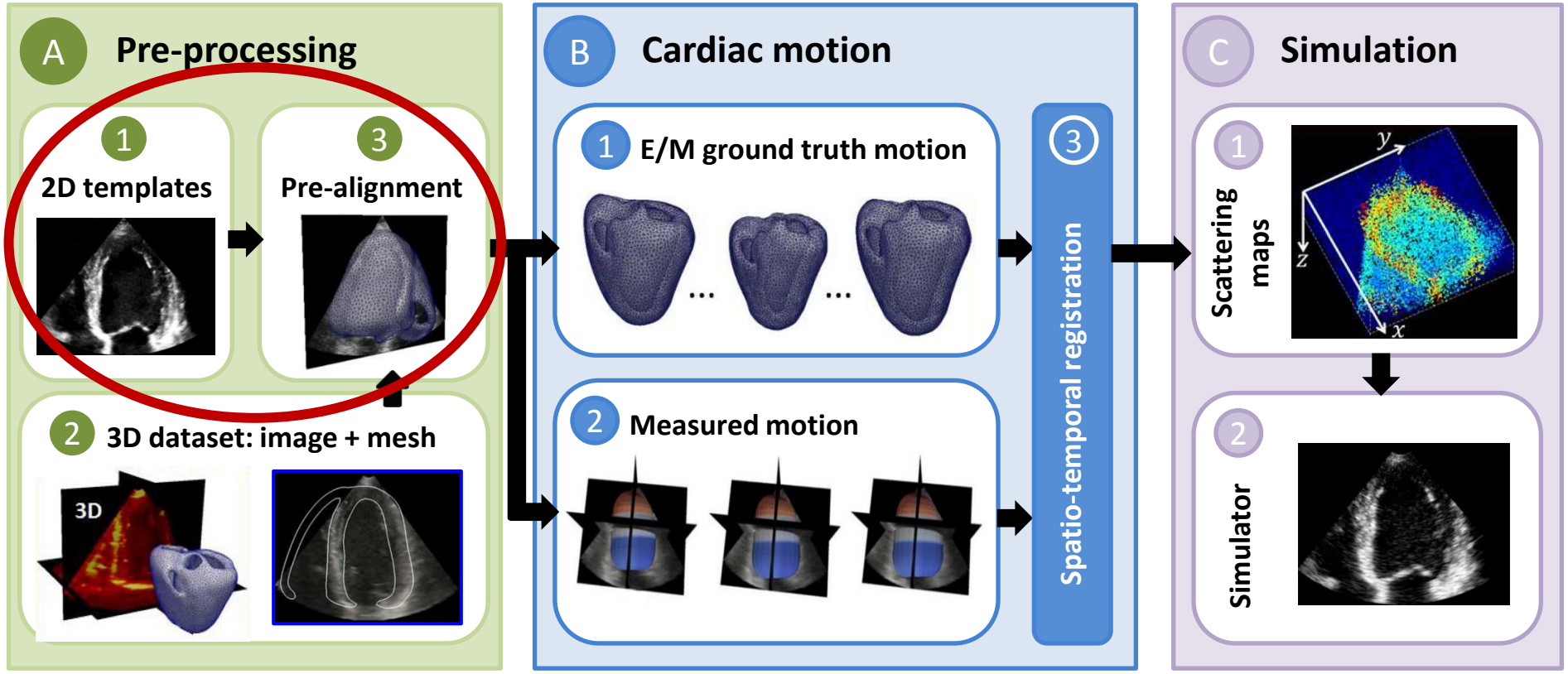
  Random positioning out of the myocardium region

