Multiwave Imaging and Elastography

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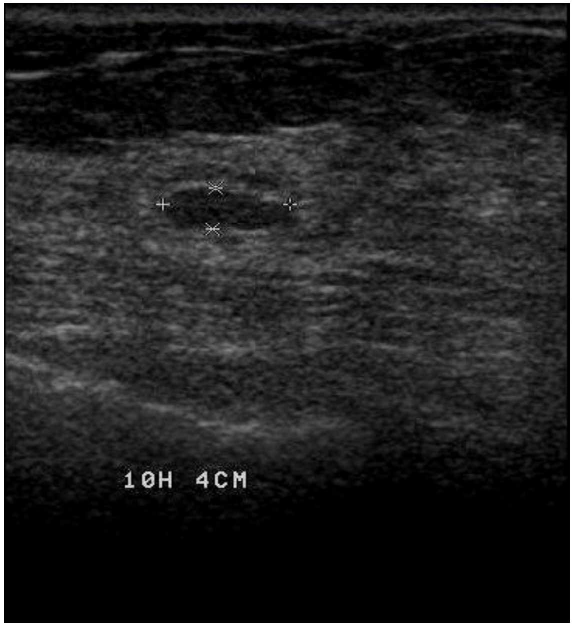
A difficult problem for radiologists : breast cancer detection

Ultrasound Images of different breast lesions

Begnin



Fibrotic

Lesion

Malign

Carcinoma

Grade II

Begnin

Viscous cyst

institut Curie

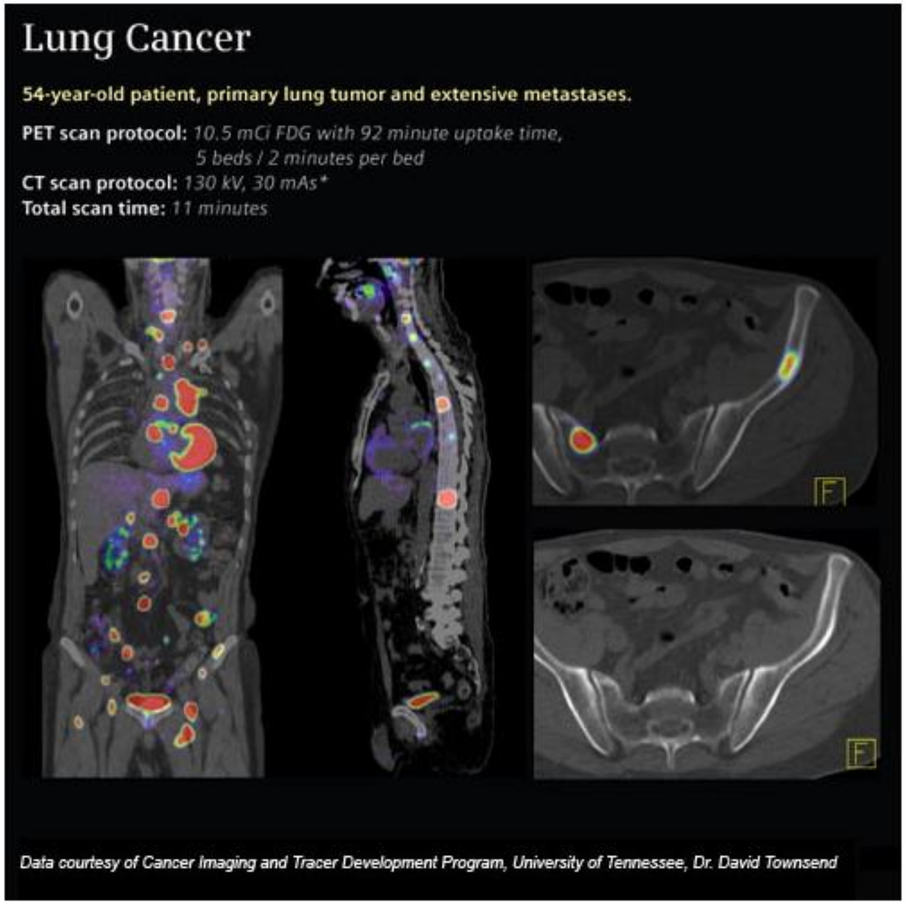
Ensemble, prenons le cancer de vitesse.

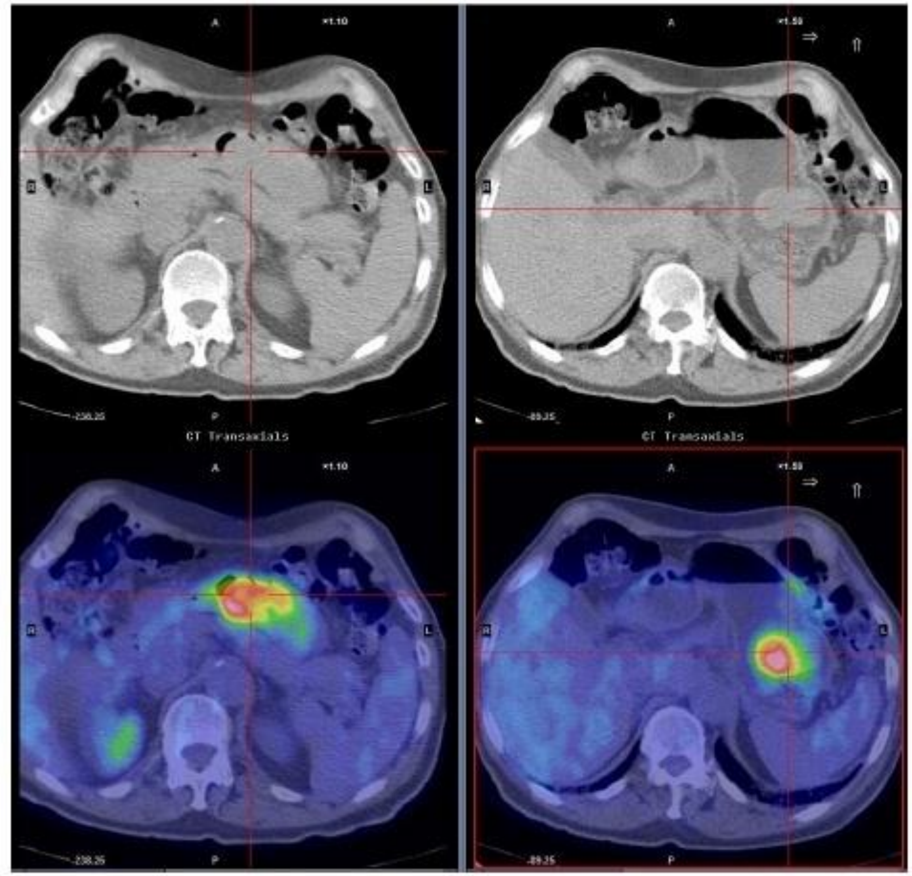
Good sensitivity but bad specificity

How to improve specificity ?

Multi-modality : superposition of two images, one morphology and one metabolic

Two examples : morphology /metabolic activity





igure 4 A dedicated single-bed position study acquired after whole body acquisition allows for active intervention and optimisation of CT acquisition protocols. This is particularly helpful in regions of complex anatomy like the neck and upper abdomen. These authors use this capacity for evaluation of gastric cancers, performing studies without and with gastric distension. The images on the left represent those with the stomach collapsed whereas those on the right are following gastric distension with an oral fluid load and buscopan to minimise gastric motility.

PET/CT Scan

PET/MRI

Multi-Modality Imaging

Superposition of 2 images each obtained with a single wave

One single wave is sensitive only to **a given Contrast** :

Ultrasound to **bulk compressibility ,**
Optical wave to **dielectric permitivity and optical absorption**,
Sonic Shear wave to **shear modulus, viscosity**
LF Electromagnetic wave to **electrical impedance, conductivity**
X ray to **density**
Gamma ray to **radio tracer distribution**
……..

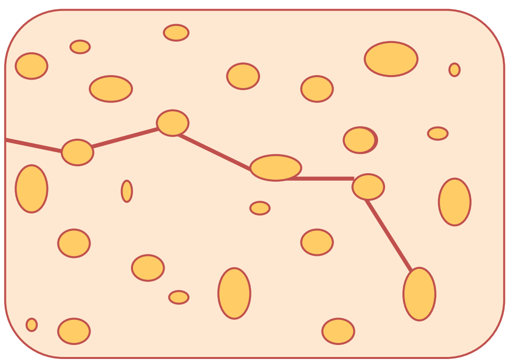
Spatial Resolution depends on wave physics laws and on sensor technology.

Spatial resolution with one-wave imaging system

Spatial resolution δ ?

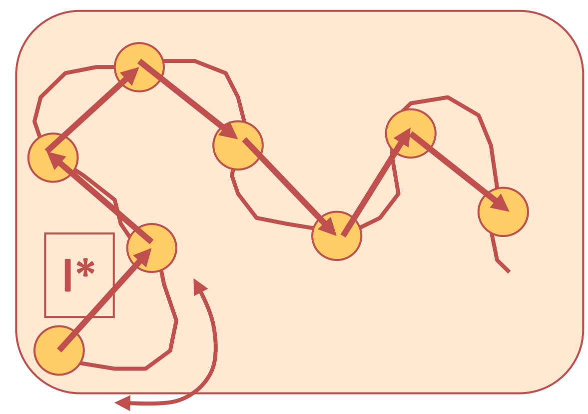
- *z* observation depth
- λ wavelength
- *l** transport mean free path

In strongly heterogeneous medium (**multiple scattering**) , waves lost their coherence on a distance called the transport mean free path *l**



Transport mean free path *l**

Distance needed for a wavefront to loose the memory of its initial direction. In all tissues ***l**> λ***



Optical wave in tissues *l ~ 500 µm**

Ultrasound in tissues , *l* * > 1 m

LF Electromagnetic waves, *l* * >> 1 m

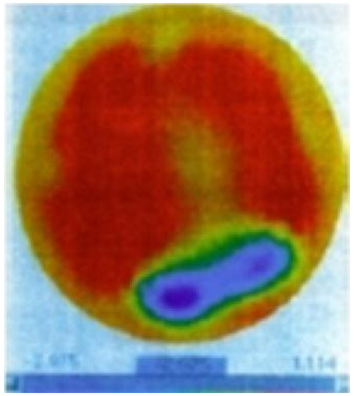
Spatial resolution with one-wave imaging system

Spatial resolution δ ? 3 different regimes

1. $z<\lambda$ **Near field Imaging**

- Elec. Impedance Tomography (EIT)
- EEG, MEG
- Near Field Optics

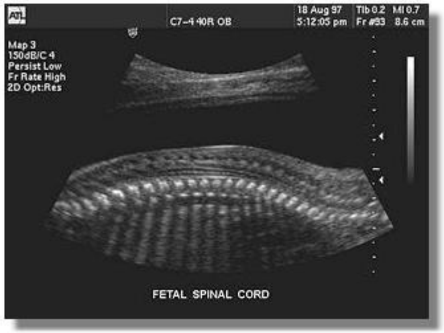
$$\delta \sim z$$



2. $\lambda<z<l^*$ **Coherent wave propagation**

- Ultrasound
- Opt.Coh.Tomography
- C.T., X-Ray diffraction

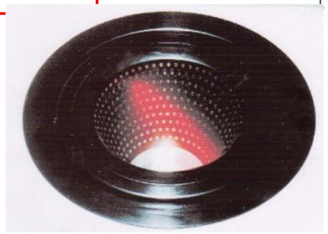
$$\delta \sim \lambda$$

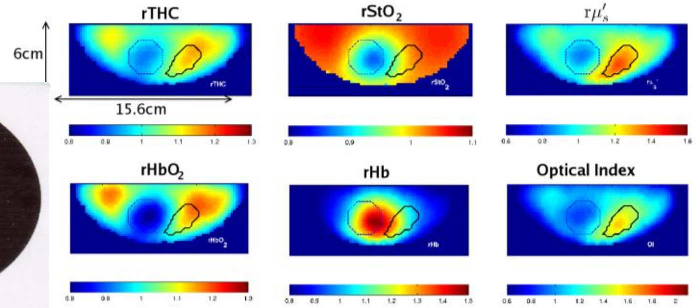


3. $\lambda<l^*<z$ **Diffusive regime**

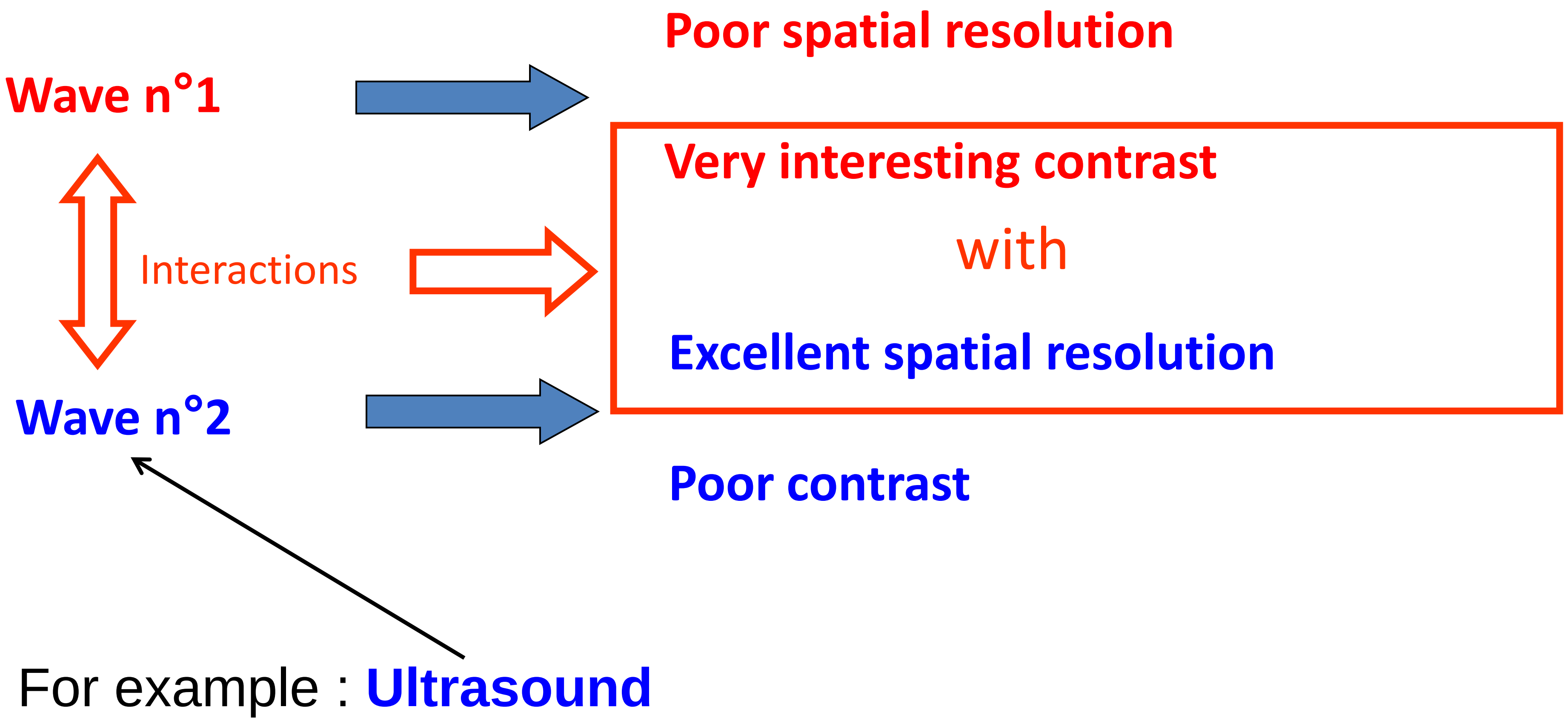
Deep optical tomography

$$\delta \sim z$$





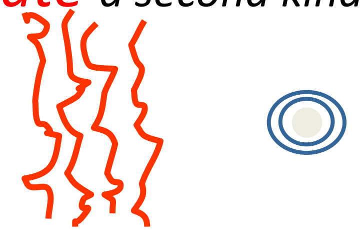
Multi-Wave Imaging: A physicist approach



How to play Multiwave Imaging ?

