International Workshop on LHC, Astrophysics, Medical and Environmental Physics. Shkodra (Albania), 6-8 October 2014

Ultrasound advanced imaging: beyond anatomy!

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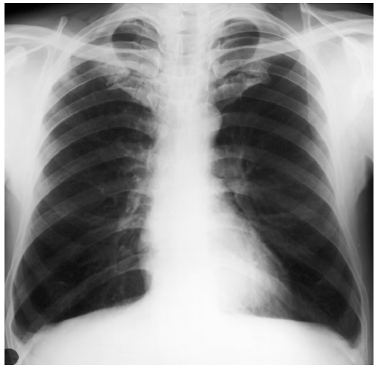
CREATIS

Introduction

Objective n° 1 in medical imaging: anatomy



X-ray

MRI

Ultrasound

What else?

Function – Tissue characterization

Examples and the corresponding evolution of ultrasound imaging

Part 1

- static elastography
- shear wave elastography
- ultrafast imaging
- photo-acoustic imaging

Tissue elasticity imaging - clinical motivation

- The objective of elastography is to prodcue a map of the stiffness of tissues

- There is strong correlation between stifness and some pathologies

Young Modulus in Breast tissue (kPa)

Normal fat	**: 18 ± 7**
Normal glandular	**: 28 ± 14**
Infiltrating carcinoma	**: 106 ± 32**

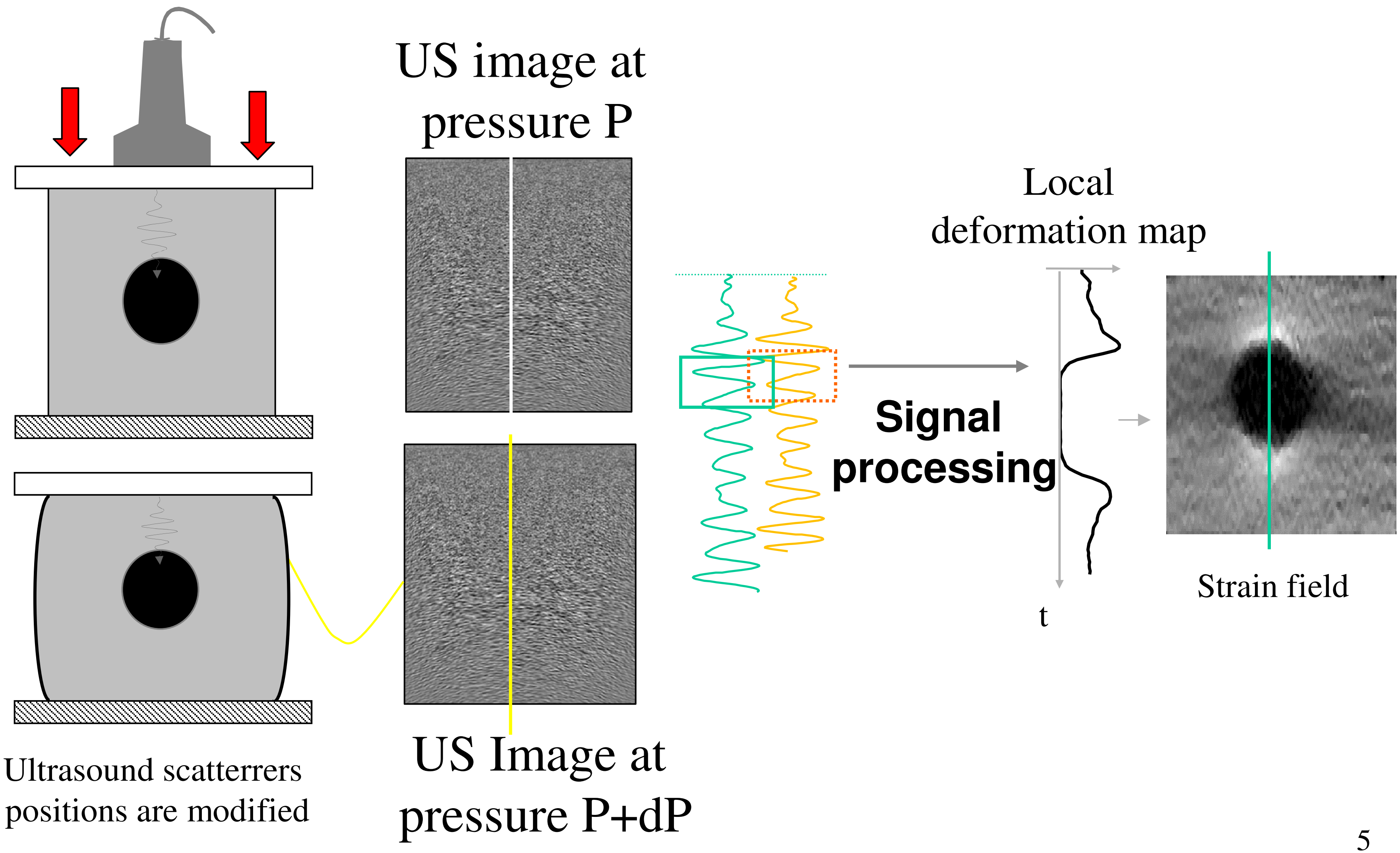
Young Modulus in Prostate tissue (kPa)

Normal anterior	**: 60 ± 15**
Normal posterior	**: 68 ± 14**
Cancer	**: 230 ± 34**

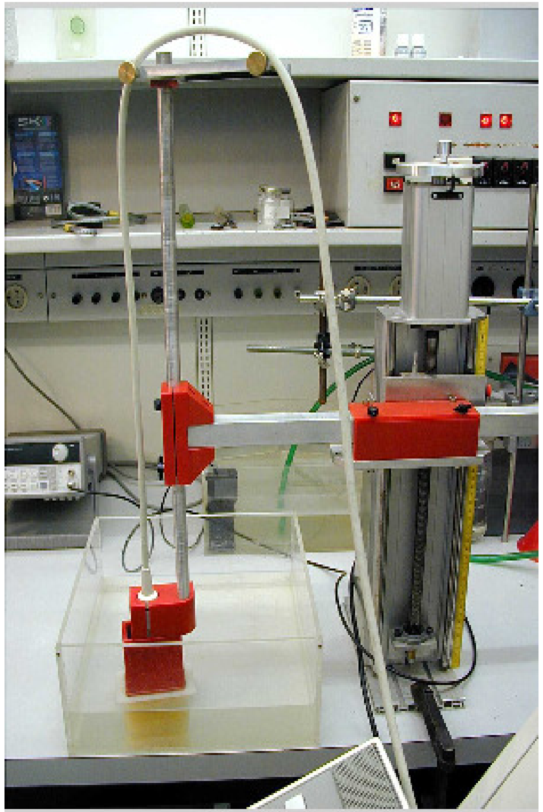
[Krouskop-98]

- The principle of static elastography is to image the deformation of a tissue under external load (palpation with the US probe)