▶ Step C-2 ➔ Physical simulation

Pipeline designed for 3D simulations

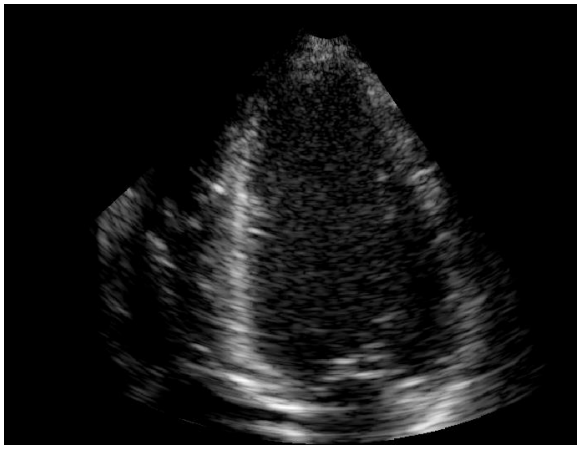


2D simulations: need additional steps

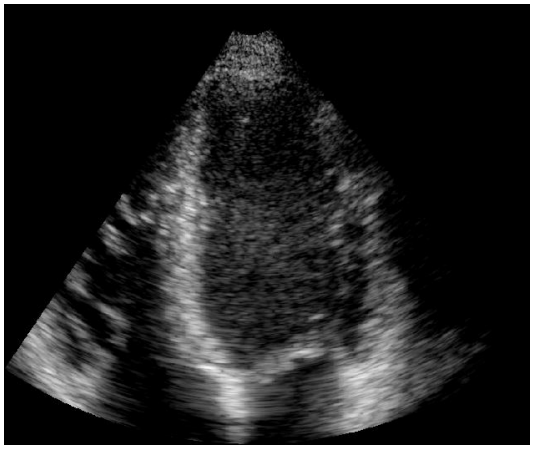


GENERATION OF REALISTIC SYNTHETIC ULTRASOUND IMAGES

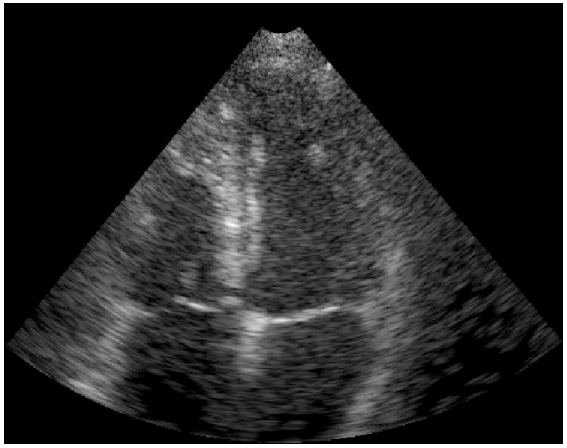
└ Ultrasound modality



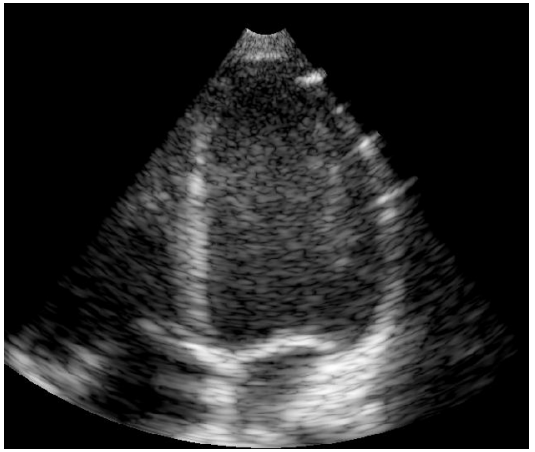
Vendor 1



Vendor 2



Vendor 3

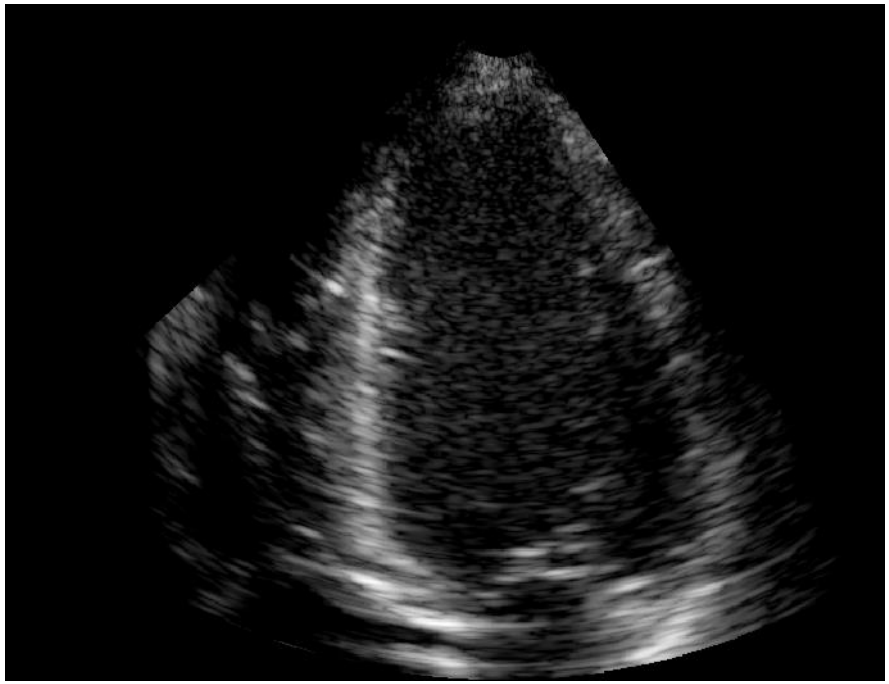


Vendor 4

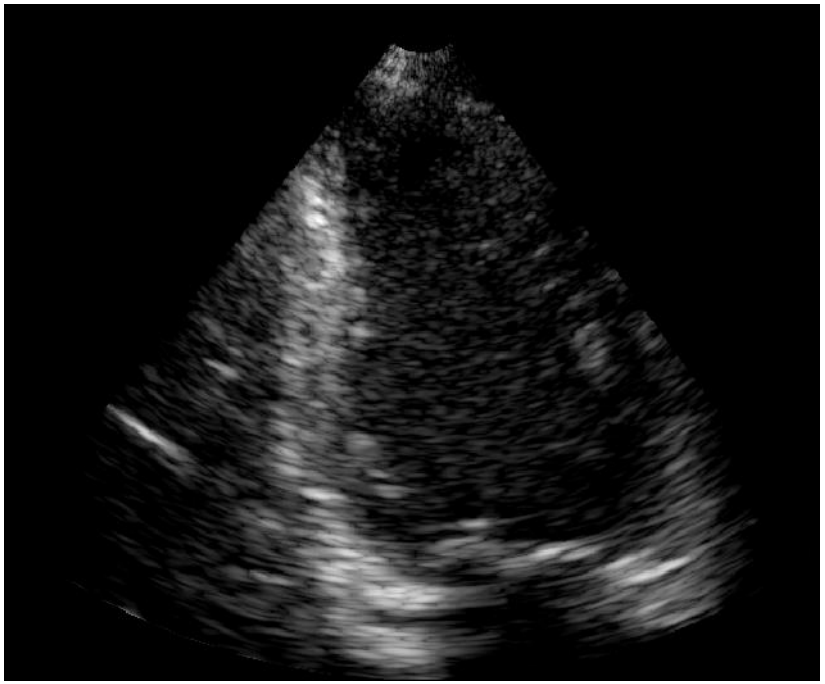
[Alessandrini et al. - TUFFC 2018]

