

– Ultrasound motion imaging –

Tracking motions in the body



by
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April 22, 2019

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

- **back to basics**: generate images from sound
- **transmit & receive** with a linear array
- **motion** in the cardiovascular system
- **generating motion** where there is none
- **algorithms** for motion tracking

back to basics

generate images from sound

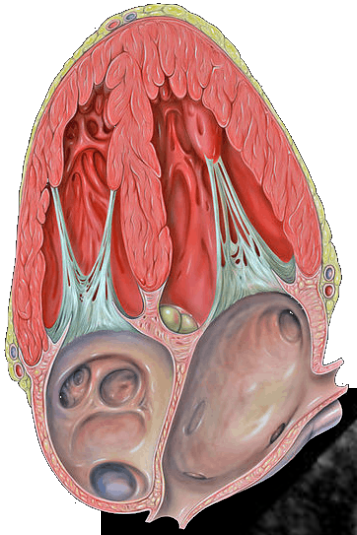
ultrasound imaging



source: www.youtube.com/watch?v=I1Bdp2tMFsY

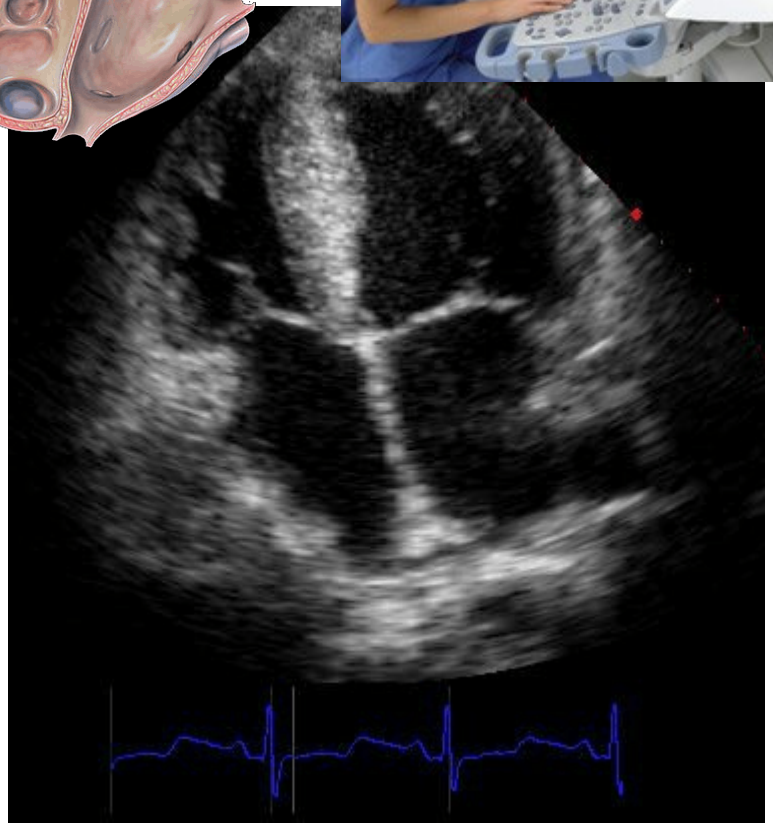
2-D ultrasound imaging







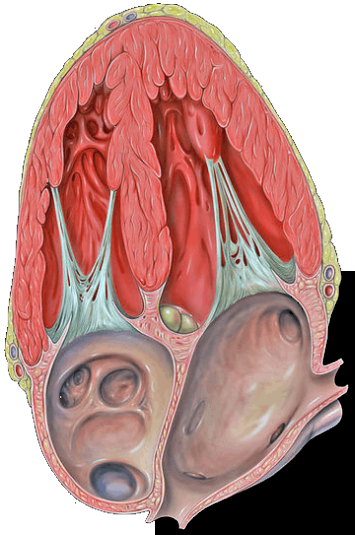




3-D ultrasound imaging

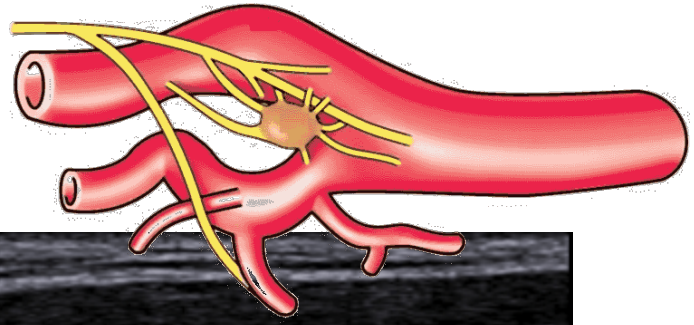


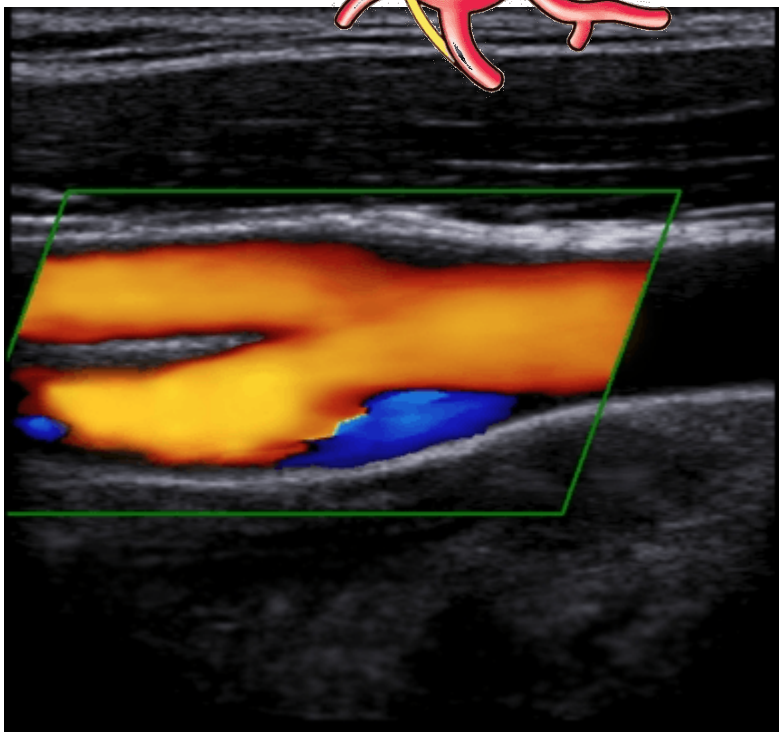


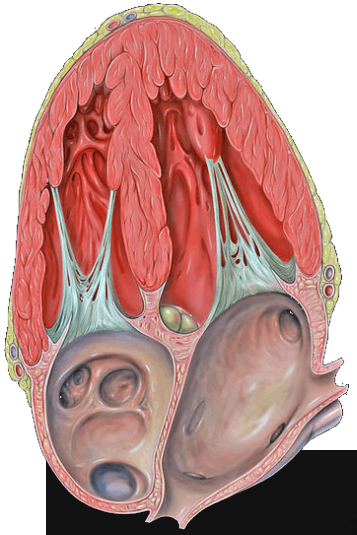


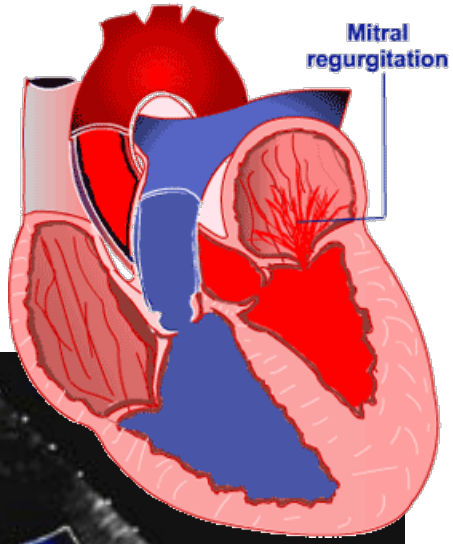


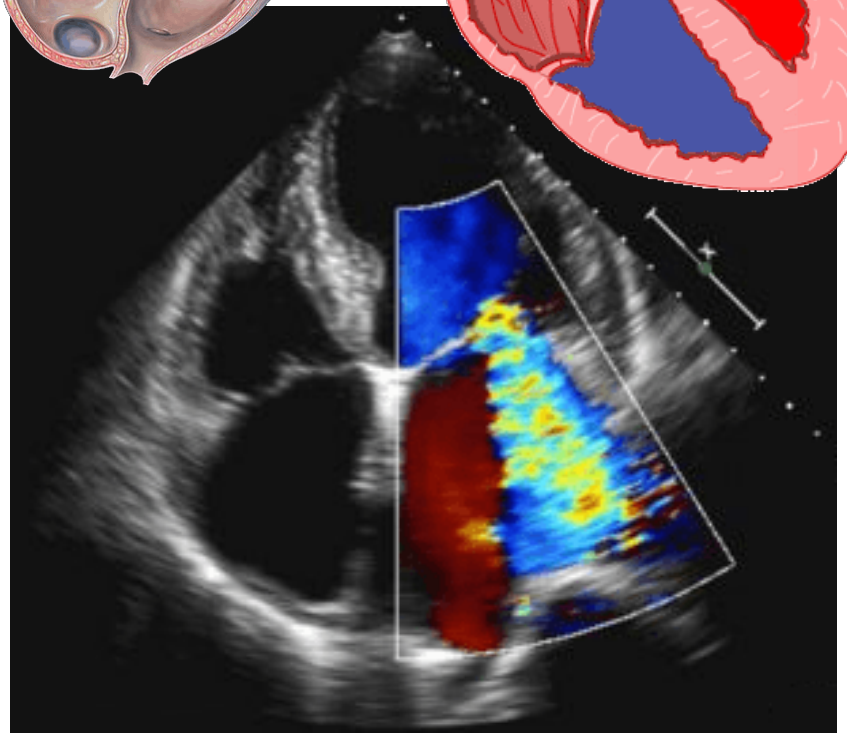
ultrasound flow imaging



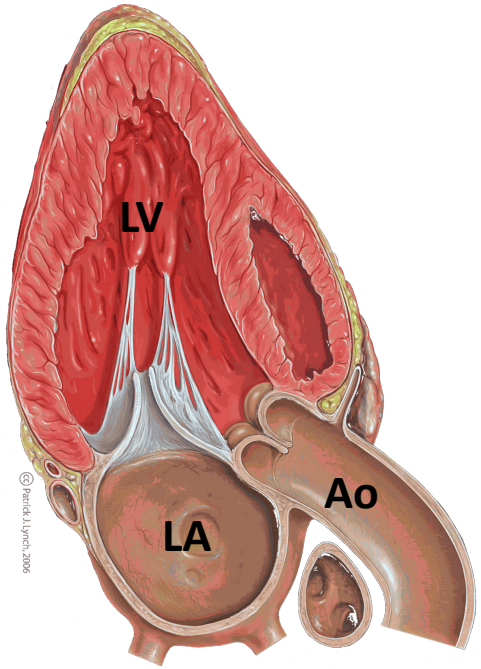


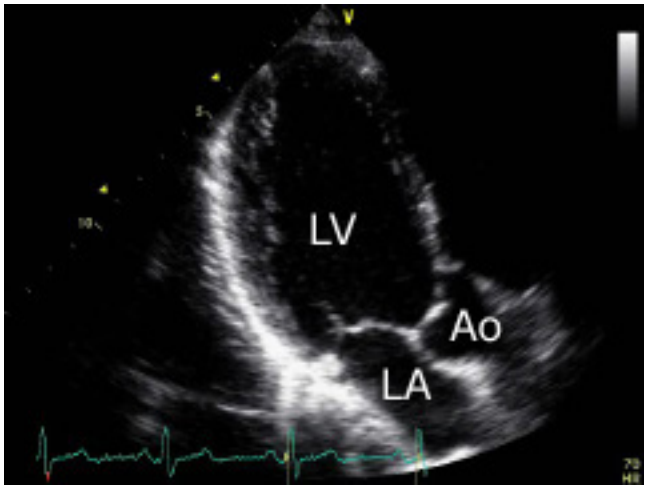




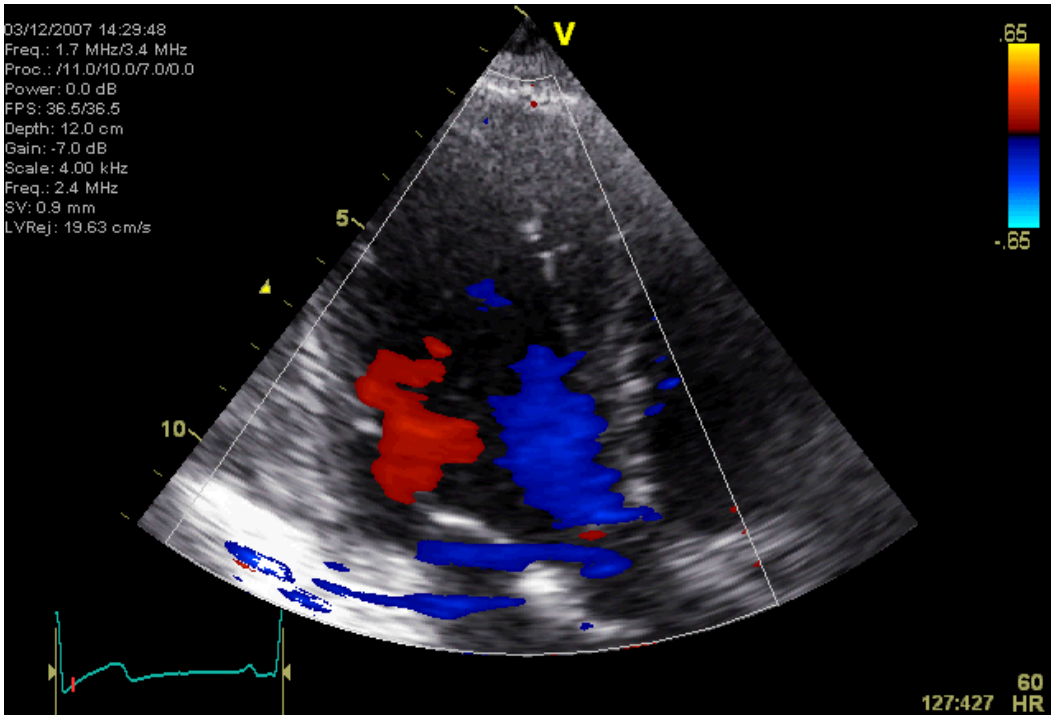


Doppler echocardiography



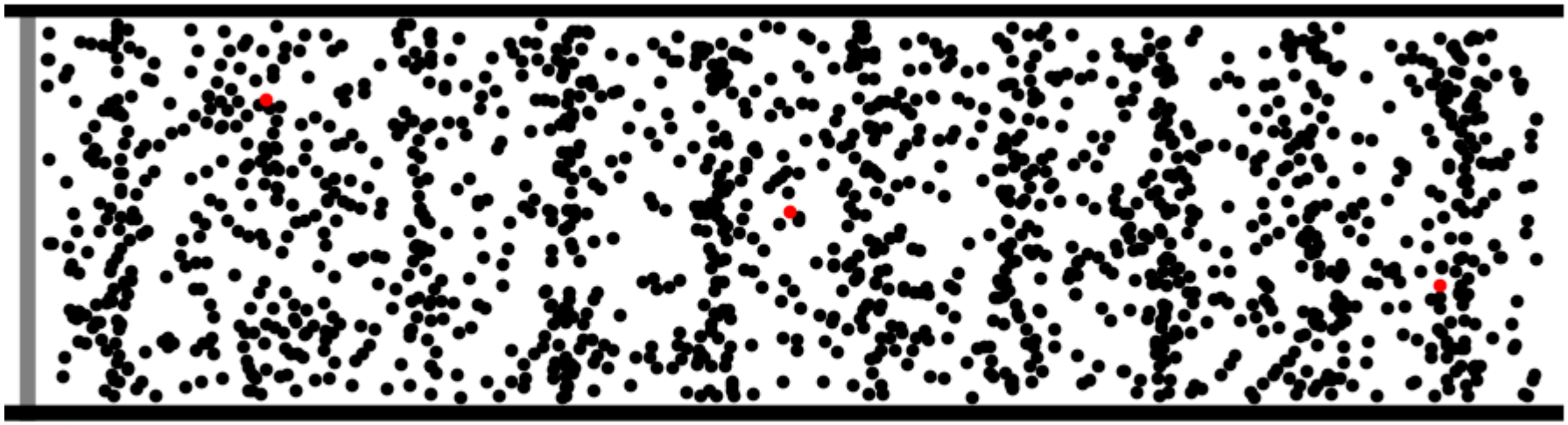


LV: left ventricle
LA: left atrium
Ao: aorta



sound wave

- Sound waves are **mechanical waves** characterized by fluctuations in density and pressure
- In a mechanical wave, a local disturbance propagates in a medium
- There is no global displacement of the material, but a temporary movement of material

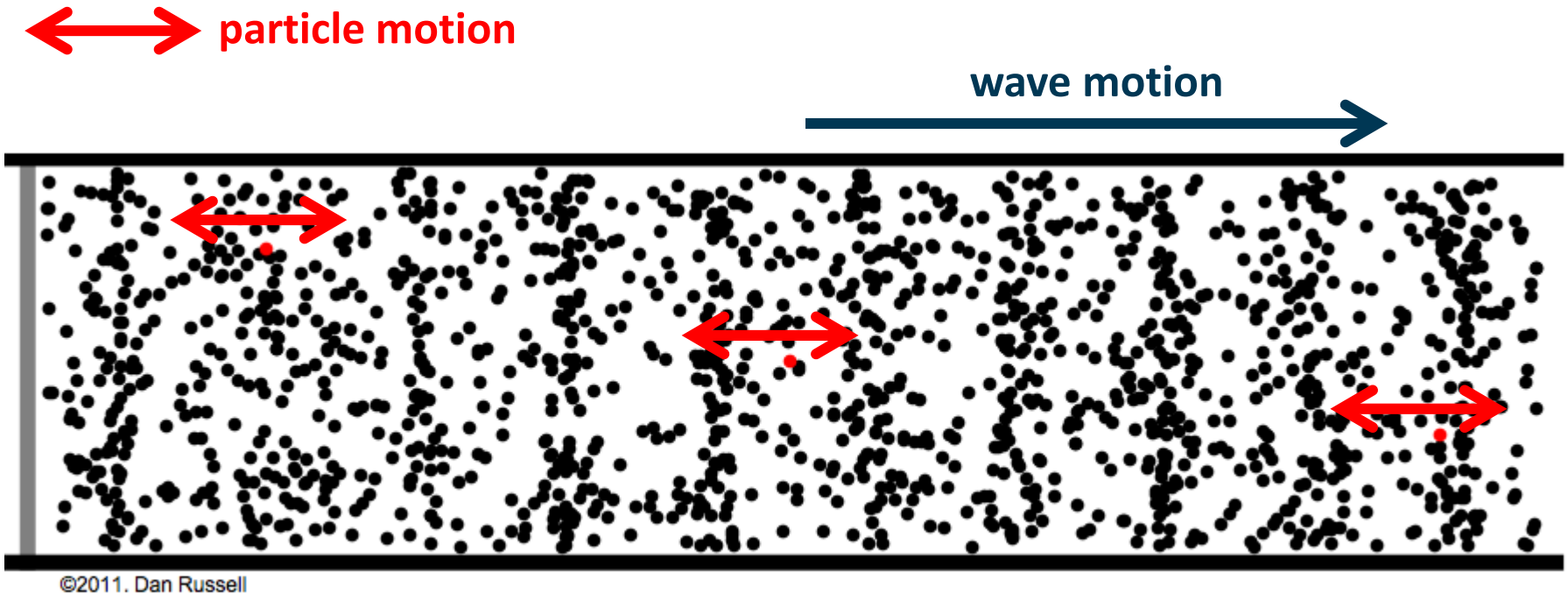


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particle velocity & speed of sound