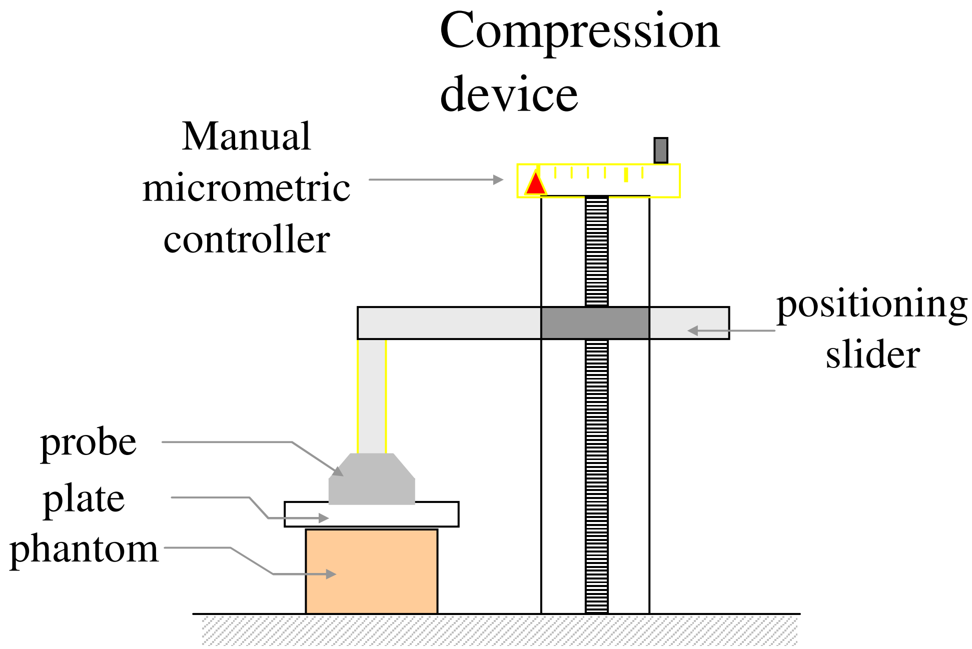
Elastography - Basic principle



In vitro results: experimental set-up

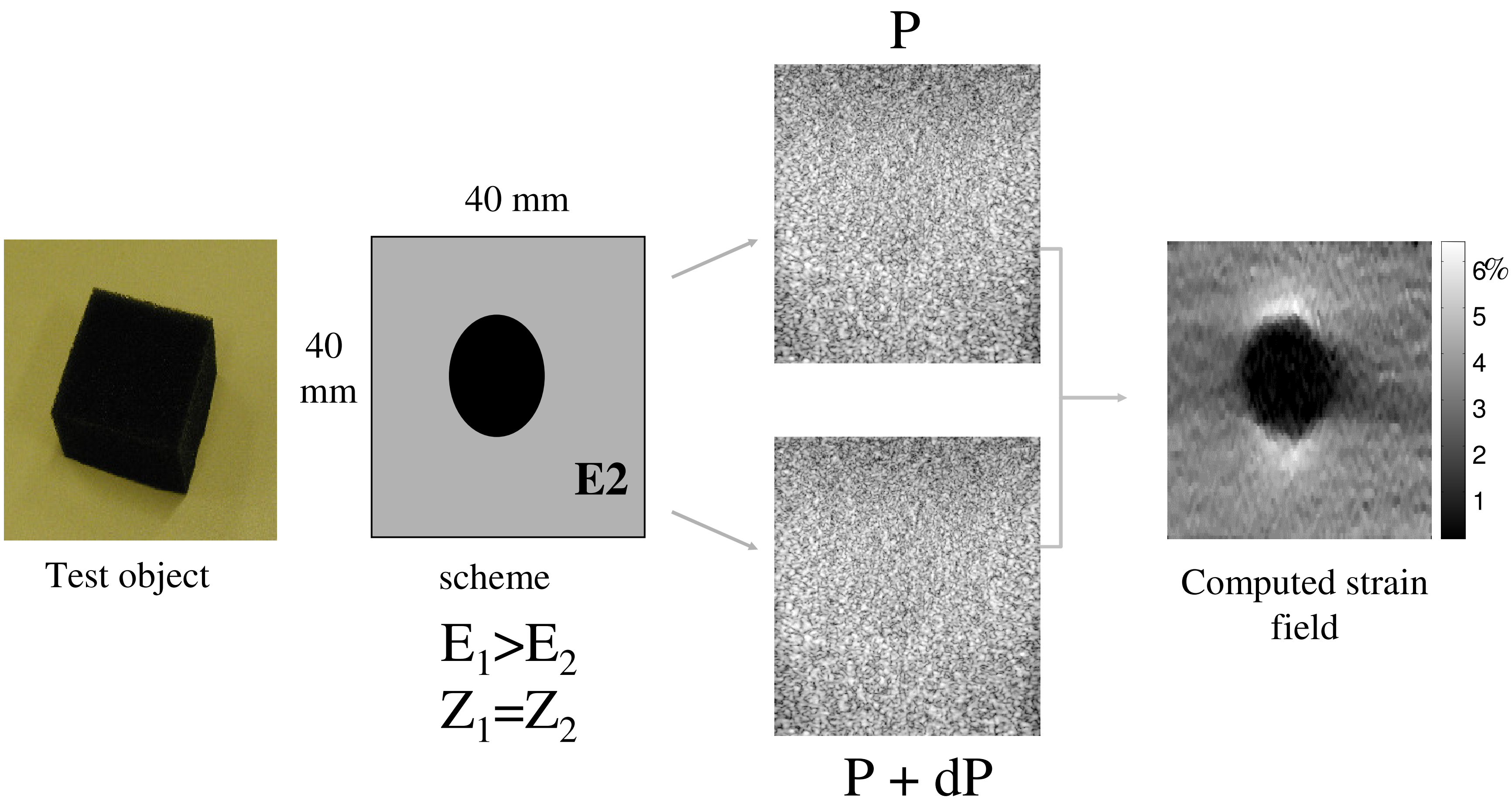


Bochum



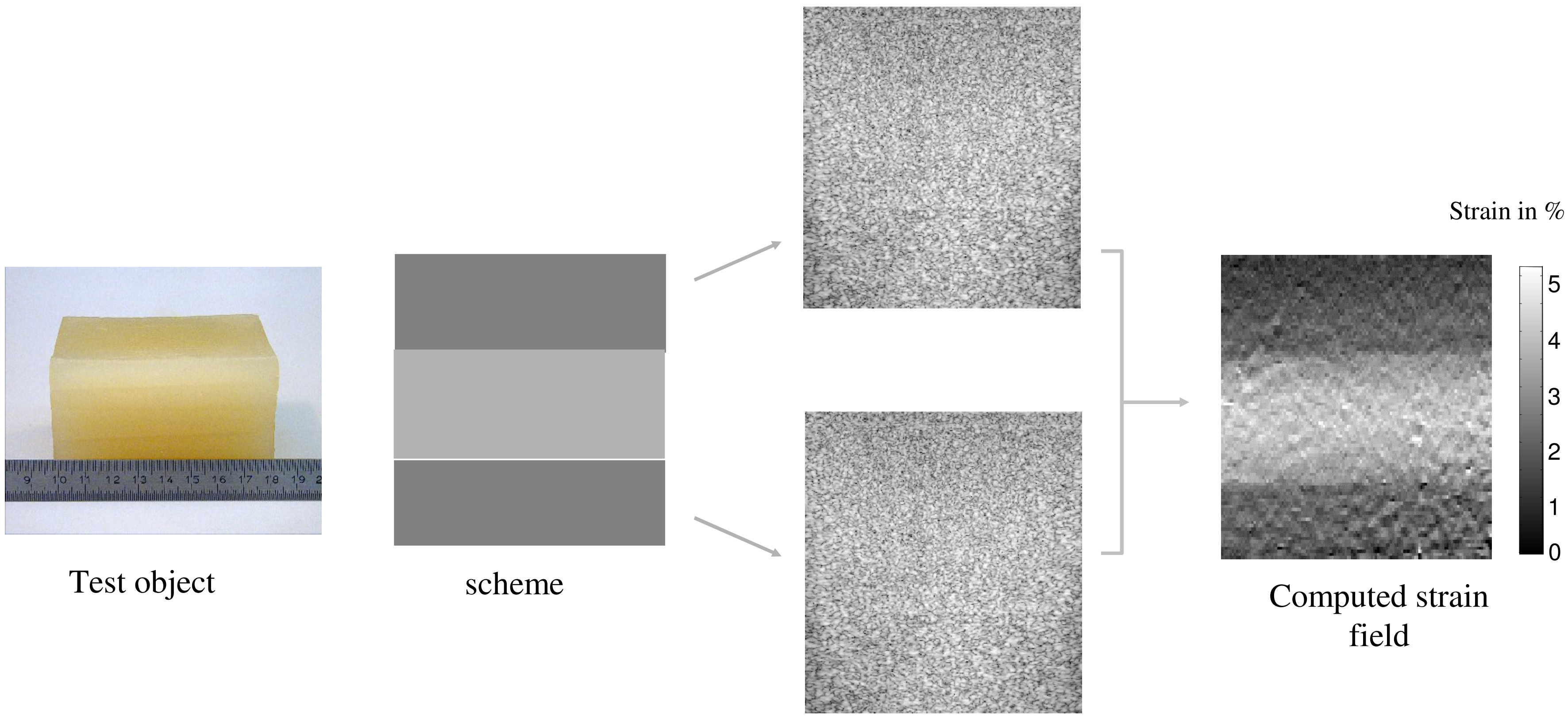
Central frequency: 7.2 MHz
Sampling frequency: 36 MHz
Displacement step precision: 0.05 mm

Results with a foam phantom



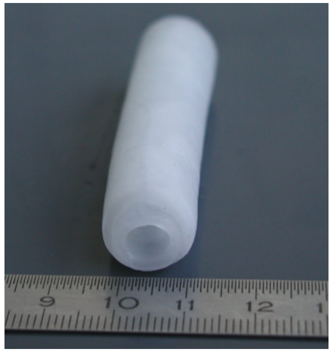
- Foam phantom containing a spherical hard inclusion in agar (diameter: 1.5 cm)
- phantom characteristics: acoustical homogeneity; compressibility
- elastogram computation: window length = 1 mm, 60 % overlap

Results with a 3-layer tissue mimicking phantom

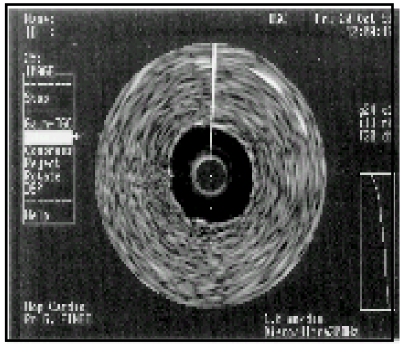


- 3-layer phantom
  - soft layer: 6% gelatine, 1% agar, 1% scatterers (SiC)
  - hard layer: 6% gelatine, 4.5% agar, 1% scatterers
- elastogram computation window length: 1 mm 60 % overlap

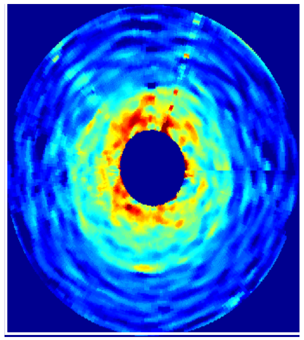
Results with a two layer cryogel phantom



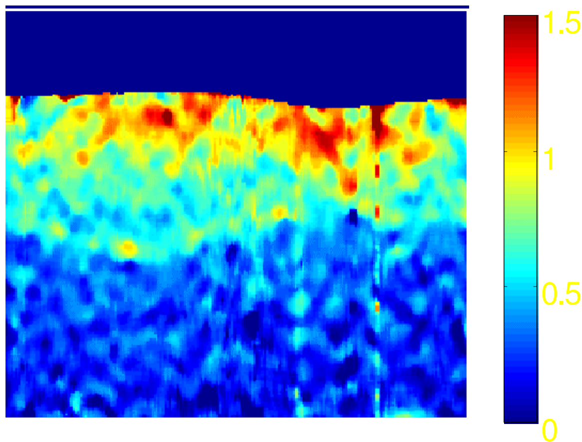
Photograph



B mode image

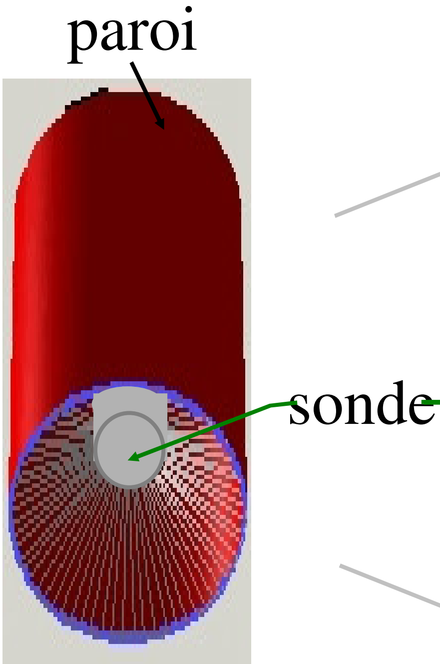


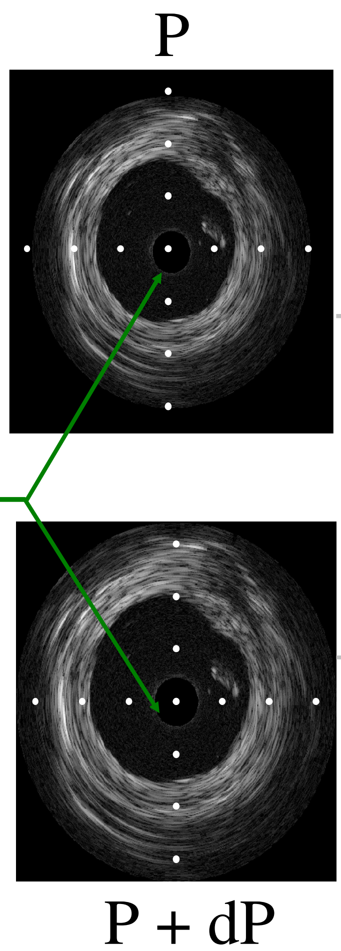
Elastogram

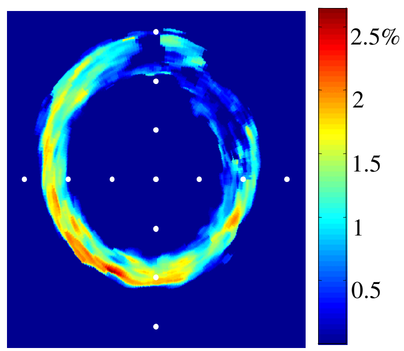


- Polyvinyl alcohol cryogel phantom
- 2 layers : soft = 1 freeze-thaw cycle, hard = 3 freeze-thaw cycle
- elastogram computation : window length = 0.25 mm, 80% overlap