Three potential Interactions between different waves

- *The interaction of the first wave with tissues* can generate *a second kind of wave*

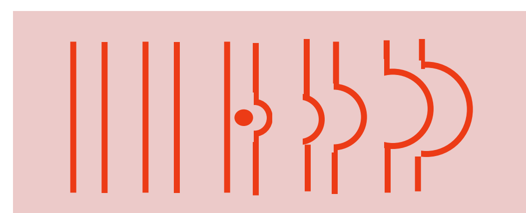


PhotoAcoustic Imaging
ThermoAcoustic Imaging

- *The first wave* ***IS TAGGED*** *locally by a second kind of wave*

AcoustoOptical Imaging
Electrical Impedance Imaging with Ultrasound

- *A first wave travelling much faster than the second one can be used to produce* a movie *of the slow wave propagation*



Transient Elastography
Shear Wave imaging (Supersonic mode)

A unique case that allows the observation of the near field of the slow wave inside the body ,

I – A wave generates a second type of wave : Photo-Acoustics

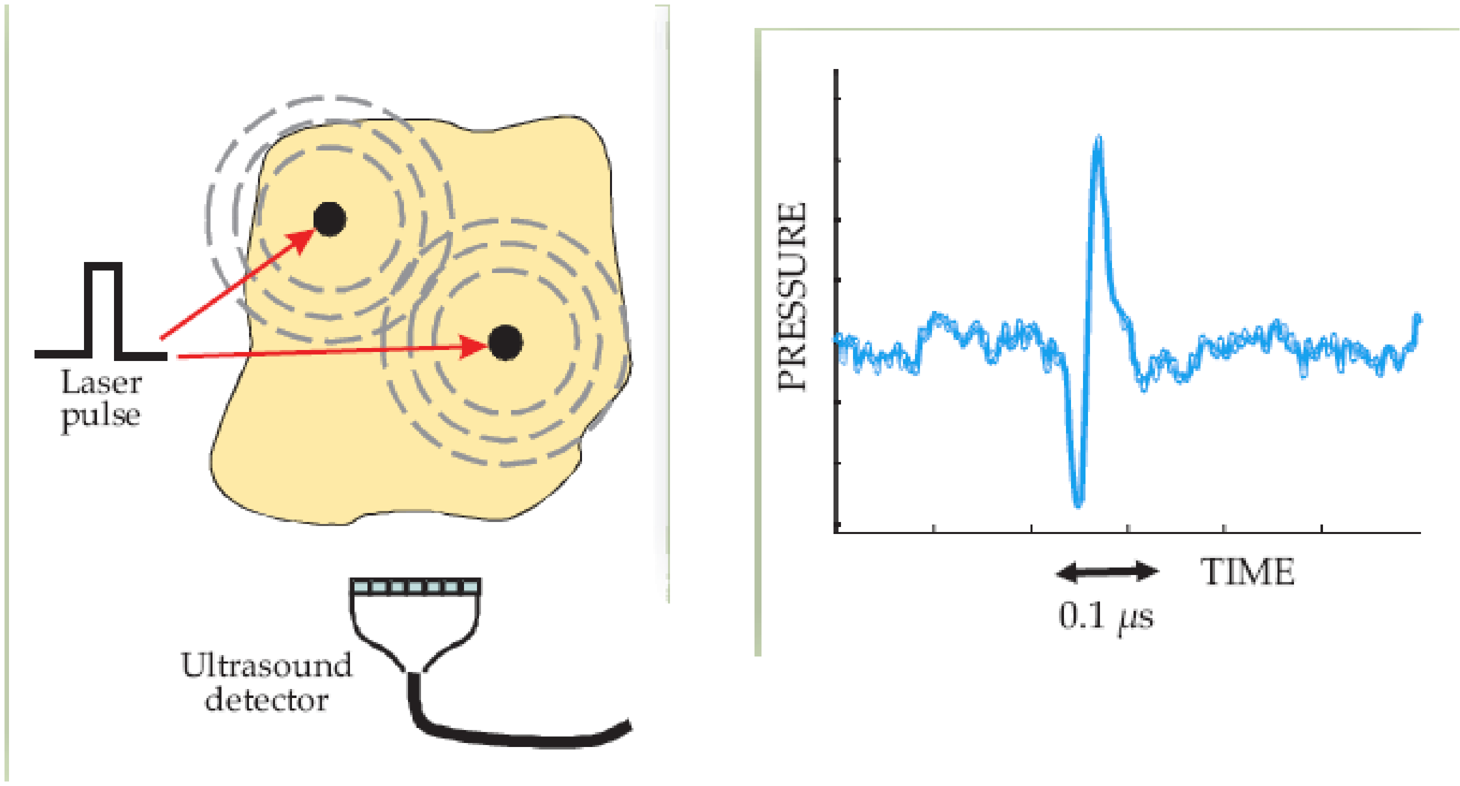
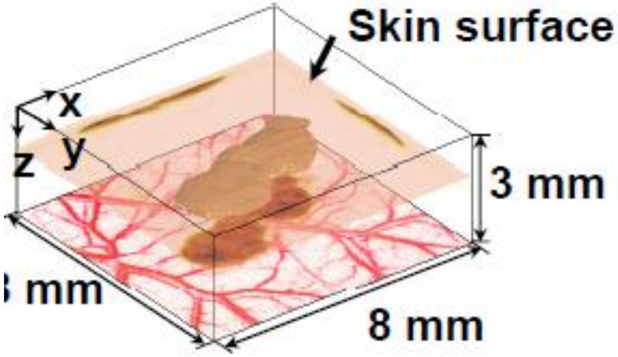


Figure 3. Photoacoustic generation and detection. Black dots in the left panel represent regions of high optical absorption. When heated by a laser pulse, they launch acoustic waves, which are picked up by an ultrasound detector. The ultrasound waveform shown in the right panel is approximately proportional to the time derivative of the optical pulse.

Photo-Acoustics



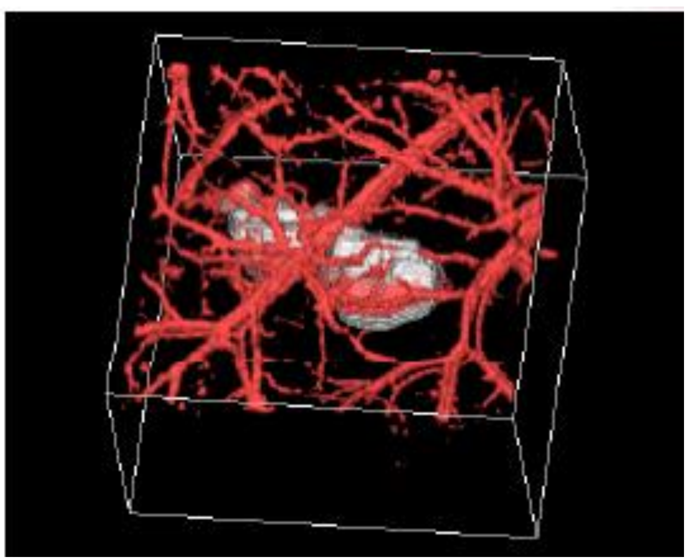


Photo-(opto)-Acoustics

$$\Delta p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\beta}{c_p}\cdot\frac{\partial H_{abs}}{\partial t}$$

$H_{abs}(\mathrm{r},t)$: Energy absorbed per unit volume per unit time ($W.m^{-3}$)

For optical absorption: $H_{abs}(\mathrm{r},t) = \mu_a(\mathrm{r}) \times \phi(\mathrm{r},t)$

$\phi(\mathrm{r},t)$: Optical fluence ($W.m^{-2}$)

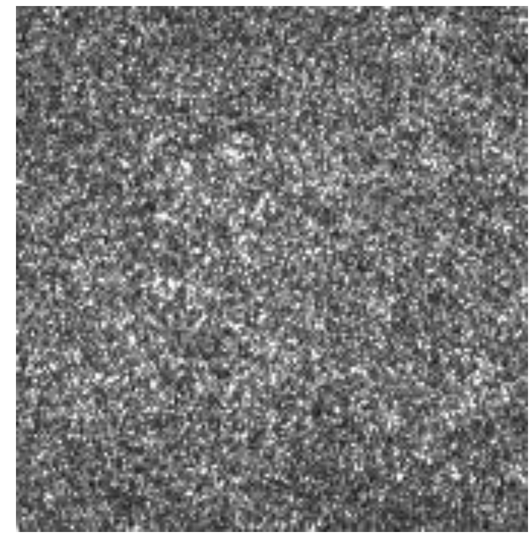
$\mu_a(\mathrm{r})$: Optical absorption coefficient ($W.m^{-2}$)

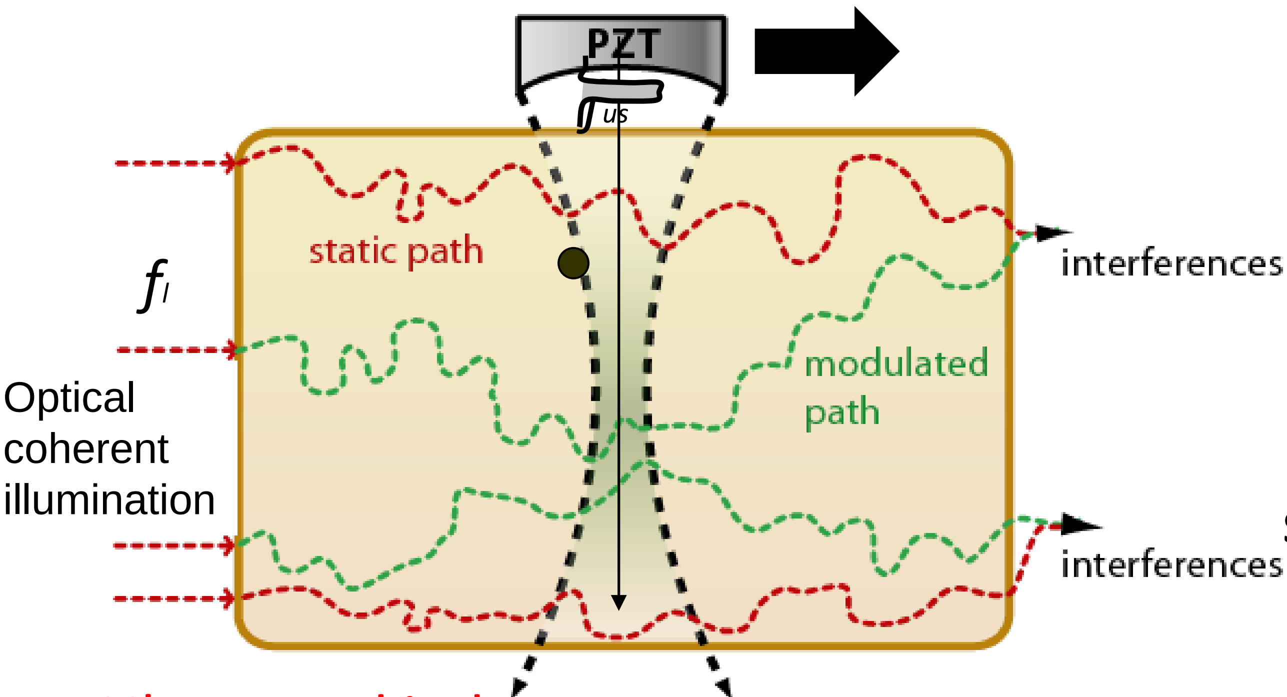
X. Wang, Y. Pang, G. Ku, X. Xie, G. Stoica, and L.-H. Wang, "Non-invasive laser-induced photoacoustic tomography for structural and functional imaging of the brain in vivo," Nature Biotechnology 21 (7), 803-806 (July 2003).

L.. V Wang, Nature Biotech 24, 848, 2006, S. Emilianov et al, Physics Today, 2009

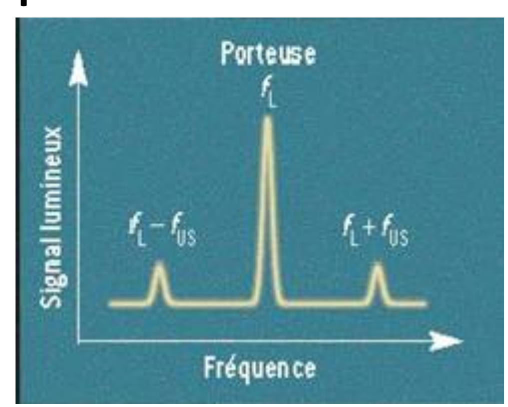
II - A wave is tagged by another wave : Tagging Photons with ultrasound

Optical Speckle





Speckle is modulated



Ultrasound induces

1. Displacement of the scattering centers
2. Modulation of the refractive index

G. Maret, LH. Wang, C. Boccara, S Leveque, F. Ramaz M. Groos

Experimental results in vitro

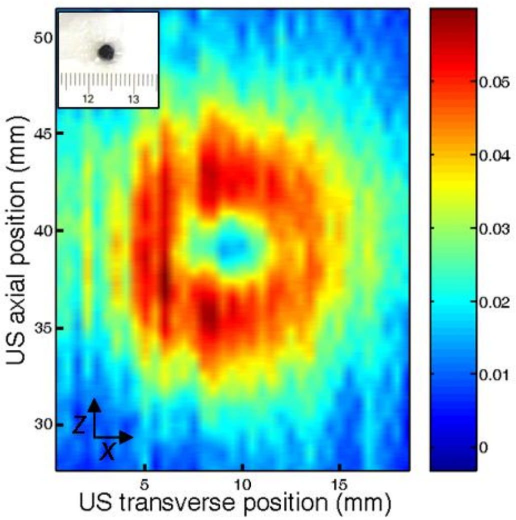
laser @790 nm + US bursts

Imaging an absorbing inclusion

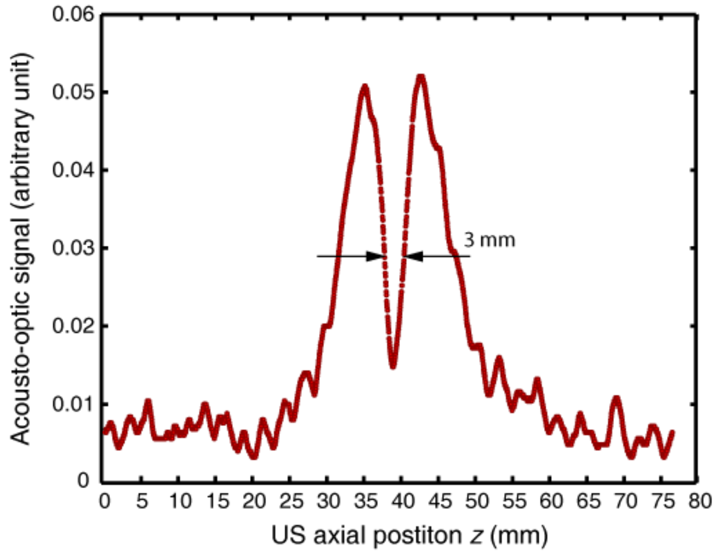
L = 2.3 cm
μs'=μs(1-g)= 6 cm^{-1}

US: 2.3 MHz, 4 cycles, 1 ms

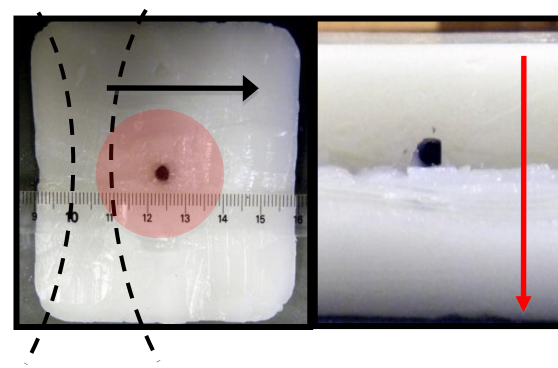
Agar Agar + Intralipid-10% + 1 inclusion 3 mm x 10 mm

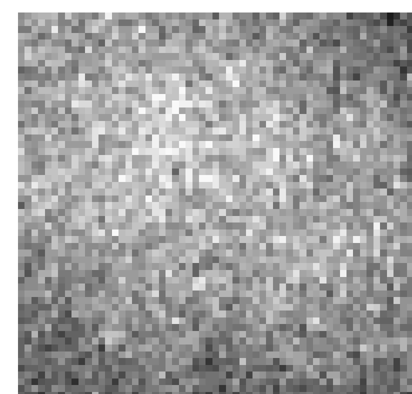


Axial resolution = 2.6 mm



Axial pattern





More difficult to implement in-vivo because the tissue speckle has a coherence time smaller than 1 ms

« Photorefractive acousto-optic imaging in thick scattering media at 790 nm with a Sn2P2S6:Te crystal »

S.Farahi, G Montemezzani, A. Grabar, JP. Huignard, F. Ramaz Optics Letters (2010)

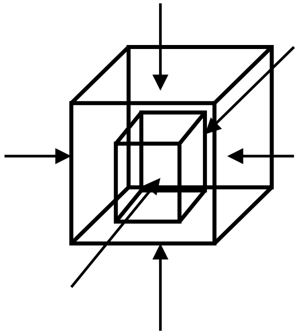
III - A wave produces a movie of another wave : Transient Elastography :

How to image elastic properties of tissues with millimetric resolution ?