Realistic synthetic 2D sequences

- **Normal case**



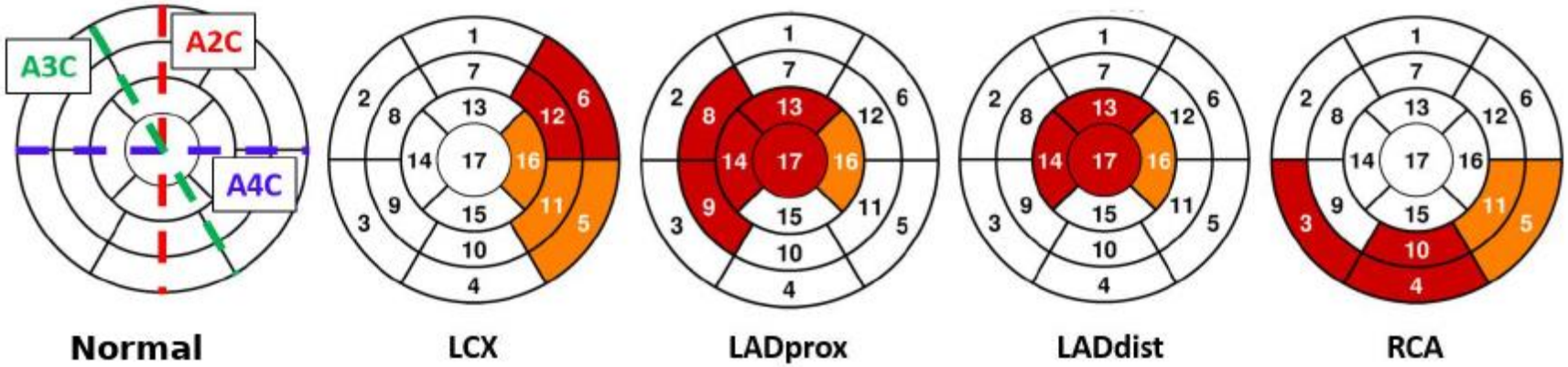
4CH



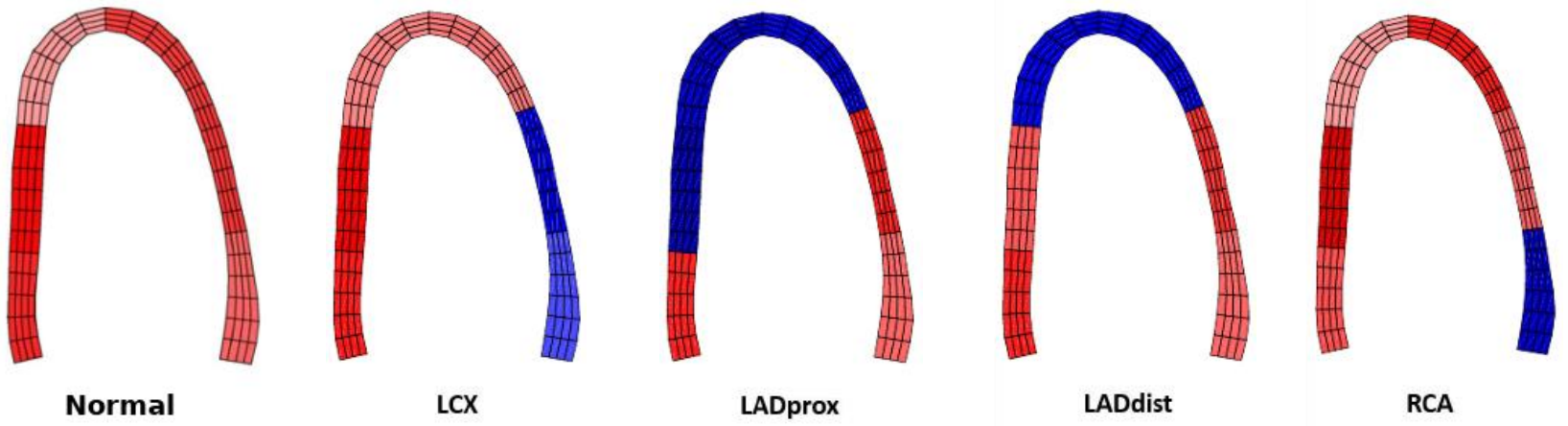
2CH

▶ E/M model ➔ introduction of controlled pathologies

Simulated ischemic region

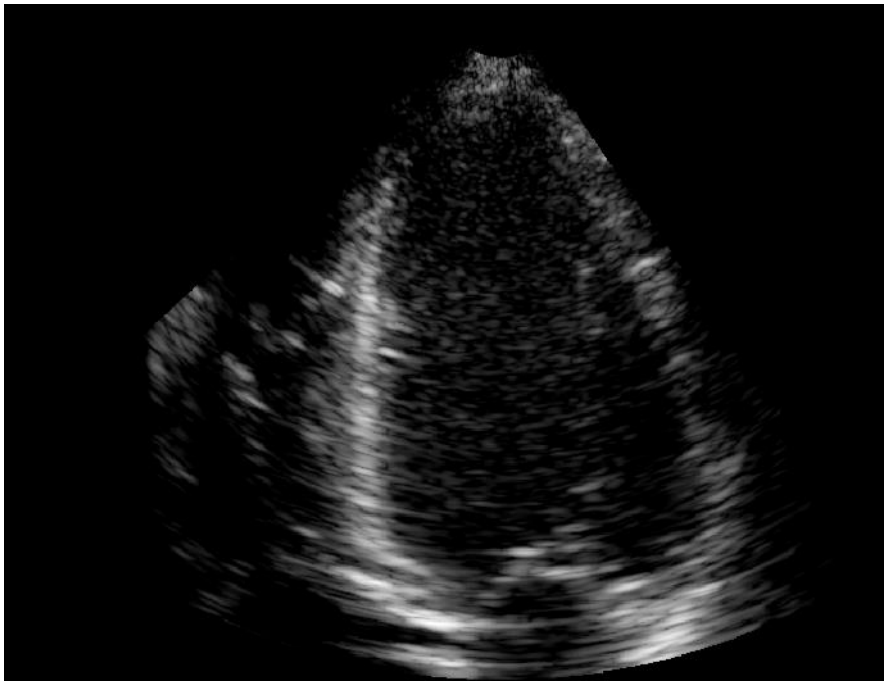


Longitudinal strain – A4C

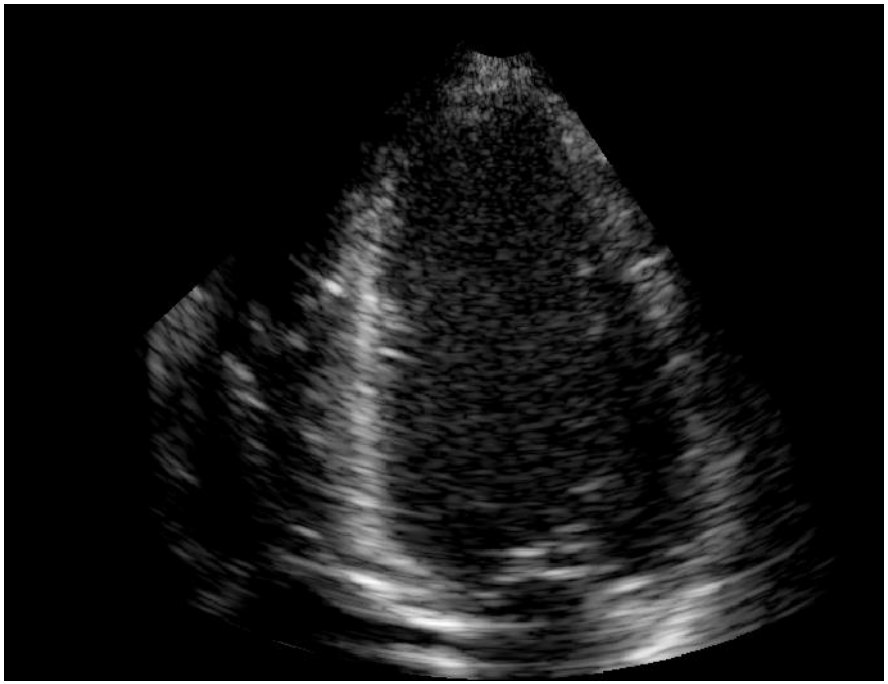


Time to play together…

- **Any diagnosis ?**



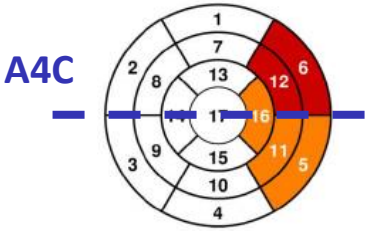
A4C

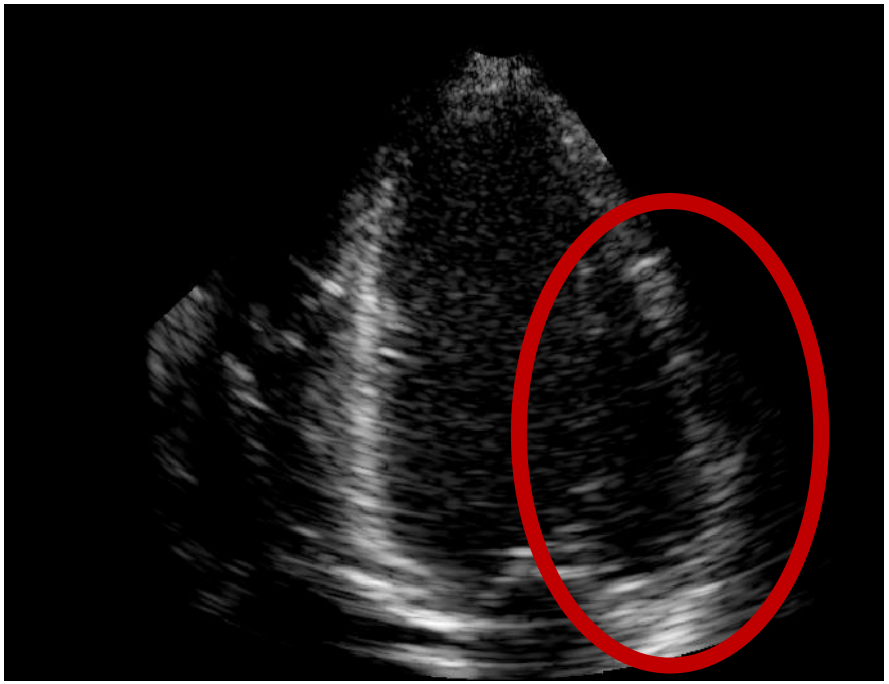


A4C

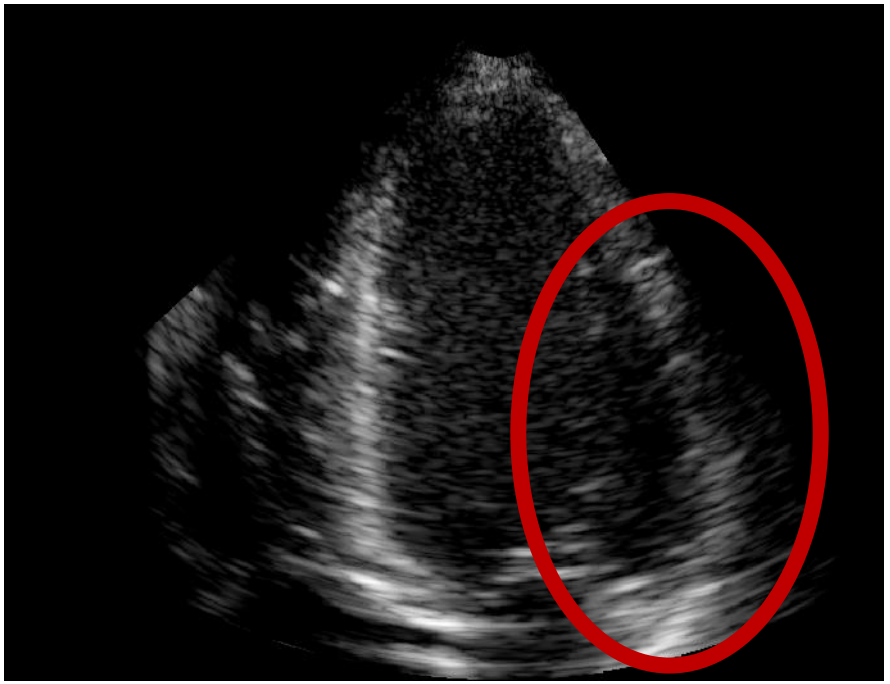
Realistic synthetic 2D sequences

- **Normal VS LCX**





A4C



A4C

Many thanks

Together, we're stronger !