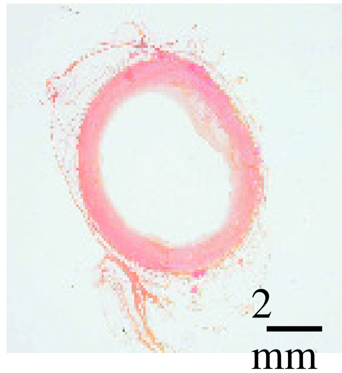
Results with a fresh excised carotid artery







Computed strain fied (%)



Histological section

Limitation of static elastography

Only qualitative / relative stiffness

Depends on the applied load

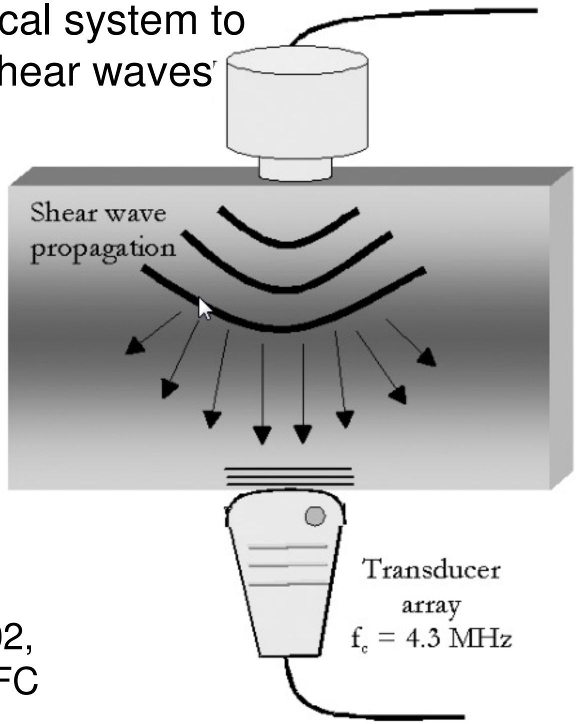
Not quantitative

➔ Shear wave elastography

The idea of shear wave elastography

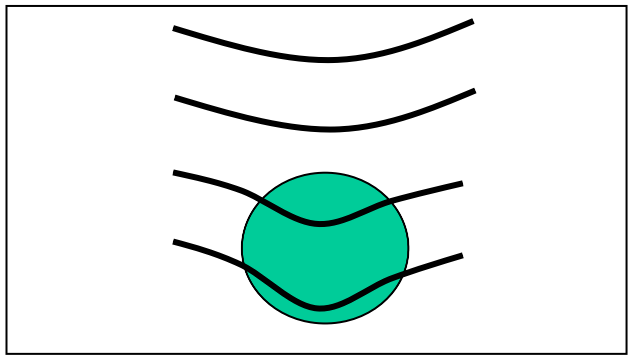
Shear wave propagation velocity is proportional to shear modulus

Mechanical system to induce shear waves



Tanter-2002, IEEE TUFFC

Shear wave propagation



Acceleration due to "harder" inclusion

US Imaging of the shear wave propagation + determination of local velcity ➔ shear wave modulus

Shear wave elastography

Shear wave have typical velocities ranging between 1-10m.s^{-1}

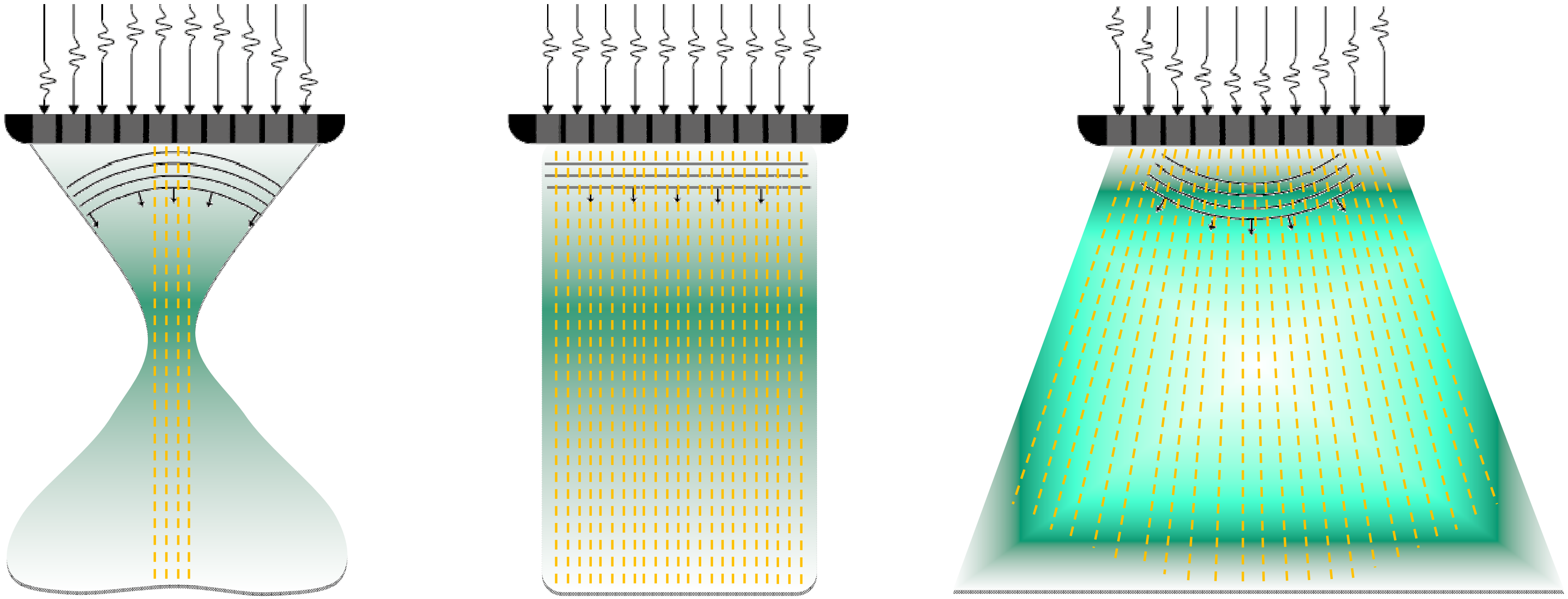
➔imaging at frame rate >> 1KHz is needed

How can ultrafast imaging be performed??

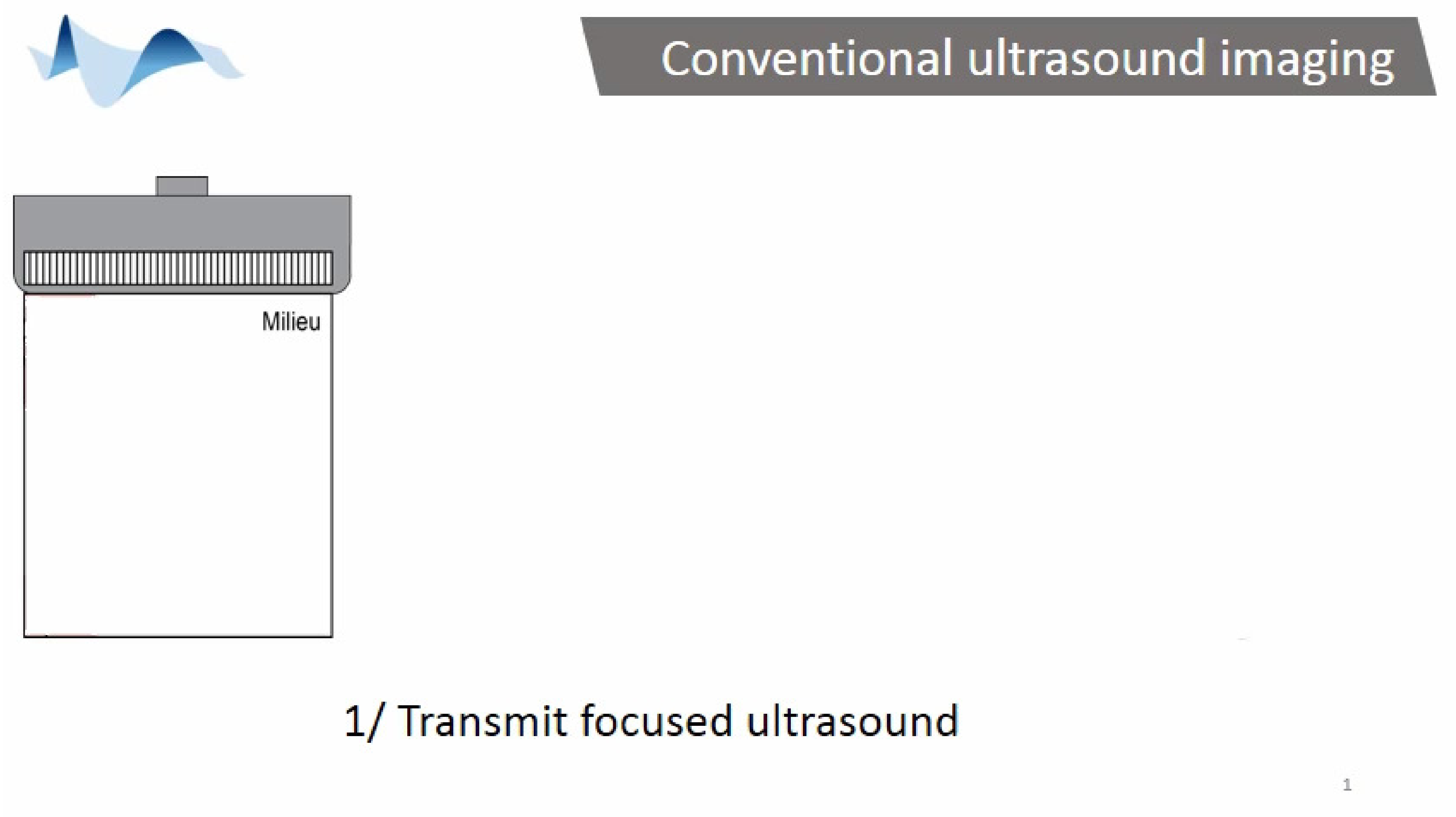
How to go faster?