What kind of mechanical waves can propagate in soft tissues ?

Two types of waves related to the two mechanical coefficients **K** and **μ** used to define the elasticity of a solid material

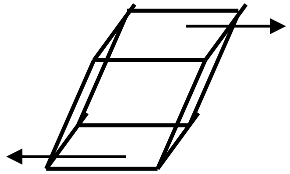
K



K Bulk Modulus (Compression) almost constant, of the order of **10^9 Pa,** Fluctuations ≈ 5%

Quasi incompressible medium

μ



μ Shear Modulus, Strongly heterogeneous, varying between **10^{2} and 10^{7} Pa**

(A. Sarvazian)

K >> μ

Young modulus

E ≈ 3 μ

Human Body Seismology : Mechanical waves in soft tissues

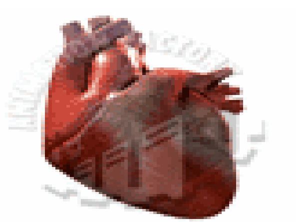
Compressional Waves propagate at $c_P \approx \sqrt{\frac{K}{\rho}}$ (≈ 1500 m.s^{-1})

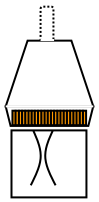
Shear waves propagates at $c_s = \sqrt{\frac{\mu}{\rho}}$ (≈ 1-10 m.s^{-1})

Two kind of waves propagating at totally different speeds !!

At **Ultrasonic** frequency, only Compressional waves can propagate, at 5MHz, **wavelength = 0.3mm.**

At **Sonic** frequency, Shear waves can propagate < 1000 Hz (High Shear Viscosity), at 200 Hz, **large wavelength = 2cm**

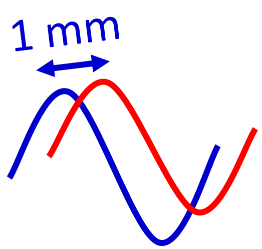




Ultrasonic radiation force

Transient Elastography : a Multiwave approach

- Generation of transient low frequency shear wave (10 Hz to 1000 Hz) with some microns amplitude



1 à 5 m.s^{-1} → 5.000 images.s^{-1} !

- One follows tissue motion induced by shear waves 5.000 times/s. Local measurement of the shear velocity and E ou μ are deduced by relation :

$$c_s = \sqrt{\frac{\mu}{\rho}} \approx \sqrt{\frac{E}{3\rho}}$$

1D Transient Elastography

1994

2001

In a first step (1994) we observed transient shear waves with a single ultrasonic transducer .
Then in 2000 a company ECHOSENS was created (45 persons) to develop the Fibroscan to get a global measurement of liver elasticity

M.Fink, S. Catheline, L. Sandrin

From 1D Transient Elastography to SuperSonic Shear Wave Imaging

Fibroscan

Aixplorer

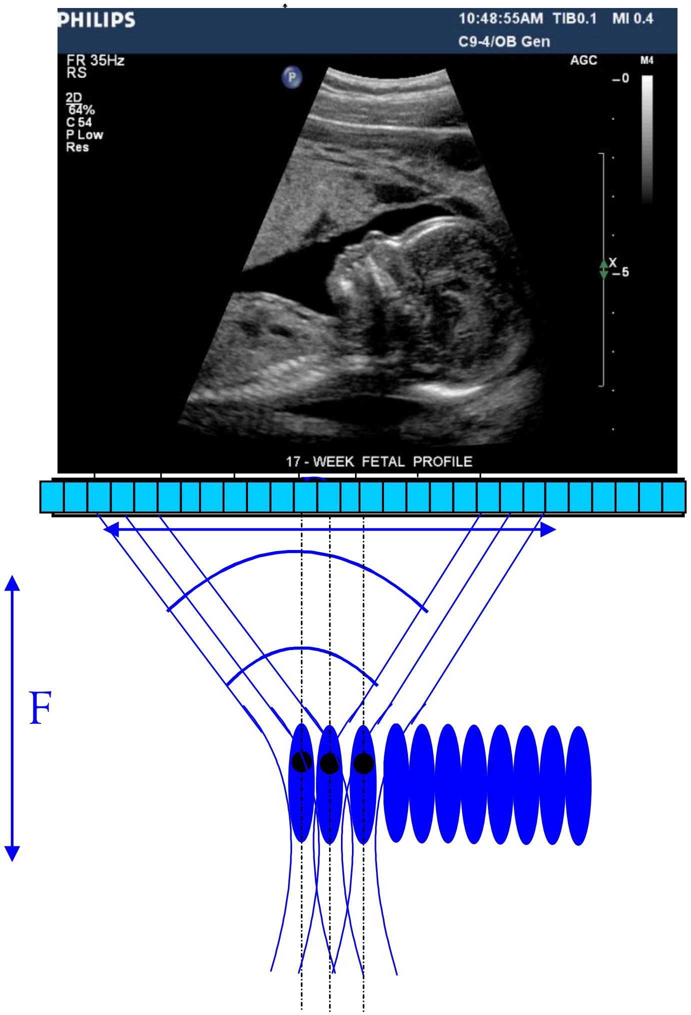
echosens

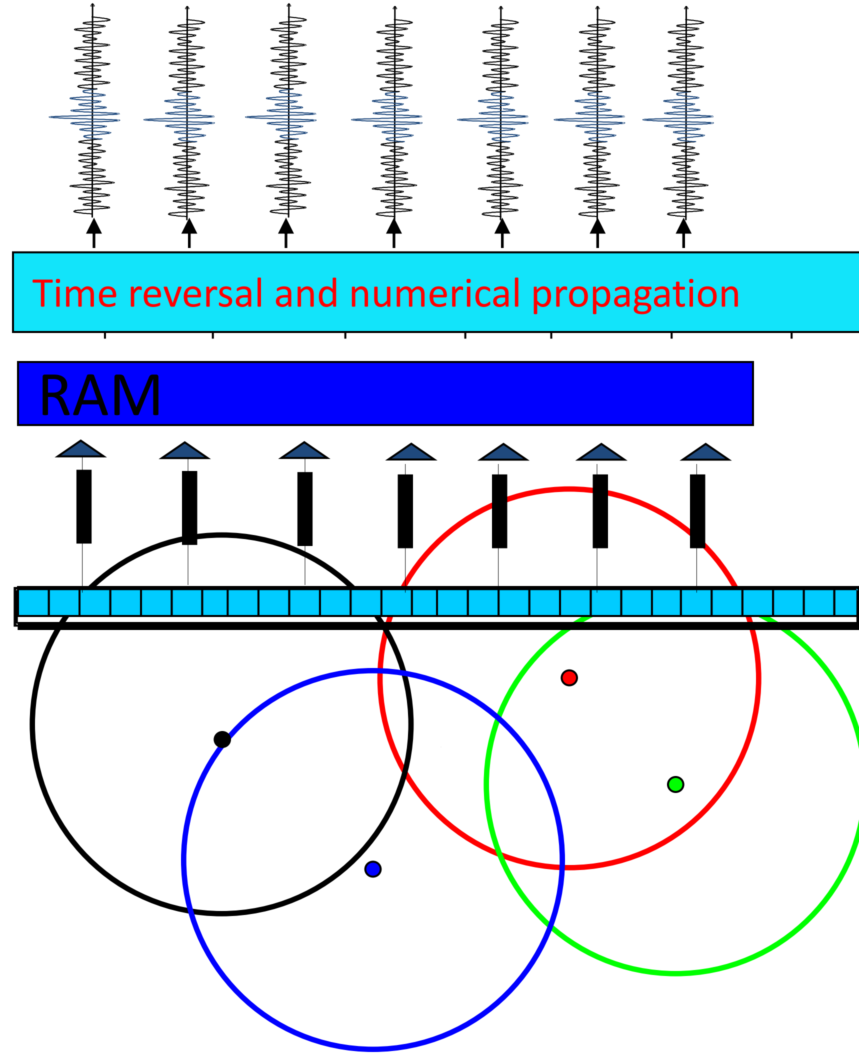
SUPERSONIC imagine

Research Work in Laboratoire Ondes et Acoustique (now Institut Langevin)

2D Transient Elastography needs an ultrafast ultrasound imaging system

How to make an ultrafast ultrasound scanner ? : Time reversal

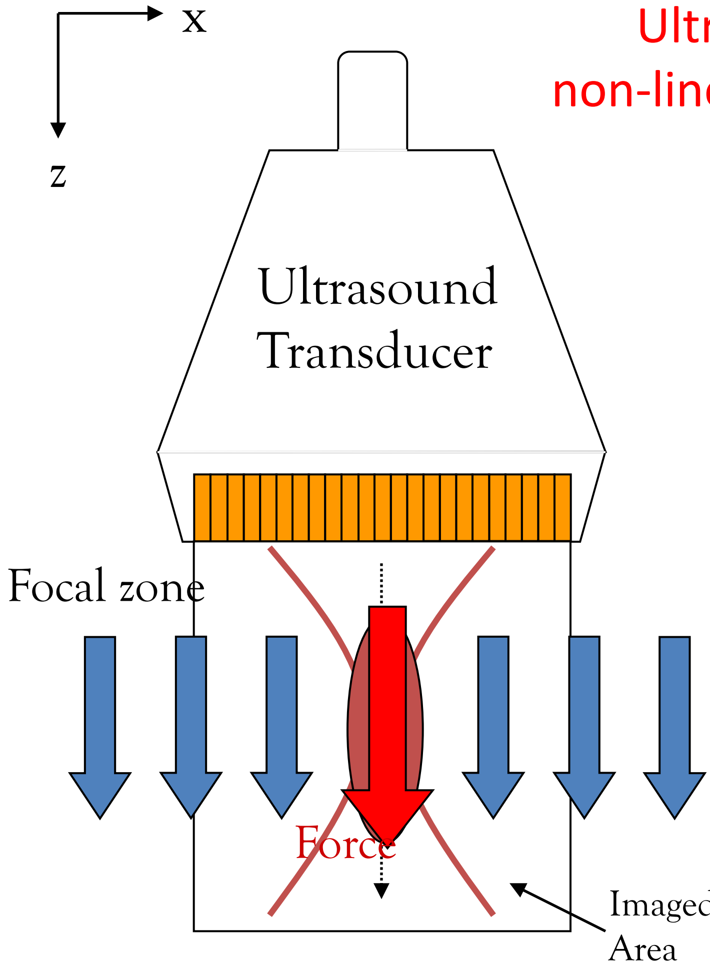




128 shots for one image,
50 frames /second

1 shot for one image,
5000 frames/s

Transient Elastography and Ultrasonic Radiation Force



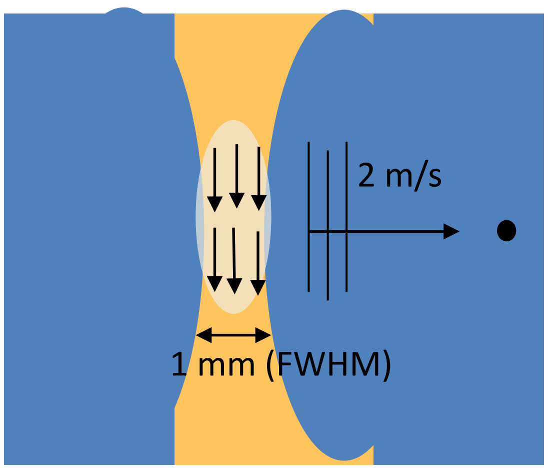
Ultrasonic Radiation Force
non-linear and dissipative effects

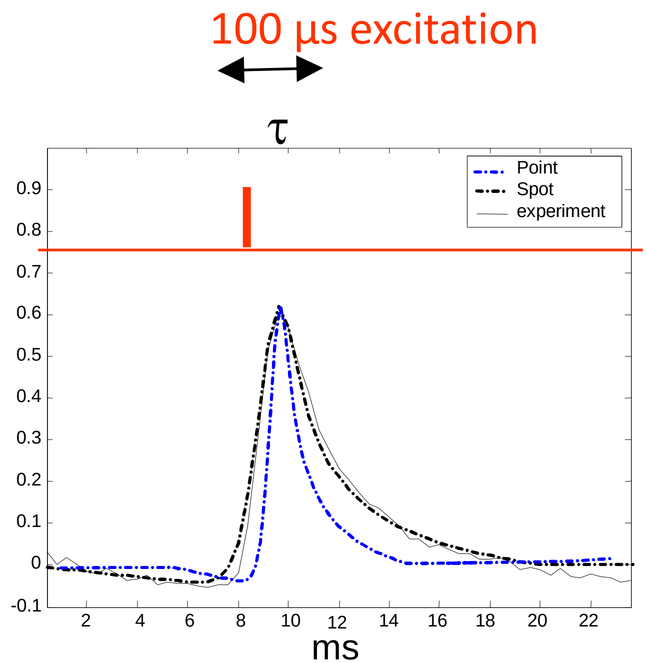
$$F(\vec{r},t) = \frac{\alpha}{\rho c^2} p^2(\vec{r},t)$$

Typical ultrasonic bursts of 100 µs to create low frequency pushes (10 micrometers displacement)

A. Sarvazian, J. Greenleaf, C. Nithingale, G. Trahey, M. Fink, M Tanter

Shear Wave Bandwidth generated by the Ultrasonic Radiation force ?