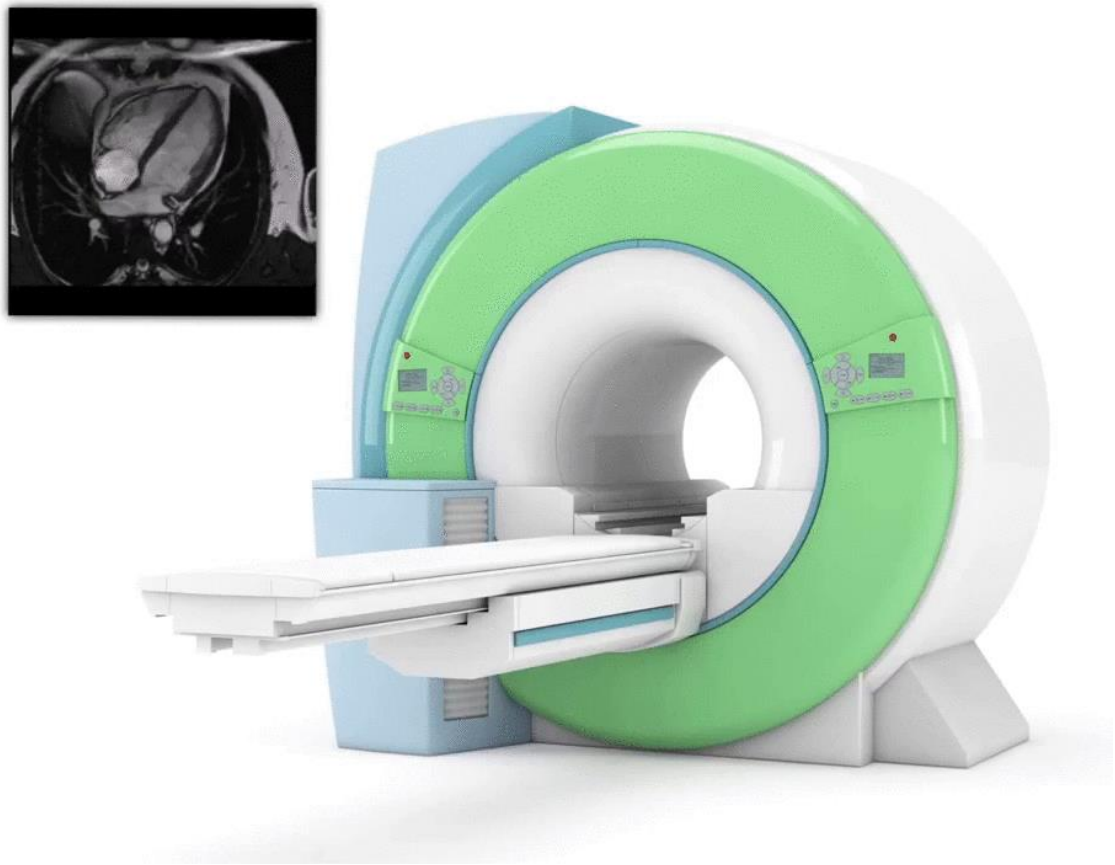
KATHOLIEKE UNIVERSITEIT LEUVEN

PHILIPS

Inria

Appendices

Icing on the cake – MR simulation…

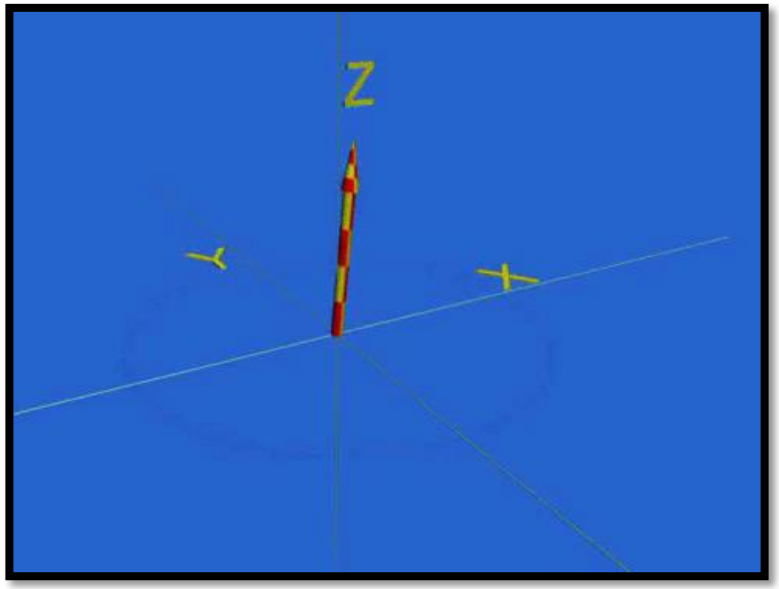


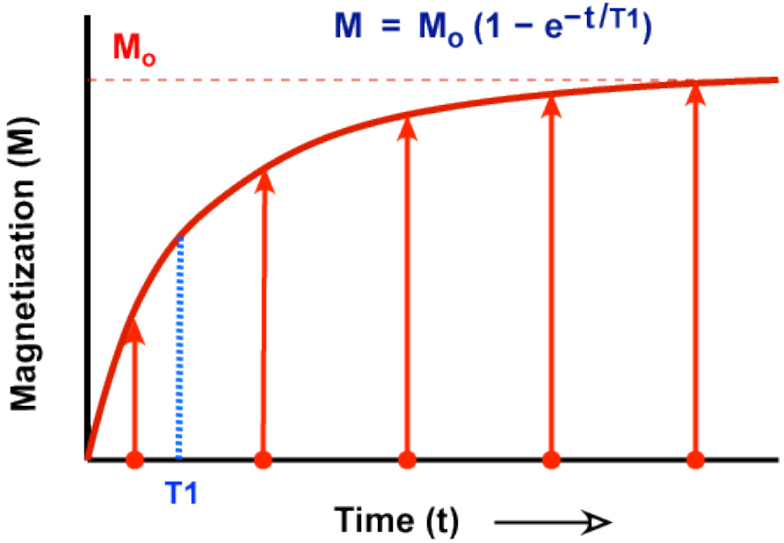
Generation of realistic synthetic images

Magnetic resonance modality

- **Physical principle**
- Physical simulator
- Proposed pipeline

Physical principle





Play with intrinsic magnetization of protons present in the human body

Generation of realistic synthetic images

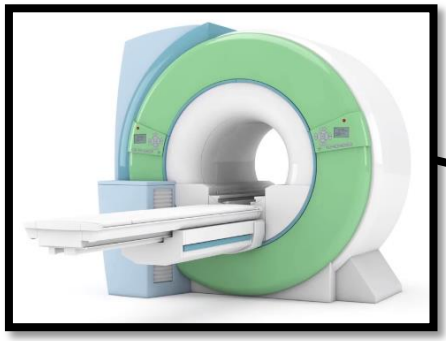
Magnetic resonance modality

- Physical principle
- **Physical simulator**
- Proposed pipeline

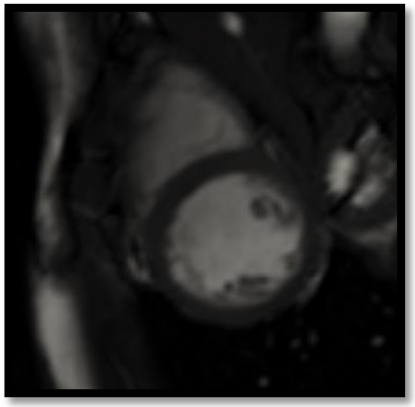
Physical simulator - ODIN

http://od1n.sourceforge.net/
[Jochimsen et al., (2006)]

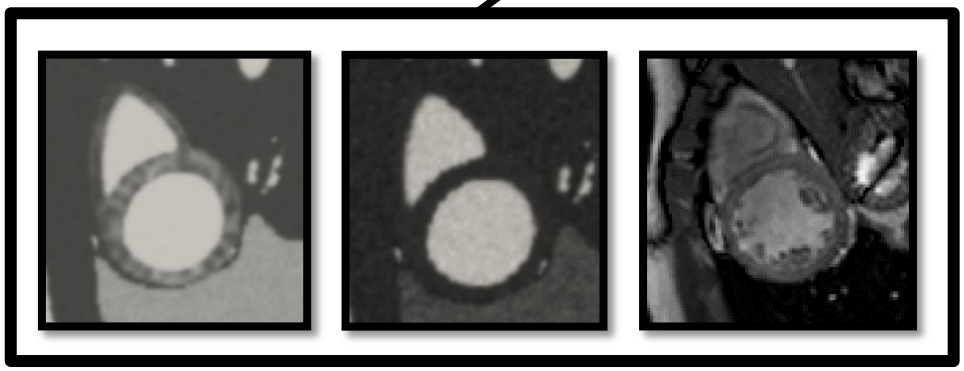
MR sequence (e.g. bSSFP)



Physical simulator



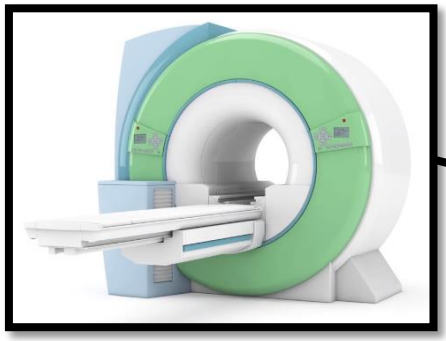
T1 / T2 / PD definition



Physical simulator - ODIN

http://od1n.sourceforge.net/
[Jochimsen et al., (2006)]

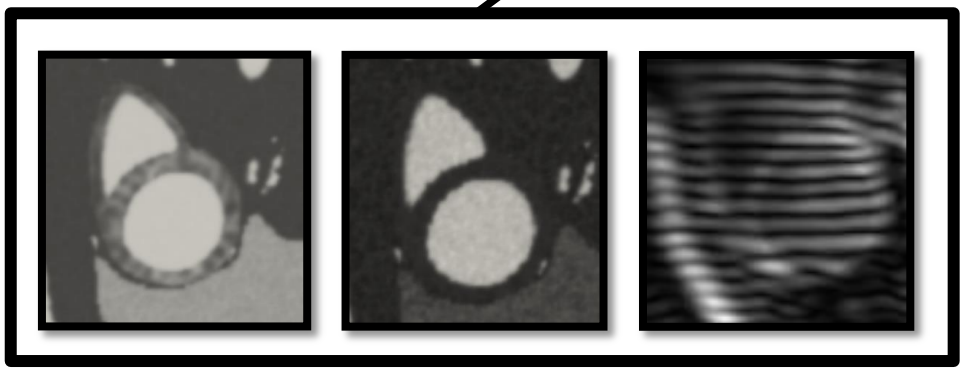
MR sequence (e.g. EPI)