Use **broad field-of-view transmit beams** with **full parallel receive beamforming:** 1 image per pulse => **4-5000 fps!**

Focused pulses | **Unfocused pulses (plane waves)** | **Defocused pulses (diverging waves)**

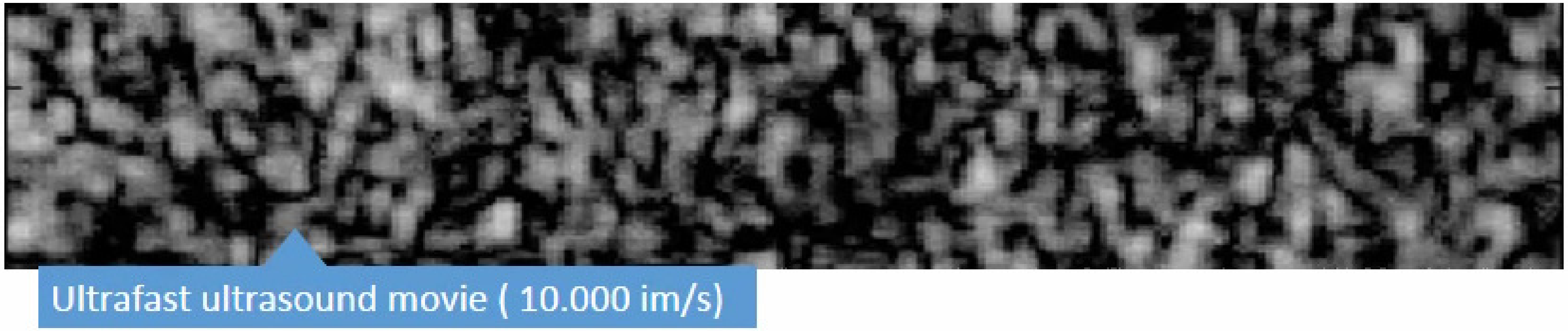


Conventional vs ultrafast imaging



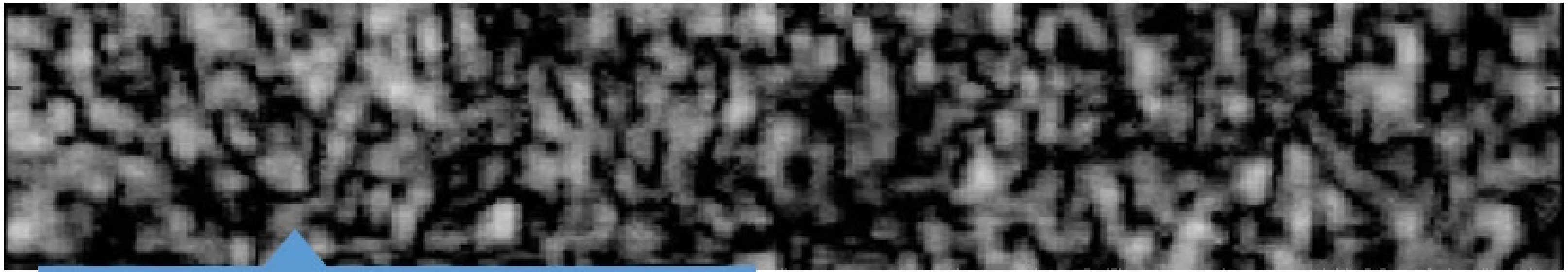
➔ Using ultrafast imaging one can image shear wave propagation

Ultrafast imaging of shear wave propagation



Local velocity estimation

Ultrafast imaging of shear wave propagation



Ultrafast ultrasound movie (10.000 im/s)

www @ Institut Langevin Paris

Shear wave elastography in the Supersonic Imagine system

The shear wave is induced using the US probe and the so-called push-beam

Ultrafast imaging is performed to image the shear wave propagation

http://www.supersonicimagine.fr/

Supersonic shear imaging

1

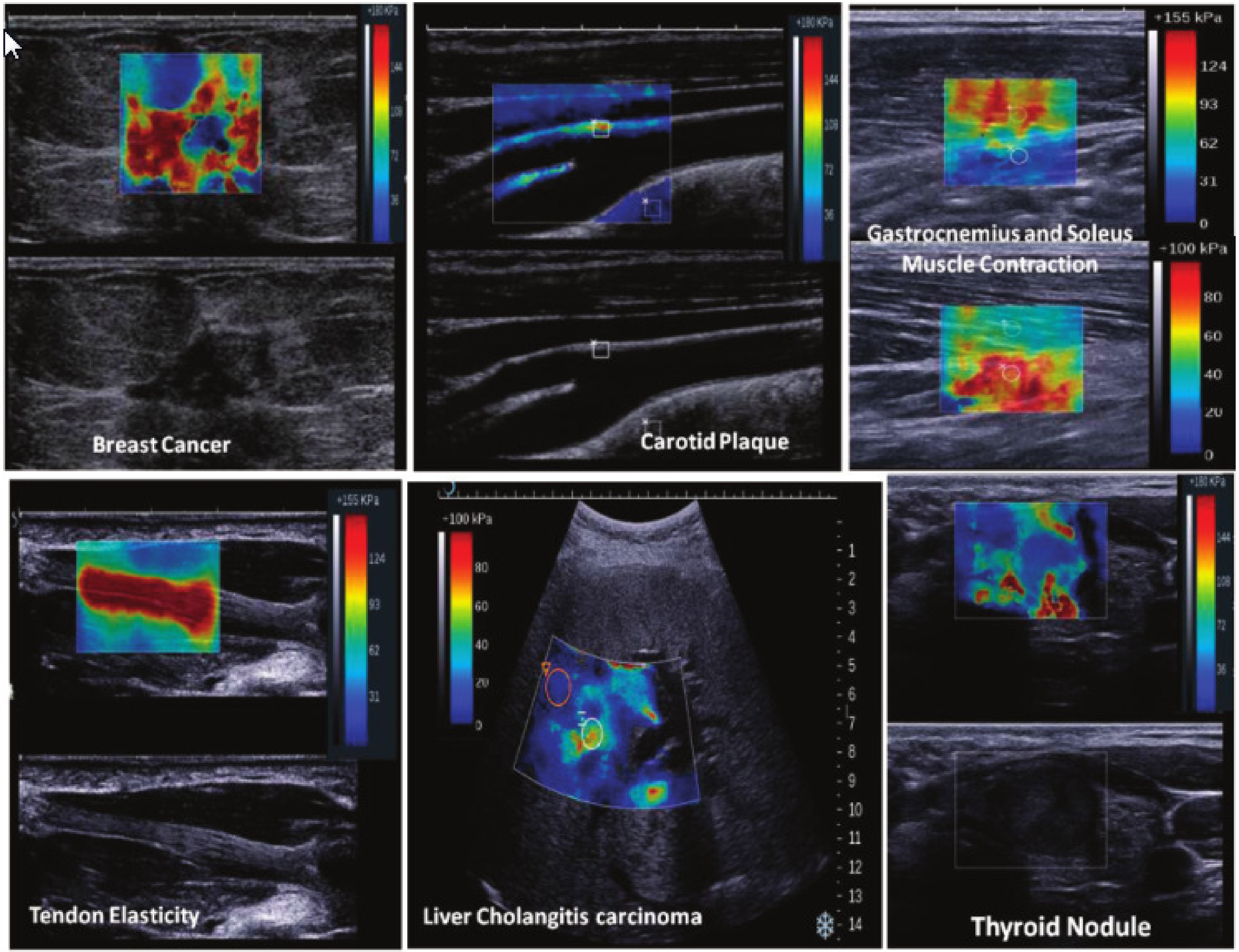


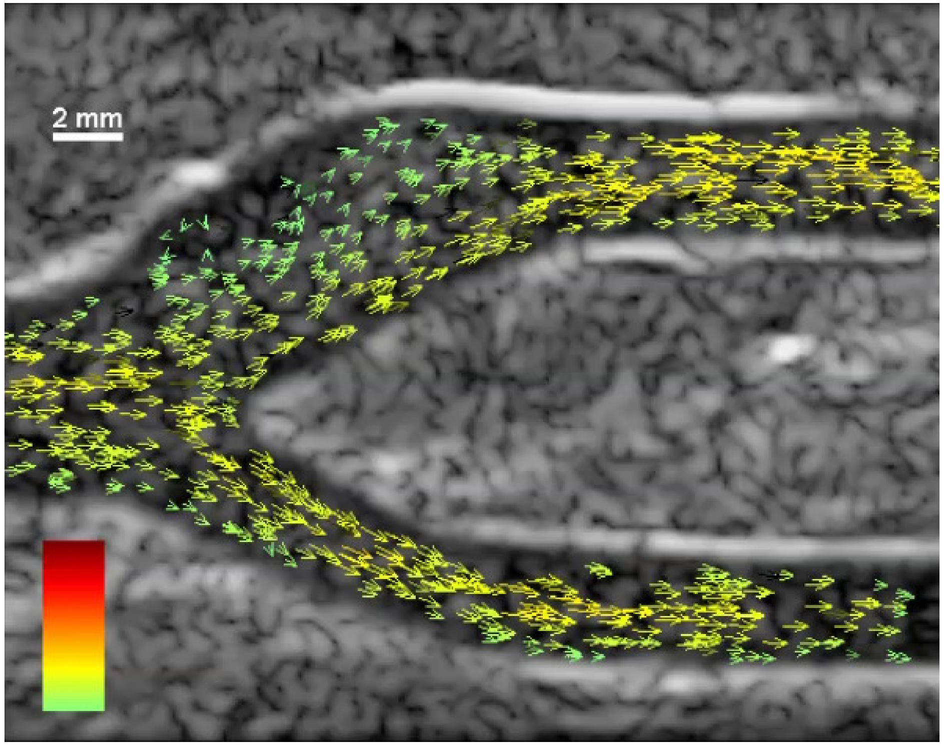
Fig. 6. Clinical examples of shear wave elastography based on the supersonic shear wave imaging (SSI) method (courtesy of Supersonic Imagin
France)

Ultrafast imaging can do many things
2 examples:

1) Complex motion visualization:
   - Blood flow
   - Cardiac flow
   - Arterial wall motion

2) Functional imaging of the Brain

1) Complex motion visualization: blood flow



Ultrafast vector flow in the carotid bifurcation of a healthy subject

Courtesy of Alfred Yu, Hong Kong University

1) Complex motion visualization: blood flow

Ultrafast vector flow in the carotid bifurcation of a subject with 50% eccentric stenosis

Courtesy of Alfred Yu, Hong Kong University

1) Complex motion visualization: cardiac flow

- Perimembranous ventricular septal defect (significant shunt)
- 36 days old, 4259 gr.