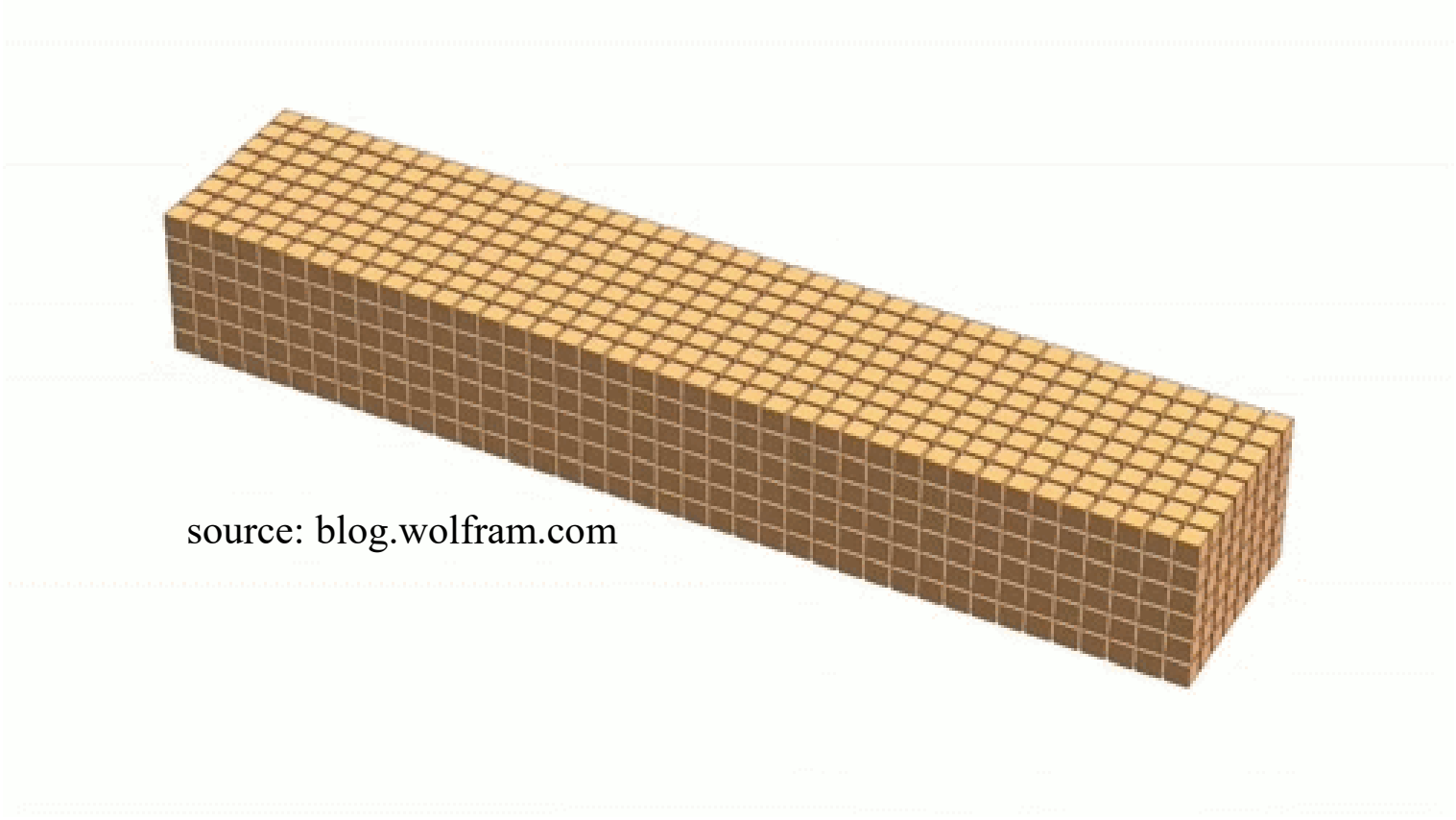
A **mechanical wave** is characterized by

- the particle velocities around their equilibrium point
- the speed of the wave (*c*)



pressure waves

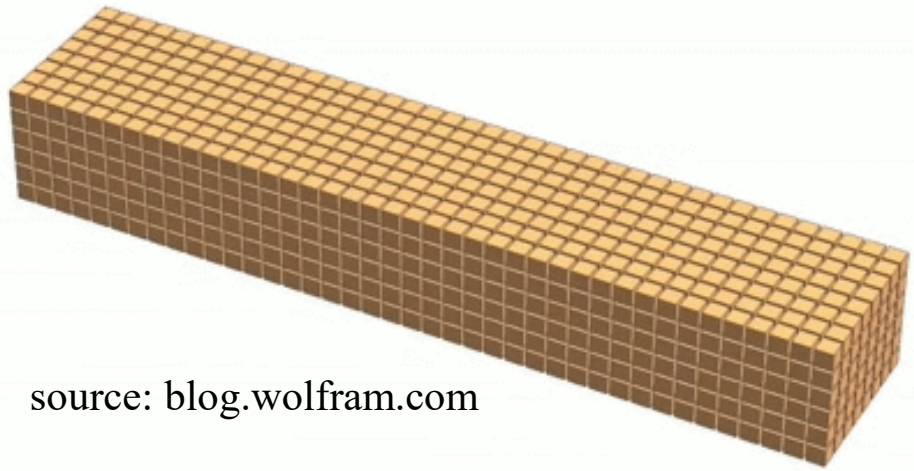
- The mode of propagation of a **pressure wave** is **longitudinal**; the particles in the solid vibrate along the direction of wave propagation
- Pressure waves are the waves commonly used in ultrasound imaging



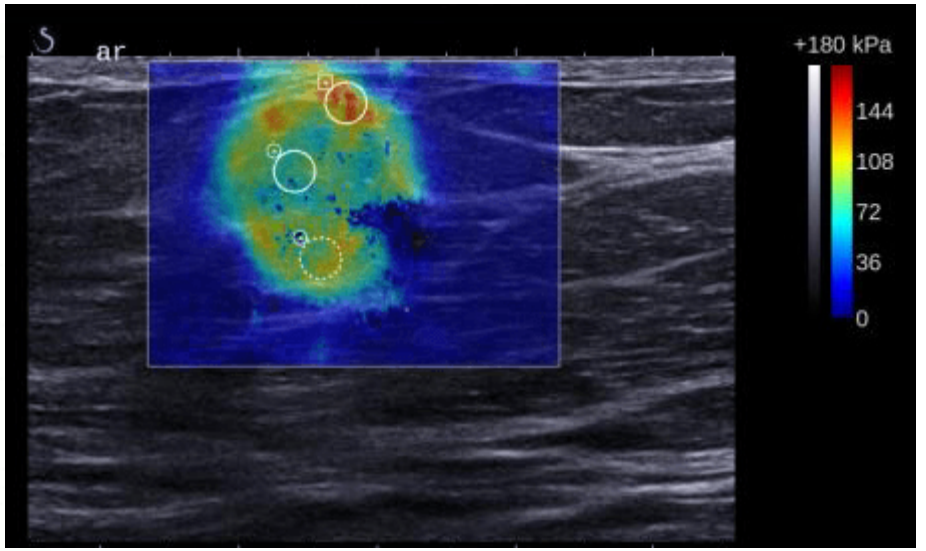
source: blog.wolfram.com

shear waves

- A **shear wave** is a **transverse** wave; the motion is perpendicular to the direction of wave propagation
- Unlike pressure waves, shear wave motion can be detected by ultrasound imaging. They are used in transient elastography and shear wave imaging



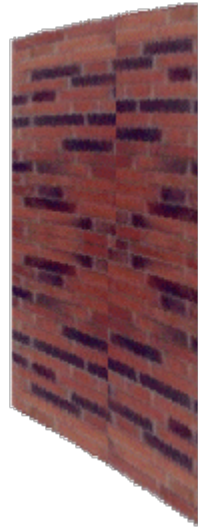
source: blog.wolfram.com

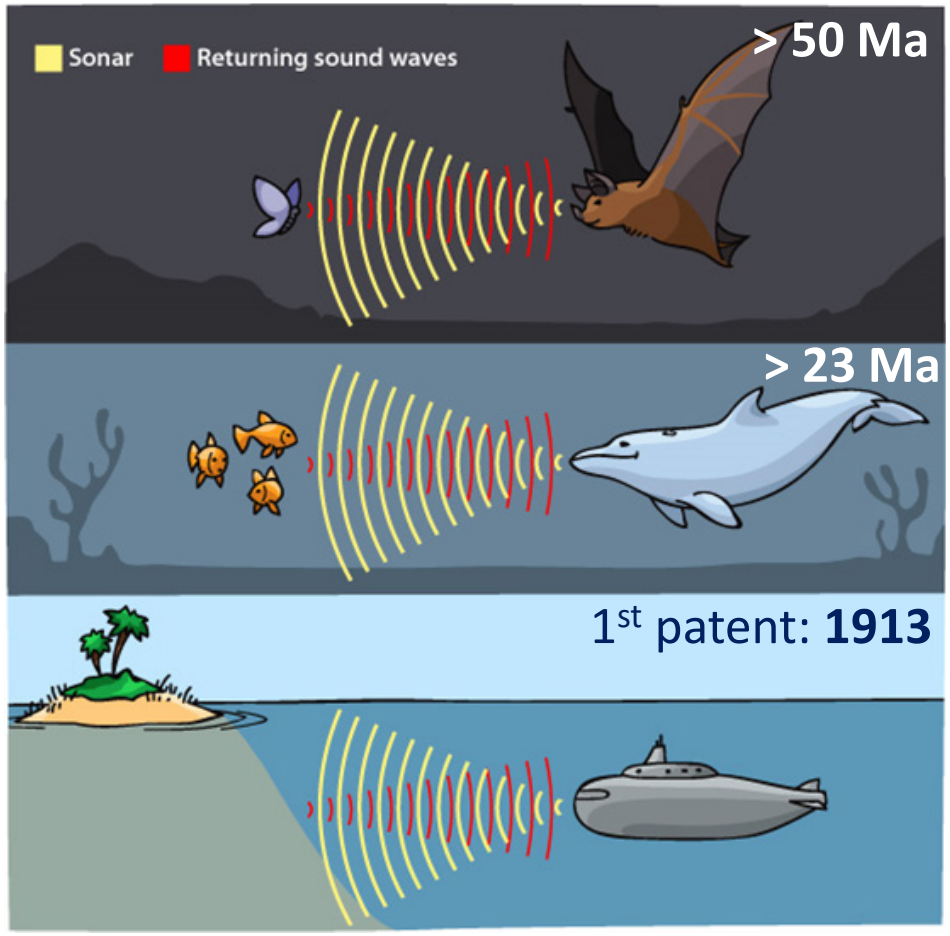


www.supersonicimagine.com

ultrasound imaging: a very (very) old concept!







- **Medical ultrasound imaging**
  - 1st used in 1956 in Glasgow
  - became widely used in the 1970s

when size matters







GE Healthcare

Vivid E9
Vivid q
Vscan



research-dedicated ultrasound

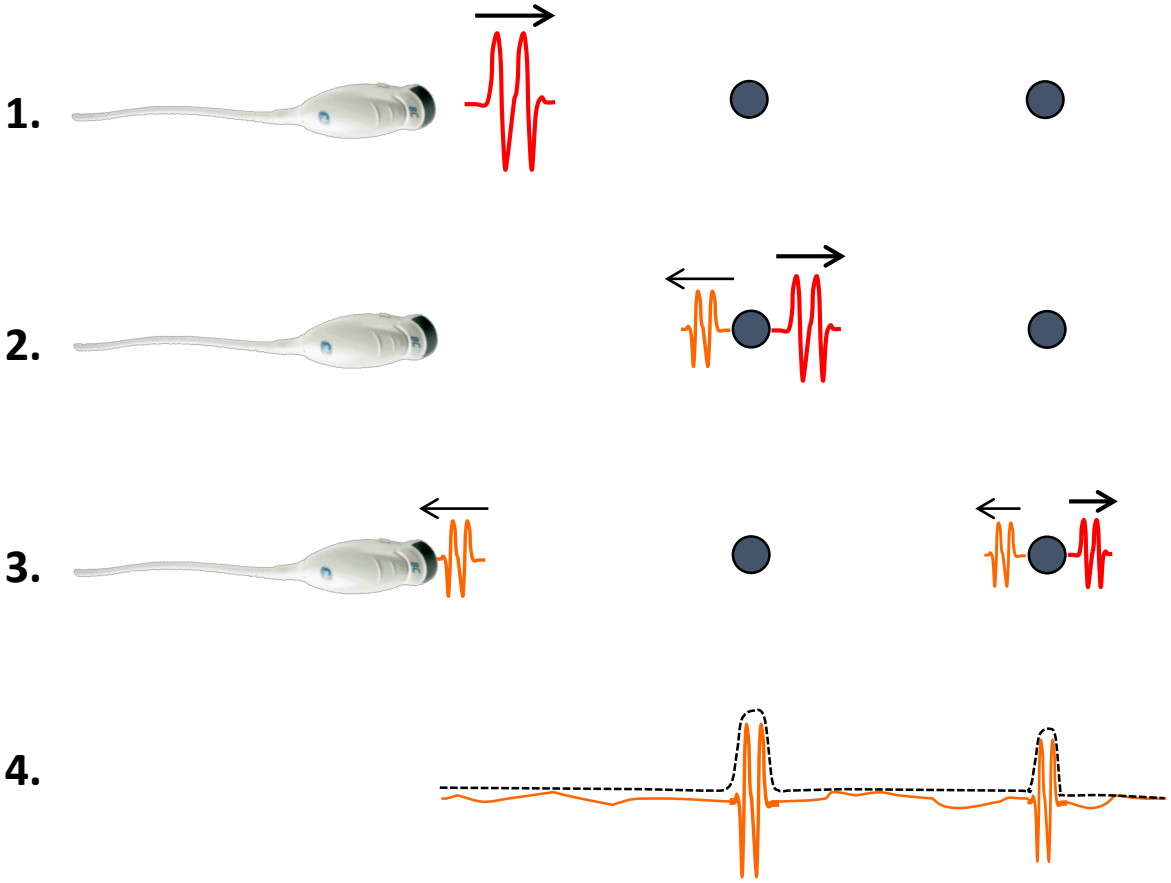


Verasonics®



generating images from sound

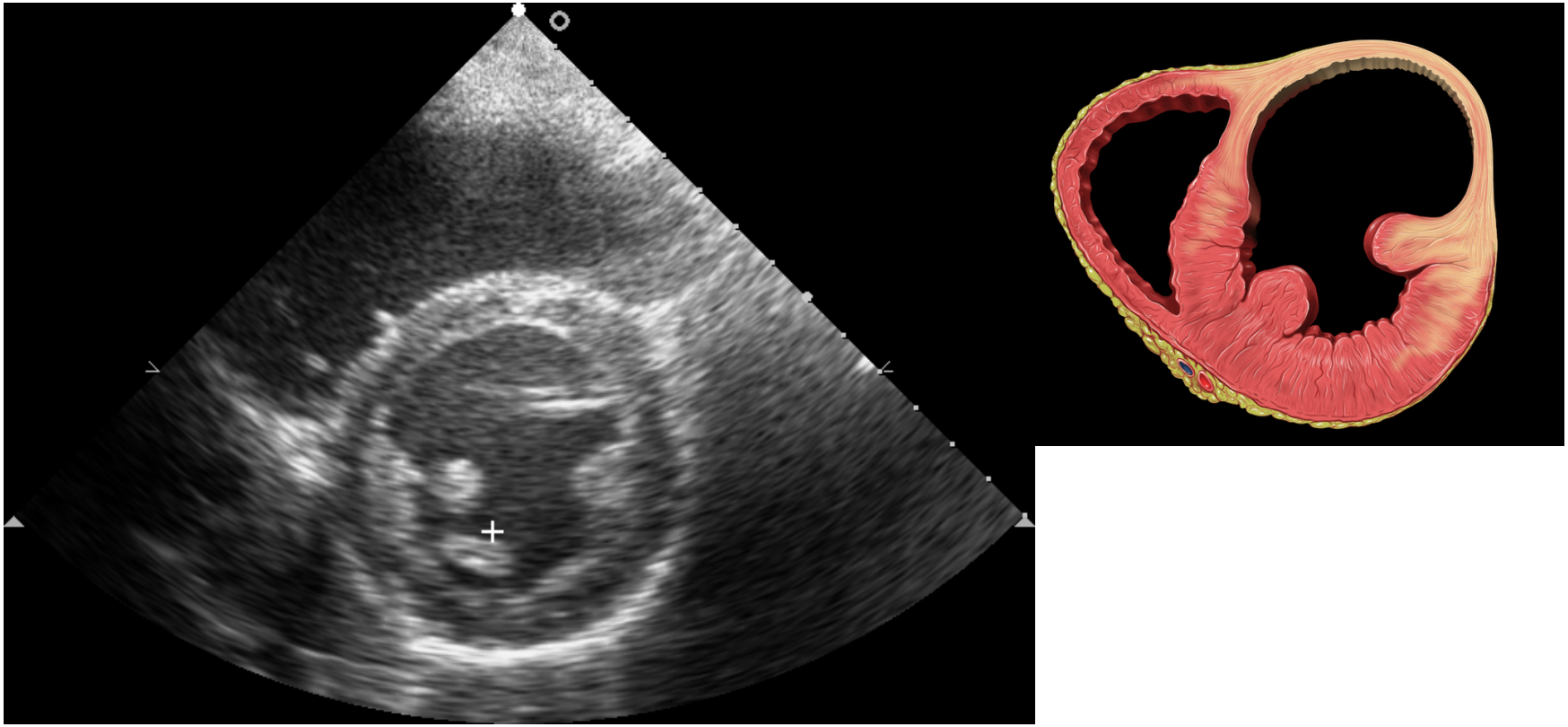
1. A short pulse is emitted by the transducer
2. The sound wave propagates in the medium
3. Reflected waves are received by the transducer
4. The real envelope of the signal generates an ultrasound image



ultrasound B-mode image

- !! the grainy appearance of an ultrasound image is NOT an image of the reflectors present in the tissue !!

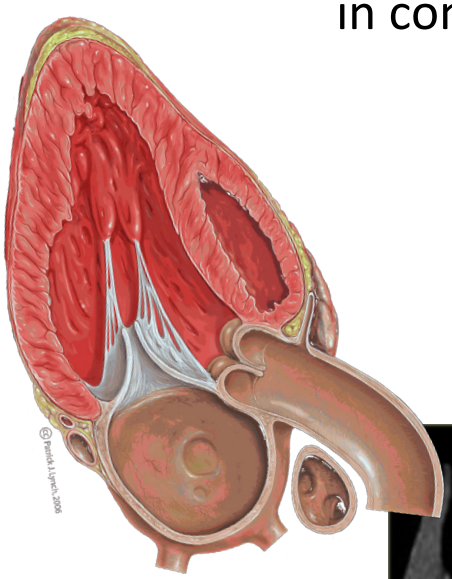
- a B-mode image is an image of the interferences generated by the summation of reflected ultrasonic waves



CMR vs. echocardiography

in comparison with MRI, ultrasound provides “lower” image quality;

BUT real-time, thus EASES MOTION QUANTIFICATION.