Physical simulator



T1 / T2 / PD definition

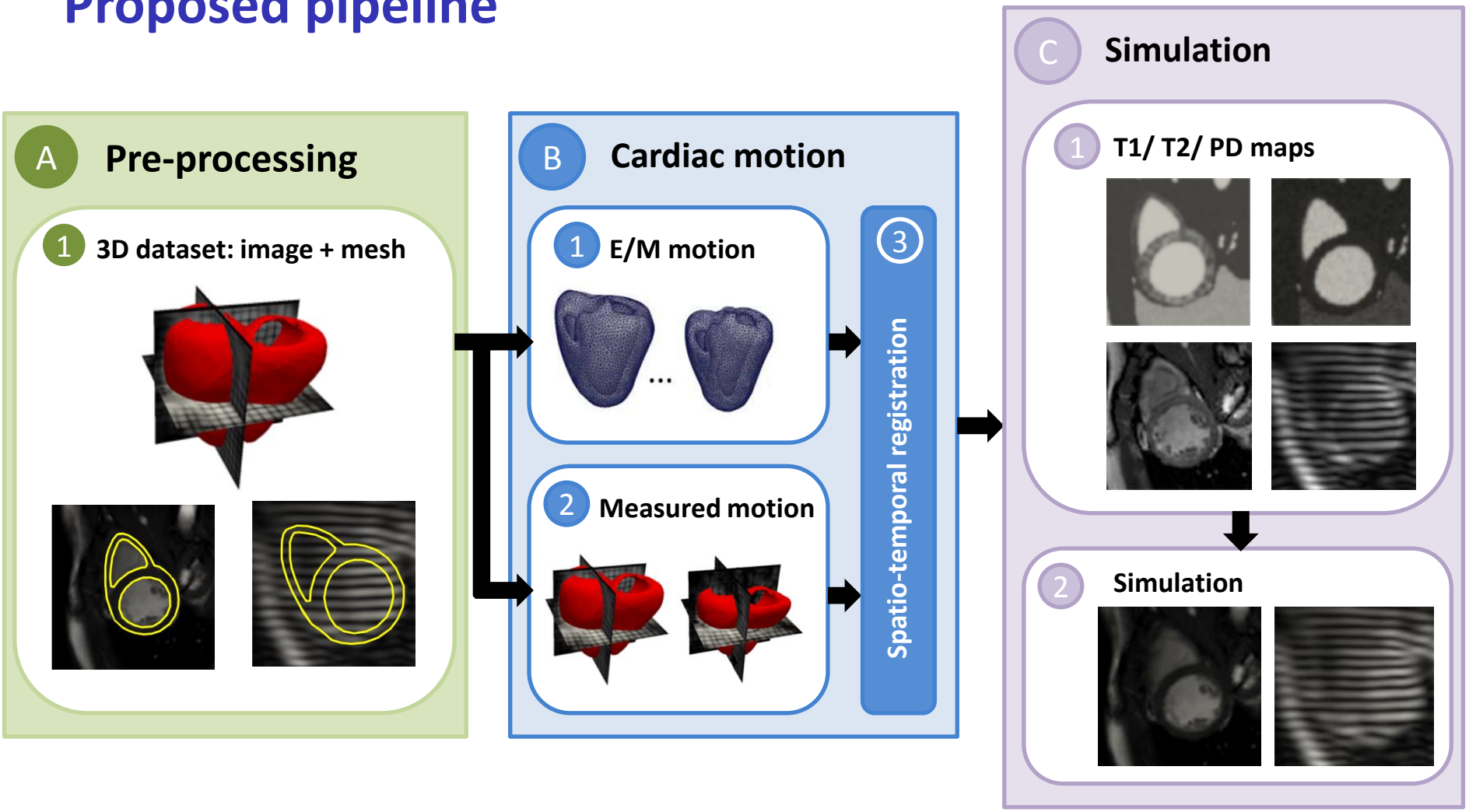


Generation of realistic synthetic images

Magnetic resonance modality

- Physical principle
- Physical simulator
- **Proposed pipeline**

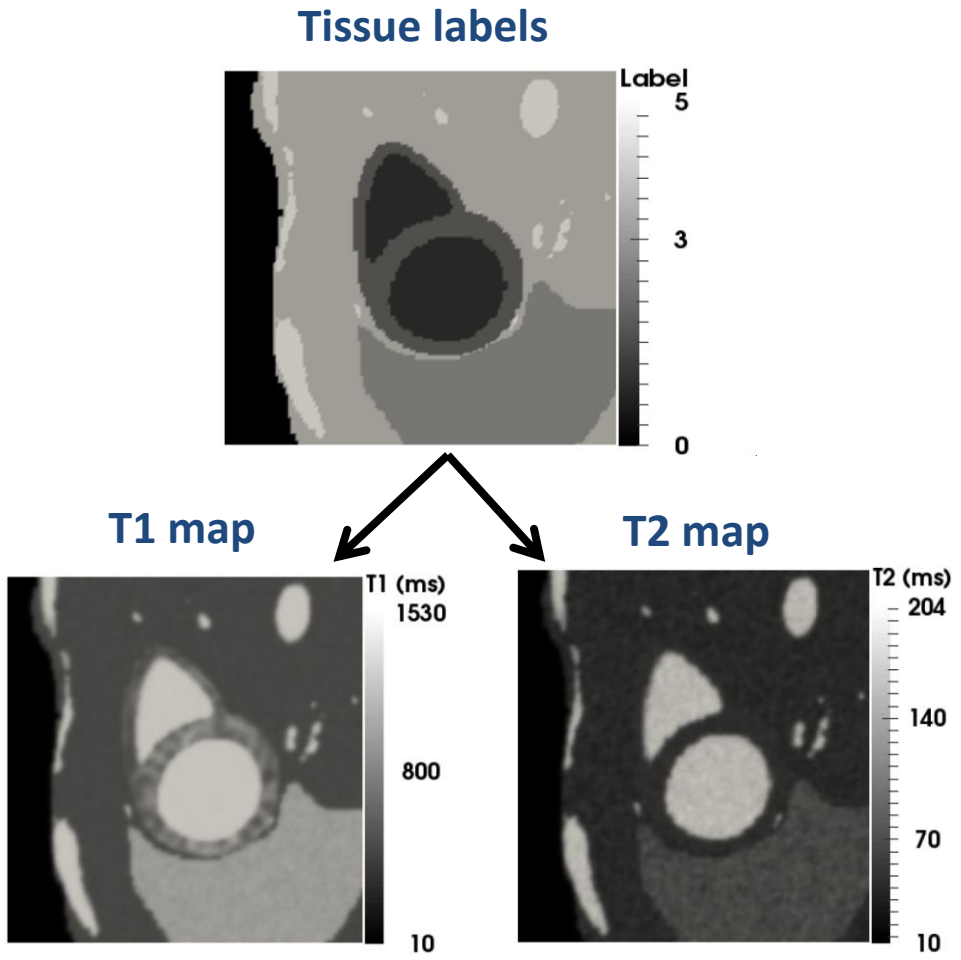
Proposed pipeline



▶ Step C-1 ➔ T1 / T2 relaxation time (ms)

Gaussian distribution
➔ μ and σ from literature

Label	Class	T1 (ms)		T2 (ms)	
		u	σ	u	σ
0	Air	0	0	0	0
1	Blood	1516	21	189	26
2	Myocardium	982	46	54	12
3	Lung	1199	117	79	29
4	Other (low)	549	52	49	20
5	Other (high)	1516	21	189	26