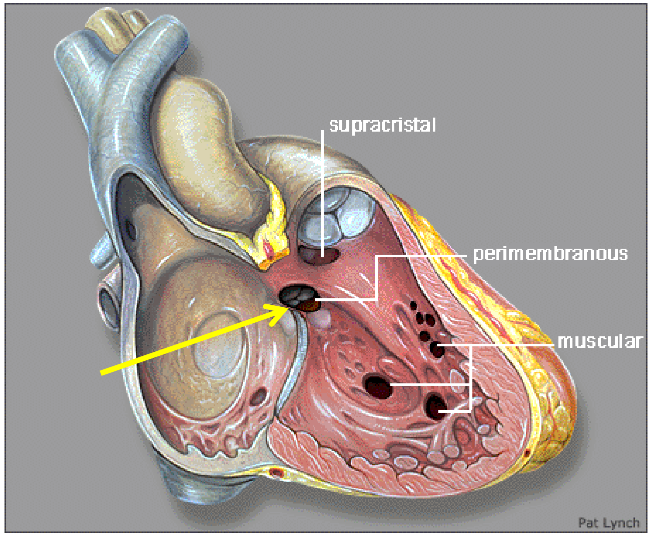
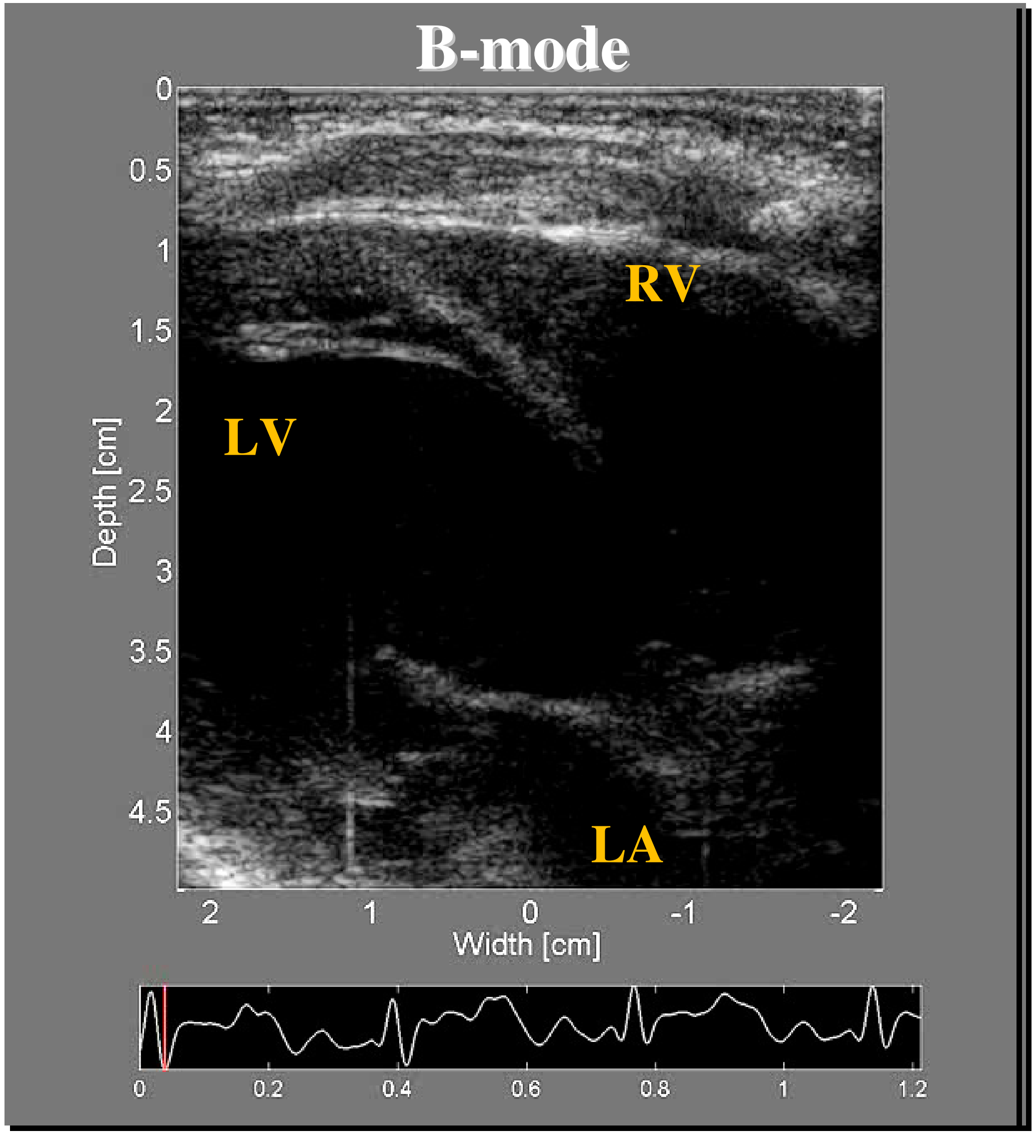


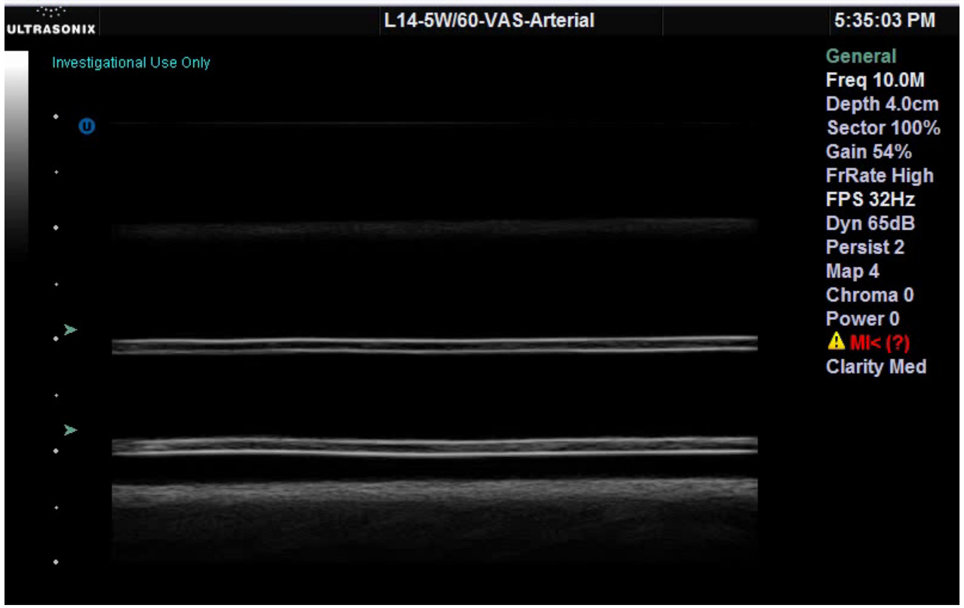
Image source: *Wikipedia, Pat Lynch*



Courtesy of Lasse Lovstakken, NTNU Trondheim, Norway

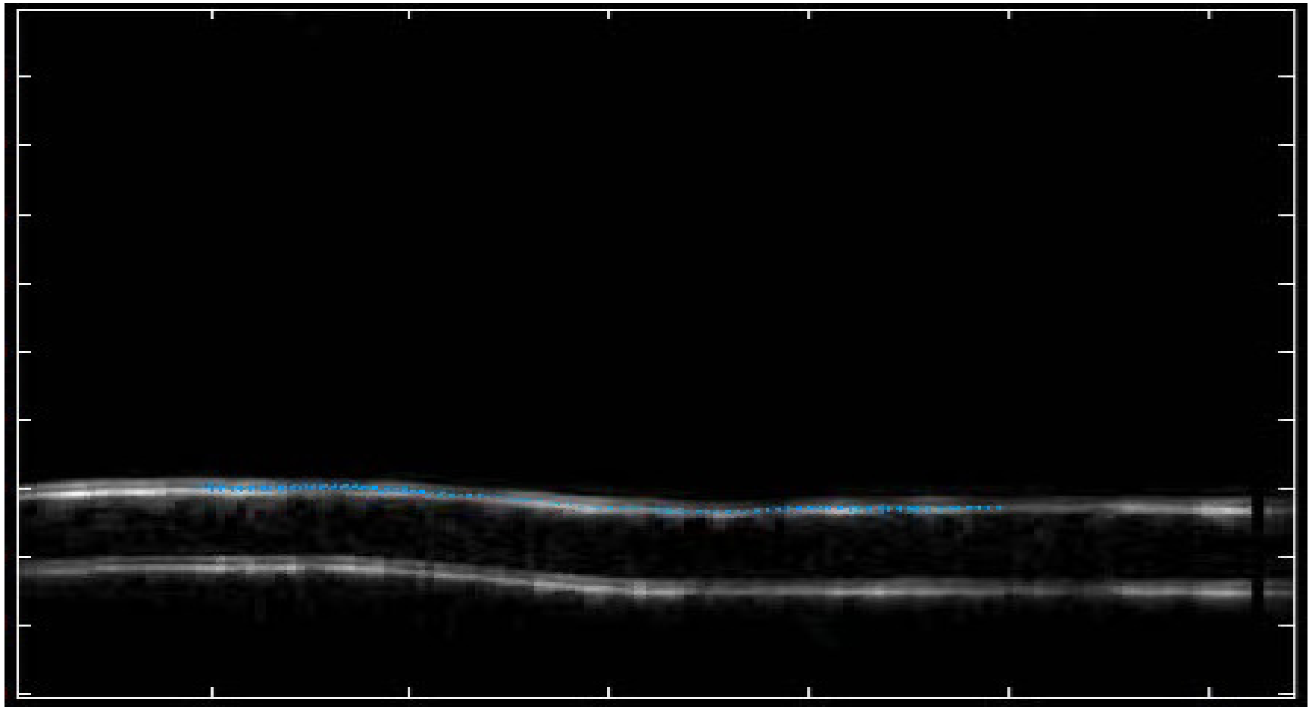
1) Complex motion visualization: arterial wall motion

Phantom: An PVA Cryogel artery phantom	Acquisiton: Ultrasonix MDP
Outer / inner diameter = 9.0 mm / 7.0 mm	128 channels Sonix Daq
peak flow rate = 8.0ml/s	Linear array L14-5W/60 128 elements ; pitch = 472 µm ; f_0 = 5MHz
duty cycle = 10%	PRF = 5000 Hz No compounding → 5000 images/s