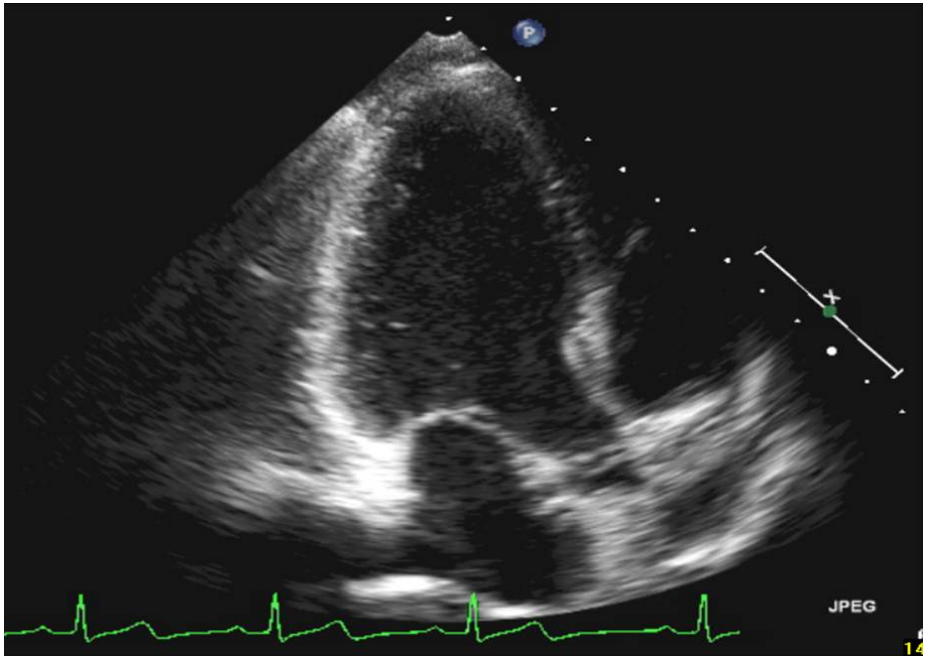


CMR



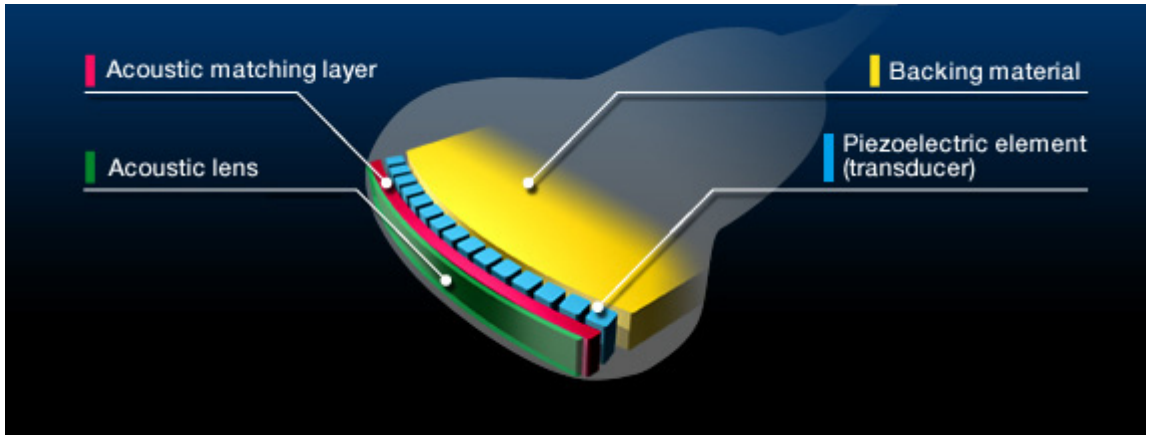


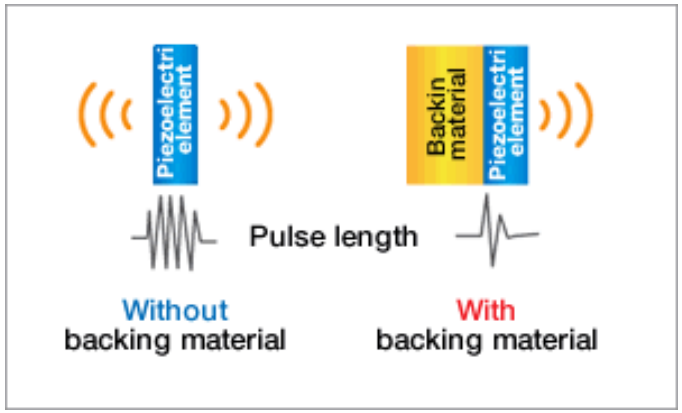
Echo

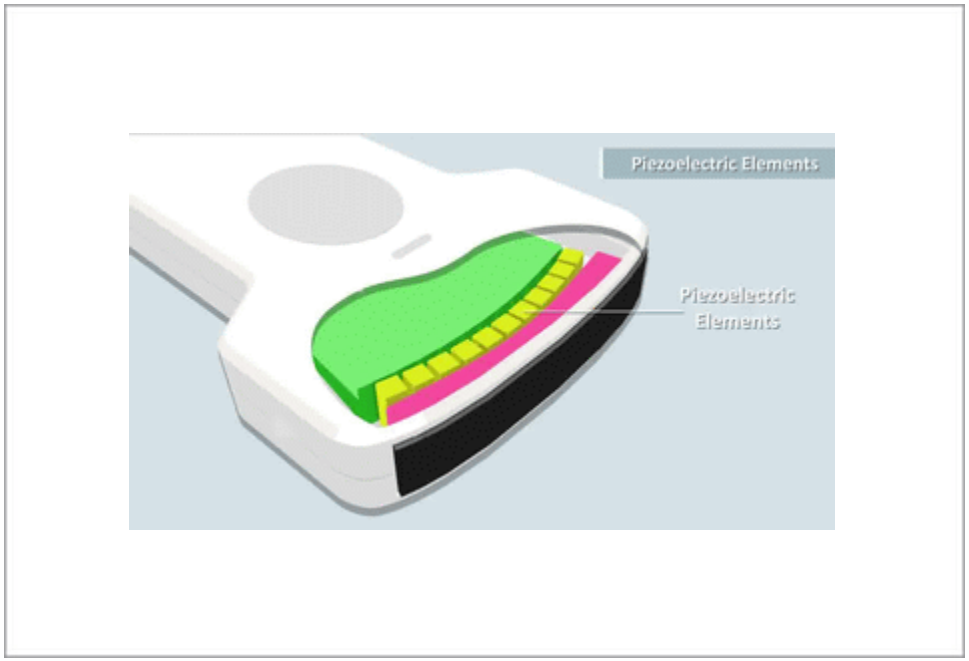


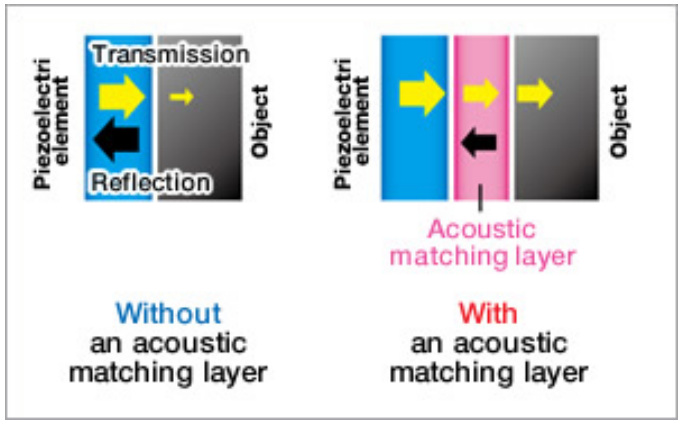
transmit & receive with an array

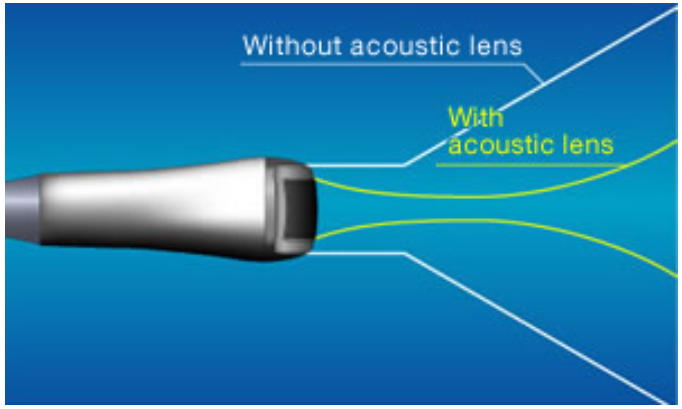
ultrasonic probe





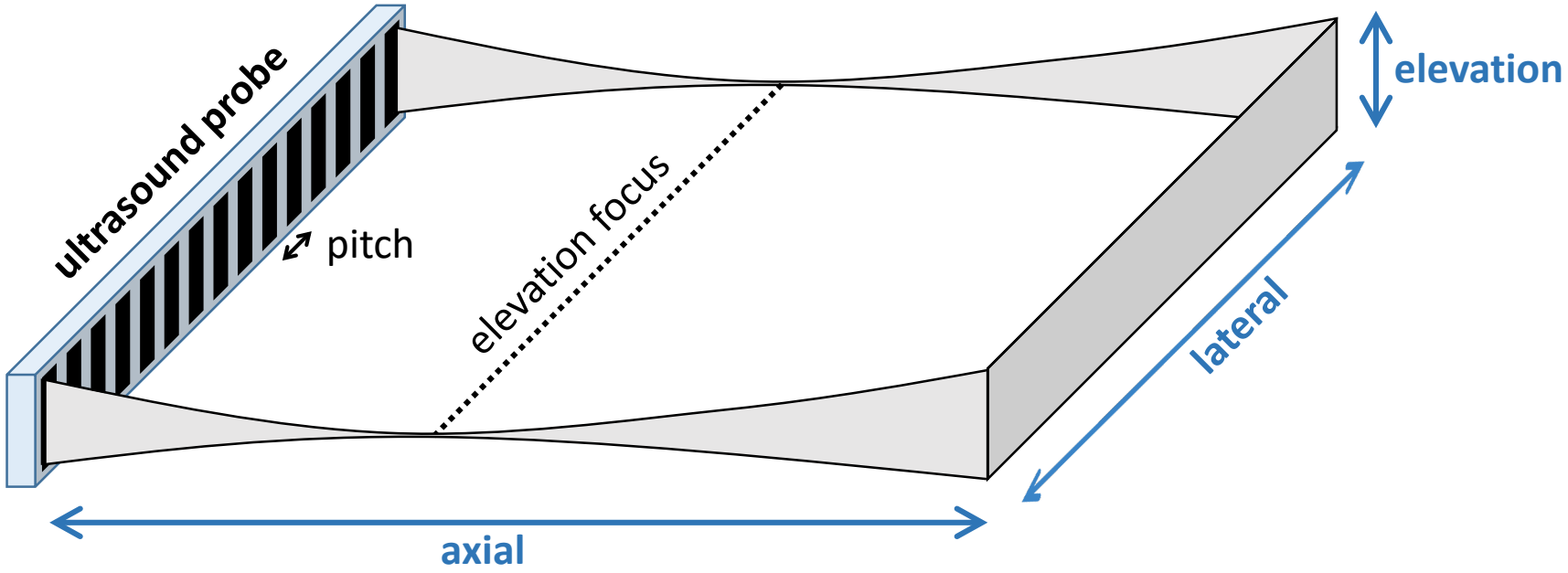






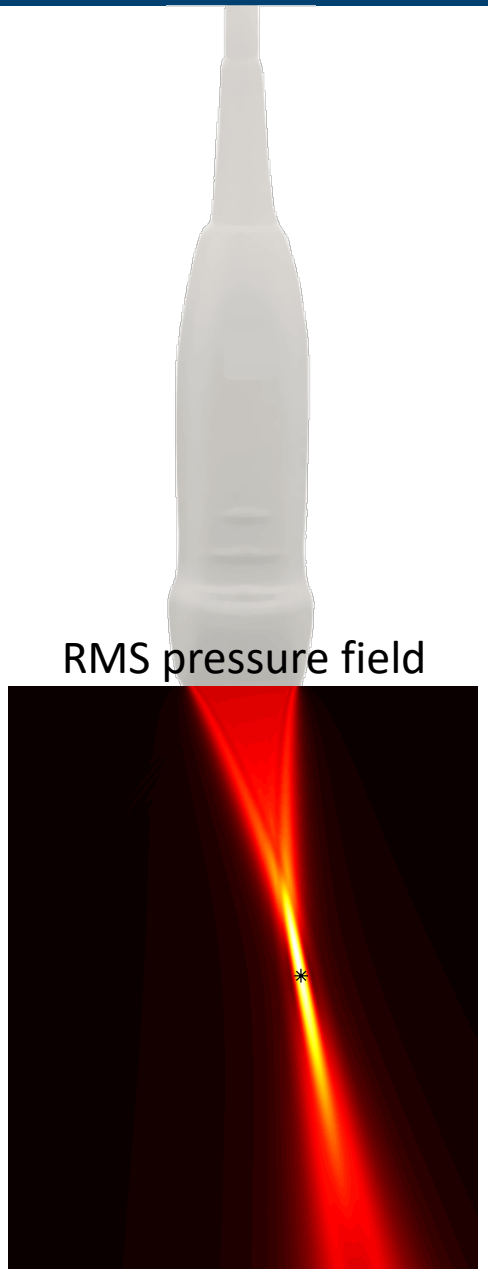
sources: www.ndk.com/en/sensor/ultrasonic/basic02.html
www.youtube.com/watch?v=cI7ULKNhVcw

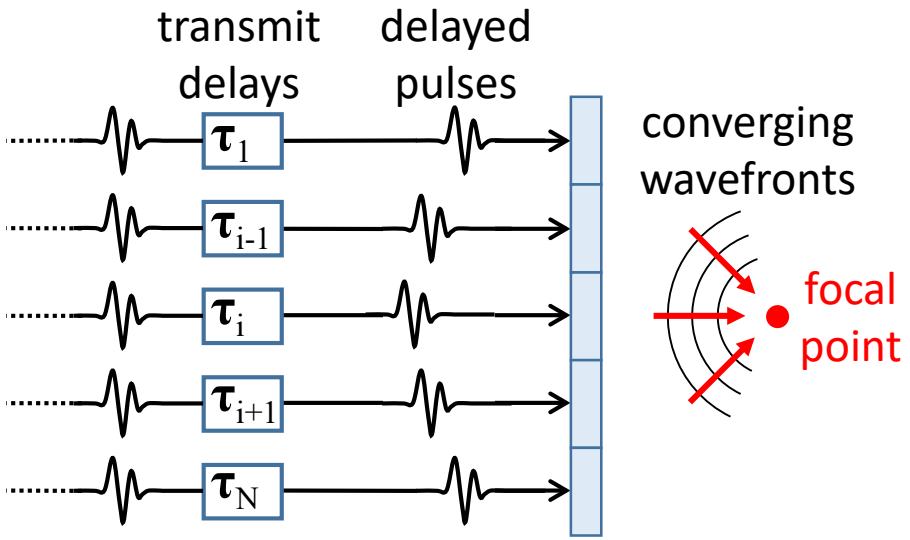
ultrasonic probe



keywords
- pitch
- axial direction
- lateral direction

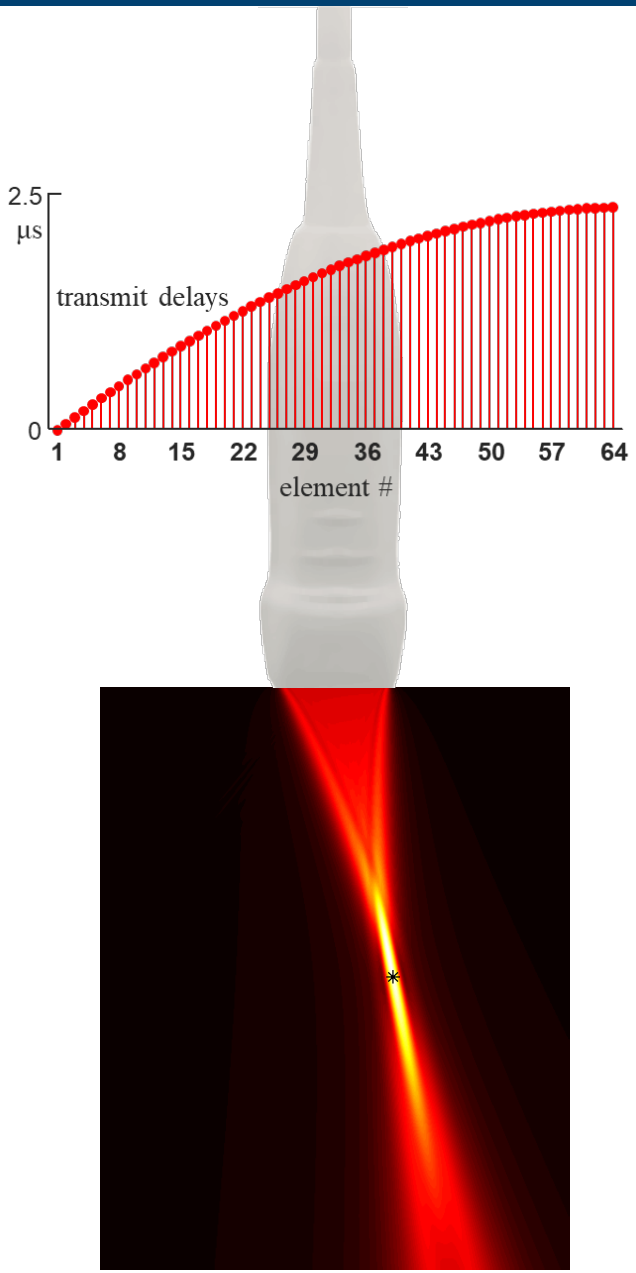
transmit focusing

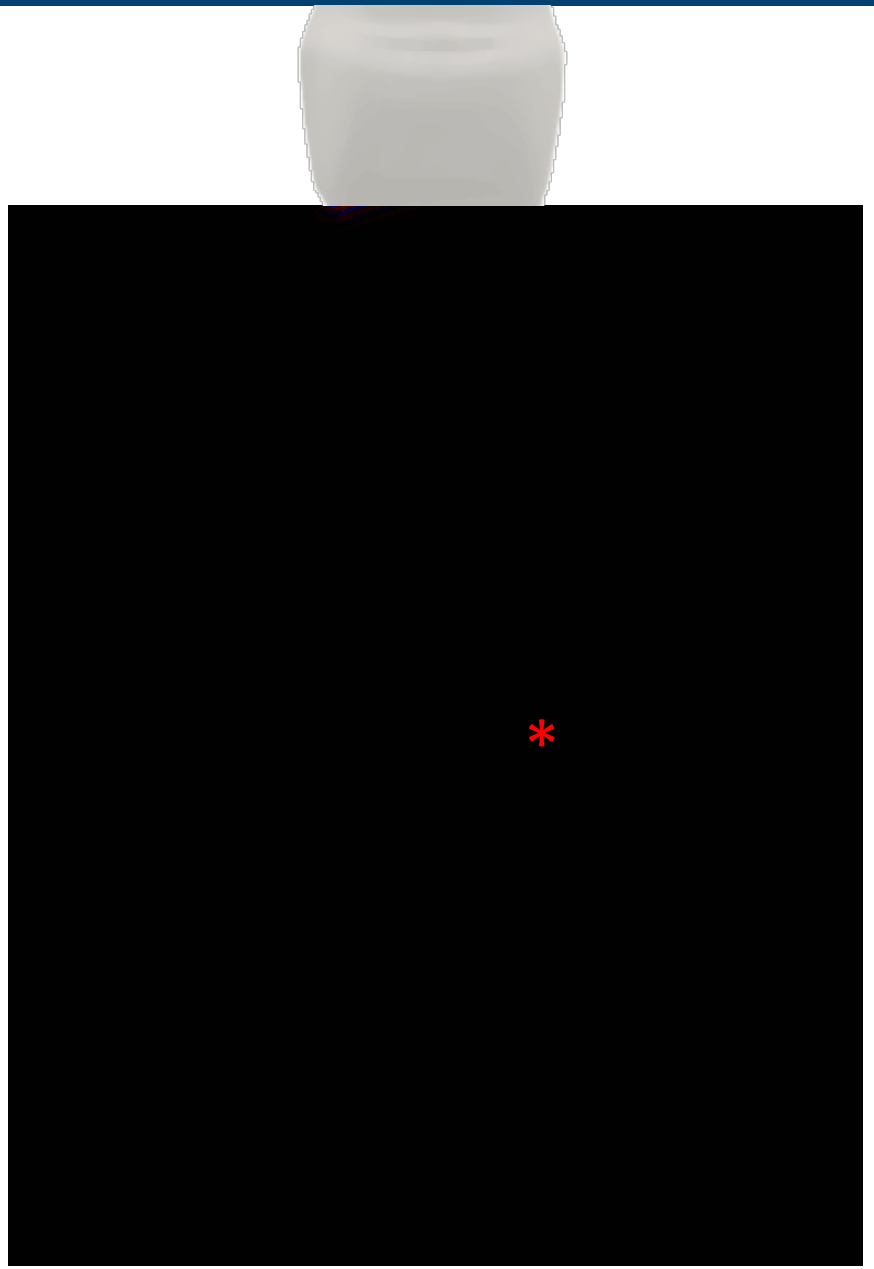




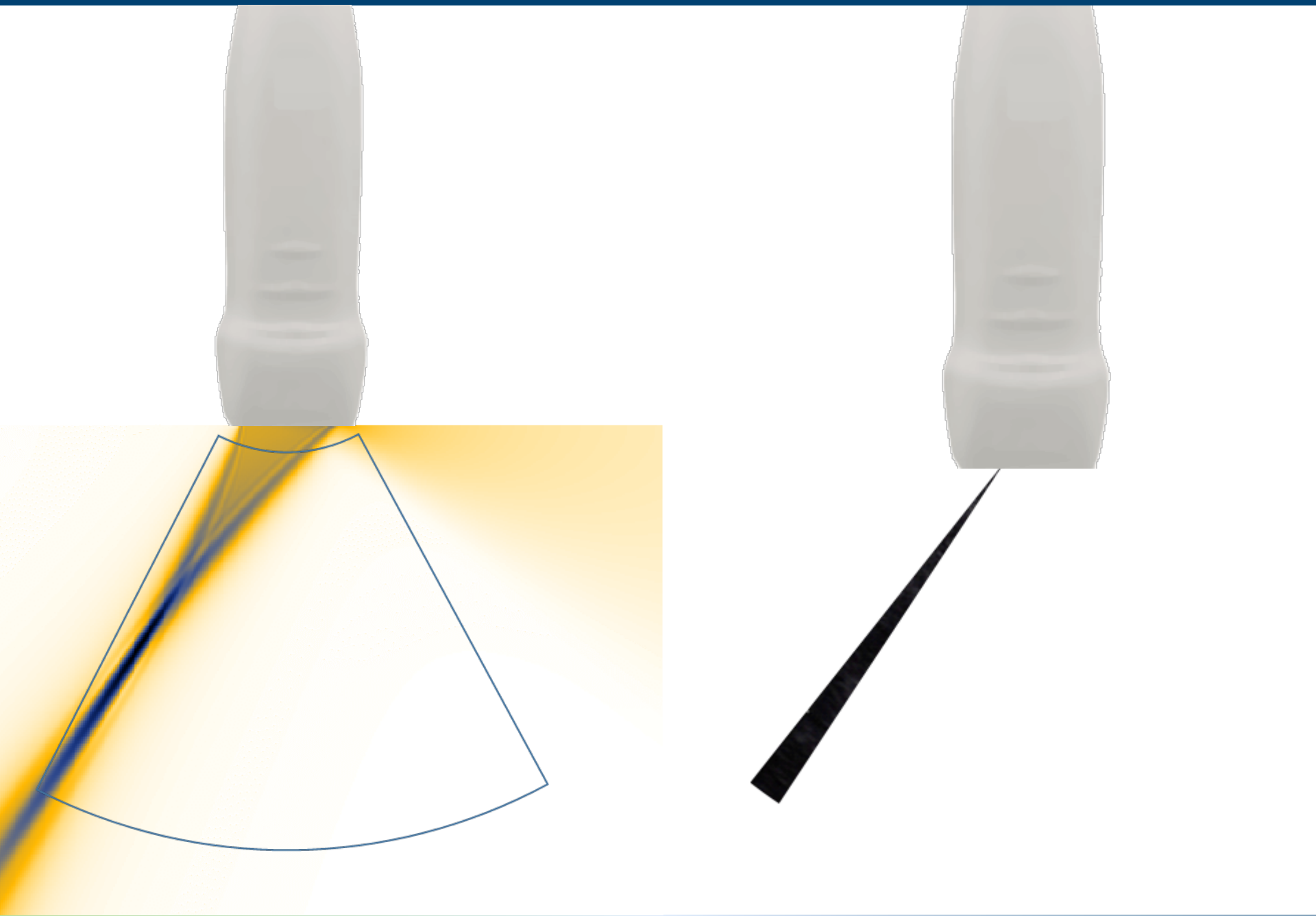
keywords
- transmit delays
- focal point