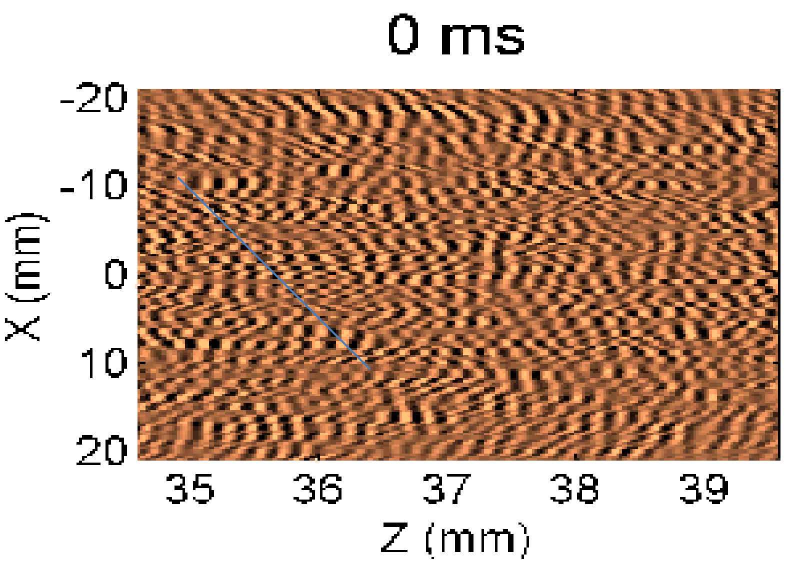
$$\tau = \frac{\lambda_{US} F}{c_{shear} D}$$

$$\boxed{f_{shear} = \frac{c_{shear} D}{4\lambda_{US} F}}$$

f_{shear}= 500 Hz

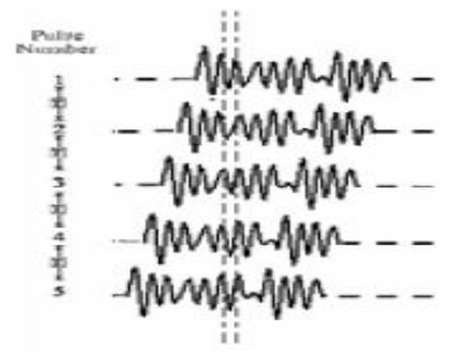
How to measure the displacements induced by shear waves ?

Tissues behave as random distributions of scatterers. **The speckle is moving with shear wave**
One repeat ultrasonic shots at high rate (> 5000 shots/s) and create an ultrafast movie



t

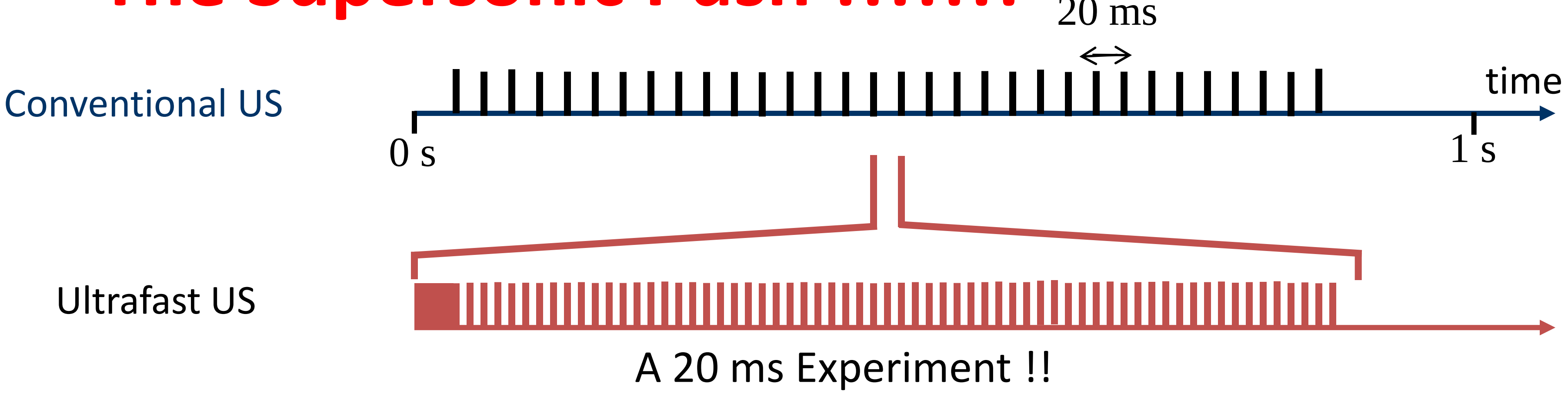
shot 1
shot 2
shot 3
shot 4
shot 5

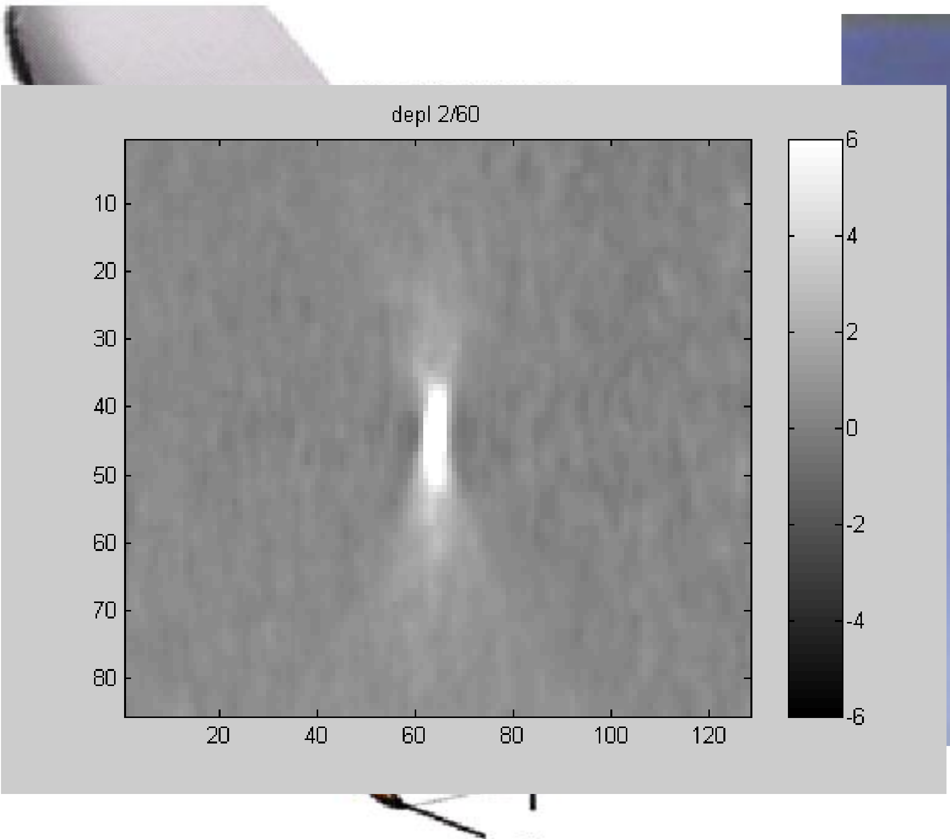


Moving window cross-correlation
gives the axial displacements $u_z(x,z,t)$

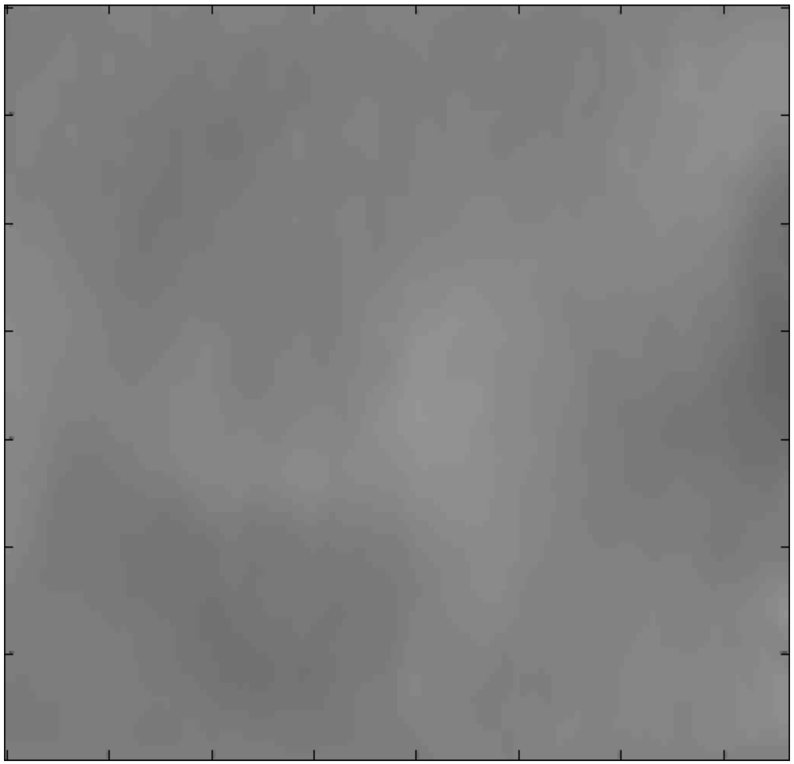
It is possible to measure **displacements of 1 μ** $(\lambda/1000)$ between 2 consecutive shots

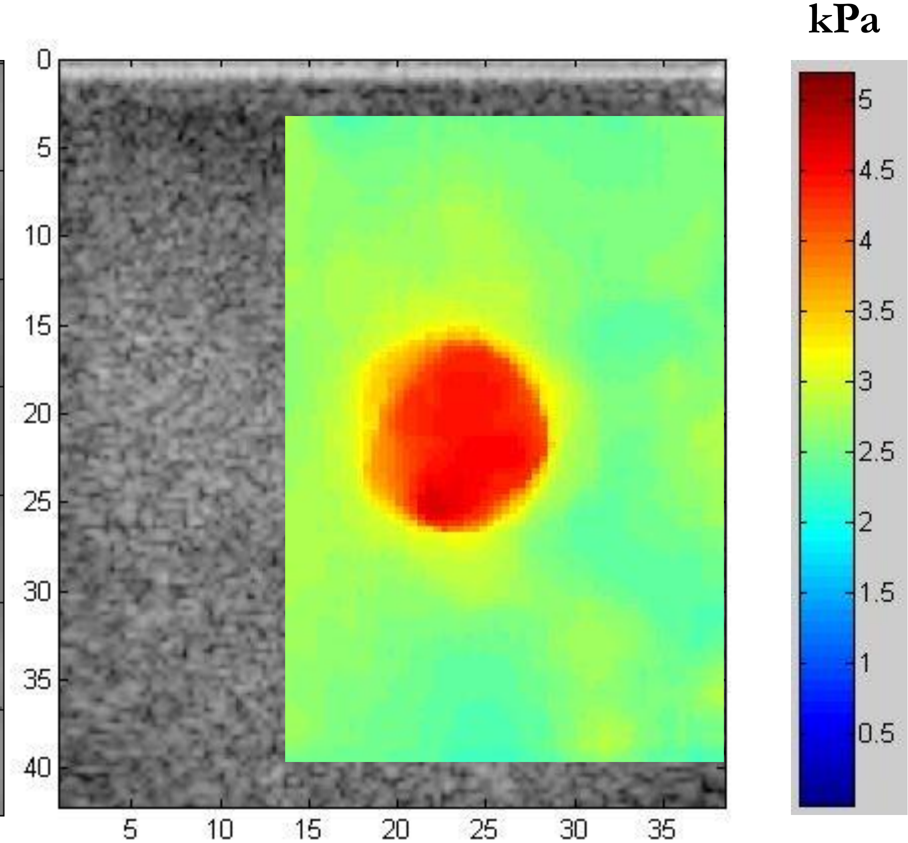
The Supersonic Push !!!!!!!





Multiwave Imaging of a hard inclusion





Movie duration 20 ms

<u>Ref:</u> ***Supersonic Shear Imaging: a new technique for soft tissue elasticity mapping.***
J. Bercoff, M. Tanter and M. Fink, IEEE Trans., April 2004

A Simple Inversion Algorithm

- Motion Equation : an ideal model : isotropic solid without dissipation

$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda + \mu) \times \vec{\nabla}(\vec{\nabla}.\vec{u}) + \mu \Delta \vec{u}$$

Compressional shear

- Assumptions:

1) The medium is considered as infinite, isotropic, purely elastic and locally homogeneous.

2) $\lambda >> \mu$ => the bulk wave propagates instantaneously, and then:

$$\rho \frac{\partial^2 u_z}{\partial t^2} = \mu \Delta u_z$$

3) $$\frac{\partial^2 u_z}{\partial y^2} << \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial z^2} \Rightarrow \Delta u_z \approx \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial z^2}$$

No diffraction outside the image plane

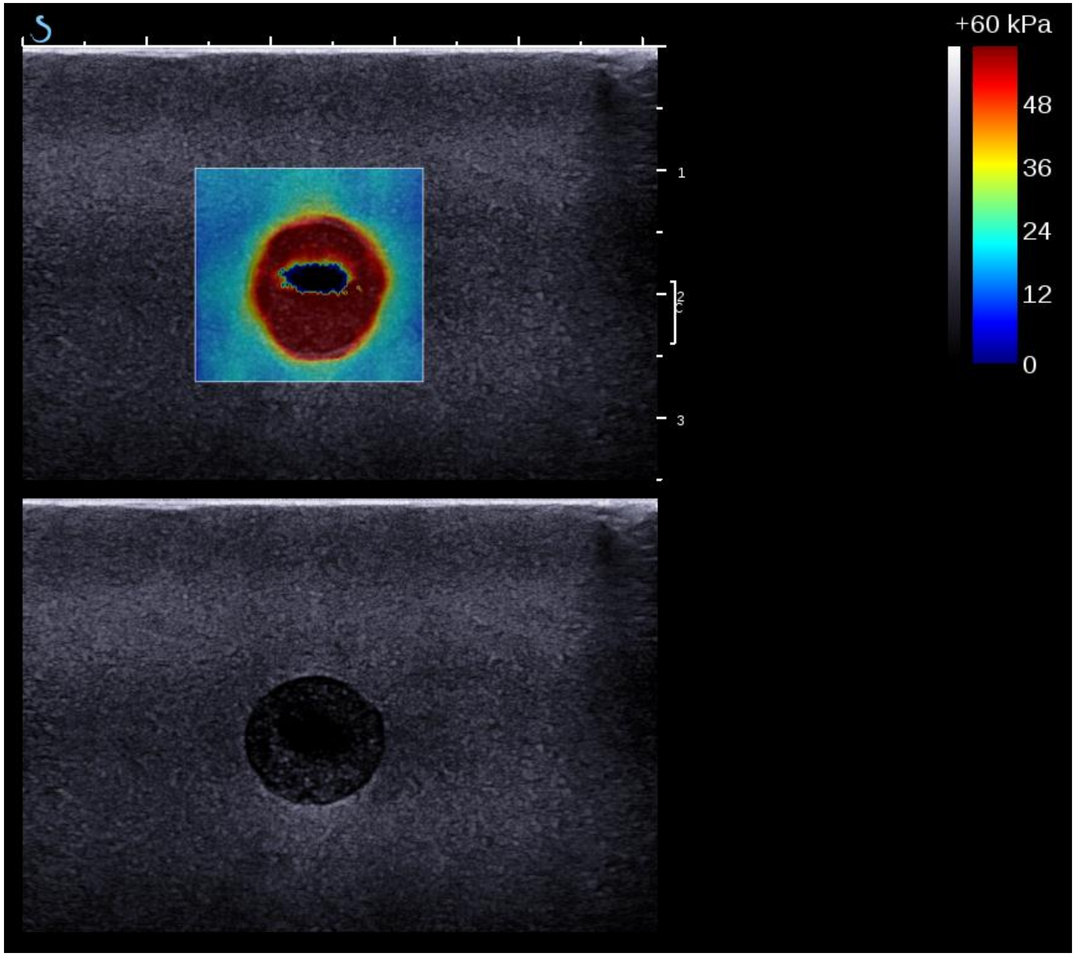
Inverse Problem

$$\rho \frac{\partial^2 u_z}{\partial t^2} = \mu \Delta u_z$$

- Local inversion algorithm

$$\mu(x,z) = \rho \frac{\left(\dfrac{\partial^2 u_z(x,z)}{\partial t^2} \right)}{\left(\dfrac{\partial^2 u_z(x,z)}{\partial x^2} + \dfrac{\partial^2 u_z(x,z)}{\partial z^2} \right)}$$

Hard Inclusion with a liquid zone



The Evolution of Ultrafast Imaging Technology

SuperSonic Imagine was founded in September 2005 by Jacques Souquet, 120 employees, Aix en Provence and Seattle