Salles et. al. IEEE IUS 2014

1) Complex motion visualization: arterial wall motion

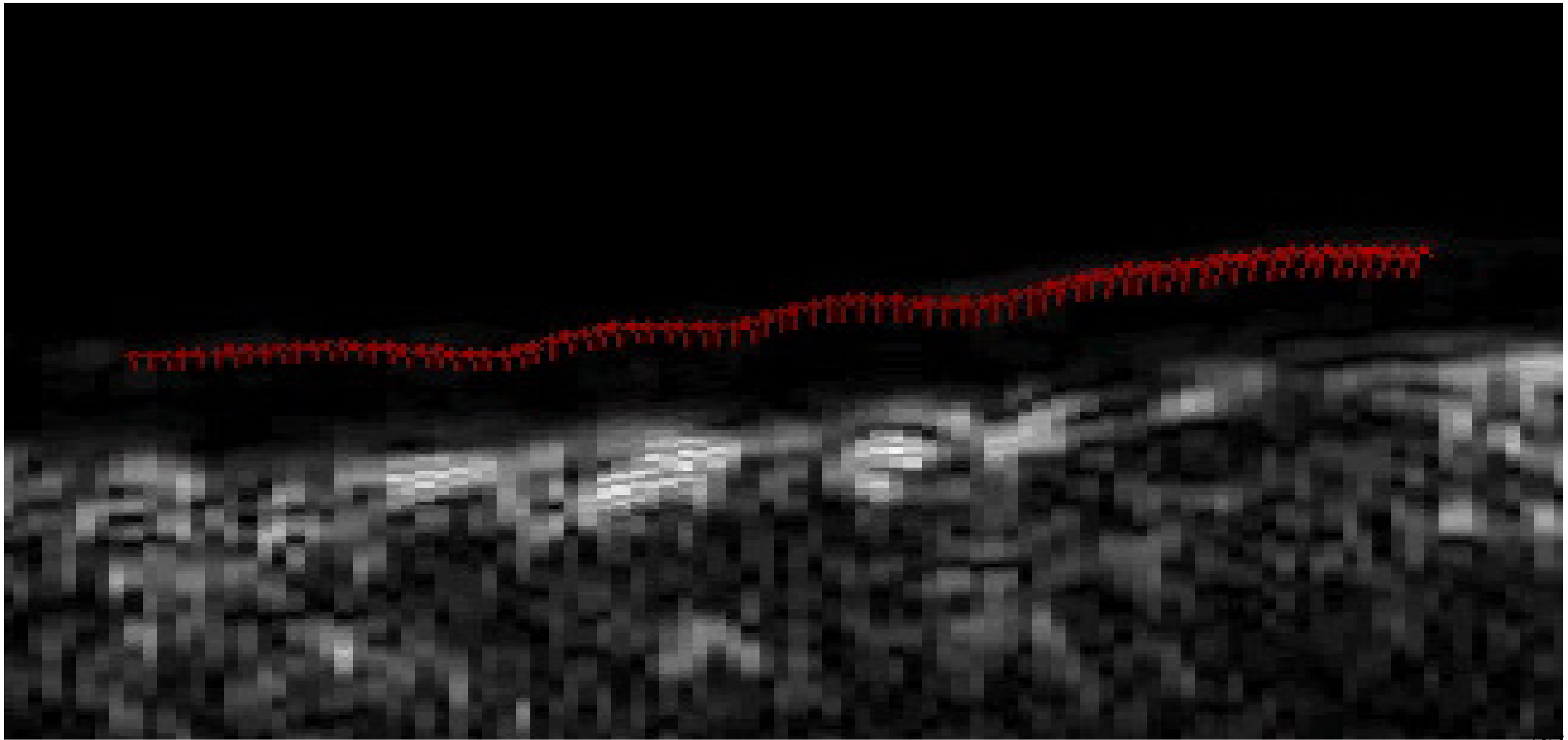


Velocity vector of the arterial wall

Salles et. al. IEEE IUS 2014

1) Complex motion visualization: arterial wall motion

In vivo heathly volunteer carotid artery



Salles et. al. IEEE IUS 2014

2) Functional imaging of the brain

Activation of the different parts of the brain is linked with an increase in blood flow

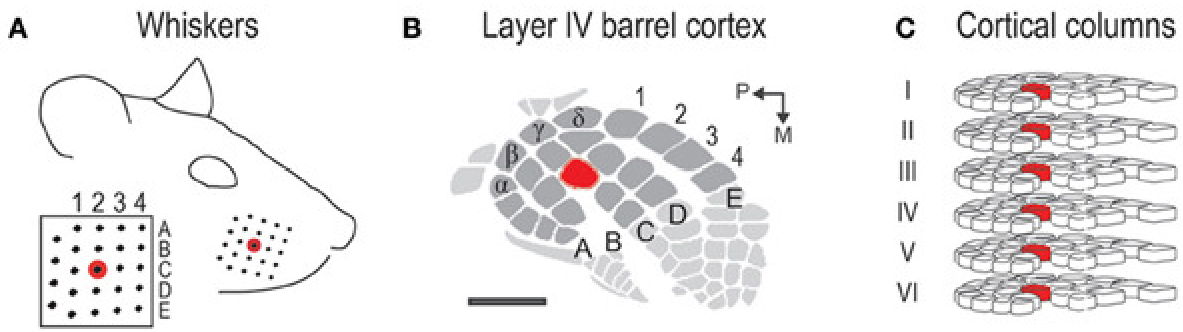
Power Doppler can give an indication of the quantity of flow in a region

For small quantities of blood conventional technique are not sensitive enough

Functional imaging of the brain with ultrasound is doone by combining ultrafast imaging and power Doppler

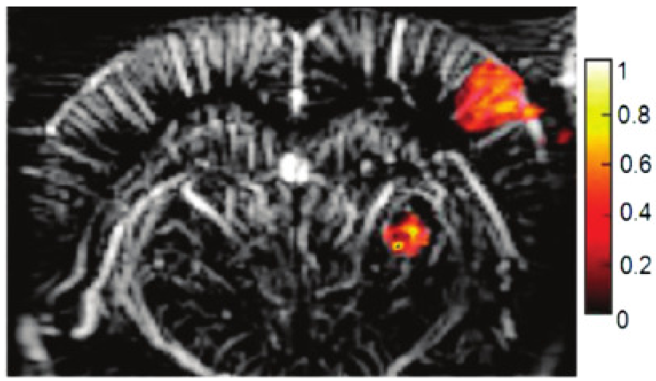
2) Functional imaging of the brain

In vivo proof of this concept was shown by imaging changes of cerebral blow volume in the micro vascularization of trepanned rat brain during whisker stimulation



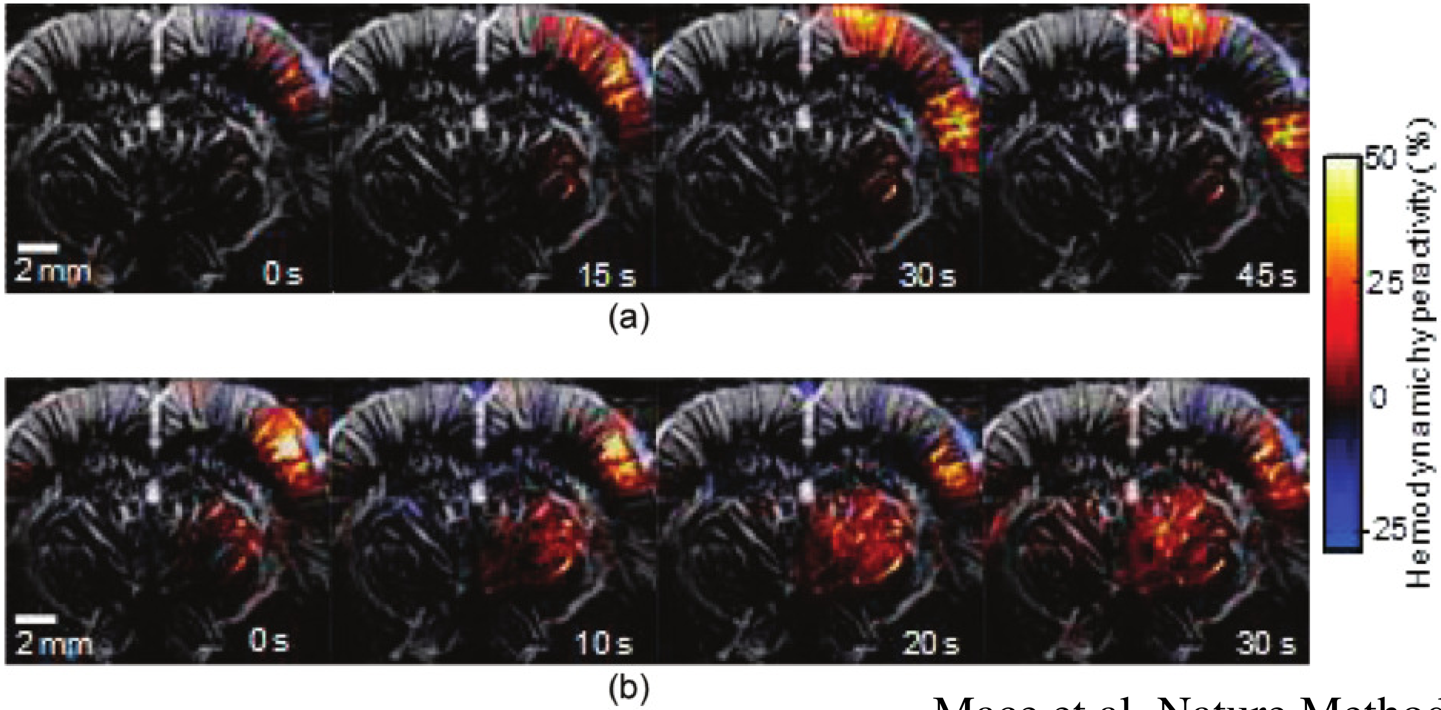
Chen Bee et. al., Front. Neural Circuits, 2012

Functional ultrasound imaging during excitation of the whiskers. Activation was clearly detected showing the excellent sensitivity and resolution of fUs imaging



Mace et.al. Nature Methods, 2011

2) Functional imaging of the brain



Mace et.al. Nature Methods, 2011

Spatiotemporal spreading of epileptiform activity for two ictal events. Brain cerebral blood volume (cBV) changes (% relative to the baseline) are superimposed on a control baseline cBV image. In (a) we can see an onset and a cortical propagation. In (b), the activity is seen spreading in the thalamus.

2) Functional imaging of the brain

Amazing potential of functional imaging of the brain by ultrasound.

One example: Imaging of the cerebral activity during fetal growth….

Examples and the corresponding evolution of ultrasound imaging

- static elastography
- shear wave elastography
- ultrafast imaging
- photo-acoustic imaging

Part 2

WHY Photo-acoustic imaging?

Optical imaging

- (+) Contrast
- (−) Resolution > ~ 1 mm
- (−) Investigation depth < ~ 5 cm
- (+) Functional information

Ultrasound imaging

- (−) Contrast
- (+) Resolution > ~ 100 μm
- (+) Investigation depth ~ 10 cm
- (−) No Functional information