transmit focusing



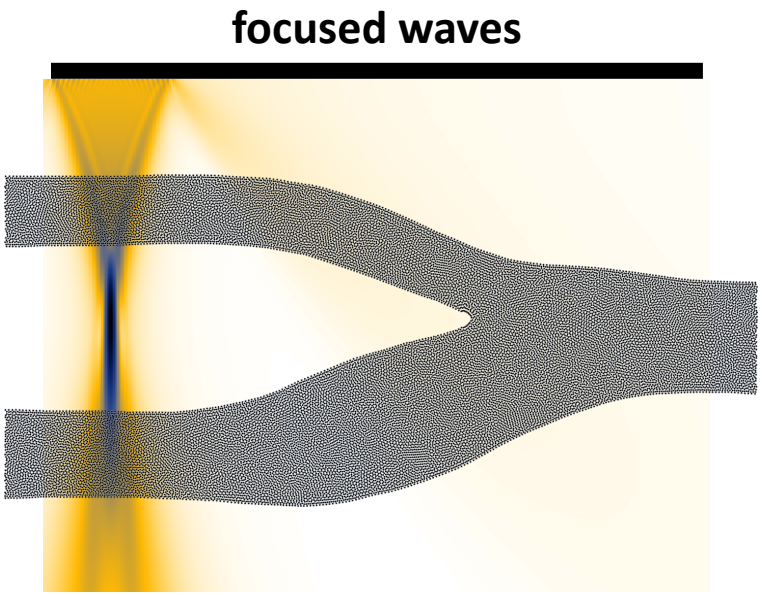


focused sequences in cardiac imaging



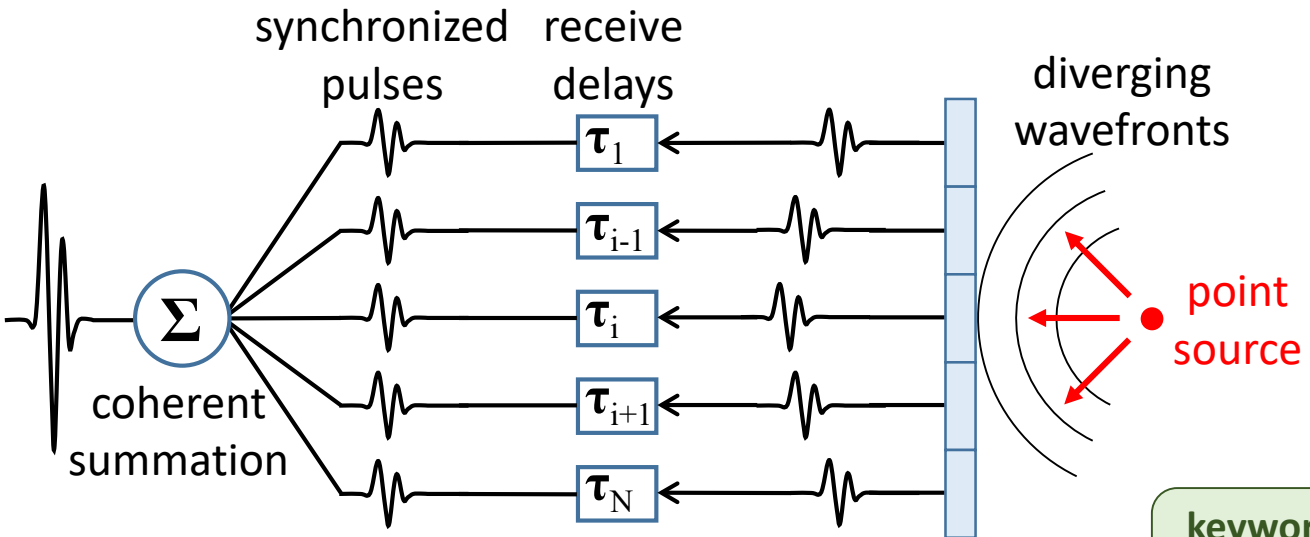
focused sequences in vascular imaging





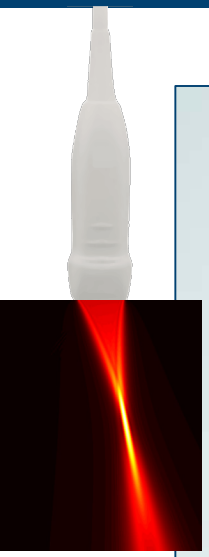
receive focusing

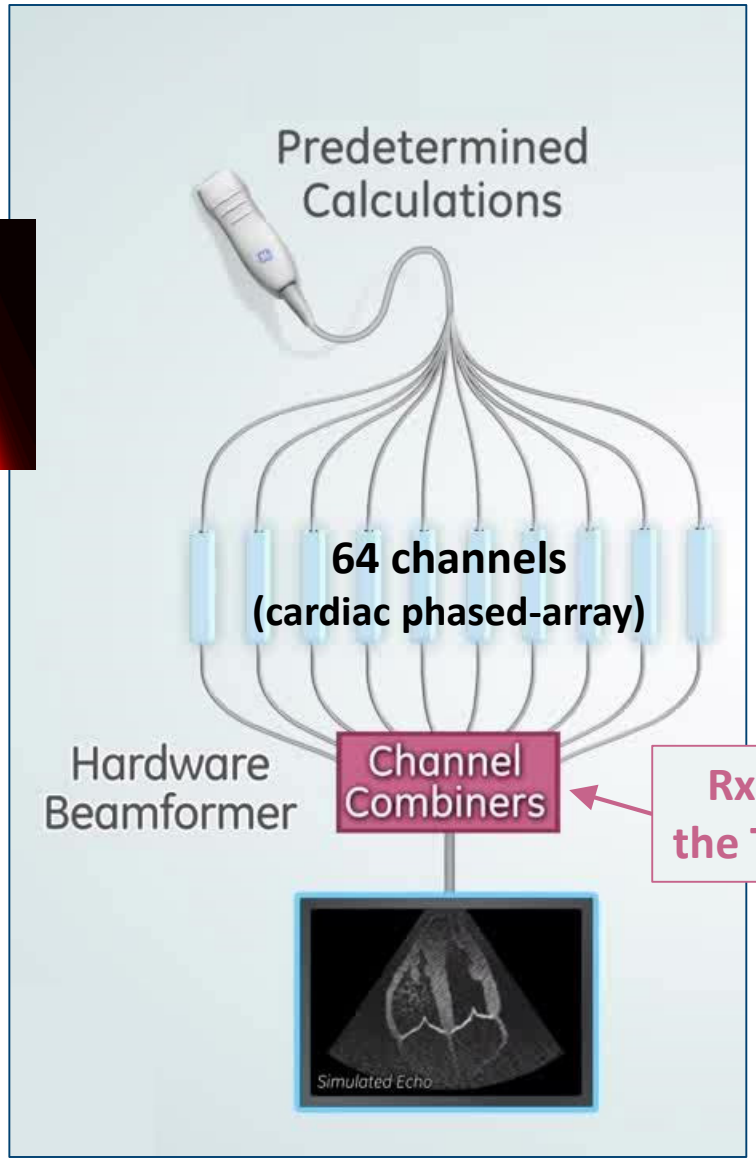
- **old-generation scanners**
  - receive focusing at the focal point only
  - hardware-based beamforming
- **new-generation scanners**
  - receive focusing everywhere
  - software-based beamforming



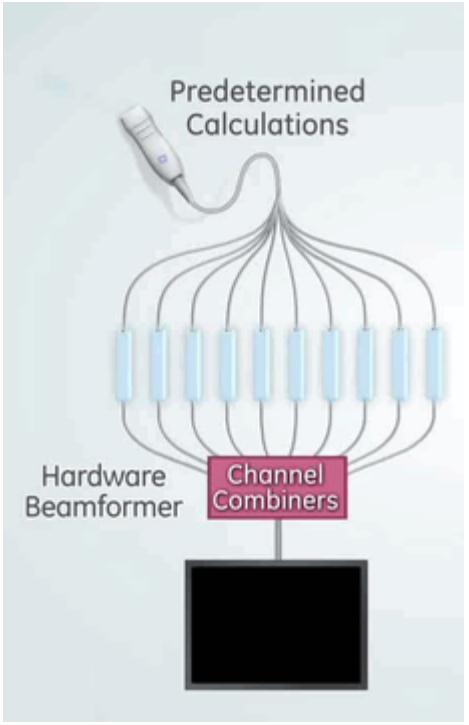
keywords
- dynamic receive focusing
- software-based beamforming

"traditional" hardware-based beamforming



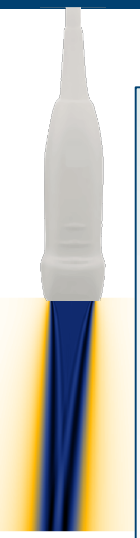


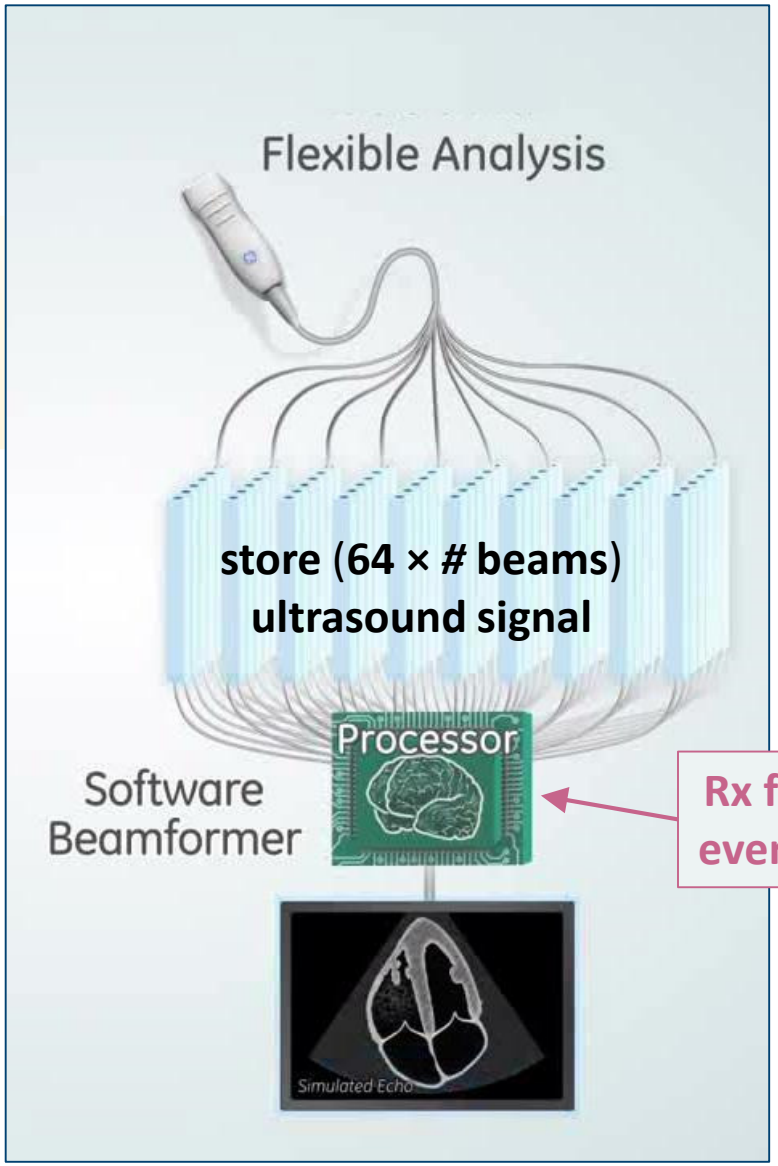
Rx focusing at the Tx focal point



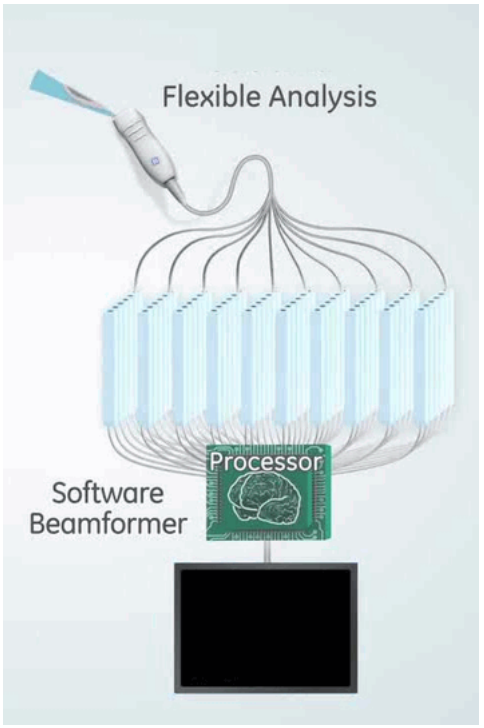
source: *GE C-Sound technology in Cardiovascular ultrasound* (www.youtube.com/watch?v=__VbO5H8iH0)

software-based beamforming





Rx focusing everywhere



source: *GE C-Sound technology in Cardiovascular ultrasound* (www.youtube.com/watch?v=__VbO5H8iH0)

ultrafast imaging

"***ULTRAFAST IMAGING***"

=

"higher frame rate than usual, for a given image quality"

- **other terms**:
  - dynamic focusing
  - dynamic beamforming
  - high-frame-rate imaging
  - plane-wave imaging
  - diverging-wave imaging
  - synthetic aperture
  - coherent imaging

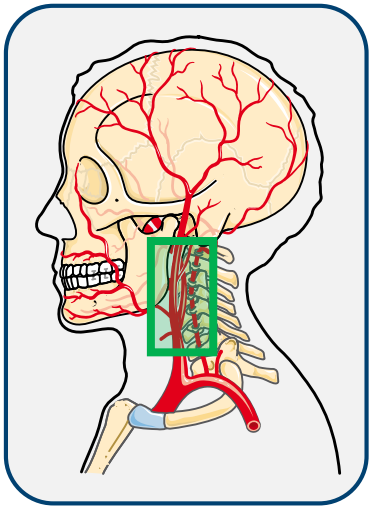
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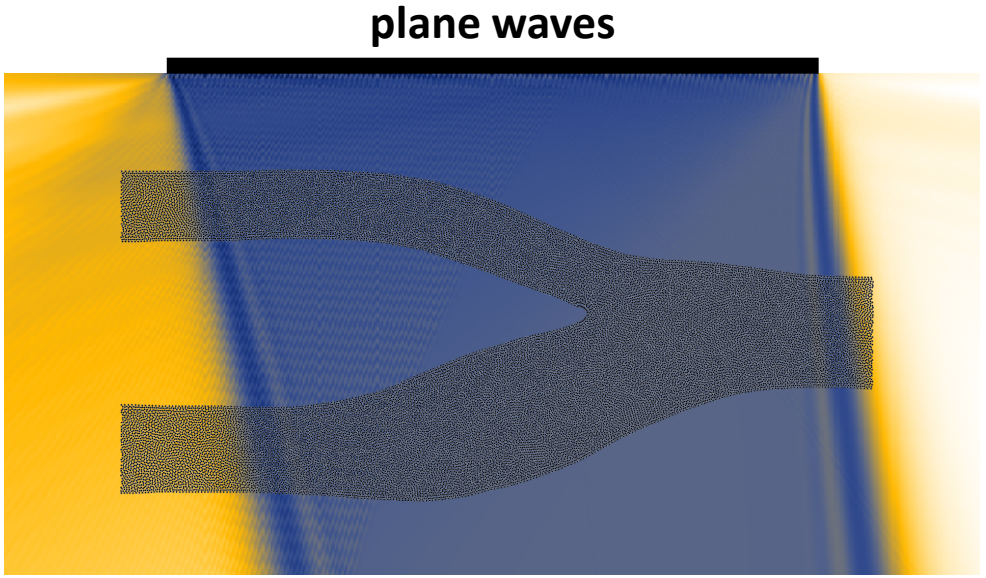
key paper

- Tanter & Fink. IEEE TUFFC 2014;61:102-119

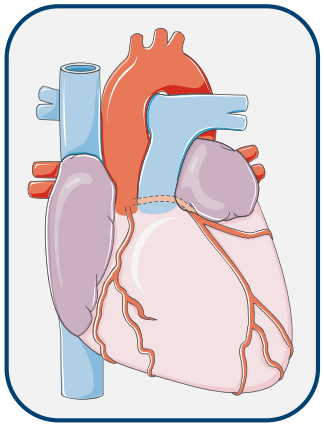
wide-wave sequences in vascular imaging



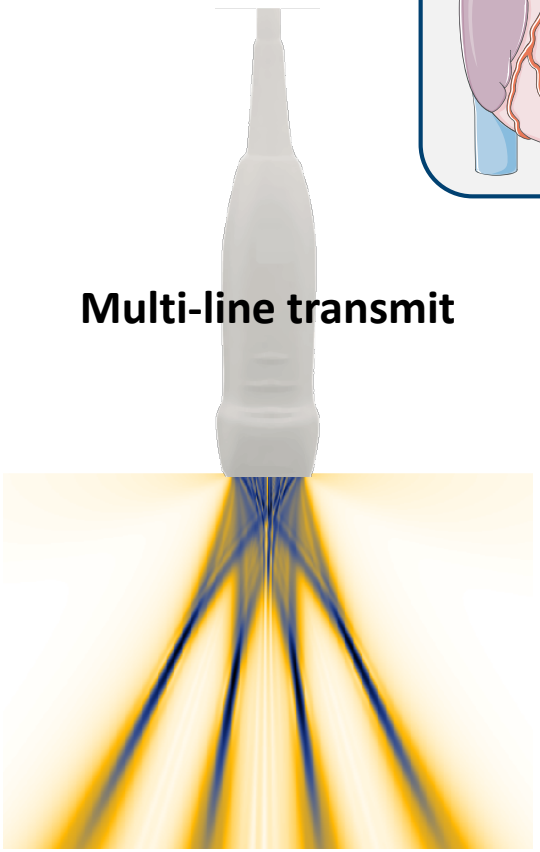




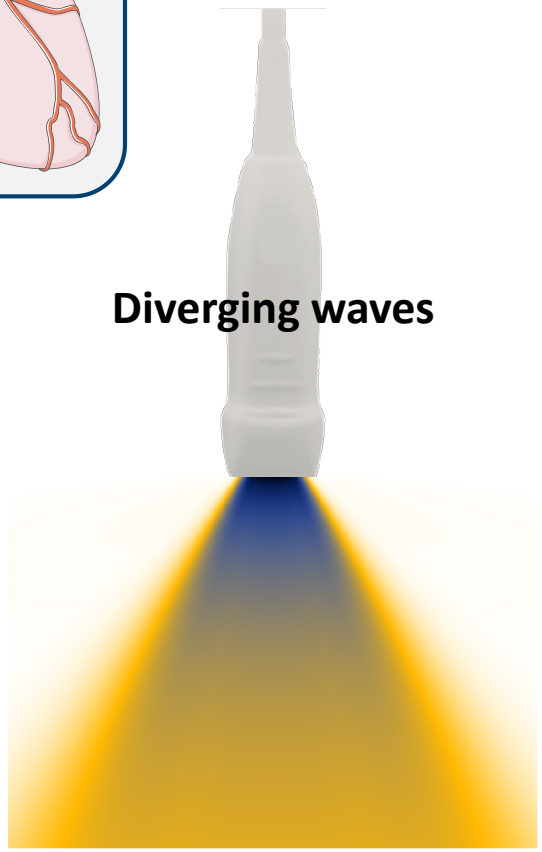
“ultrafast” sequences in cardiac imaging