Time Reversal Prototype

1996-2002

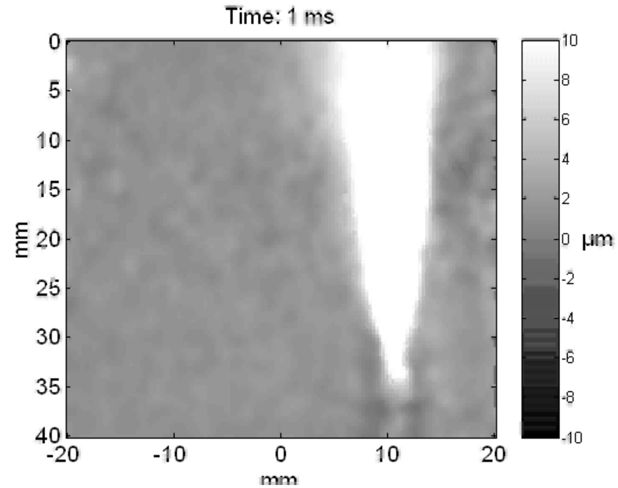
HDI 1000

2004-2005

Prototype V1

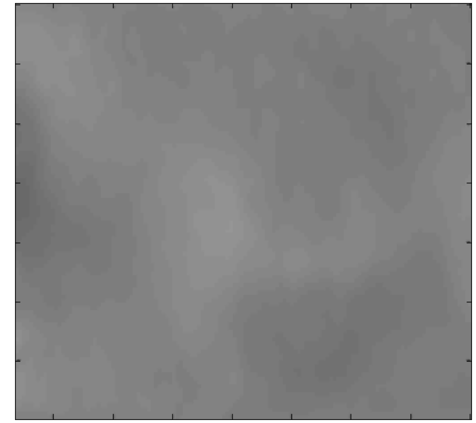
2006-2007

Echographic System with Real-time and Quantitative Elastography



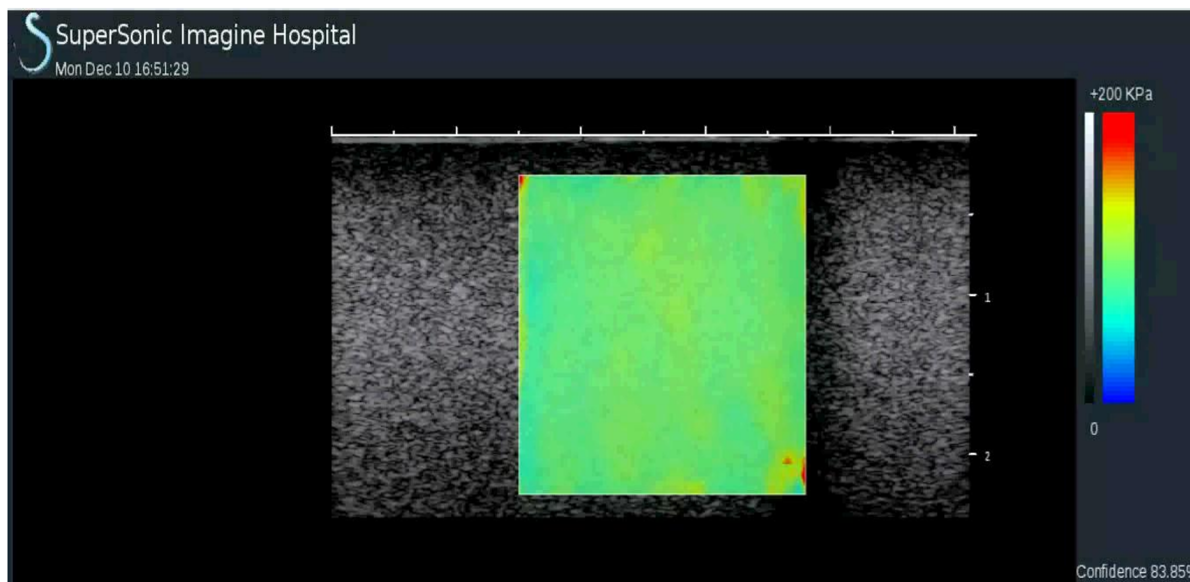
First SSI experiment : May 2002

45 Minutes processing



SSI Prototype 2006

some seconds processing



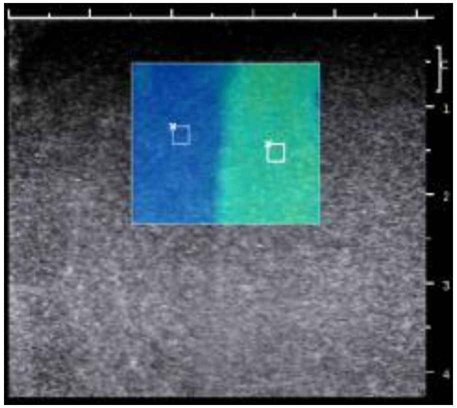
October 2007

0.2 seconds processing

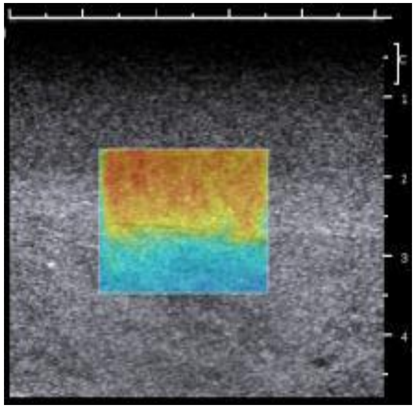
Supersonic Shear Wave Imaging: Spatial resolution

Axial and lateral resolution in a two layers medium : around 1 mm

Lateral resolution



Axial resolution

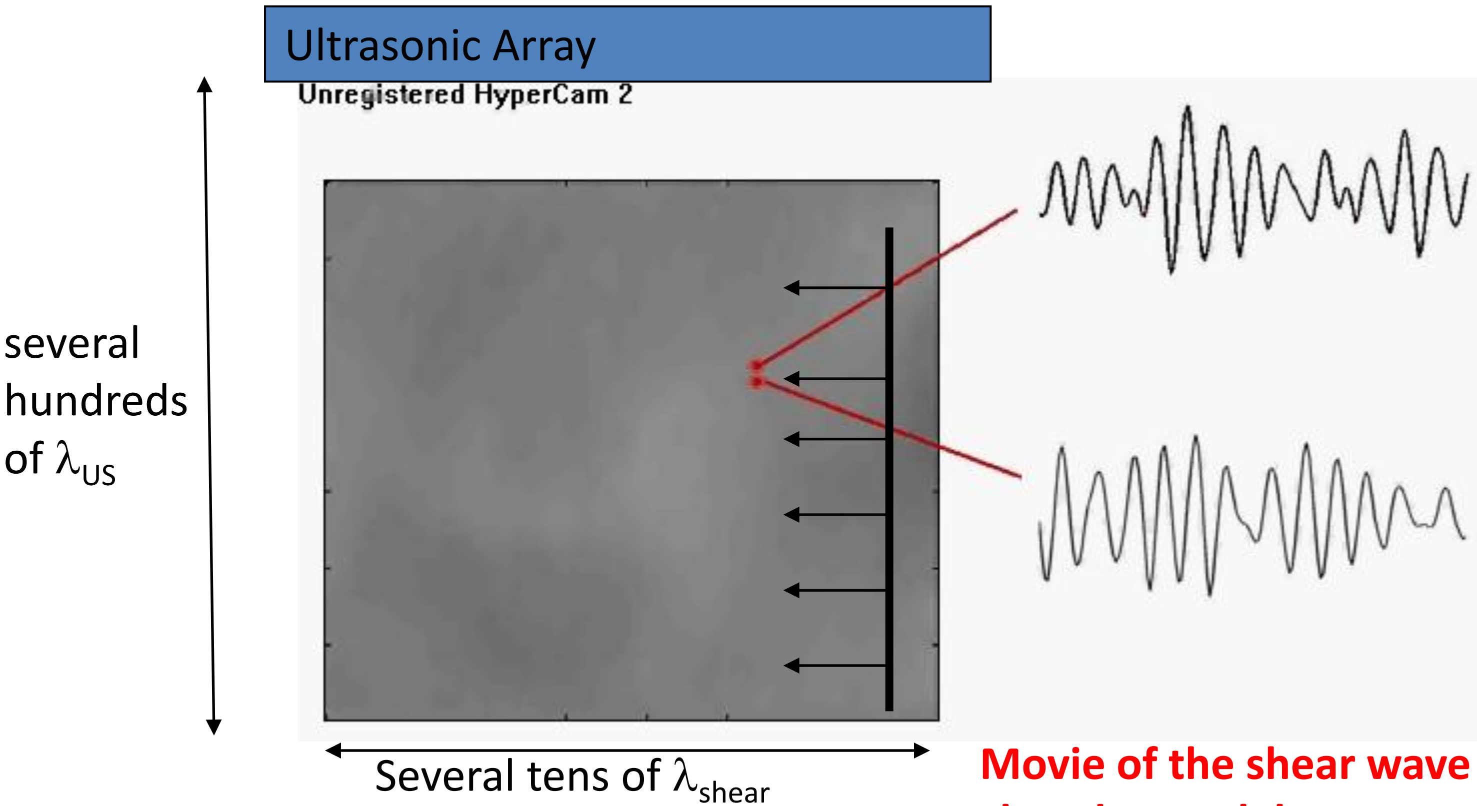


Elasticity contrast	Axial Res (mm)	Lateral Res (mm)
2	1	1.1
3	1.2	1.2
10	1.3	1.1

Multiwave imaging and super-resolution

Shear wavelength : typicaly 10 mm

Spatial resolution on the shear modulus : 1 mm (λ_{US})



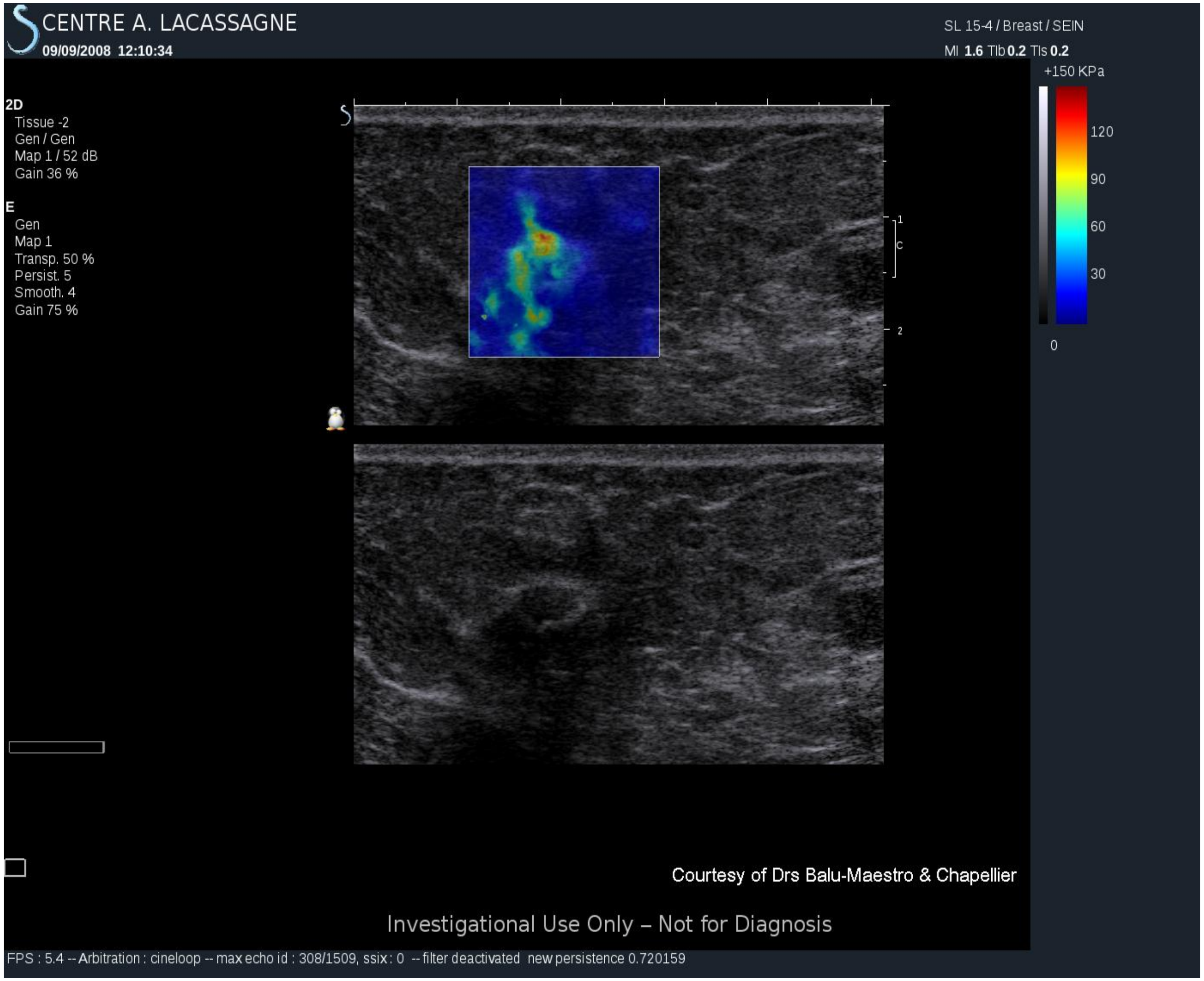
Movie of the shear wave near-field closed to each heterogeneities

Multi-Wave Imaging allows to get the Contrast of One Wave with the Resolution of the Second Wave

Medical applications of Elasticity Multiwave Imaging

- Breast
- Tyroid
- Liver
- Kidney
- Muscle
- Vascular
- Cardiac
- Eye
- Prostate
- Monitoring therapy (RF ablation, HIFU)

Breast Imaging

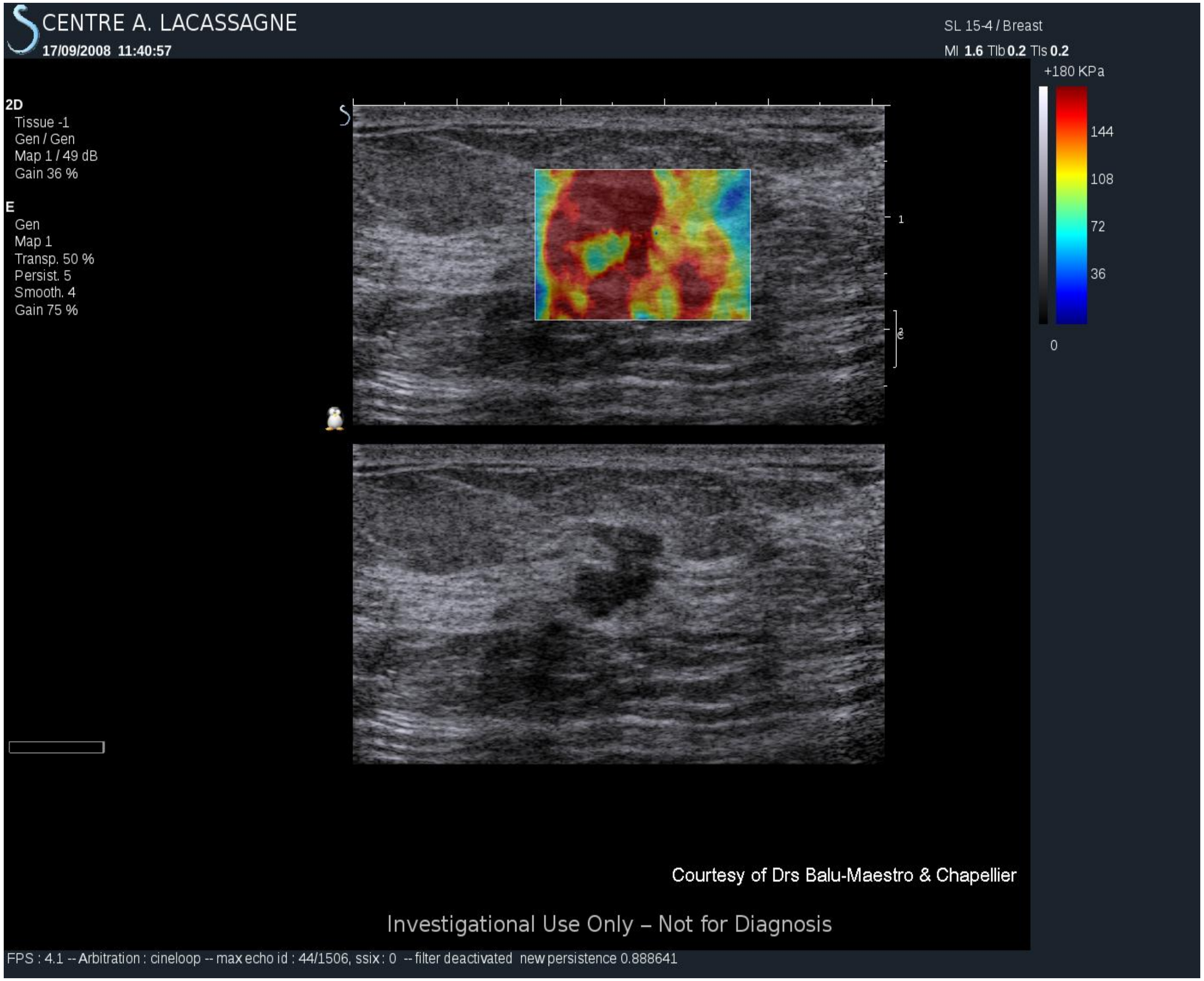


Invasive ductal carcinoma

This secondary lesion is an IDC Grade III & HR+ of 15mm.