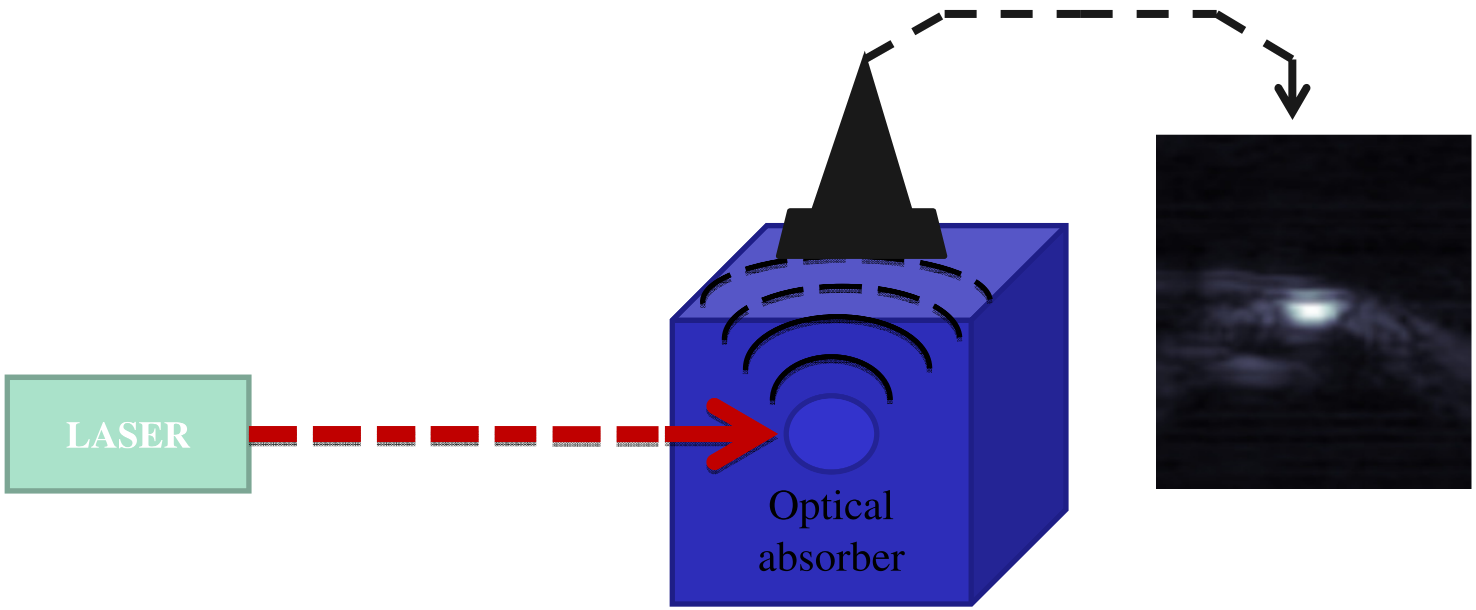
Photo-acoustic imaging

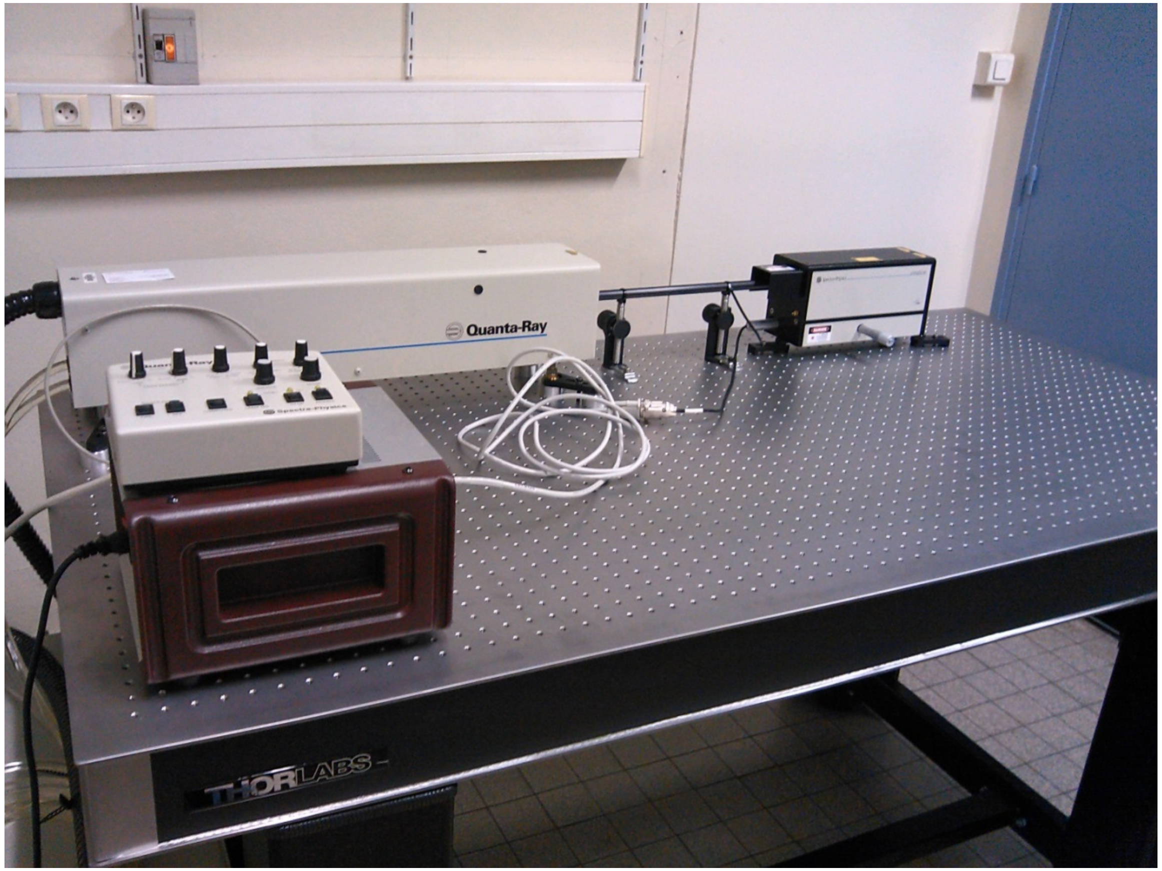
- (+) Contrast (optical abosption)
- (+) Resolution of Ultrasound
- (+) Depth of investigation
- (+) Functional information due to optical absorption
- (+) Non invasive, non inonizing

Physical principle

Ultrasound generation with light

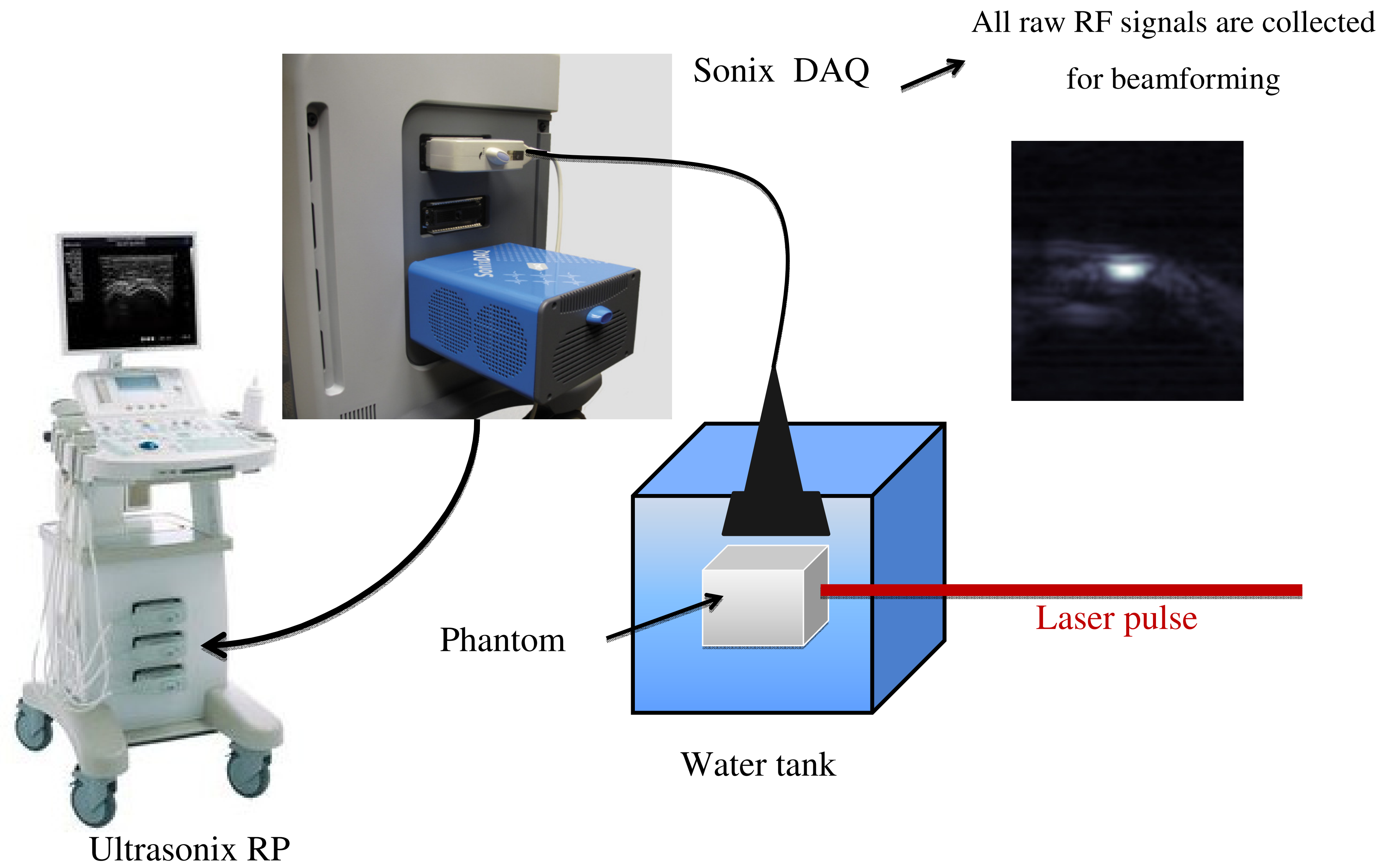
Laser pulse → **Local absorption by tissues** → **Thermal expansion** → **Acoustic wave**