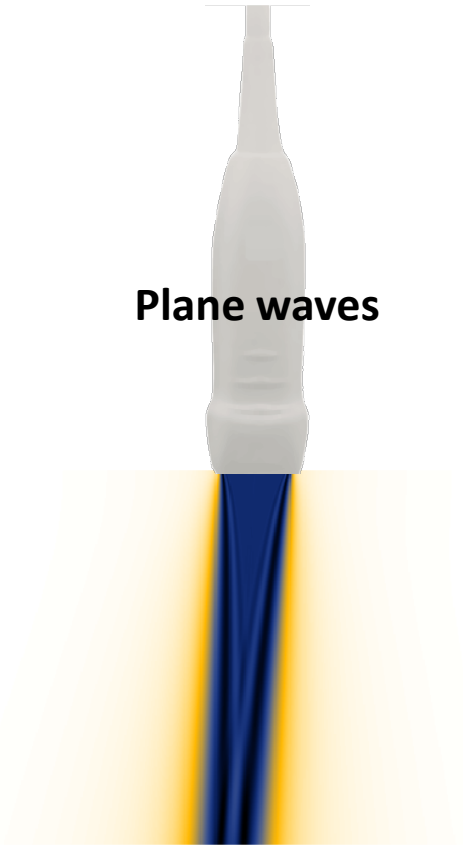
Multi-line transmit



Diverging waves



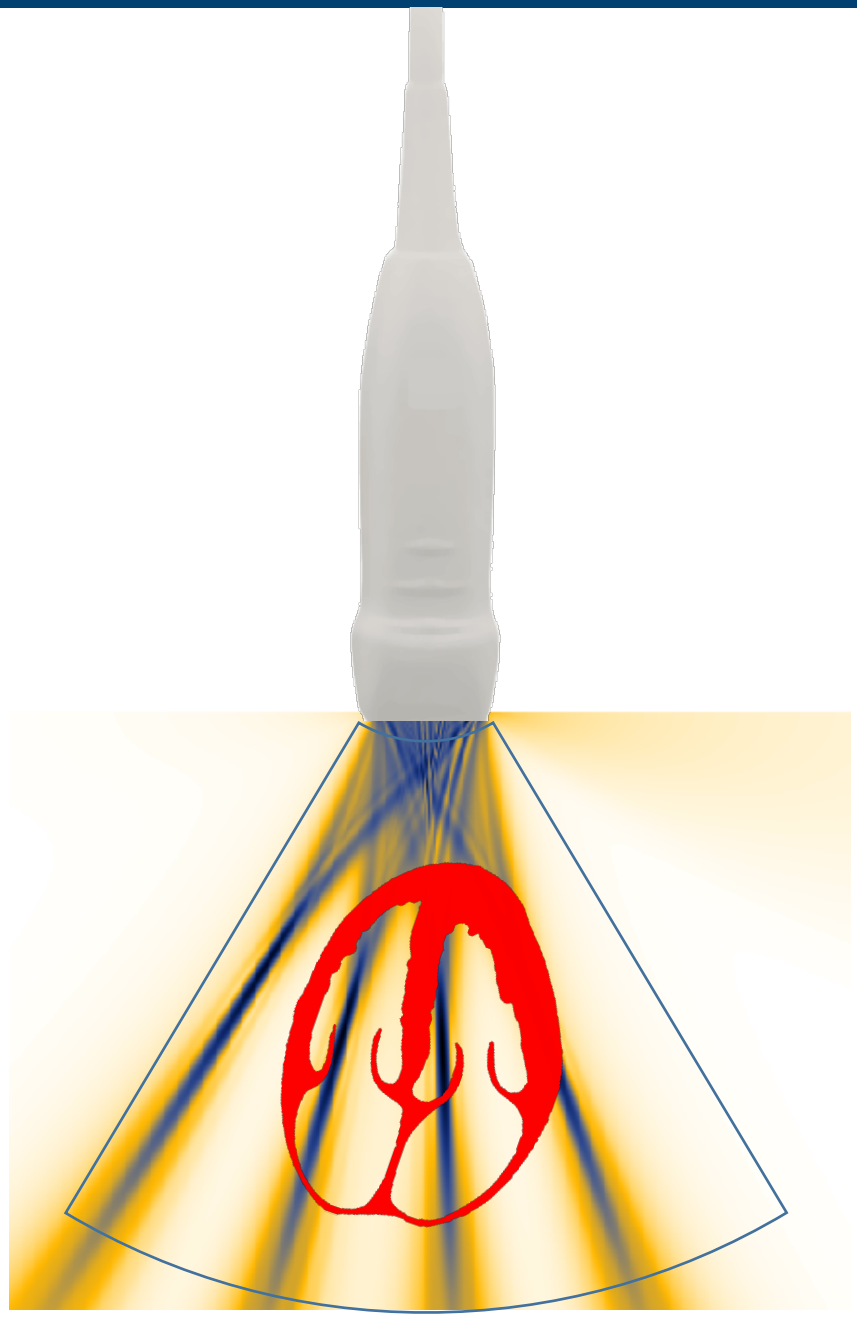
Plane waves



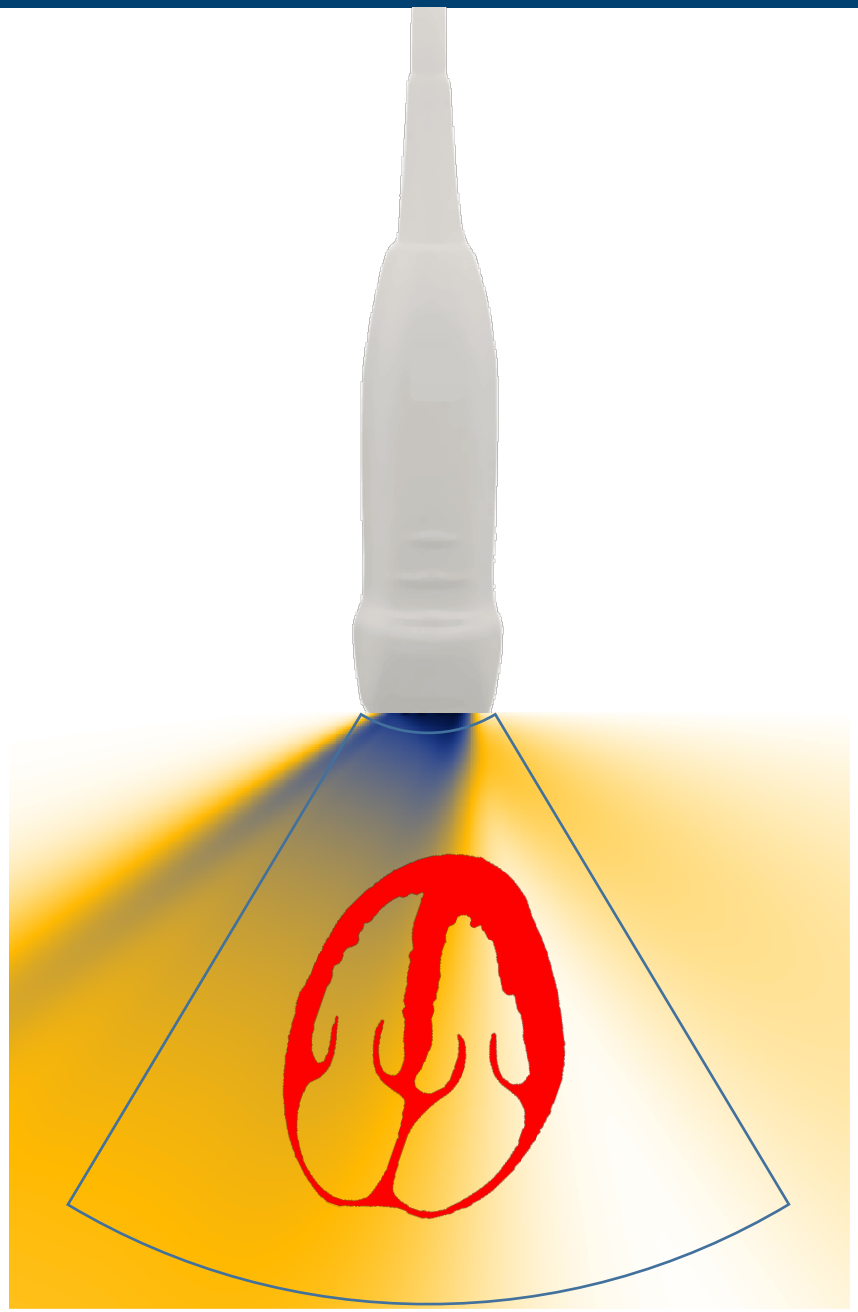
key paper

- Cikes *et al*. J Am Coll Cardiol Img 2014;7:812-823

multi-line transmit



diverging-wave transmit



plane-wave transmit



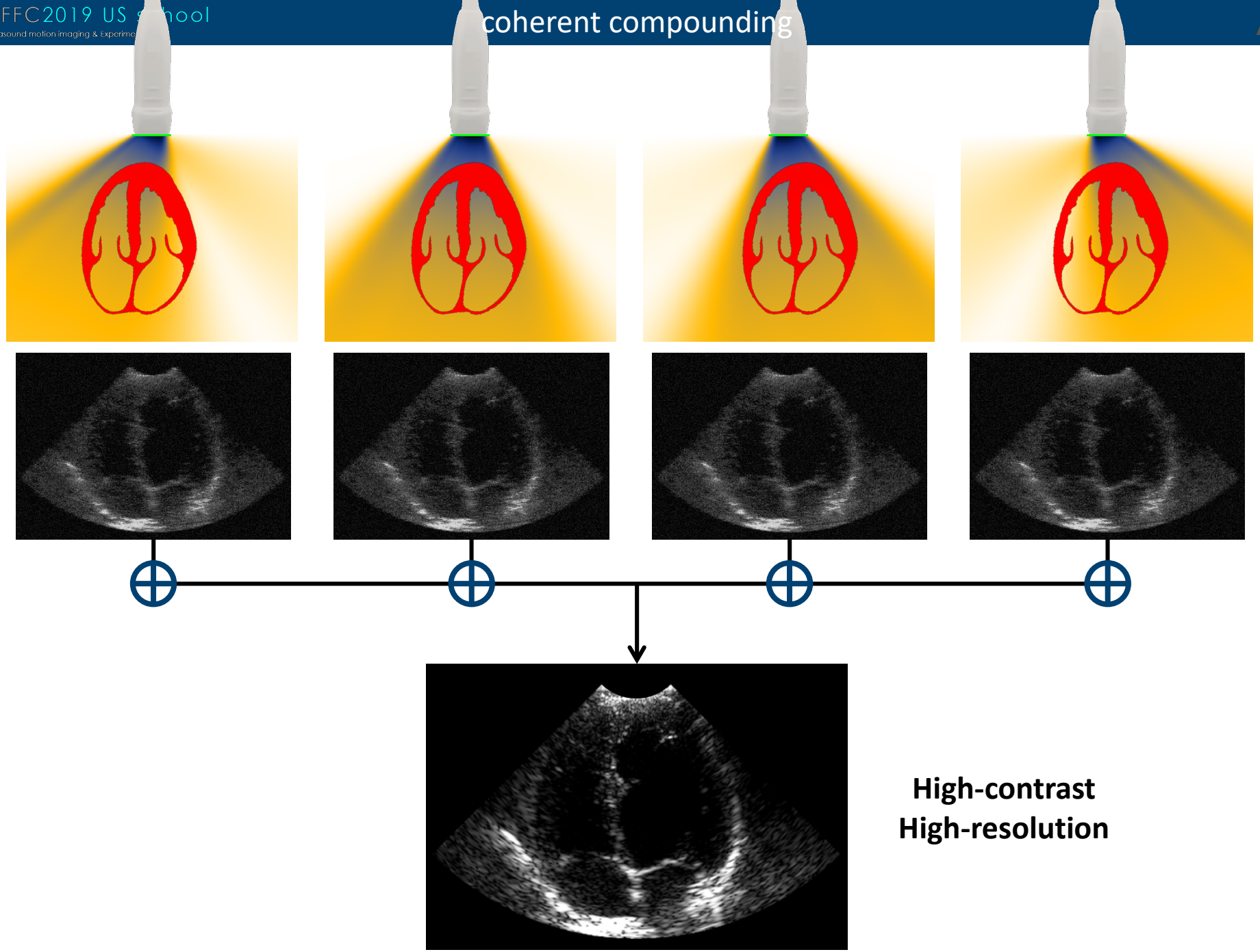
software-based beamforming in clinical scanners

- **focused transmit imaging**
  - soon, no longer used

- **non-focused transmit** + **software-based beamforming**
  - software running on Graphics Processing Units
  - <u>examples</u>:
    - GE: *cSound* software with *True Confocal Imaging*
    - Philips: ***n****SIGHT imaging*
    - Siemens: *IN Focus Coherent* Technology



coherent compounding

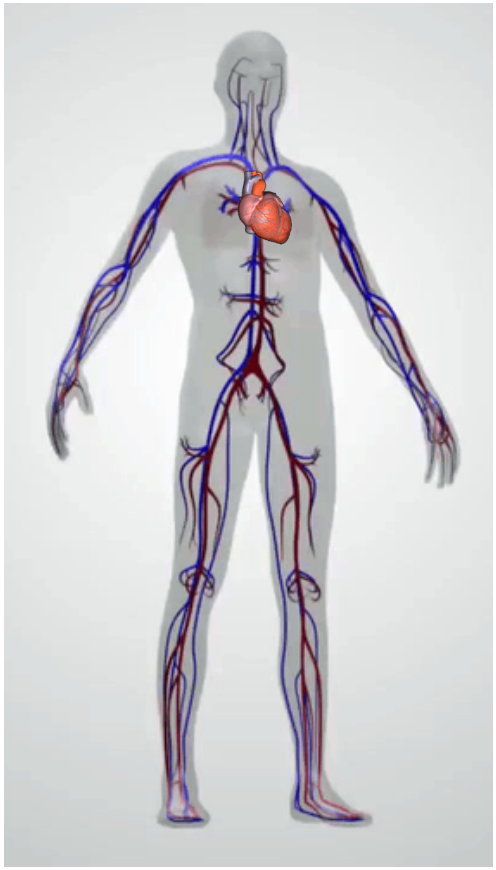


High-contrast
High-resolution

MOTION

in the cardiovascular system

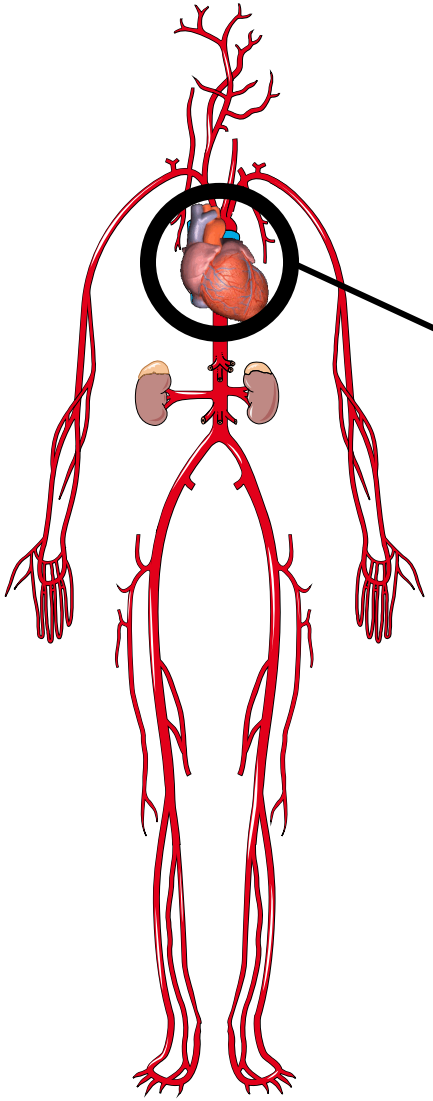
motion in the CV system



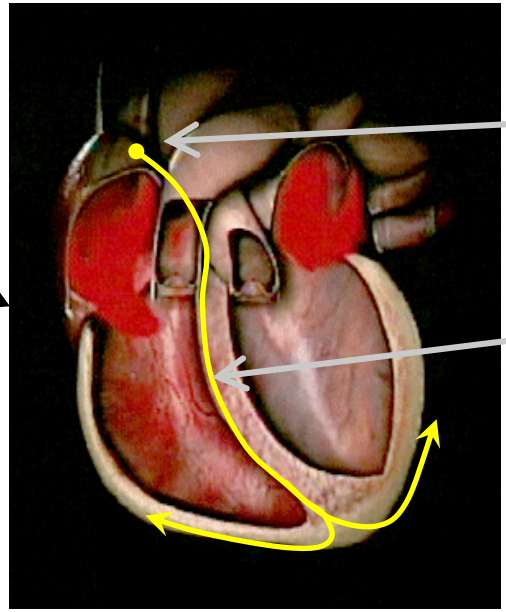
- **Most of the macroscopic motions in the body occur in the cardiovascular system**
  - The heart is the main motor

- **Different techniques to detect motions**
  1. **Block matching** (very popular)
  2. **Doppler** (popular)
     a. vector Doppler / transverse oscillations
     b. intraventricular vector flow mapping
  3. Optical flow (less popular)
  4. Point set or Image registration (little used)

motion in the heart: electrical activation



Electrical activation of the heart

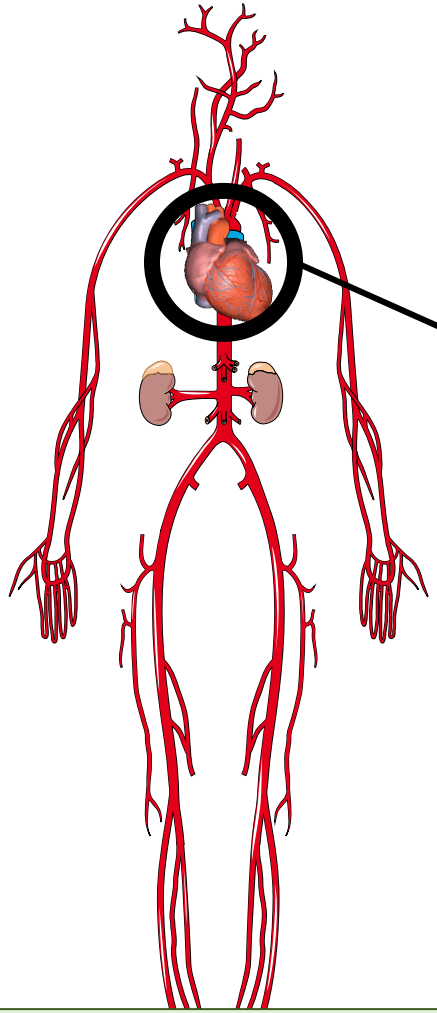


sinoatrial node (the heart's pacemaker)

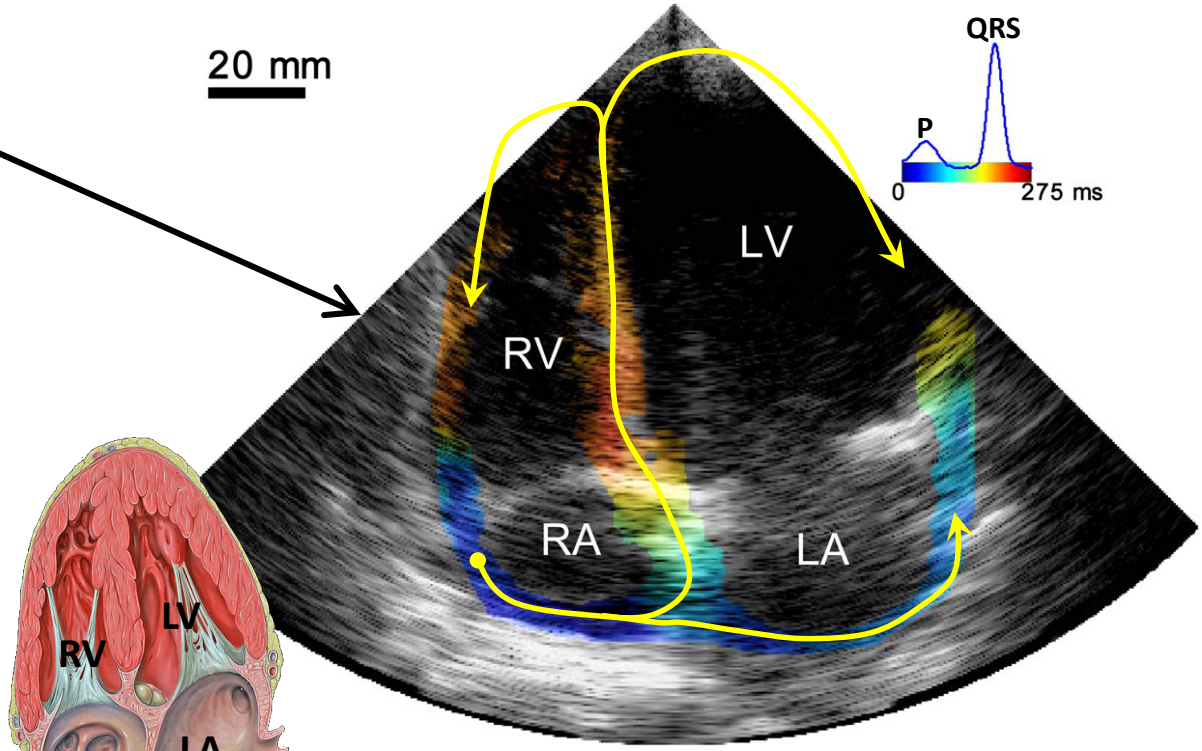
bundle of His

motion in the heart: electrical activation (cont'd)