▶ Step C-1 ➔ Proton density

US simulation

Backscattered amplitude
➔ Bmode image

$$a_i = 10^{\frac{dB_{range}}{20}\left(\frac{I}{I_{max}}-1\right)}$$

MR simulation

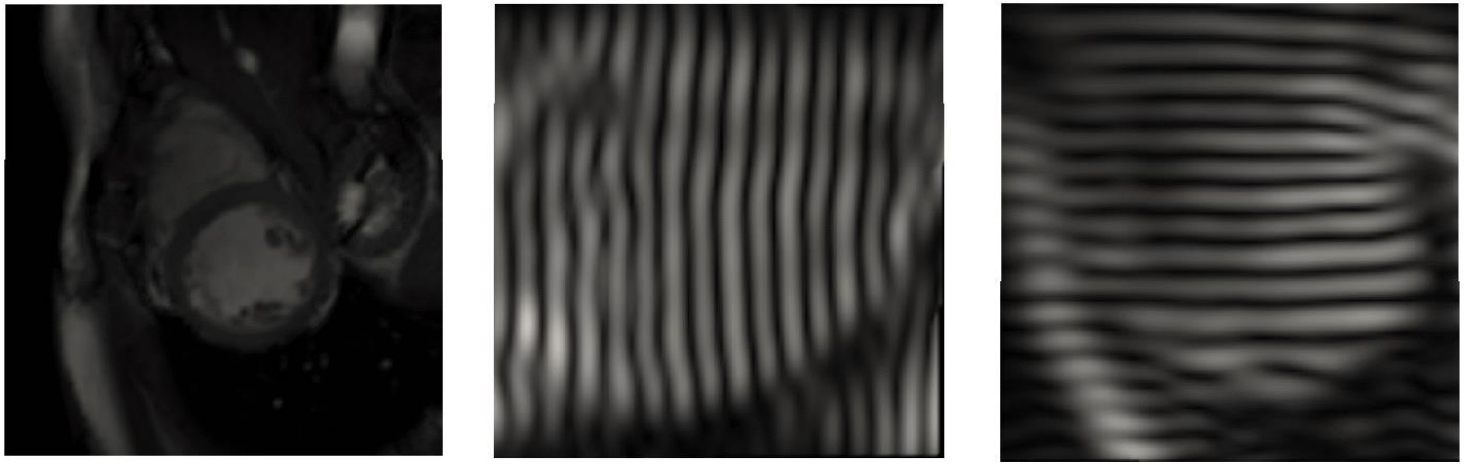
Proton density
➔ MR image intensity

Using analytic MR formulas

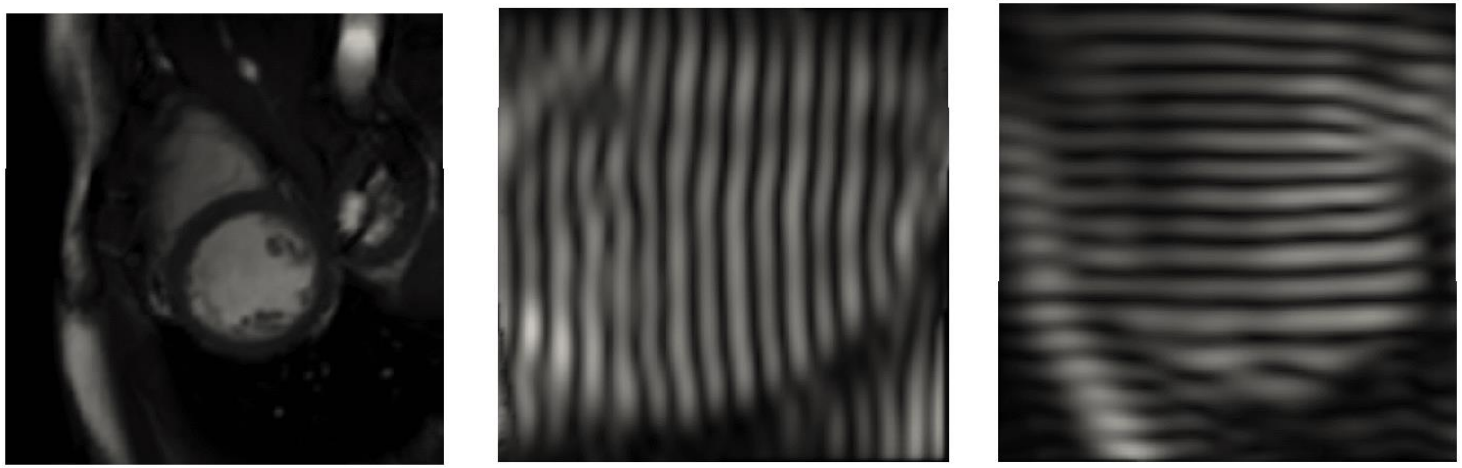
$$PD = f(I, T_1, T_2)$$

▶ Step C-2 ➔ Simulations

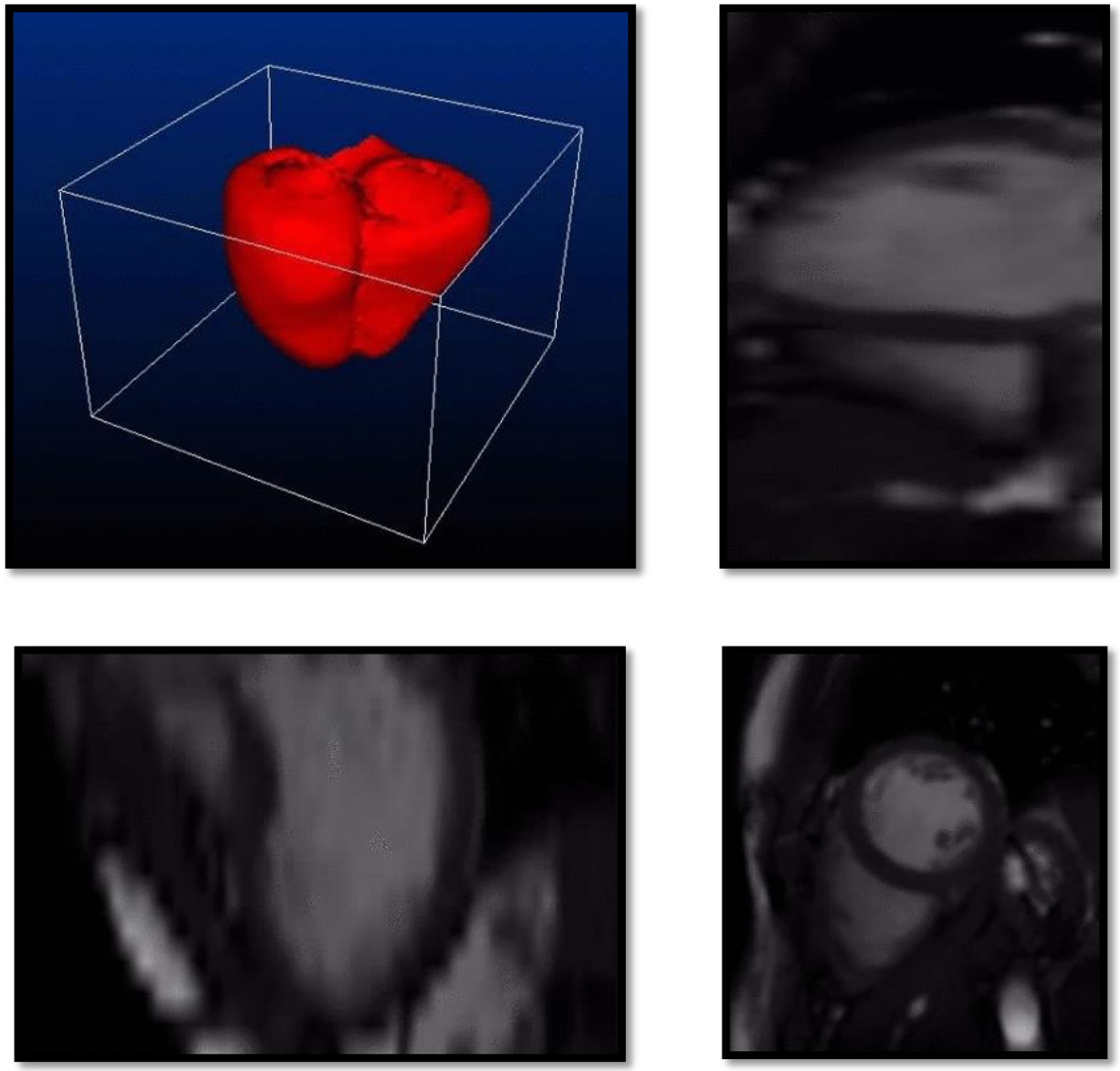
Template



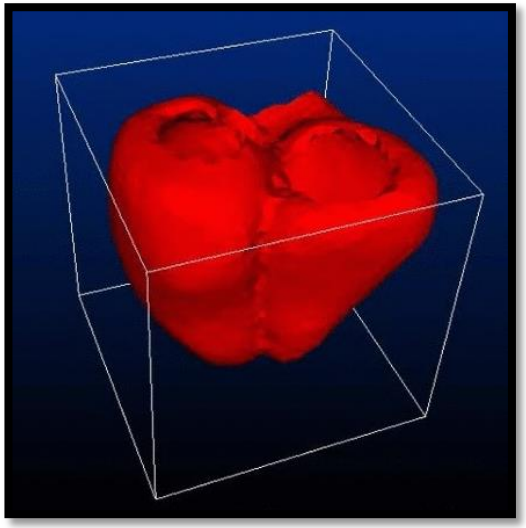
Simulated



3D cine MR sequence

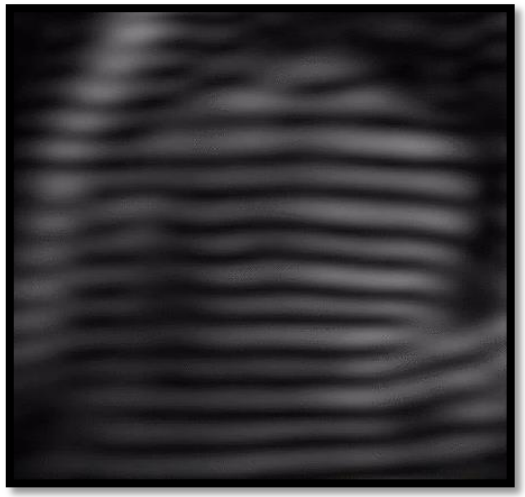


3D tagged MR sequence (channel 1)