Emax > 150kPa in the center of this 3mm lesion.

Breast Imaging

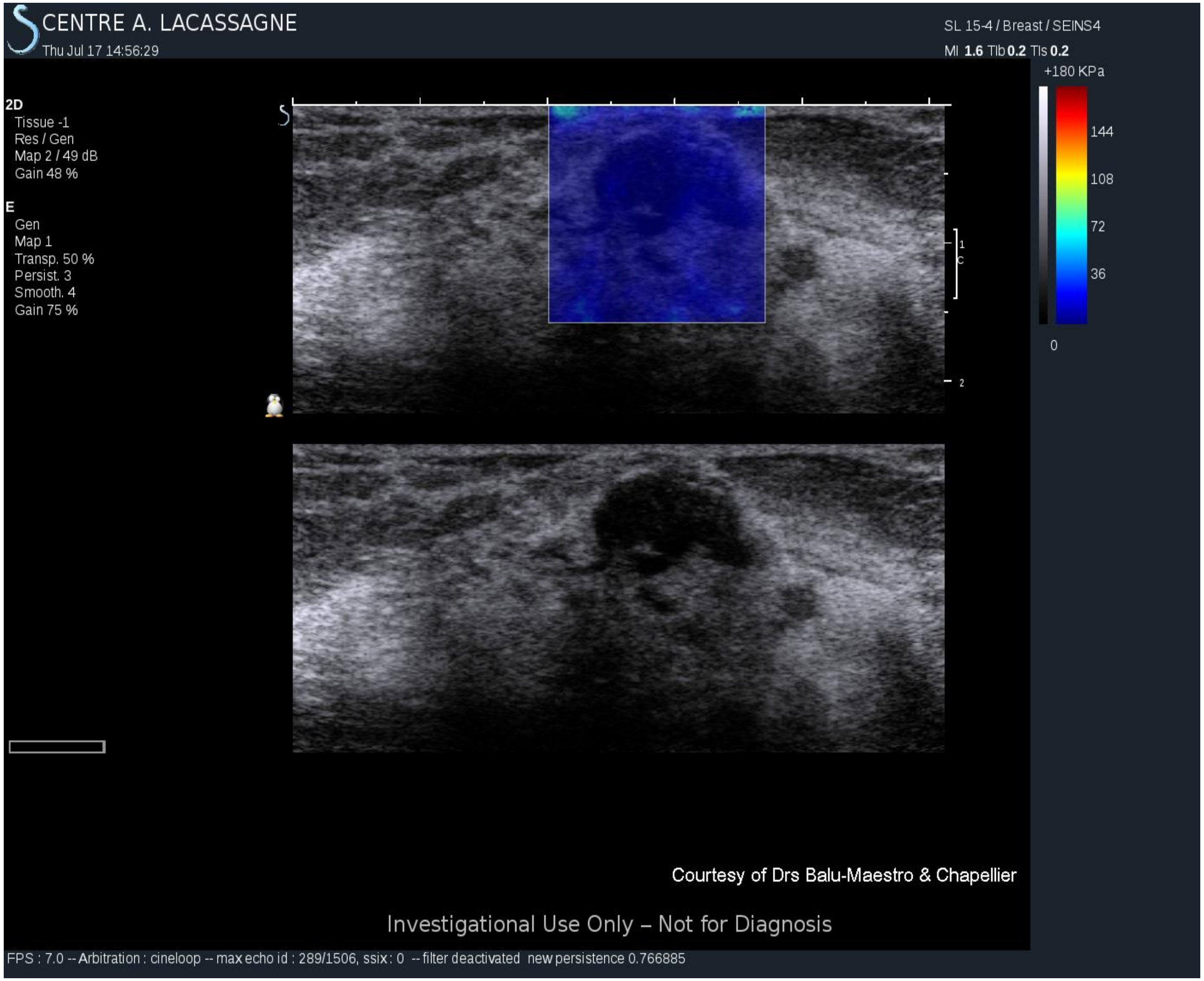


IDC Grade I, partially necrotic center proved by histology.

Emax > 200kPa on surrounding tisue.

E = 70kPa in the center.

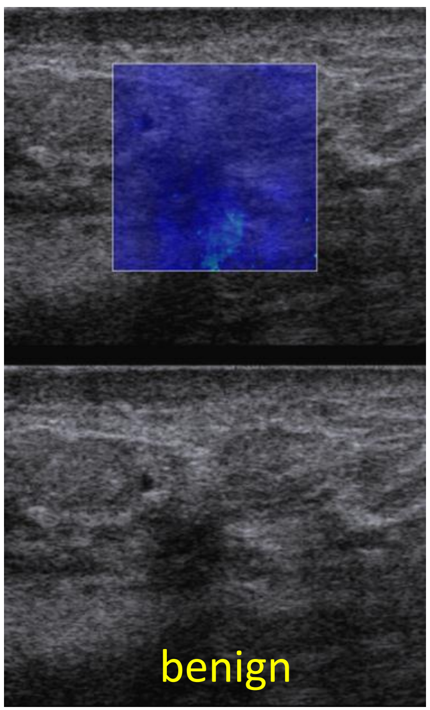
Breast Imaging

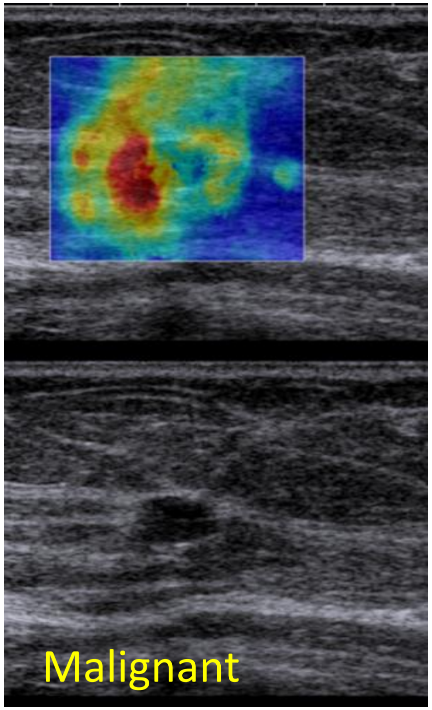


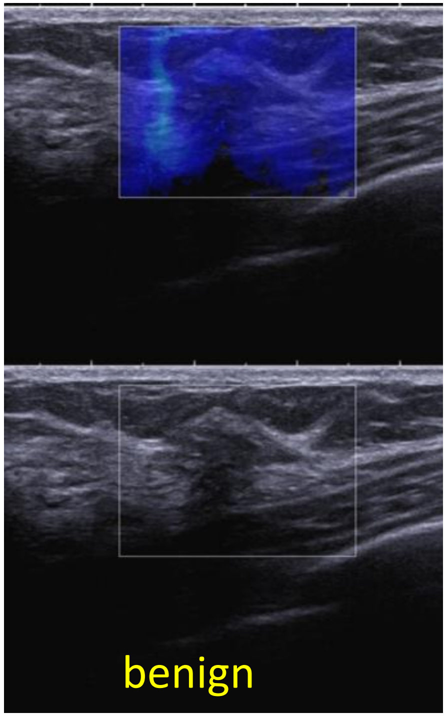
Fibro-adenoma

Emean < 30kPa and totally homogeneous.

Diagnostic impact in breast :