(method: RF tracking)



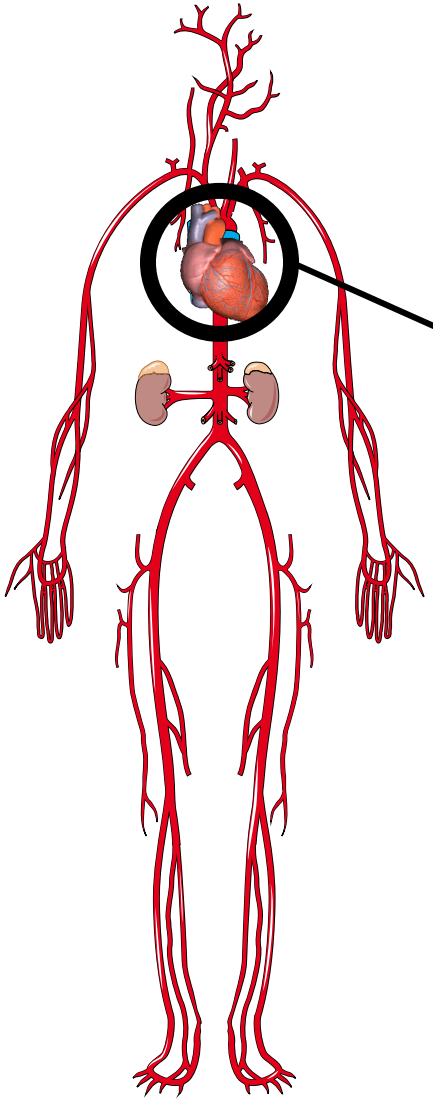
Electrical activation of the heart



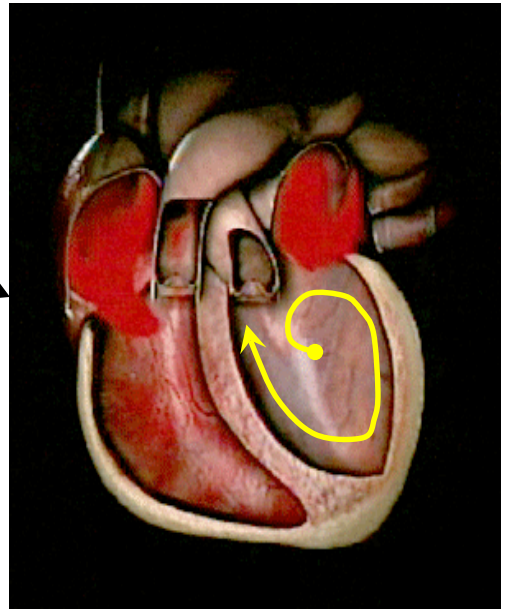
key paper

- Provost *et al*. PNAS 2011;108:8565-8570

motion in the heart: blood flow

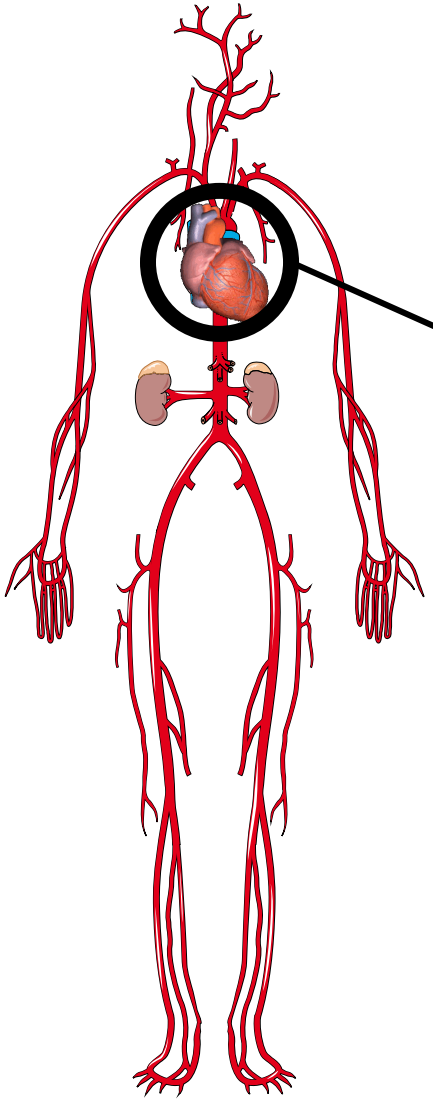


Intracardiac flow

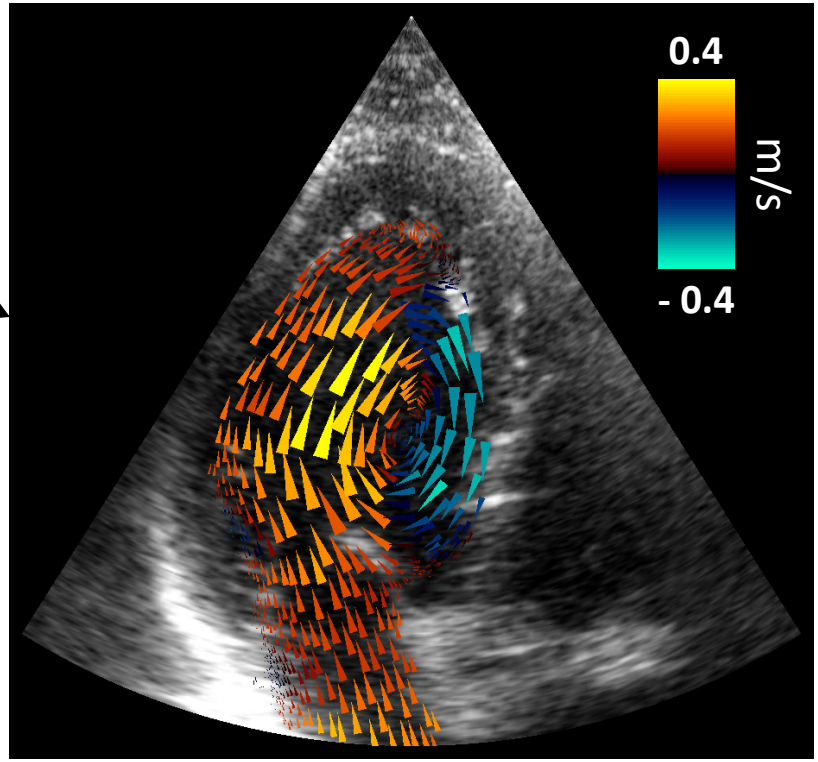


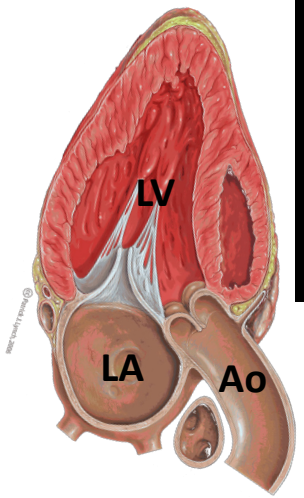
motion in the heart: blood flow (cont'd)

(method: intraventricular VFM)



Intracardiac flow



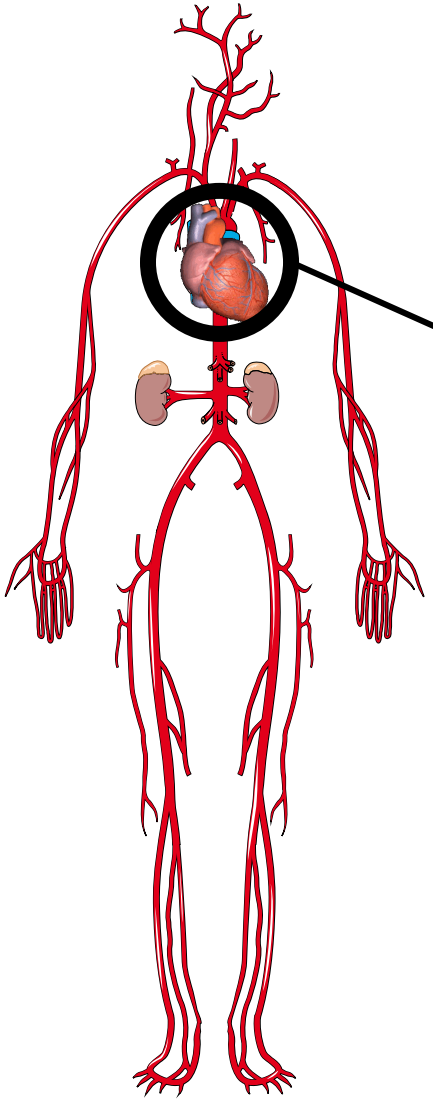


key paper

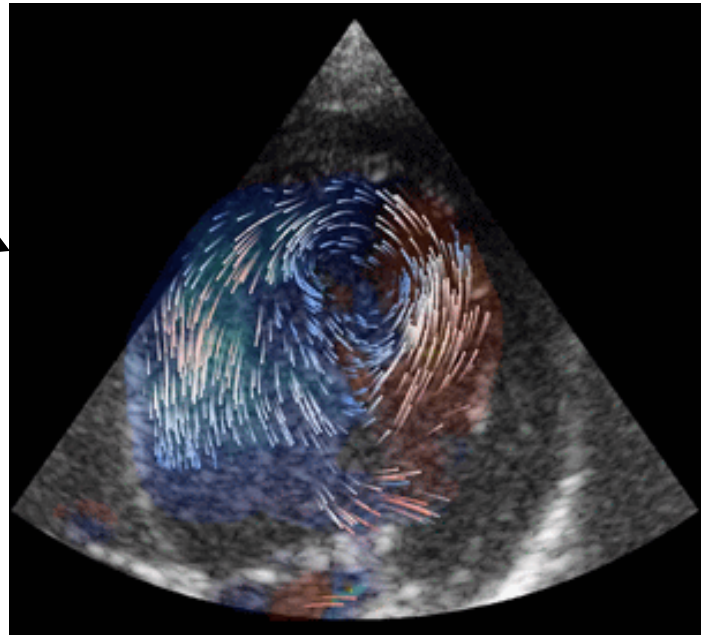
- Garcia *et al*. IEEE TMI 2010;29:1701-1713

motion in the heart: blood flow (cont'd)

(method: speckle tracking)

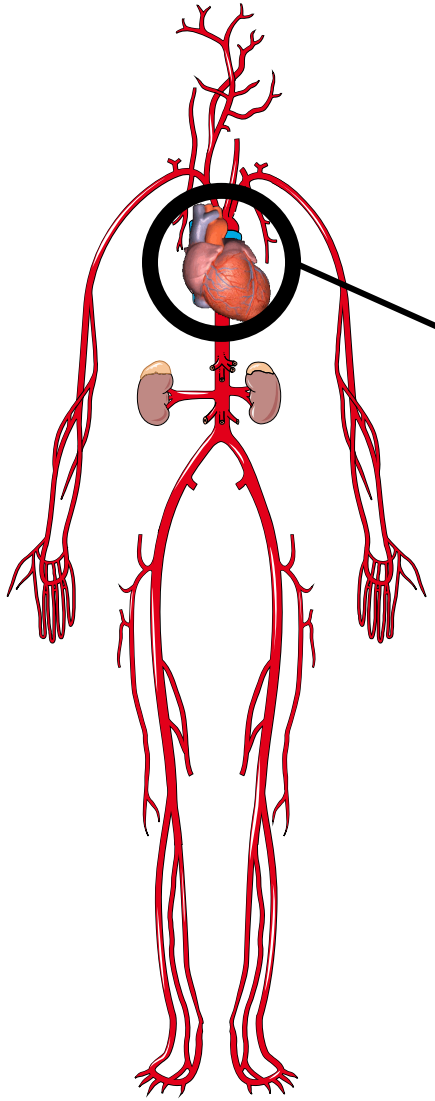


Intracardiac flow



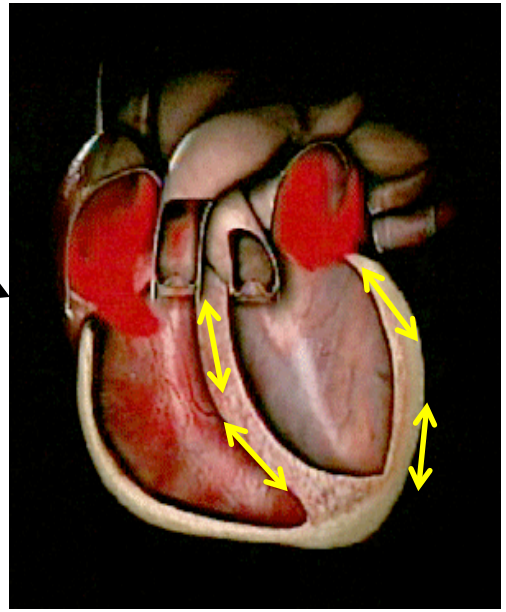
Siri Ann Nyrnes & Lasse Løvstakken, NTNU, Norway.
Luc Mertens, SickKids, Toronto, Canada.

motion in the heart: myocardium



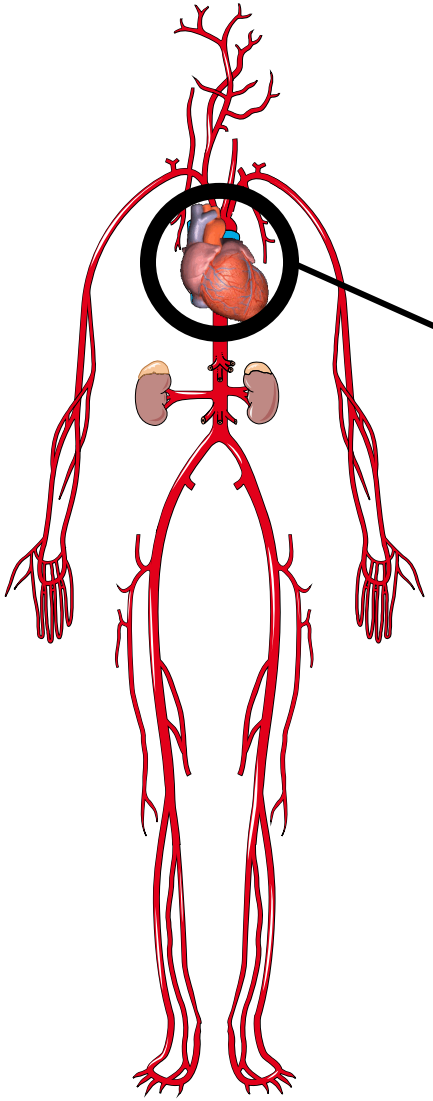


Myocardial strain



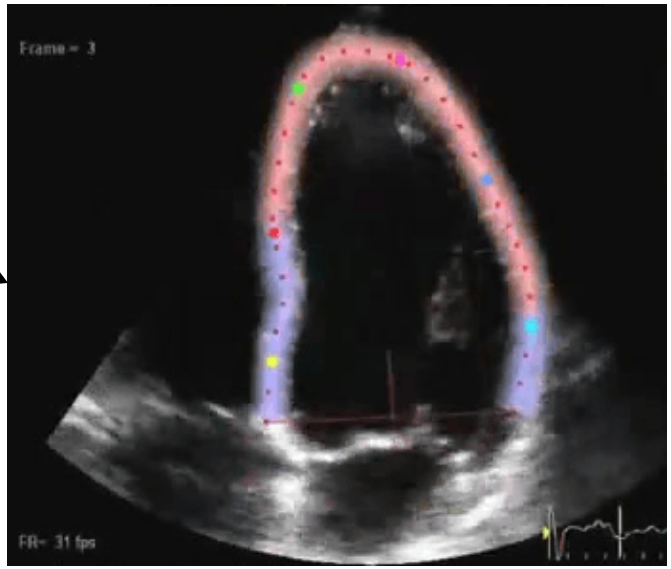
motion in the heart: myocardium (cont'd)

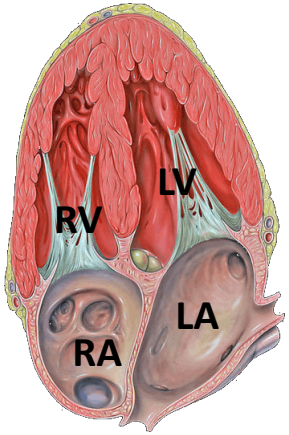
(method: speckle tracking)





Myocardial strain



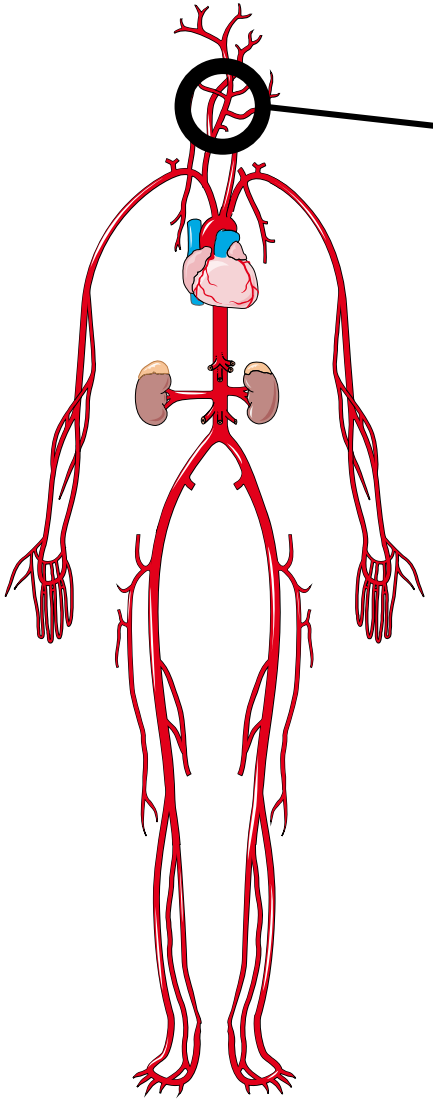


book chapter

- Garcia *et al*. IET doi:10.1049/pbhe013e_ch26

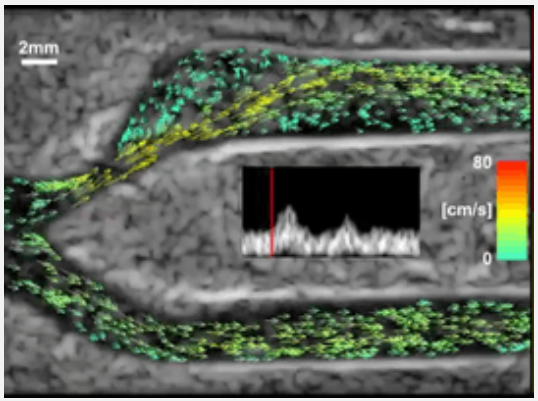
flow motion in the arteries: carotid

(method: vector Doppler)