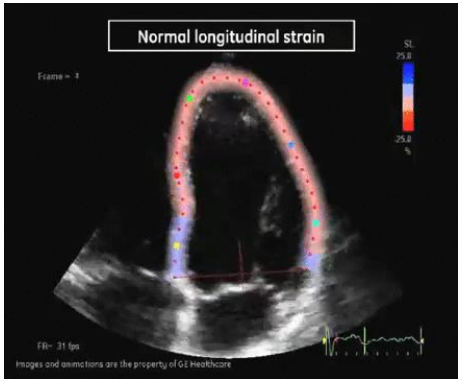


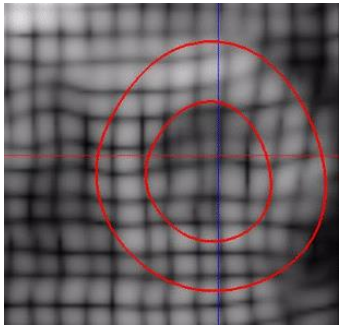


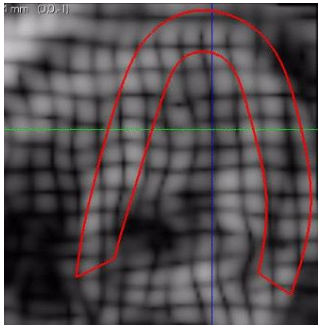




Cardiac imaging for diagnosis

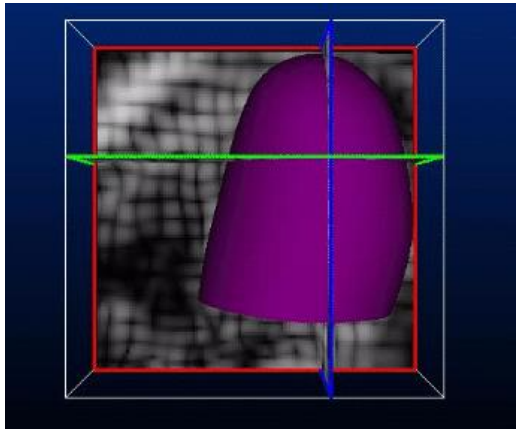






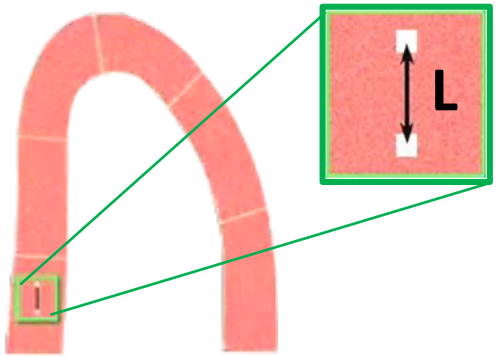




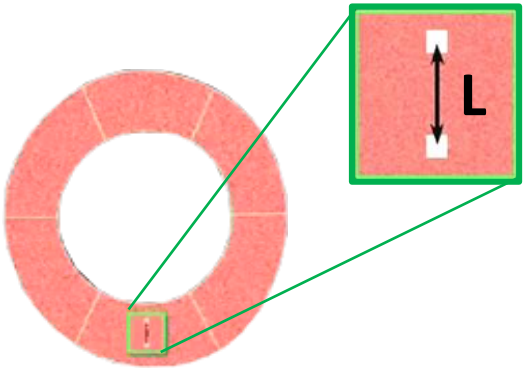


Strain computation

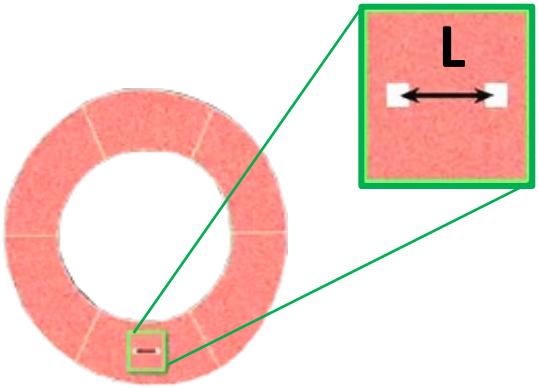
Longitudinal



Radial



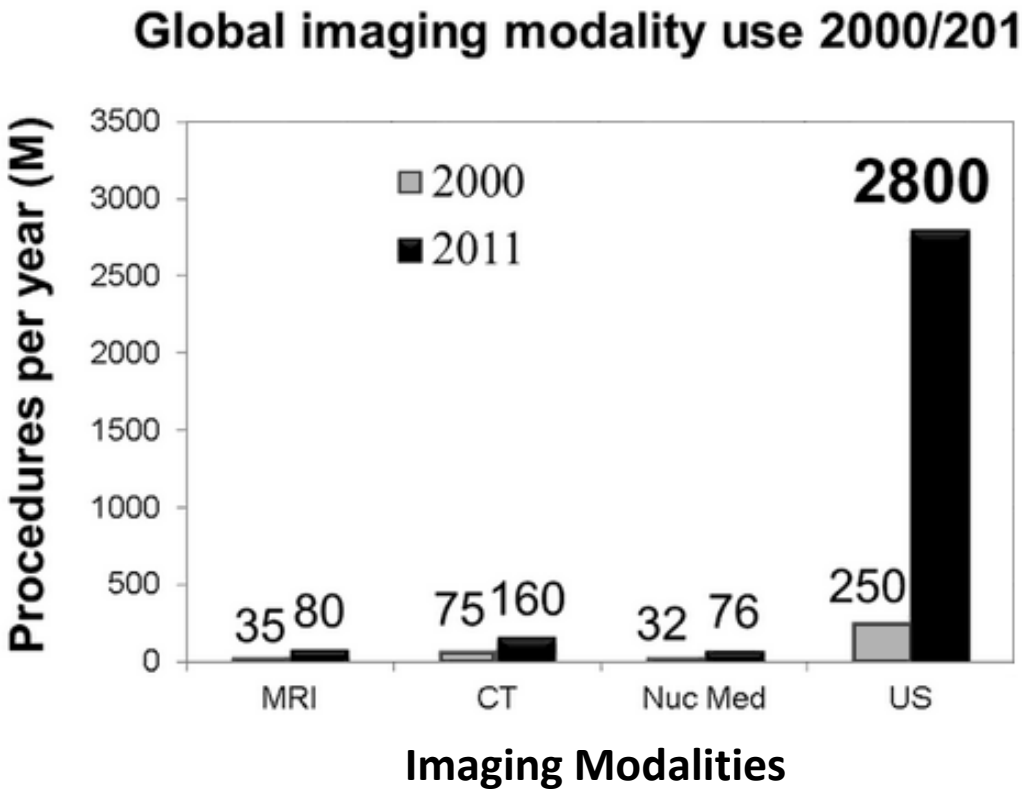
Circumferential



Normalized deformation

$$e = \frac{\Delta L}{L}$$

Ultrasound and other diagnostic imaging modalities

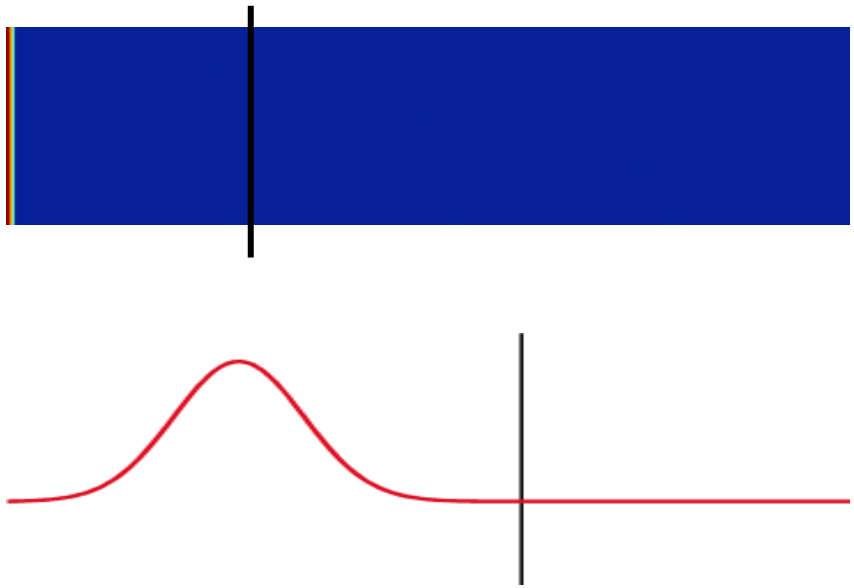


Thomas L. Szabo. 2014
Diagnostic Ultrasound Imaging: Inside Out

Interaction between wave and medium

▶ Reflection

- Due to a change of impedance between two media
- The interface should be smooth with dimensions higher than λ



$$R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

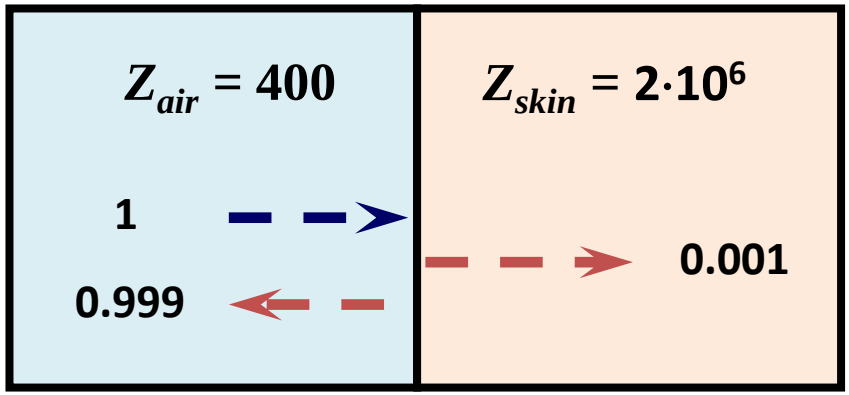
$$T = \frac{2\,Z_1\,Z_2}{(Z_1 + Z_2)^2}$$

$$R + T = 1$$

Interaction between wave and medium

▶ Reflection

Medium	Z (kg/m²/s) x 10⁶
air	0.0004
skin	2





- No transmission between air and skin !
- Need to use ultrasound transmission gel