Courtesy of François Varray, CREATIS, University of Lyon

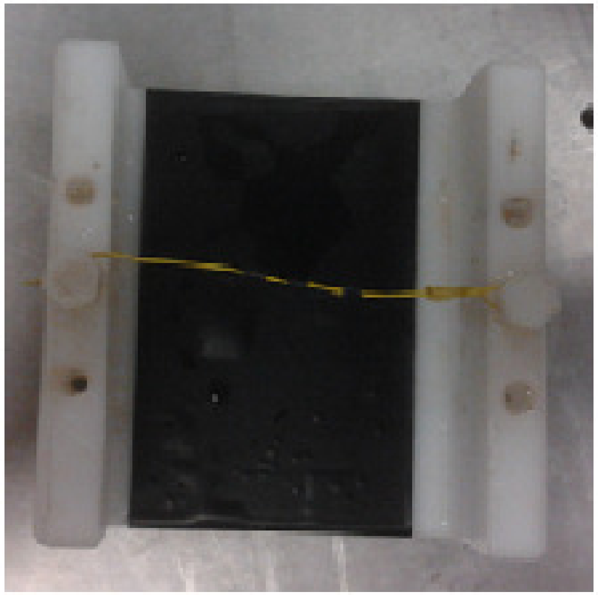
Acquisition setup

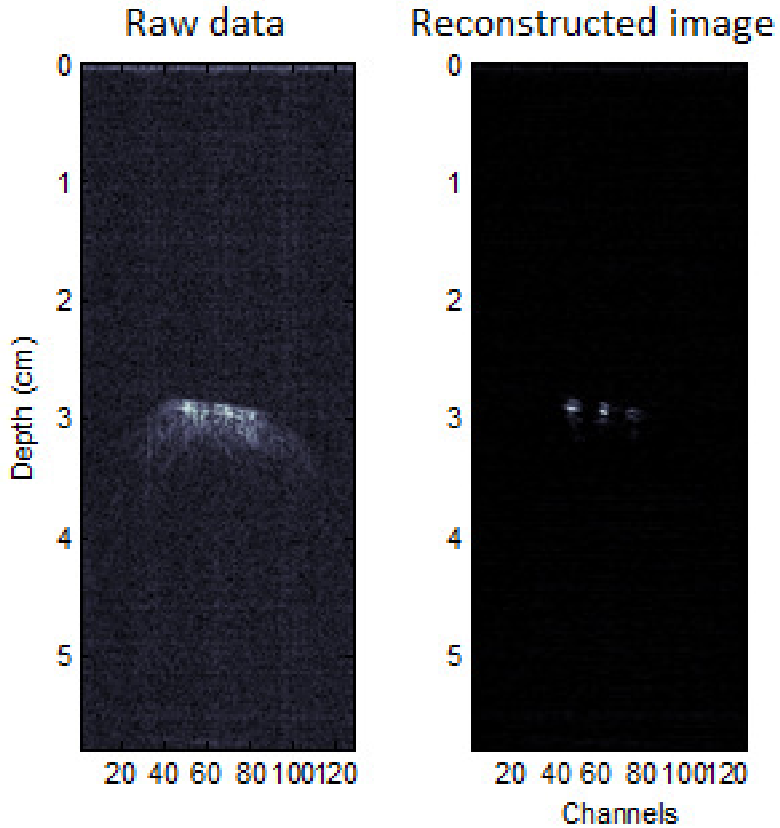


Courtesy of François Varray, CREATIS, University of Lyon

Simple experiment with wires as absorber

- Several optical absorbers



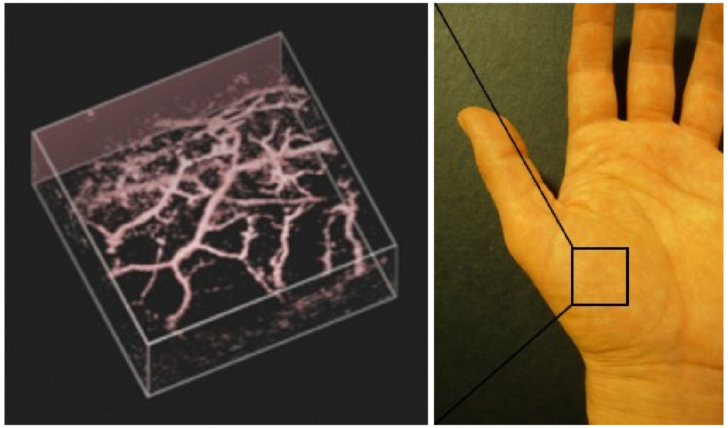


Courtesy of François Varray, CREATIS, University of Lyon

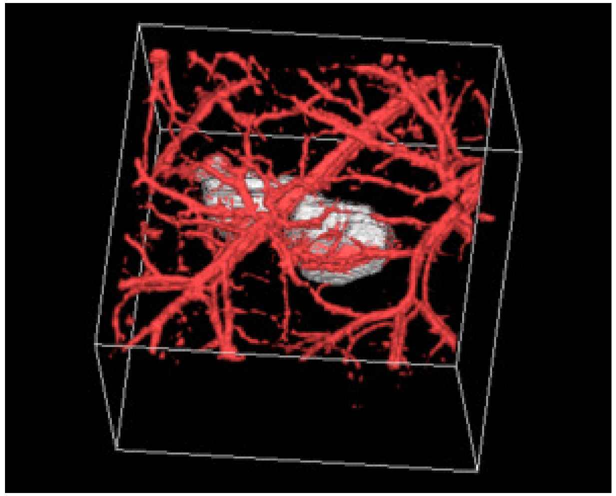
Applications

Vascularization

Cancer ➔ abnormal vascularization

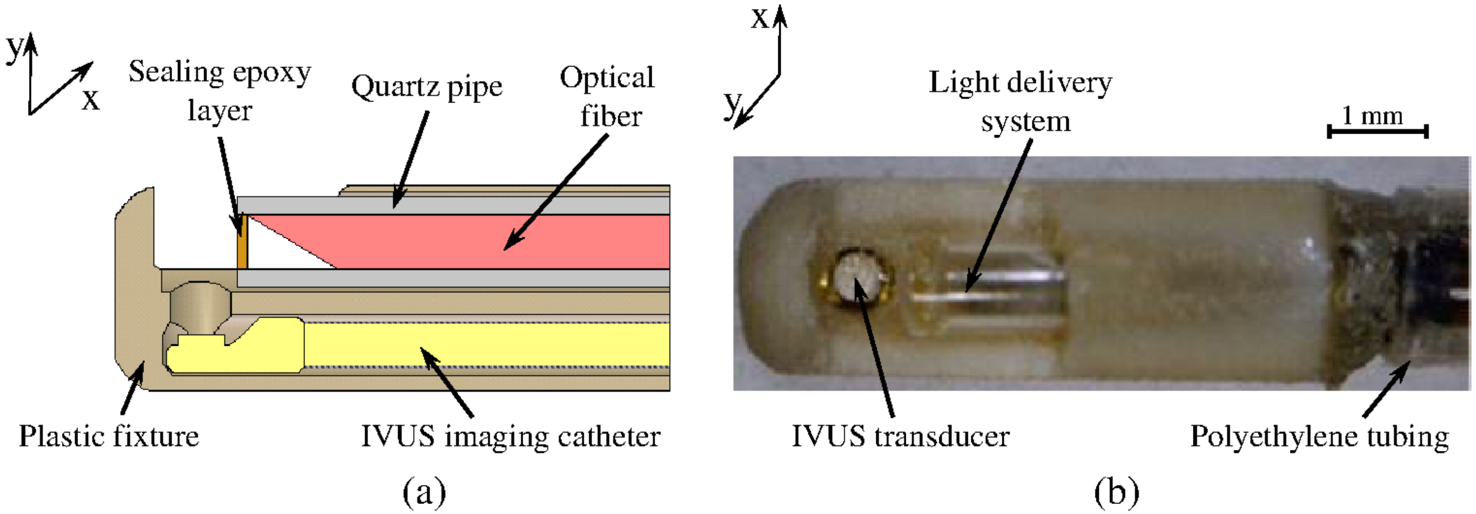


In vivo PA image of the hand vascularization. *UCL PA Imaging Group*



3D photoacoustic imaging of melanoma *in vivo. Zhang et.al. Nature Biotechnology 2006*

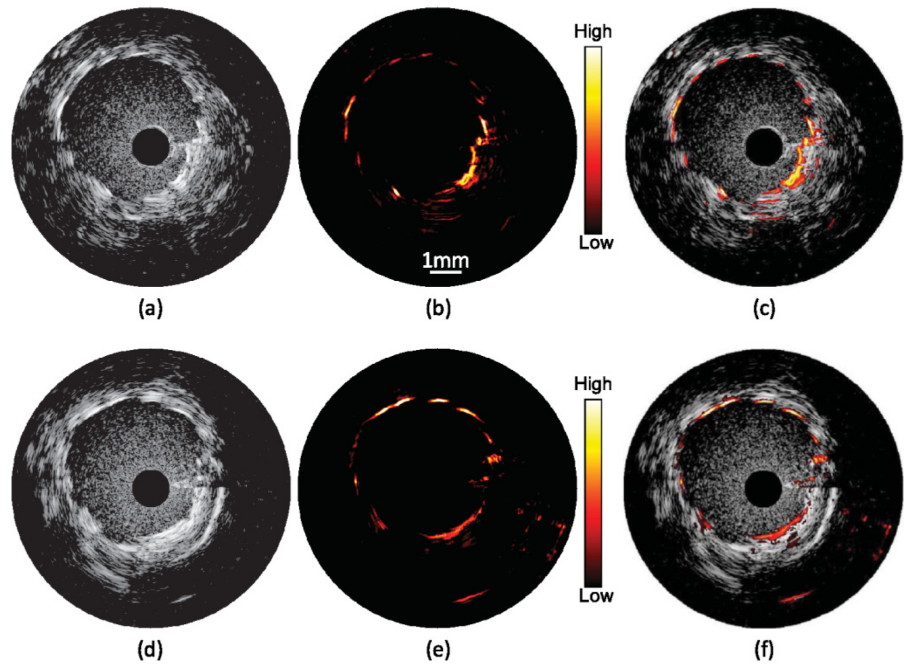
Applications



Karpiouk et.al, *J. Biomed. Opt*. 2012

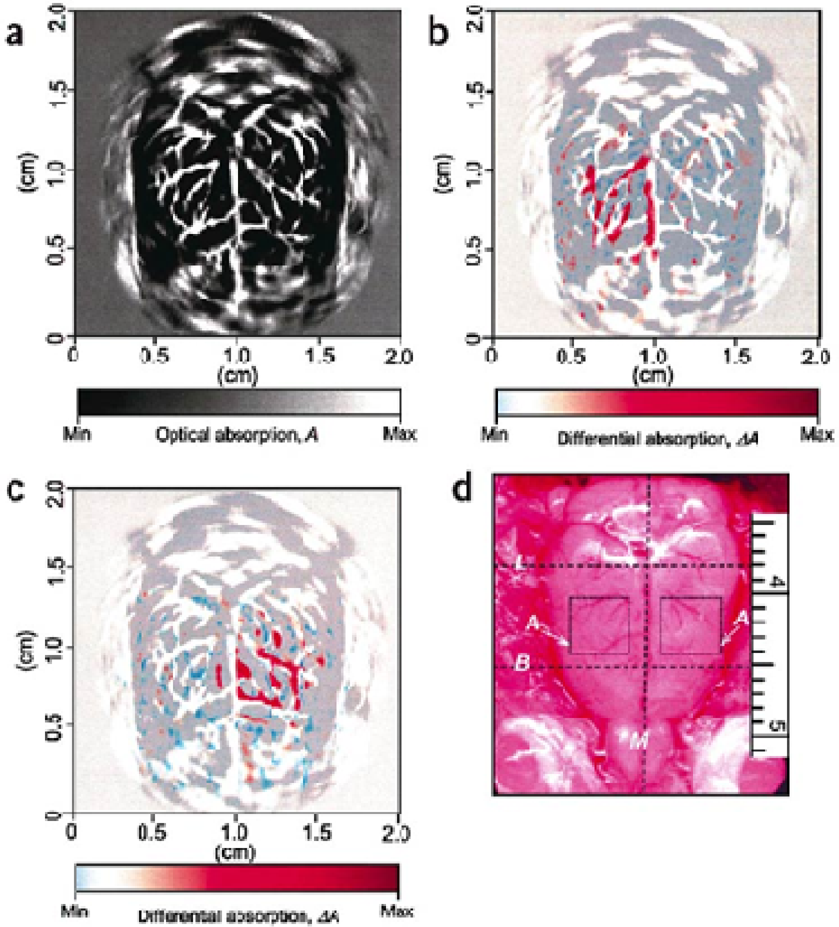
Intra-vascular photo-acoustic,

vascularization of the plaque



Applications

Functional imaging of the brain



Cerebral hemodynamic changes in response to whisker stimulation, Wang et. al. *Nature Biotechnology,* 2003

Ultrasound advanced imaging: beyond anatomy!

- Elasticity
- Cardiac function
- Vector flow
- Arterial wall motion
- Functional imaging of the brain (ultrafast imaging or photo-acoustics)
- Vascularization using photo-acoustics