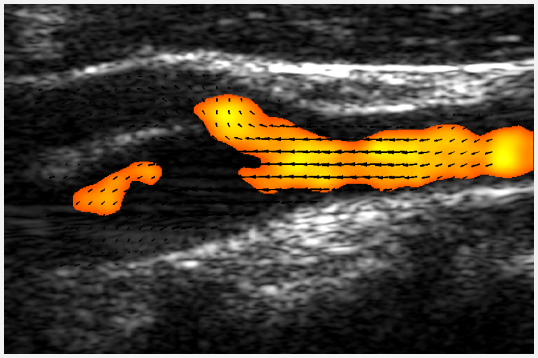




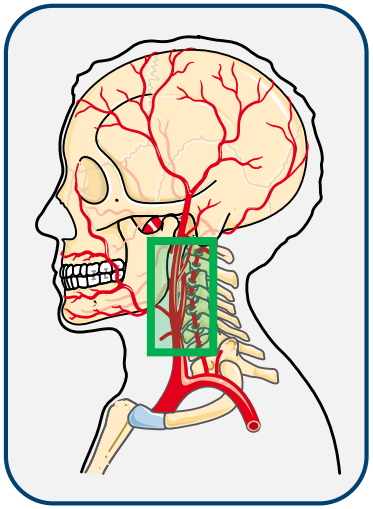
Shahriari *et al*. Phys Med Biol 2018



Yiu *et al*. Ultrasound Med Biol 2014



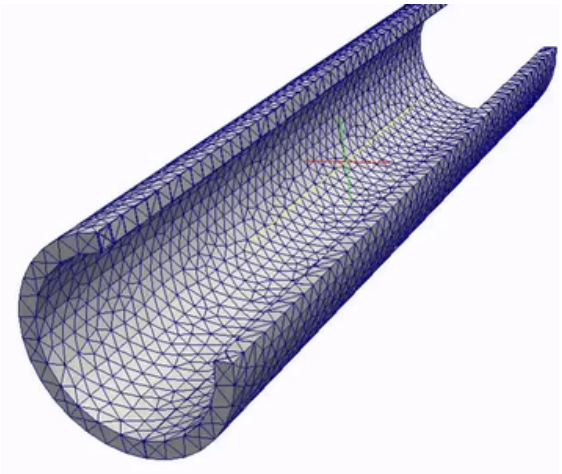
Madiena *et al*. IEEE TUFFC 2018



key paper

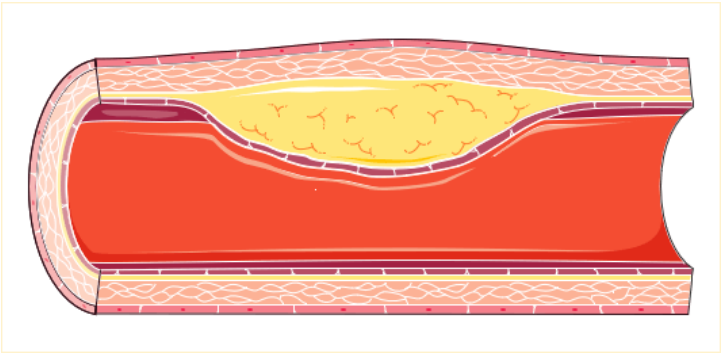
- Jensen *et al*. IEEE TUFFC 2016;63:1704-1721

motion of the arterial wall



- **Pulse wave propagation**

the pulse wave velocity determines arterial stiffness

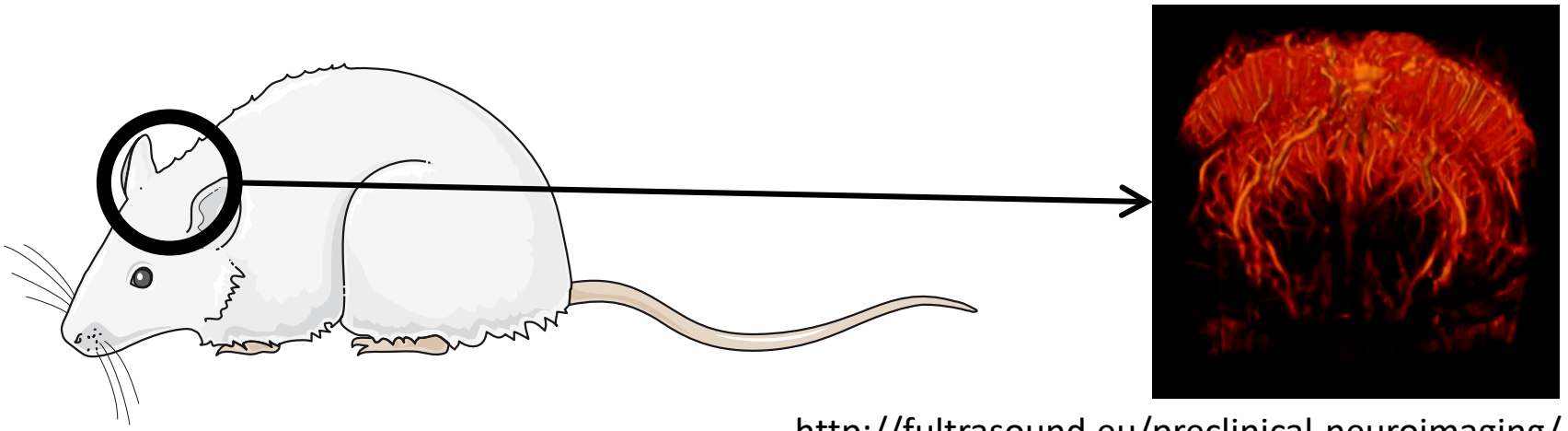


- **Arterial distensibility**

the natural radial motion allows elastography

functional ultrasound

(method: power Doppler)



http://fultrasound.eu/preclinical-neuroimaging/

Note: fUS does not measure velocities but detects where blood motion is present

key paper

- Deffieux *et al*. Curr Opin Neurobiol 2018;50:128-135

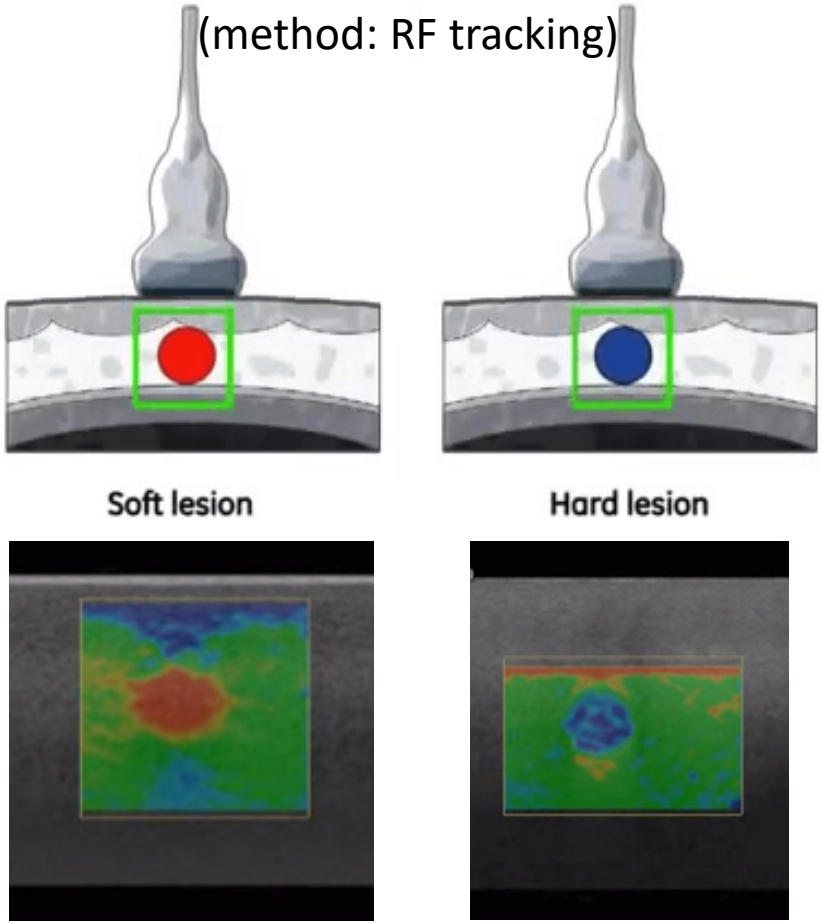
generating

MOTION

where there is none

elastography

(method: RF tracking)

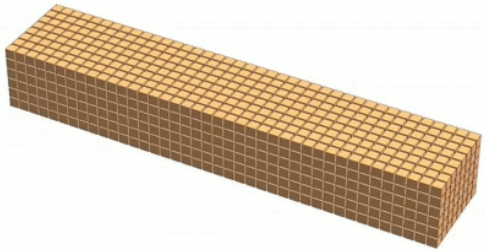


Motion, if not present naturally, can also be induced by:

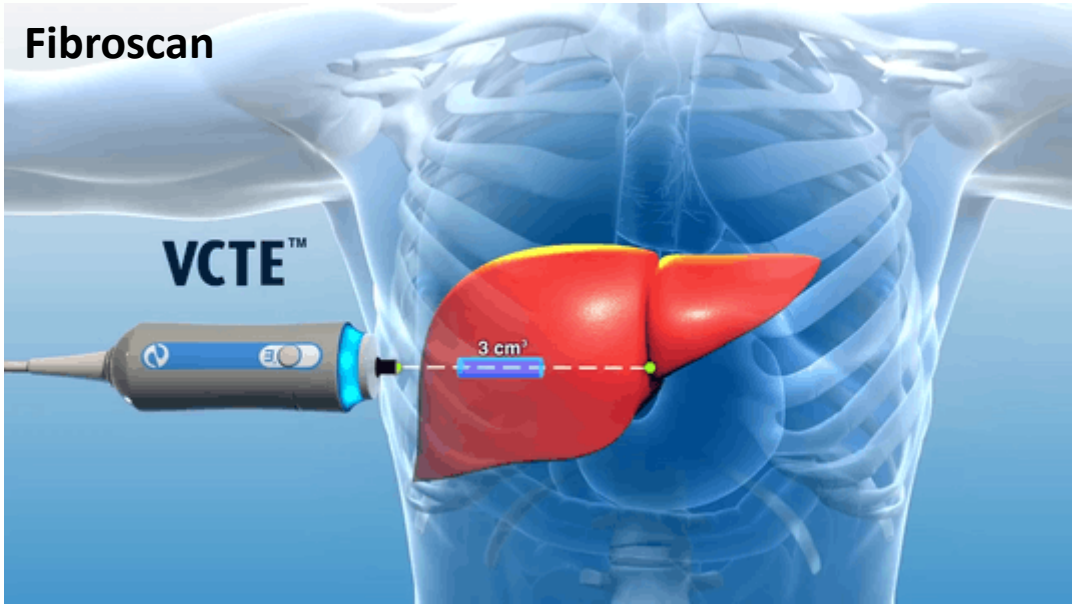
- **mechanical compression**
- mechanical push
- acoustic push by focused beams

source: www.youtube.com/watch?v=eSASqTk4Wuw

transient elastography



- The motion of a shear wave is perpendicular to the direction of wave propagation
- The stiffer the medium, the faster the wave is
- If the medium is **homogeneous**: $E \propto \rho c_S^2$

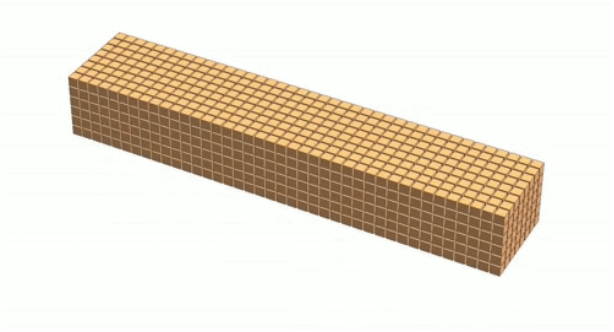


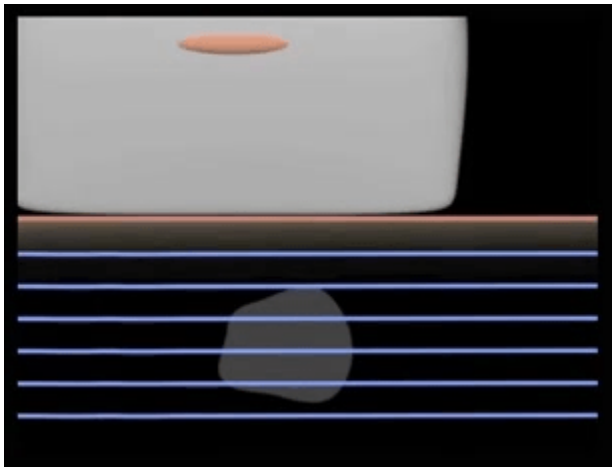
Motion, if not present naturally, can also be induced by:

- mechanical compression
- **mechanical push**
- acoustic push by focused beams

source: www.youtube.com/watch?v=J97lWzEeO2Q

shear wave elastography





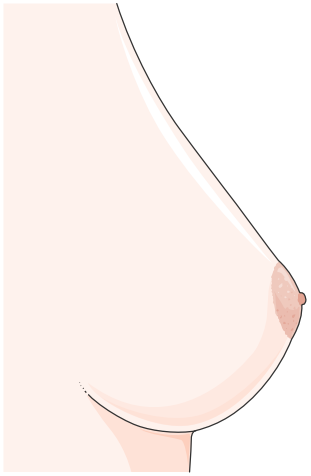
Motion, if not present naturally, can also be induced by:

- mechanical compression
- mechanical push
- **acoustic push by focused beams**

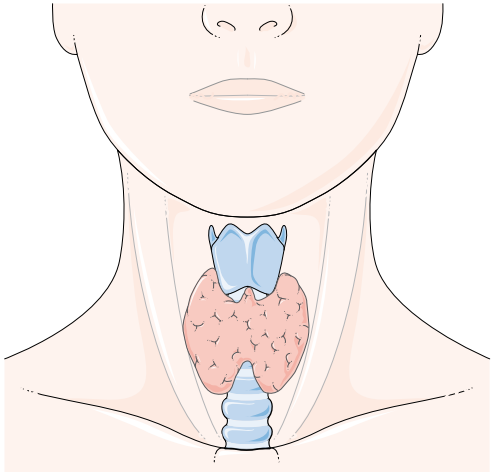
source: www.youtube.com/watch?v=v51DQMYw_Vs

some applications of elastography

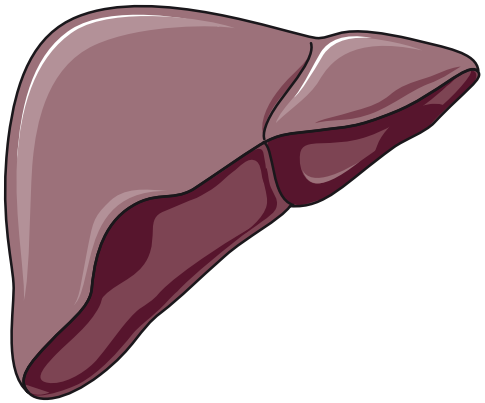
Elastography is used where manual palpation was already widespread