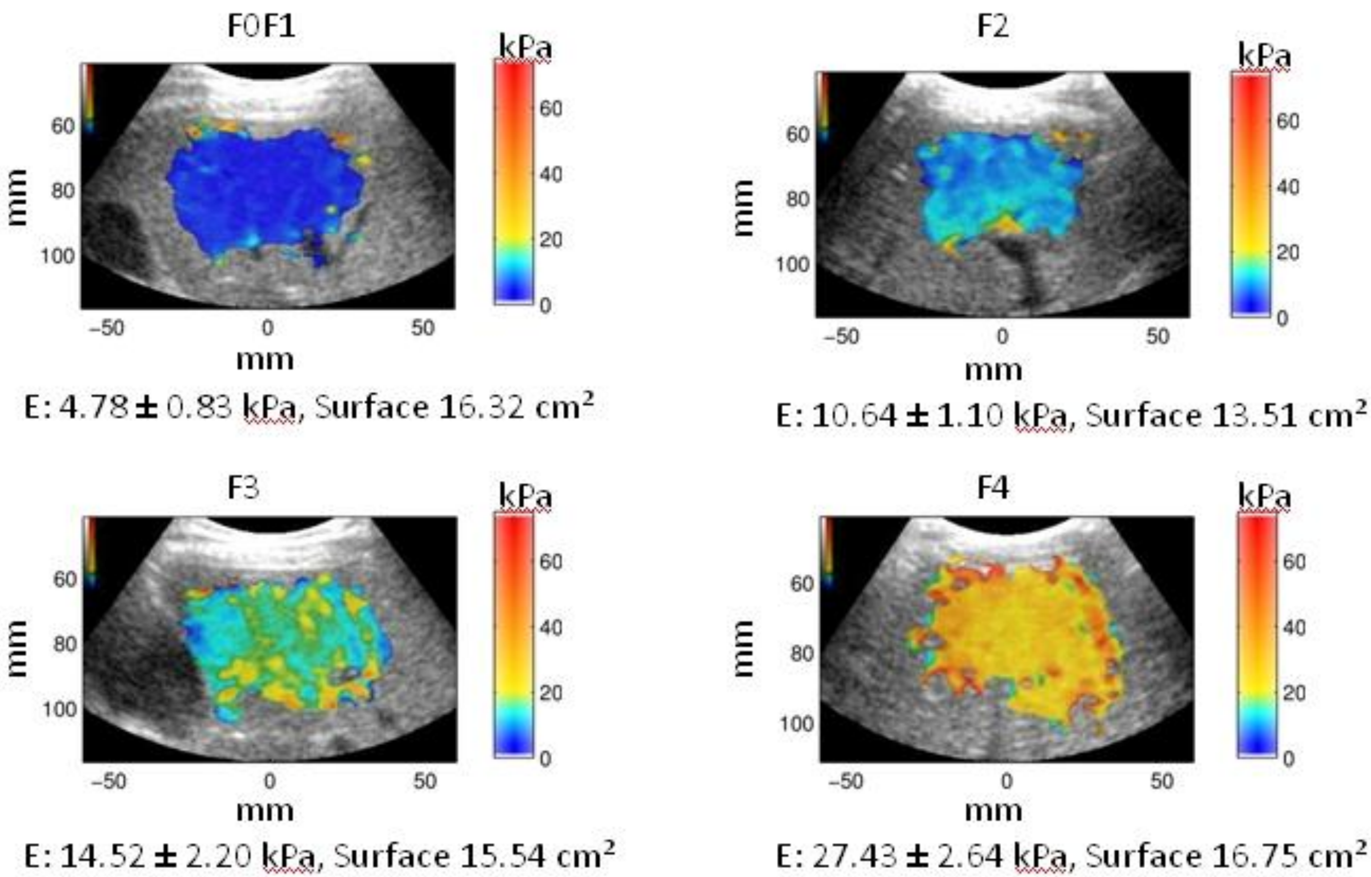


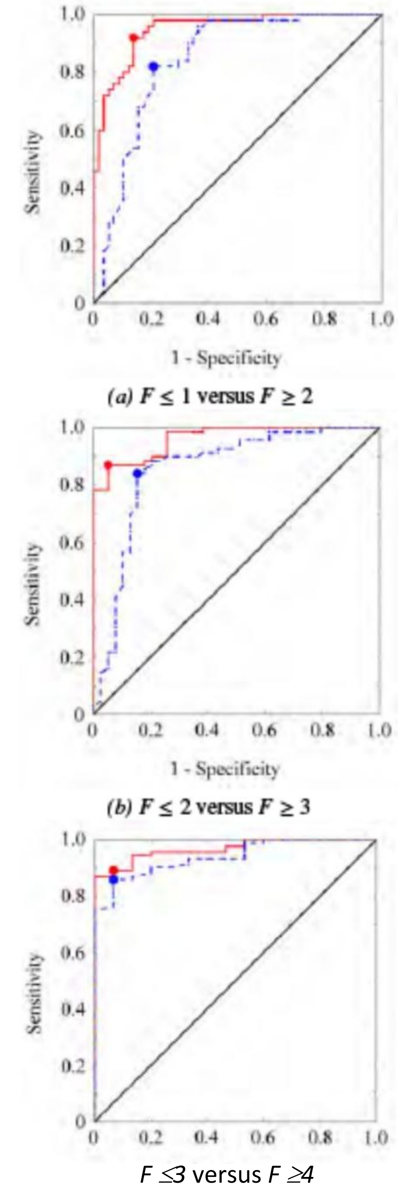




Shear Wave Imaging for Liver fibrosis Staging

Clinical Study on 118 patients with Hepatitis C

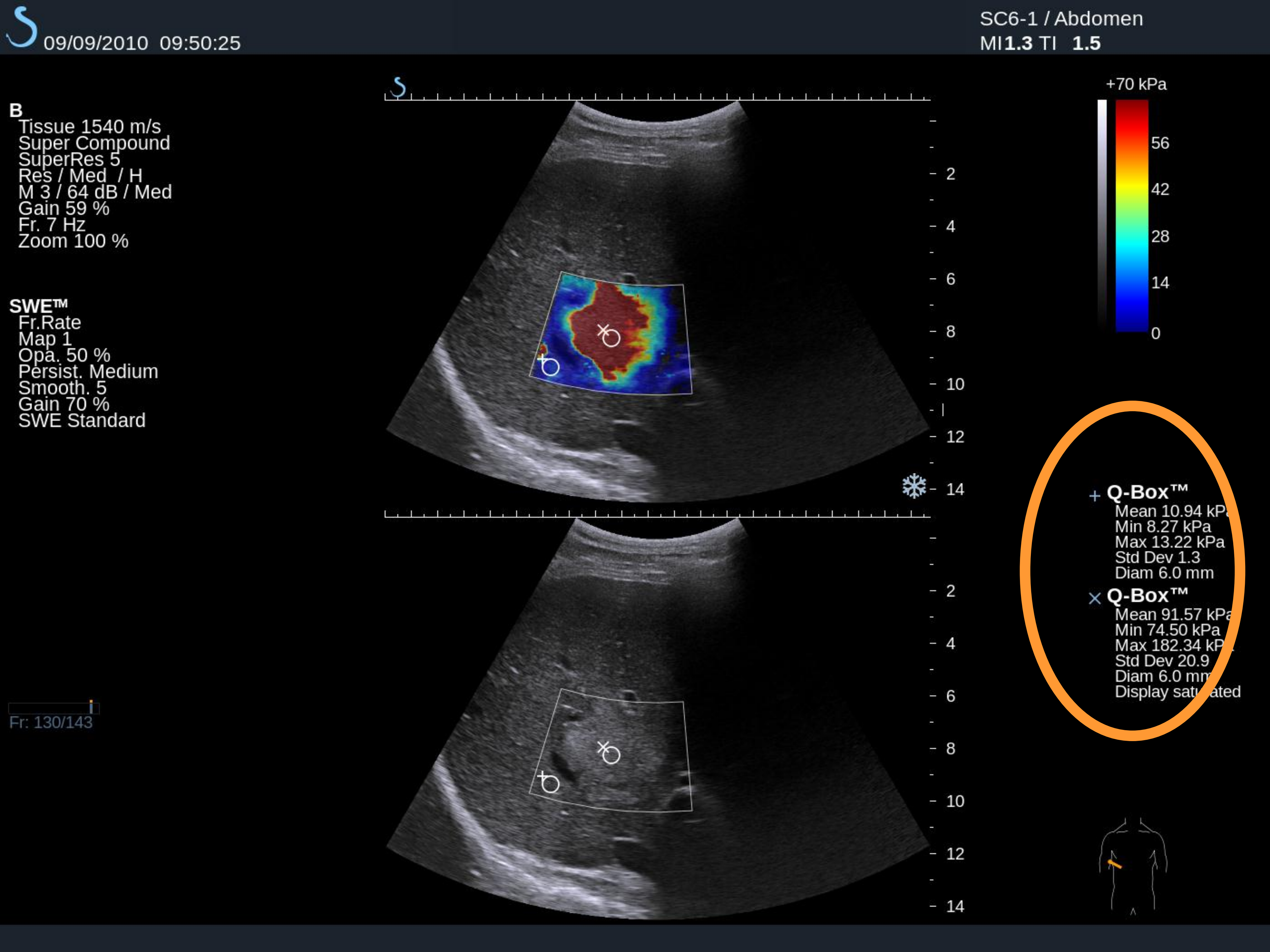




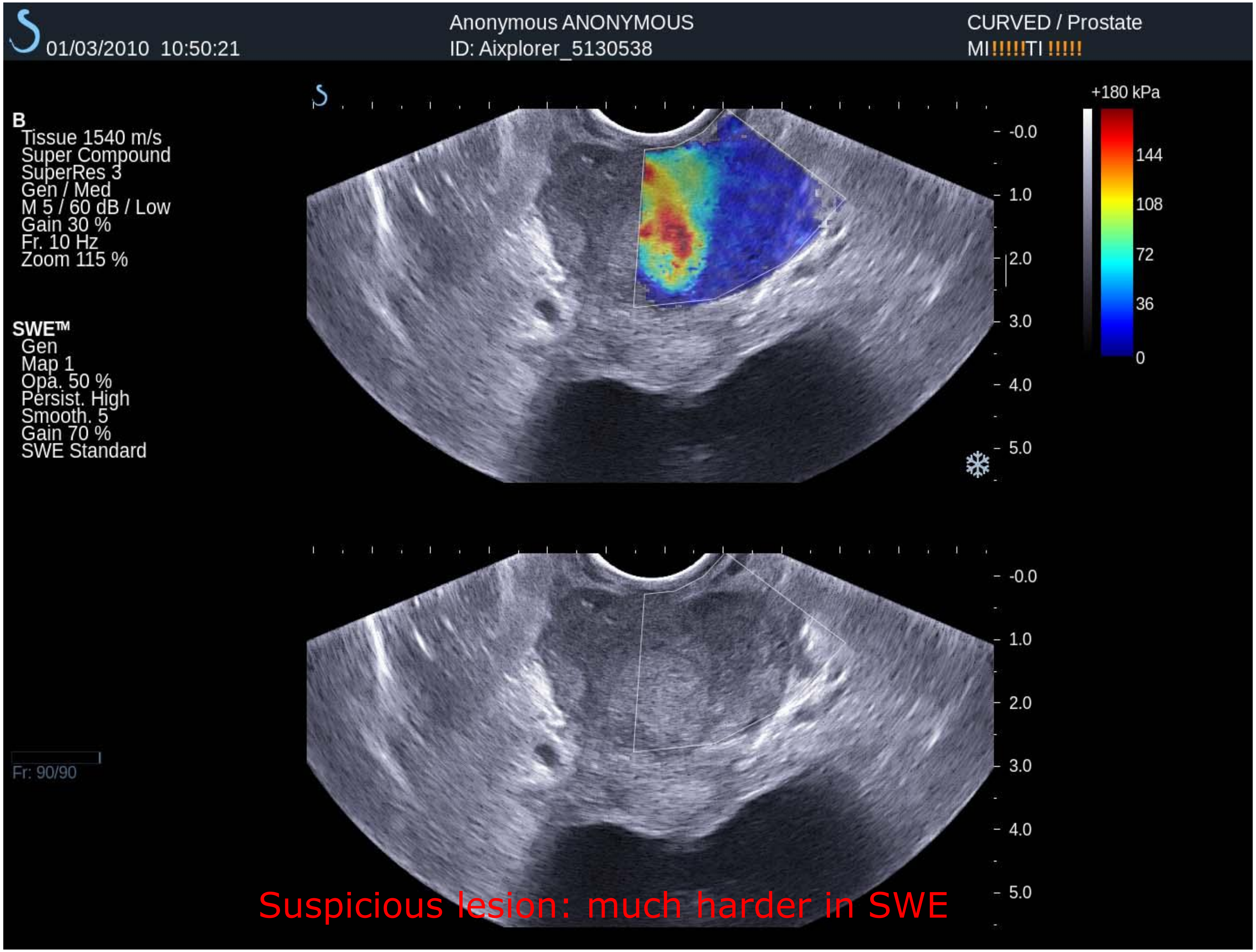
S.W.I.

Fibroscan®

Bavu E., Gennisson J.-L., Couade, M. Bercoff j., Mallet V., Fink M. Vallet-Pichard A., Nalpas B., Tanter M., Pol S. Non-invasive liver fibrosis staging using supersonic shear imaging: A clinical study on 113 HCV patients., under review, 2010.


09/09/2010 09:50:25
SC6-1 / Abdomen
MI 1.3 TI 1.5
B
Tissue 1540 m/s
Super Compound
SuperRes 5
Res / Med / H
M 3 / 64 dB / Med
Gain 59 %
Fr. 7 Hz
Zoom 100 %
SWE™
Fr.Rate
Map 1
Opa. 50 %
Persist. Medium
Smooth. 5
Gain 70 %
SWE Standard
Fr: 130/143
+70 kPa
56
42
28
14
0
2
4
6
8
10
12
14
+ Q-Box™
Mean 10.94 kPa
Min 8.27 kPa
Max 13.22 kPa
Std Dev 1.3
Diam 6.0 mm
× Q-Box™
Mean 91.57 kPa
Min 74.50 kPa
Max 182.34 kPa
Std Dev 20.9
Diam 6.0 mm
Display saturated

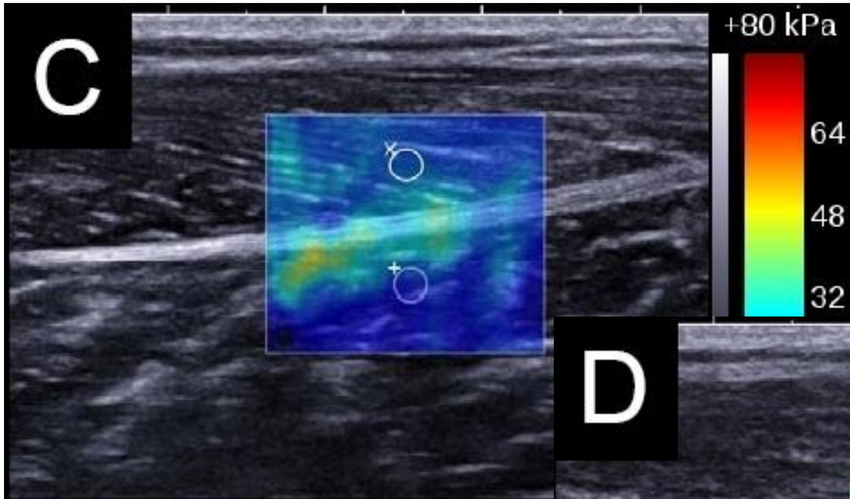
Prostate – multiwave imaging



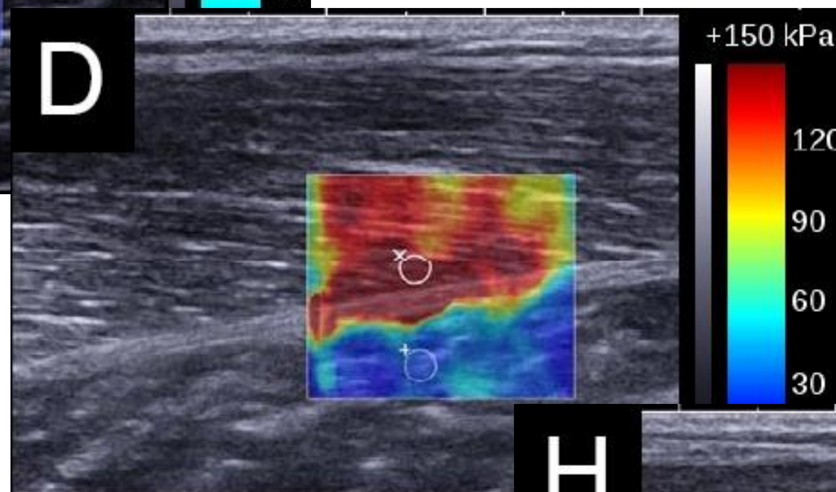
Suspicious lesion: much harder in SWE

Dynamics of Muscle Contraction

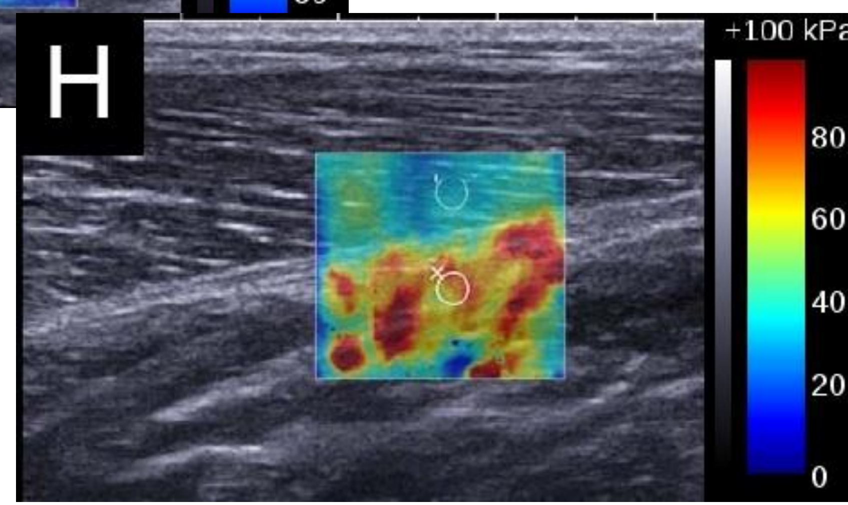
Coll. M. Shinohara, K. sabra,
Georgia Tech. University, Usa



Gastrocnemius
Contraction



Soleus
Contraction

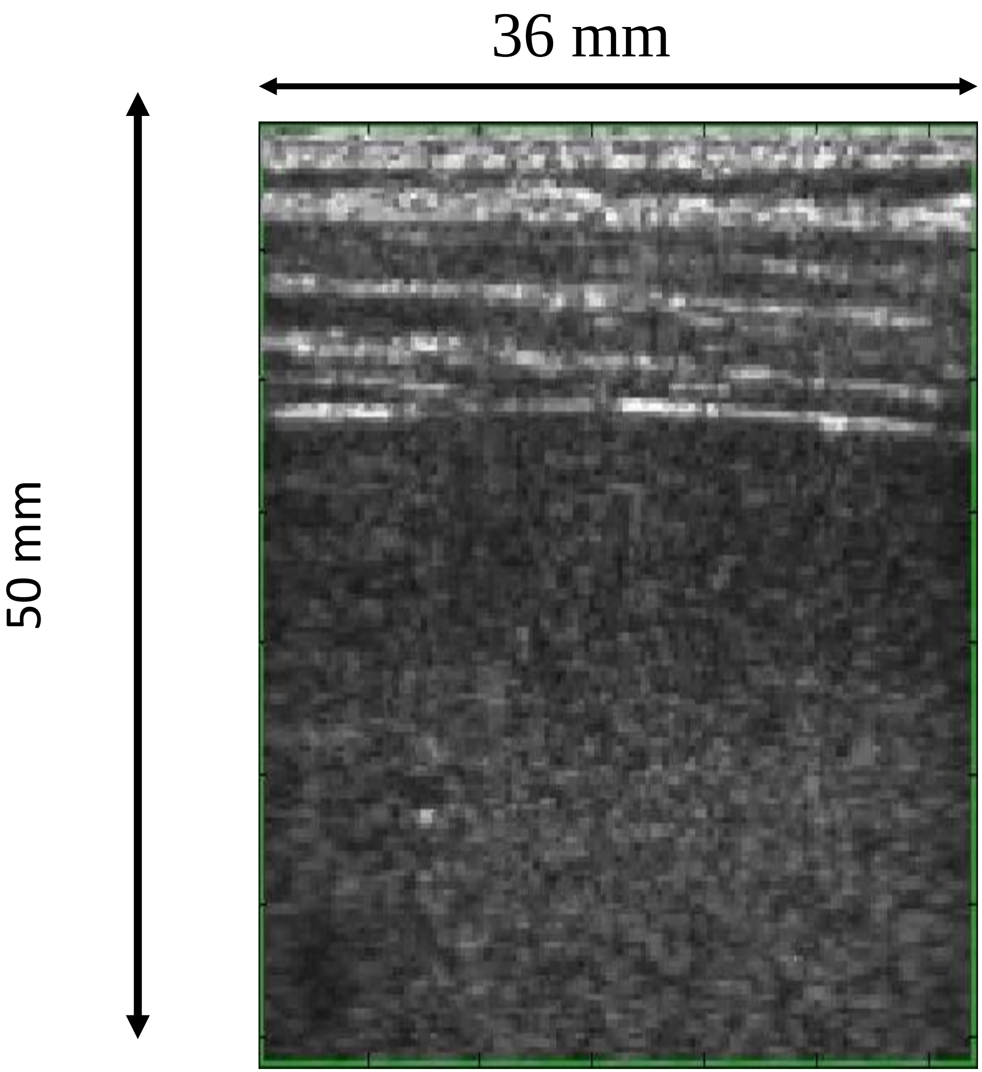


Shinohara S., Sabra K., Genisson J.-L., Fink M., Tanter M.
"Real-time visualization of muscle stiffness distribution with ultrasound SWI during muscle contractions », Muscle and Nerve, June 2010

Shear Wave Dispersion

- Does the shear wave velocity depends of frequency ?
- Does $c_s = \sqrt{\frac{\mu}{\rho}}$ always valid ?
- Origin 1 : viscosity
- Origin 2 : guides wave