Interaction between wave and medium

▶ Refraction

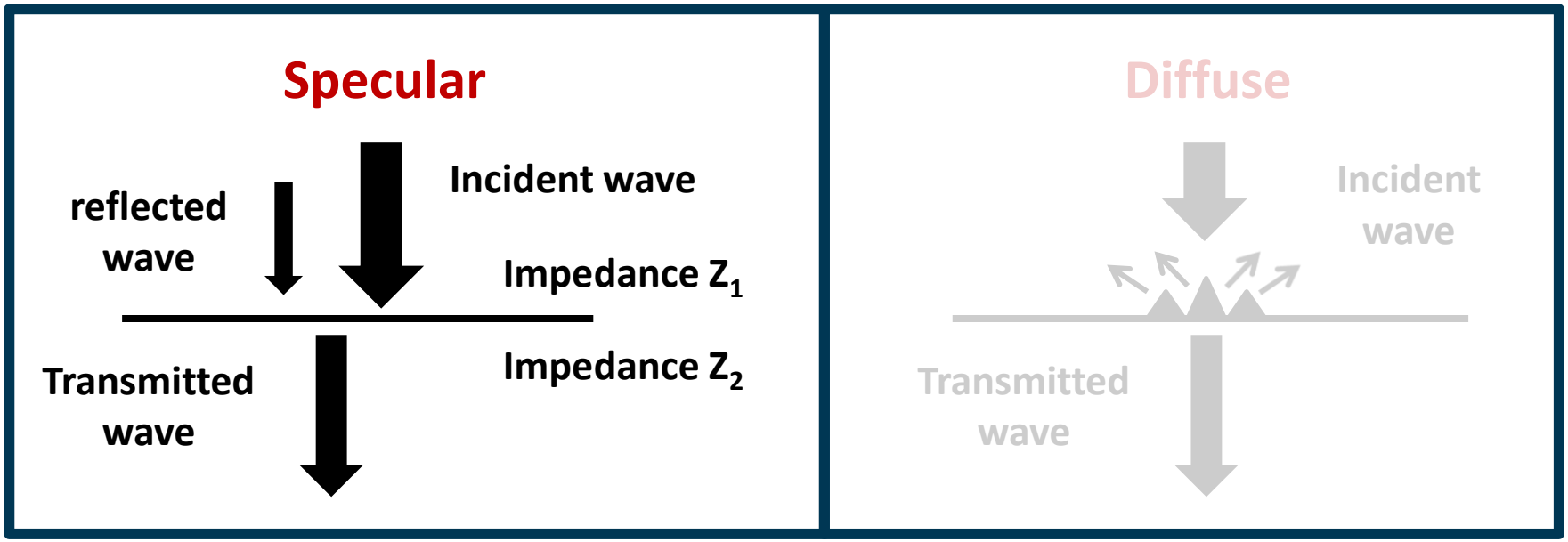
- Oblique incidence between wave and interface
- The interface should be smooth with dimensions higher than λ





$$\frac{\sin \theta_i}{c_i} = const$$

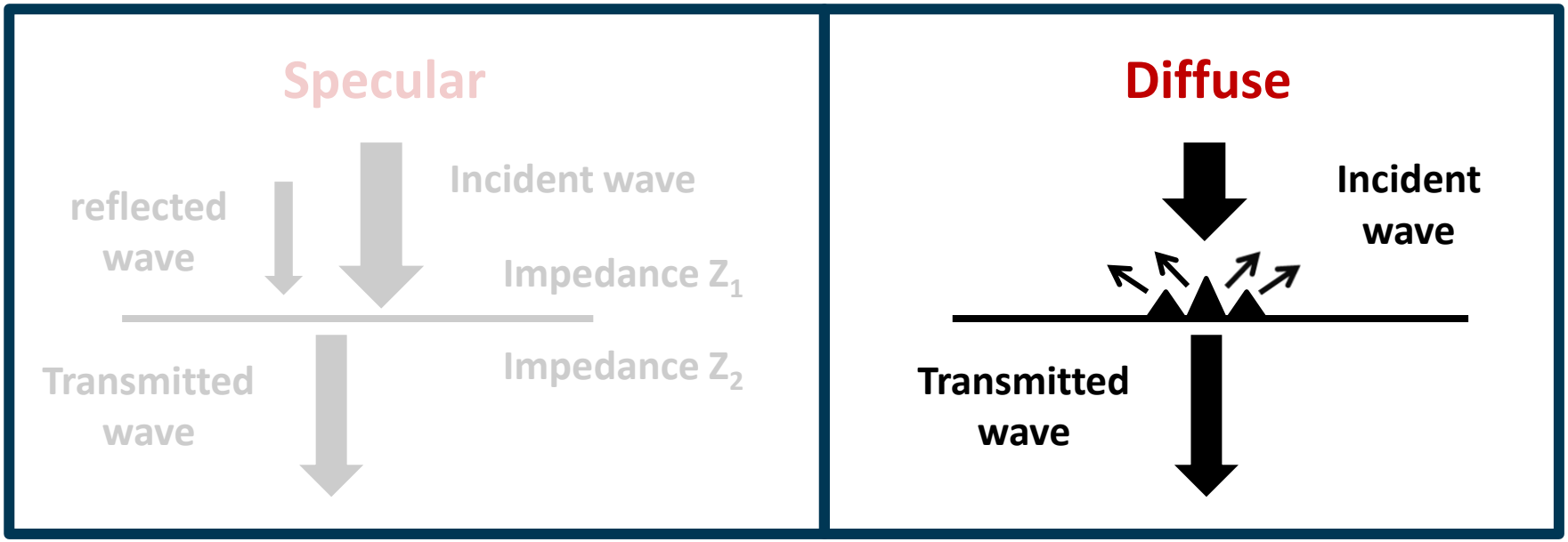
Interaction between wave and medium



▶ Specular

- Large reflector (dimensions $> \lambda$)
- Smooth surface (*e.g.* bone)

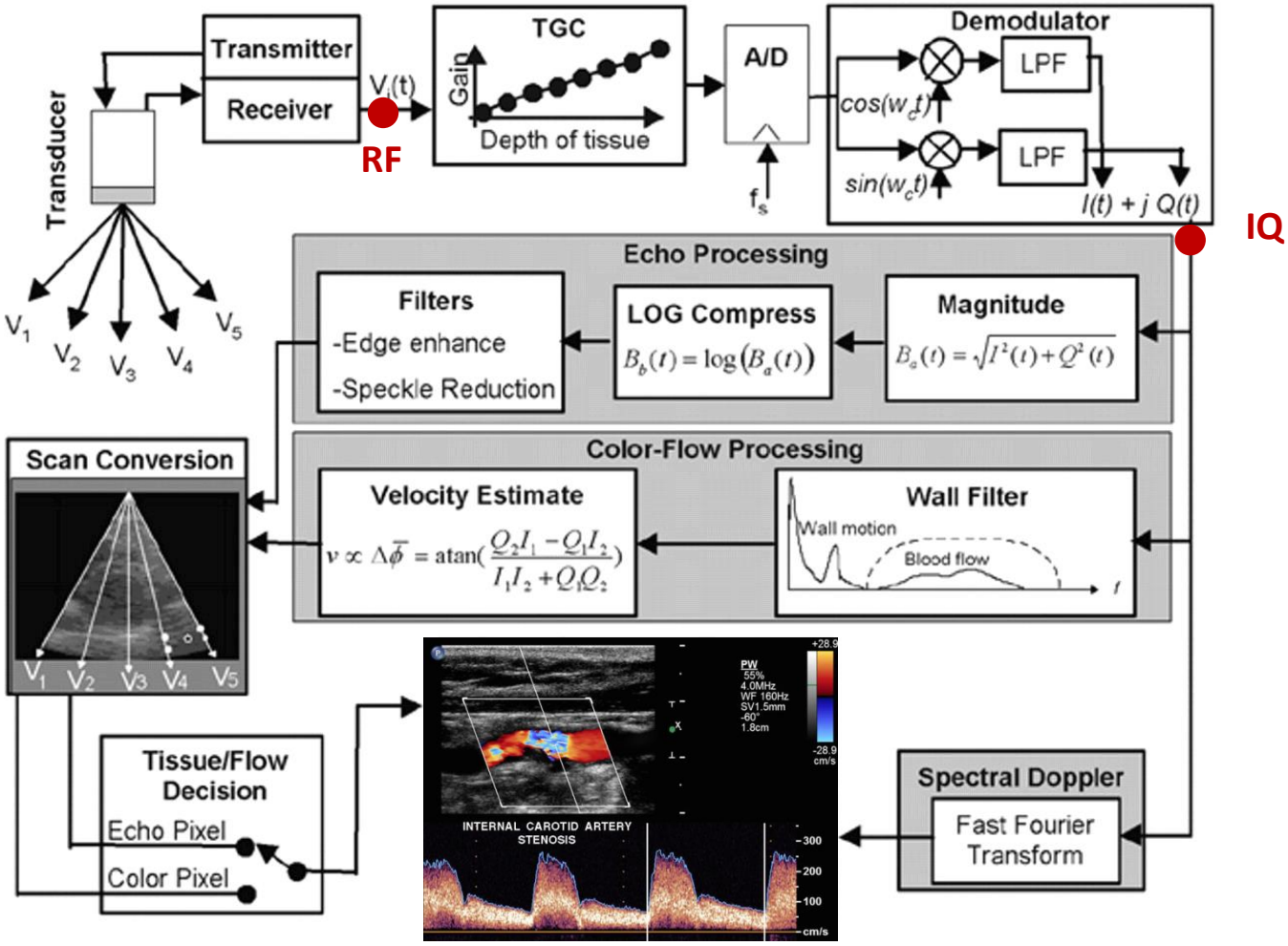
Interaction between wave and medium



- **Diffuse**
  - Rough surface (*e.g.* smooth tissue)
  - Wave is reflected in several directions

MODELING OF ULTRASOUND WAVES AND IMAGE RECONSTRUCTION

└ Ultrasound image formation



York et al.

Annu Rev Biomed Eng 1999

RF = radio-frequency signal
IQ = in-phase/quadrature