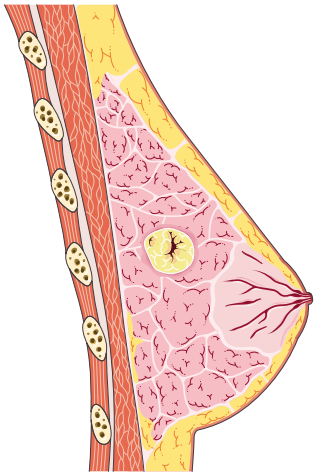
Breast cancer

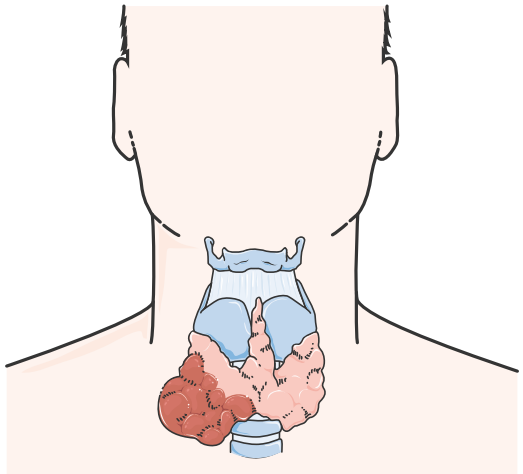


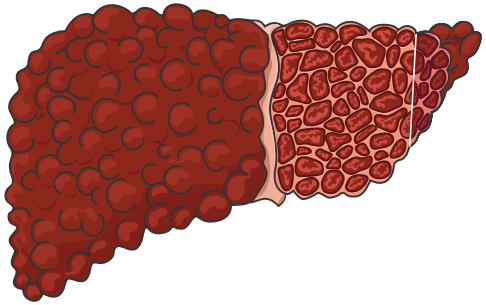
Thyroid cancer



Cirrhosis

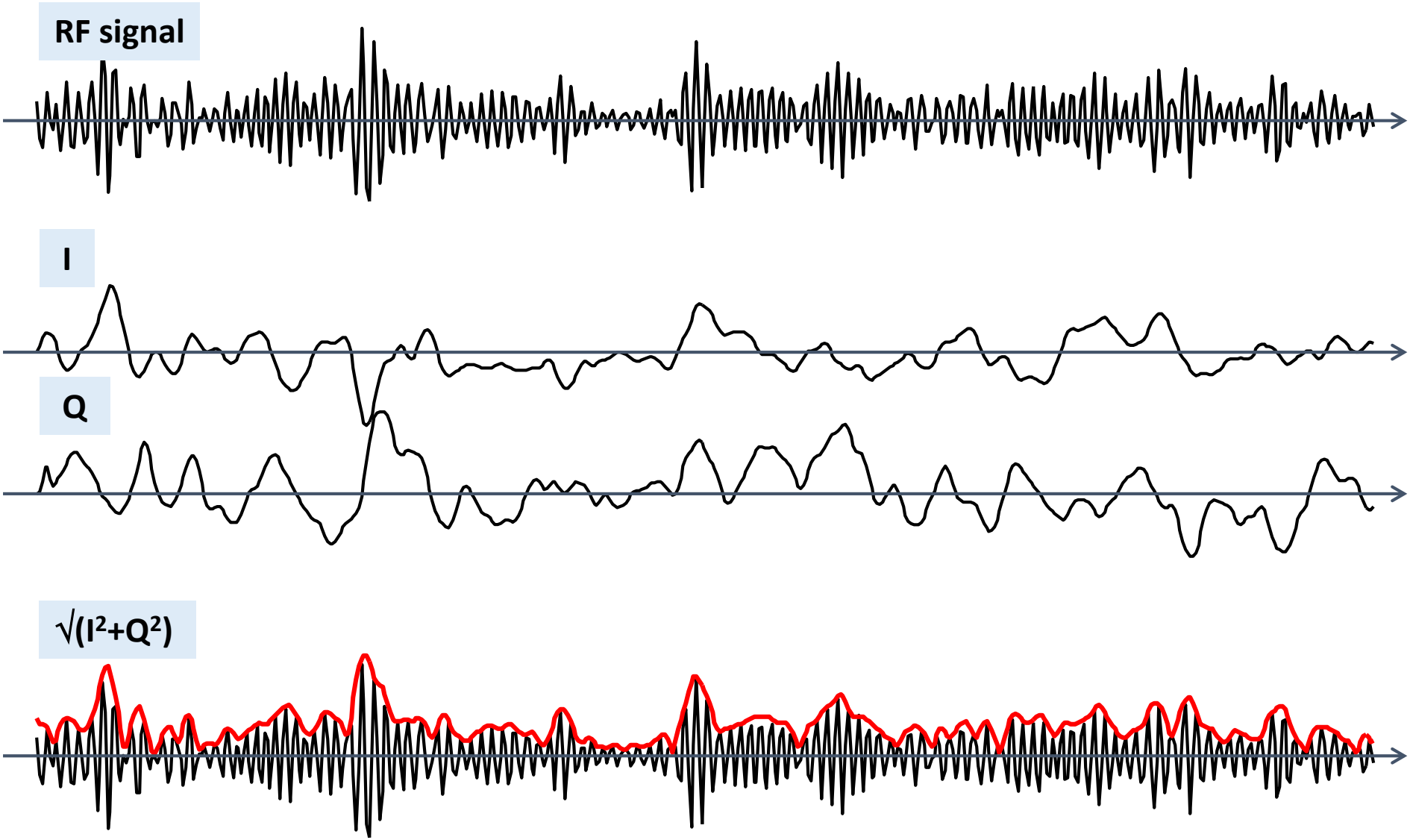






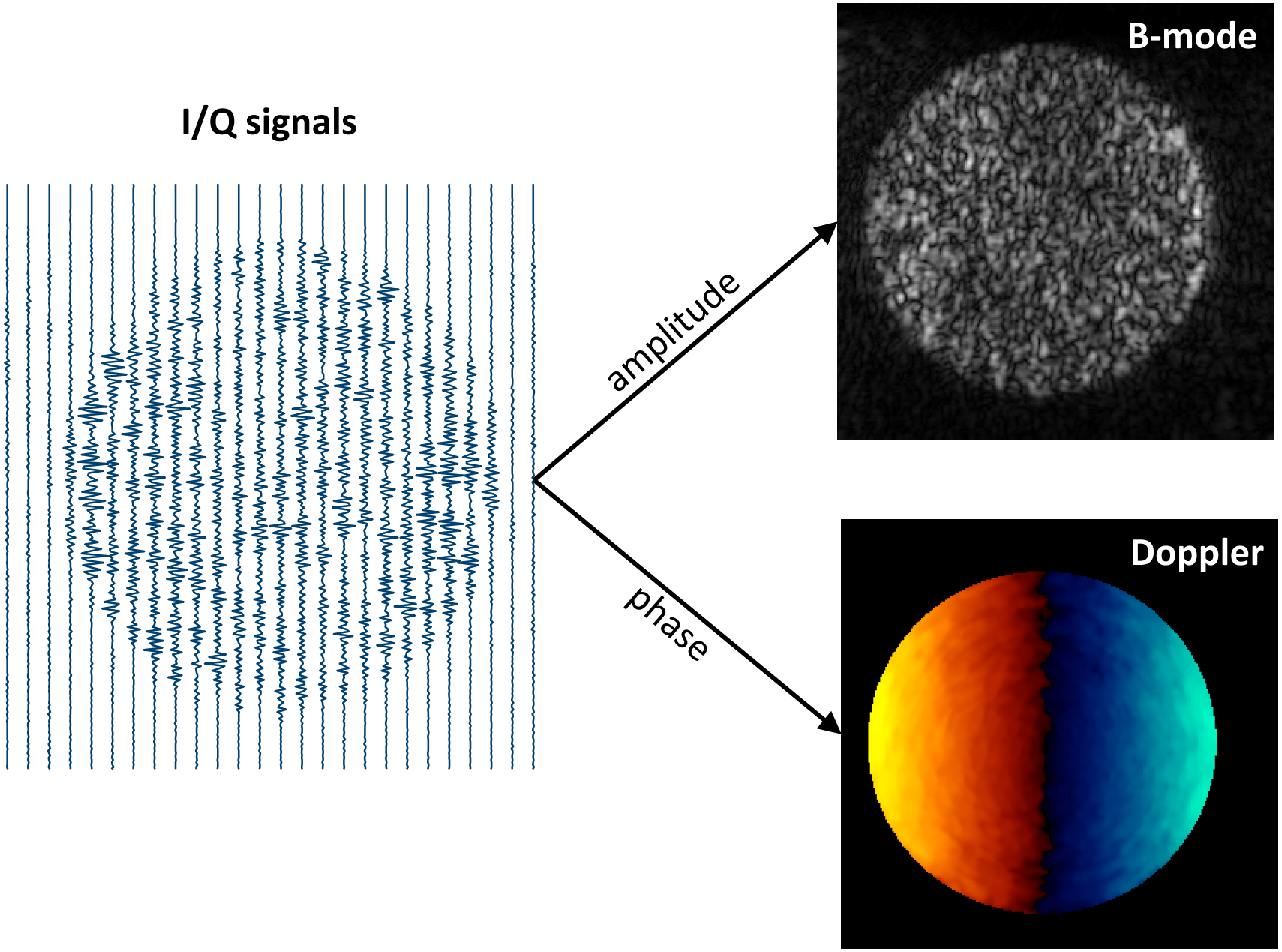
algorithms for motion tracking

RF *vs.* I/Q signal

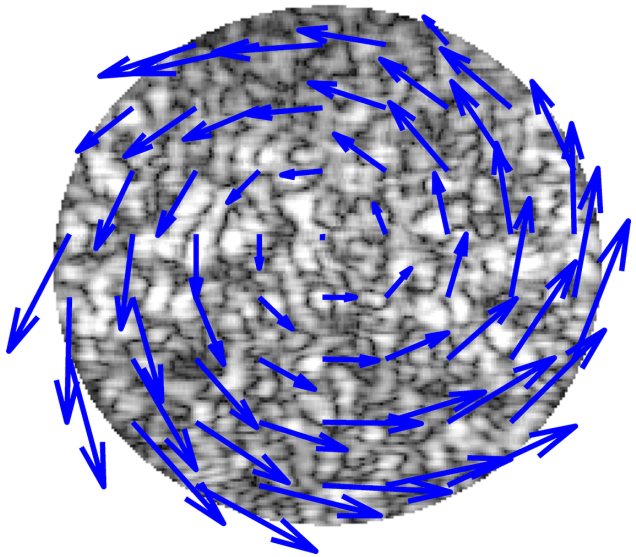


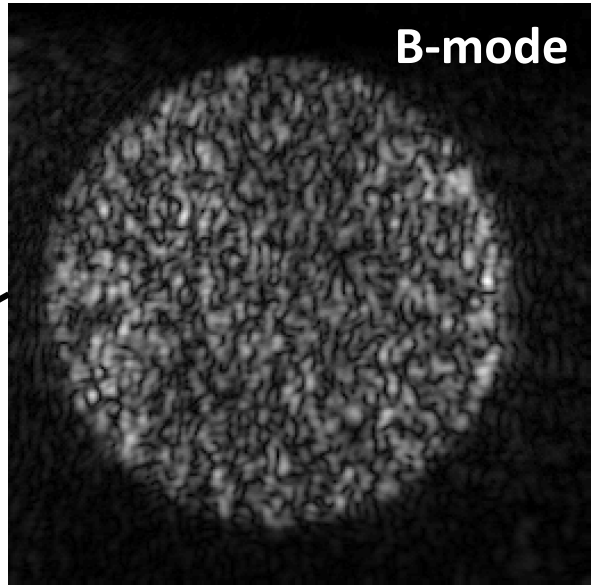
(more details later)

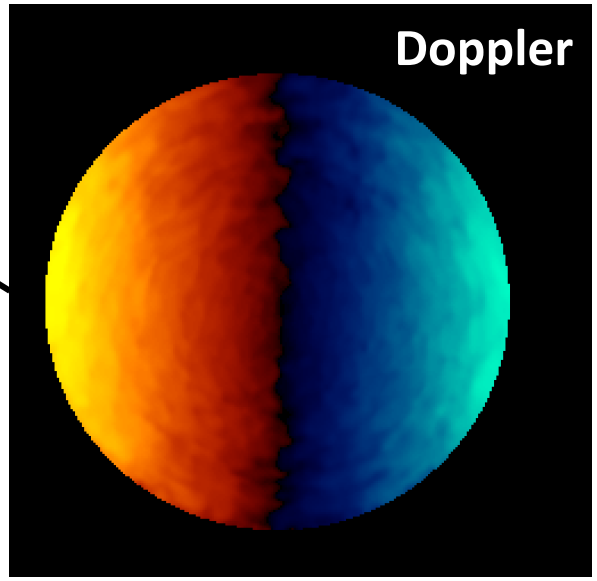
retrieve images from I/Q signals



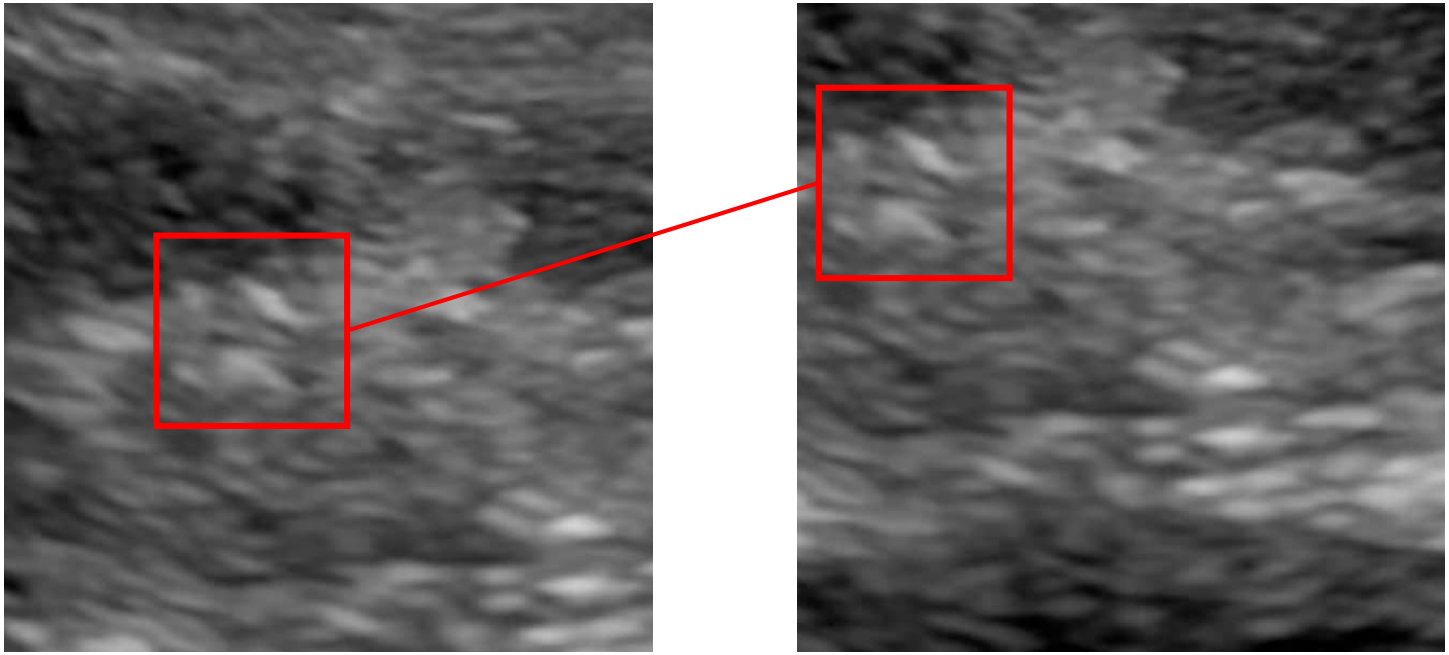
retrieve motion from ultrasound images



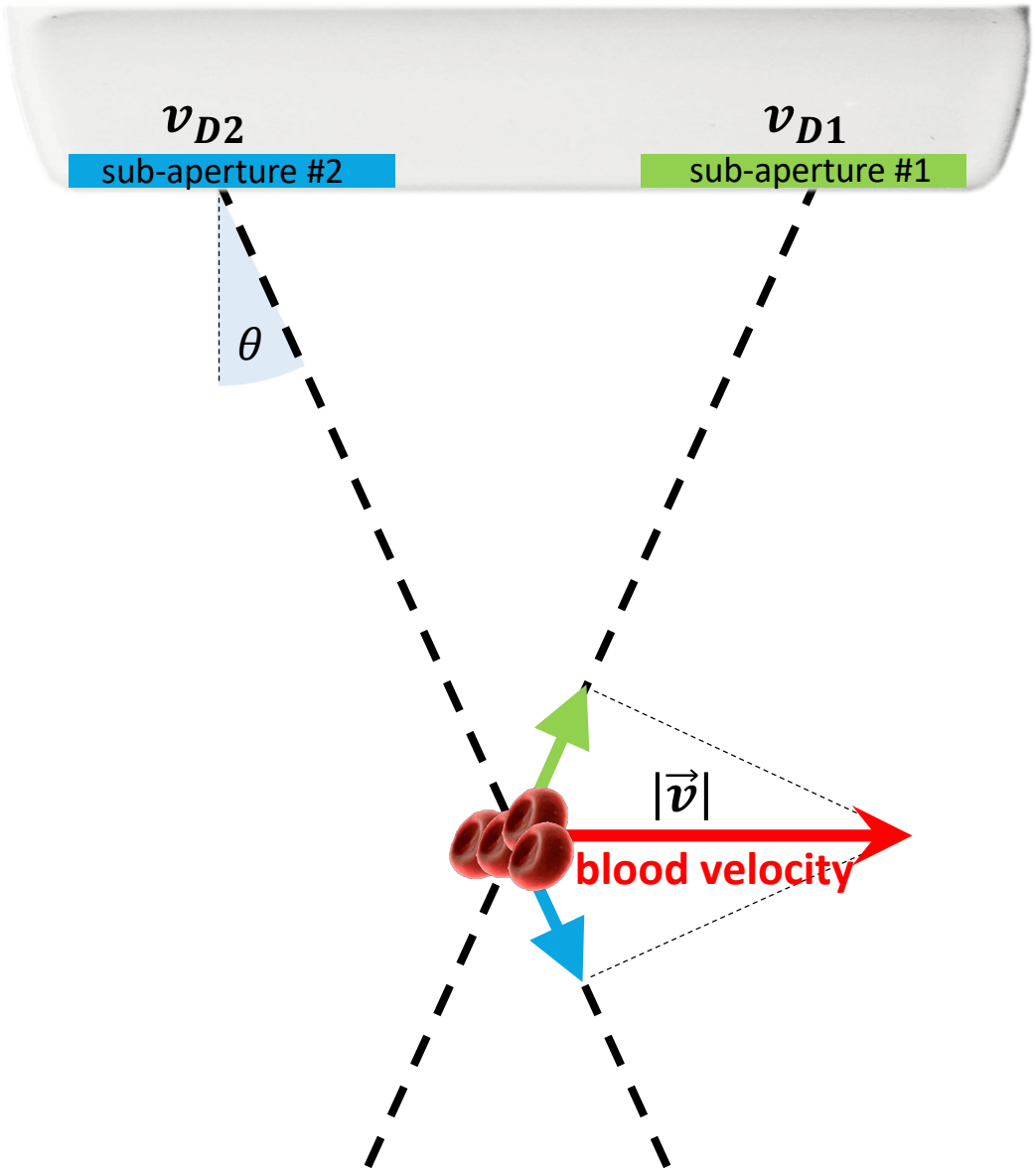




block matching



vector Doppler: one example



definition

- The ***material derivative*** $\frac{\mathrm{D}}{\mathrm{D}t}$ is a temporal derivative that follows motion.
- It computes the time rate of change of some quantity for a material element moving with a velocity $\vec{v}$

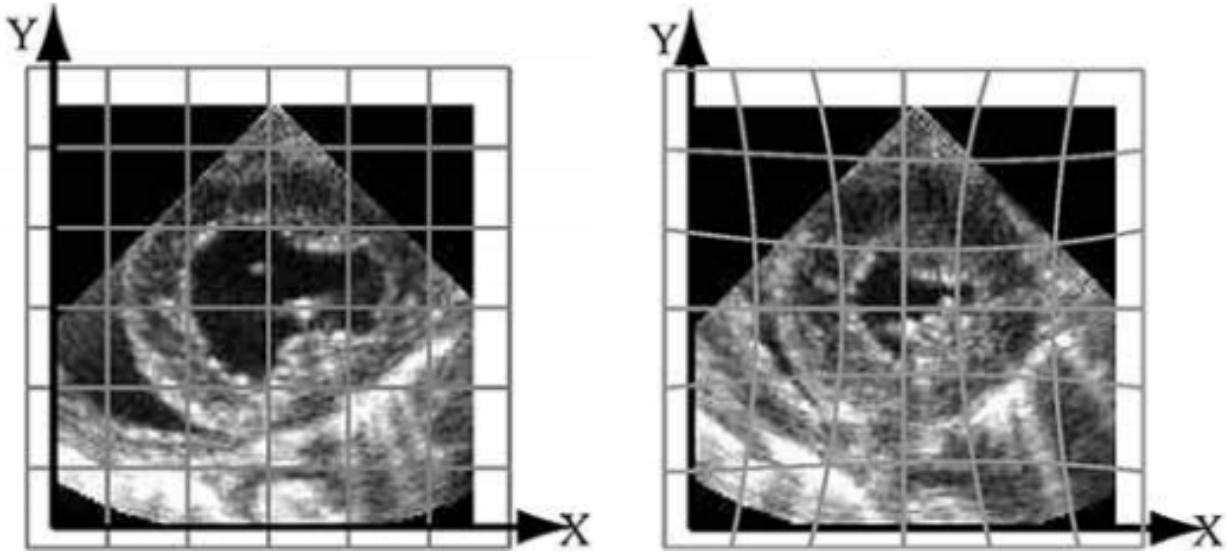
$$\boxed{\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla}}$$

- **Optical flow methods**

  Hypothesis: Image intensity $I(t)$ is conserved through motion

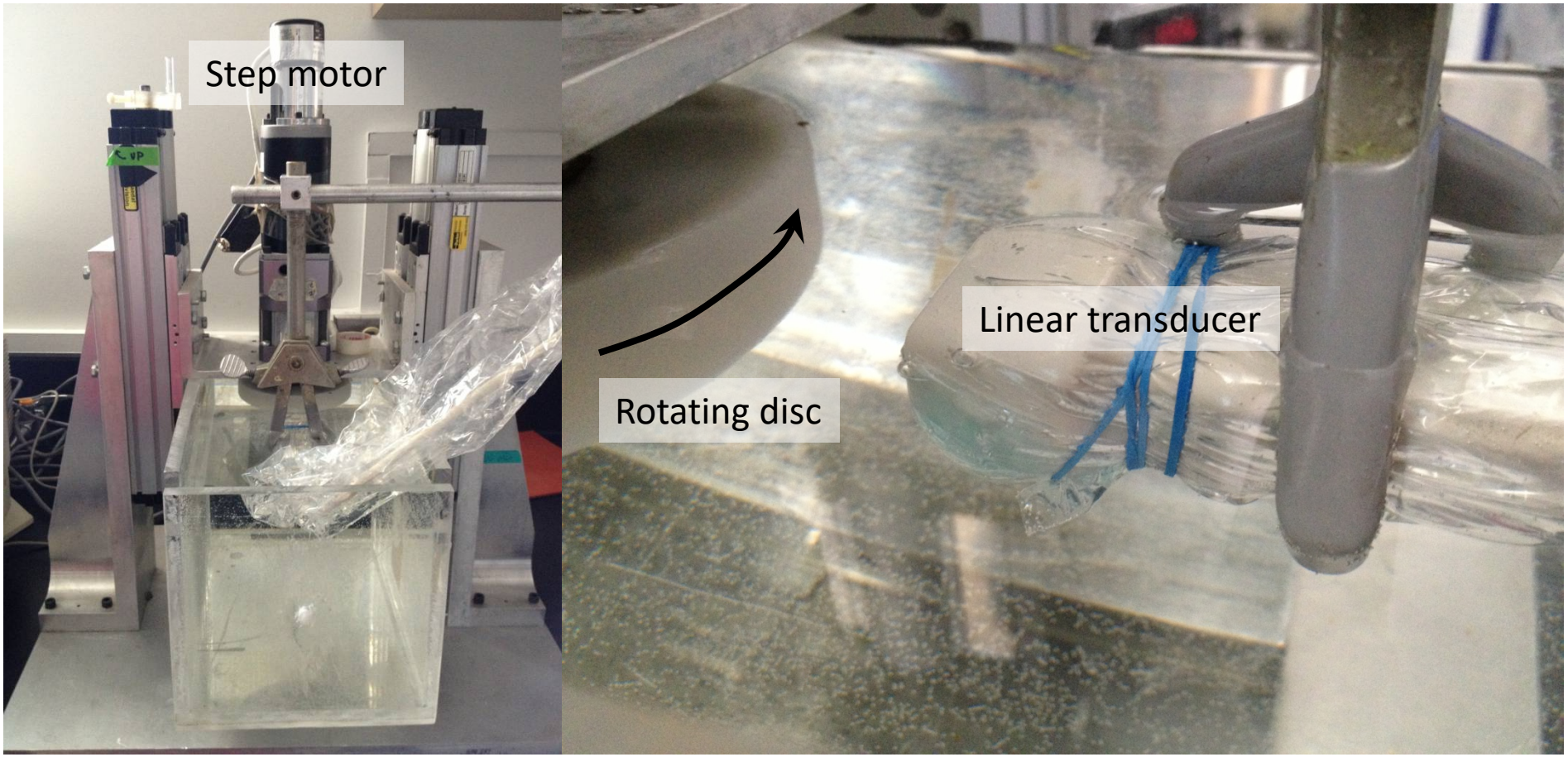
  It follows that: $\frac{\mathrm{D}I}{\mathrm{D}t} = 0 \implies \boxed{\frac{\partial I}{\partial t} + \vec{v} \cdot \vec{\nabla} I = 0}$

elastic image registration



source: Heyde, …, D'hooge.
doi: 10.1109/TMI.2012.2230114

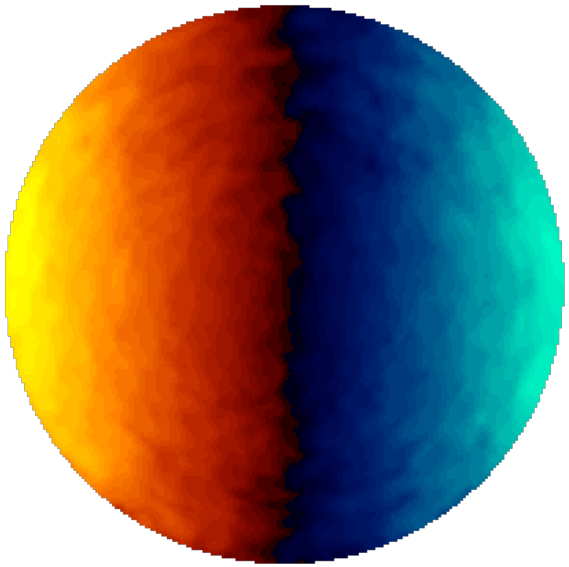
experiment: vector Doppler in a rotating disc

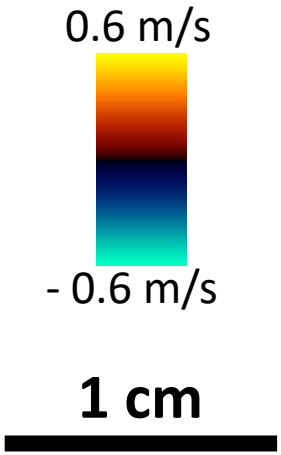


- 5-MHz linear array
- PRF = 10,000 Hz
- 32 transmits of non-steered plane waves

experiment: vector Doppler in a rotating disc (cont'd)

Color Doppler





vector Doppler