SuperSonic Shear Imaging : Liver in vivo



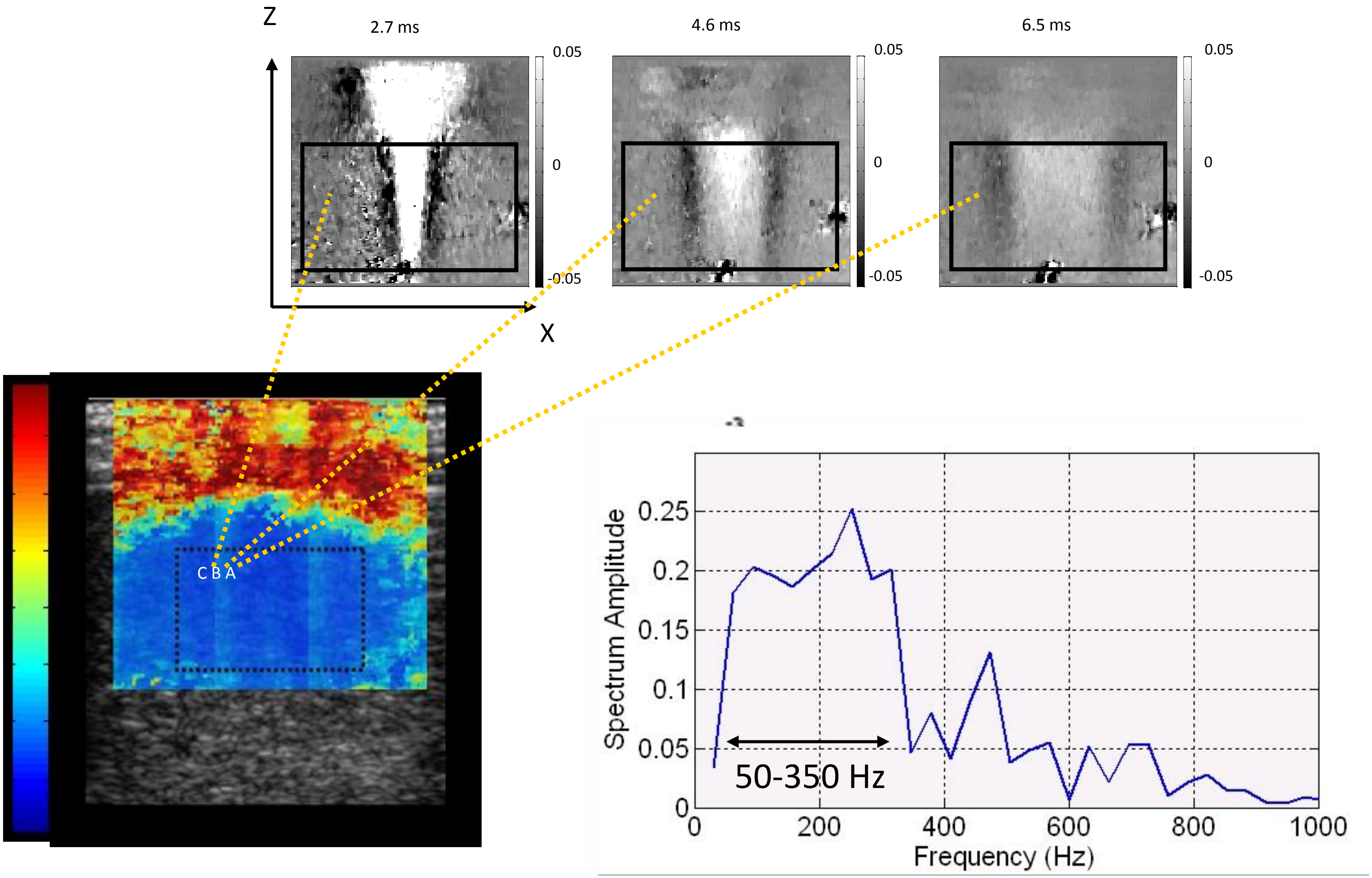
2000 frames per second

26 Years old healthy volunteer

- Intercostal Exam
- Linear Probe L7-4
  4-7 MHZ 128 elts.
- Mechanical Index
  Push 1.4
  Imaging 0.7
- ISPTA Push+ Imaging
  600 $mW.cm^{-2}$
- Less energy deposit than
  Color Doppler !!!

M. Tanter, G. Montaldo, T Deffieux,
JL Gennisson, J Bercoff, M.Fink

Tissue Rheology with Shear wave dispersion

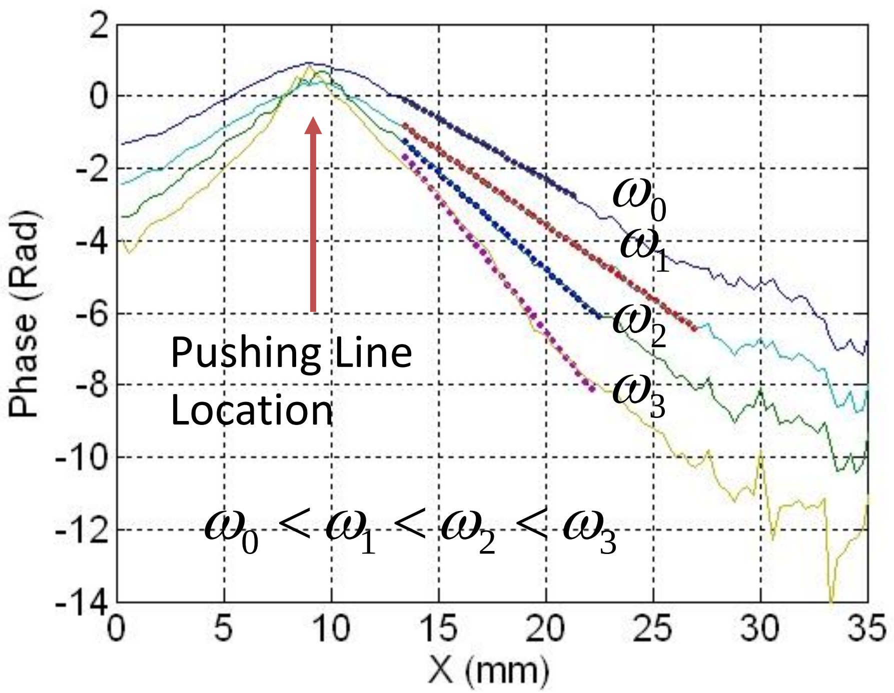


Can we assess viscoelastic properties of tissues using SSI ?

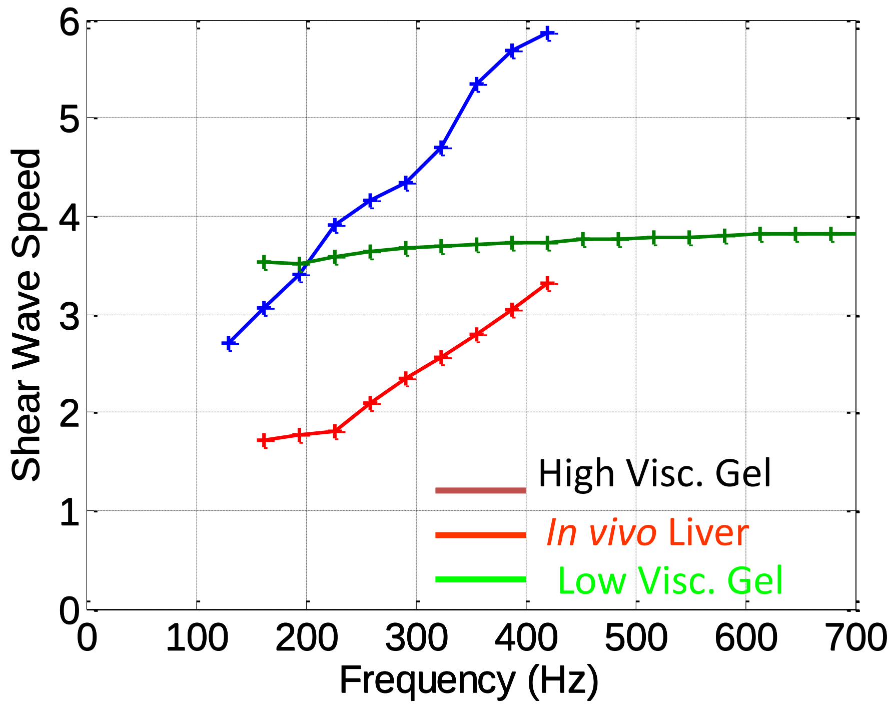
SuperSonic Wave Generation → **Plane Wave Approximation** is valid !!!

$$e^{j(kr-\omega t)} \approx e^{j(kx-\omega t)} \approx e^{-L_a x}.e^{-j\phi(x)}$$

$$\phi(x) = \frac{\omega}{c} x$$

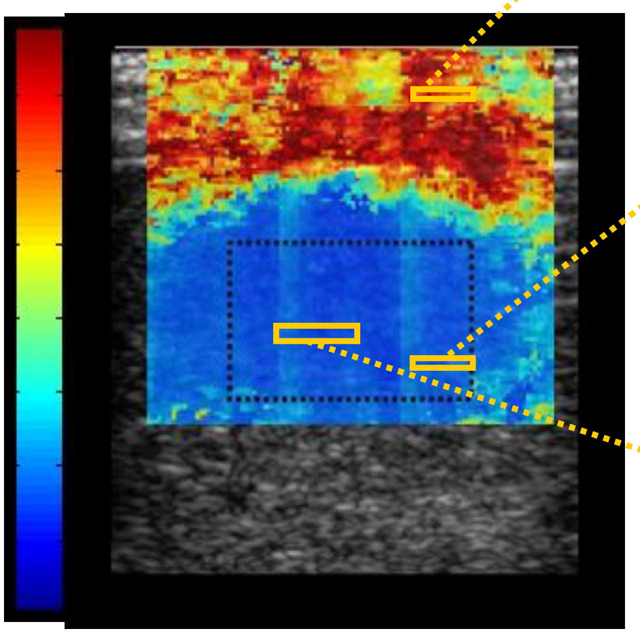


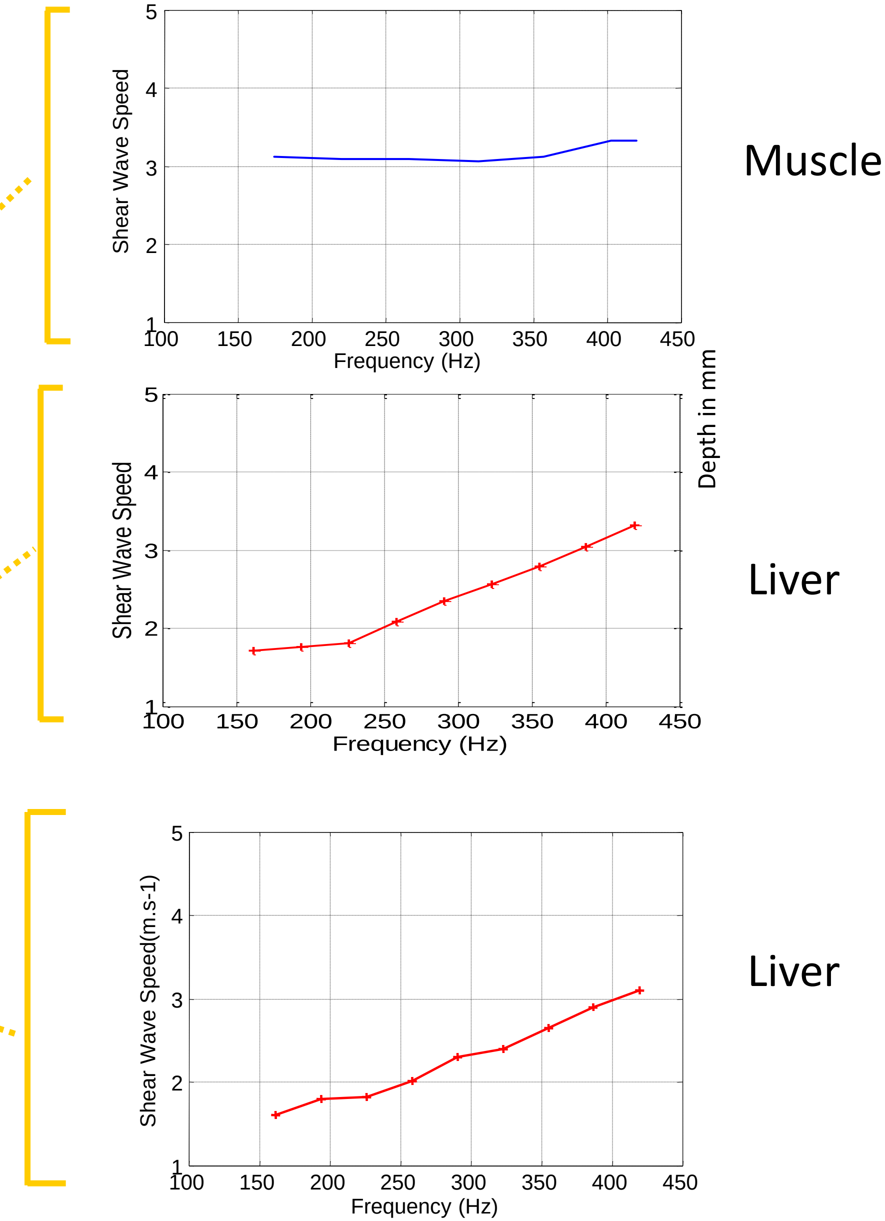
Shear Wave Phase Speed (m.s^{-1})
Versus Frequency



Can we assess viscoelastic properties of tissues using SSI ?

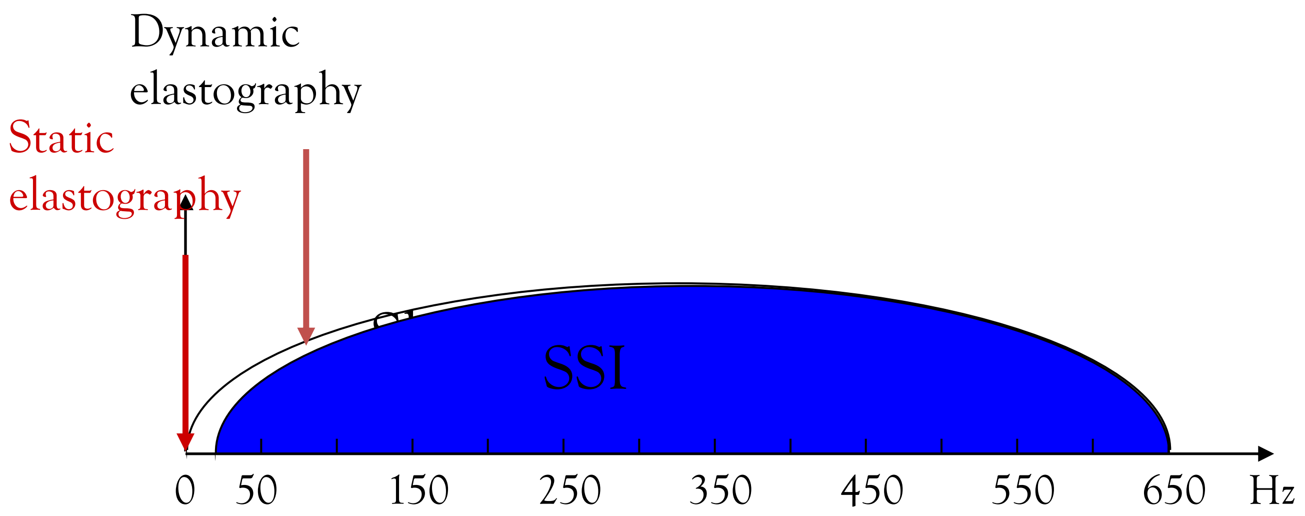
It can even be local !
A concept of real-time
«Shear Wave Spectroscopy »

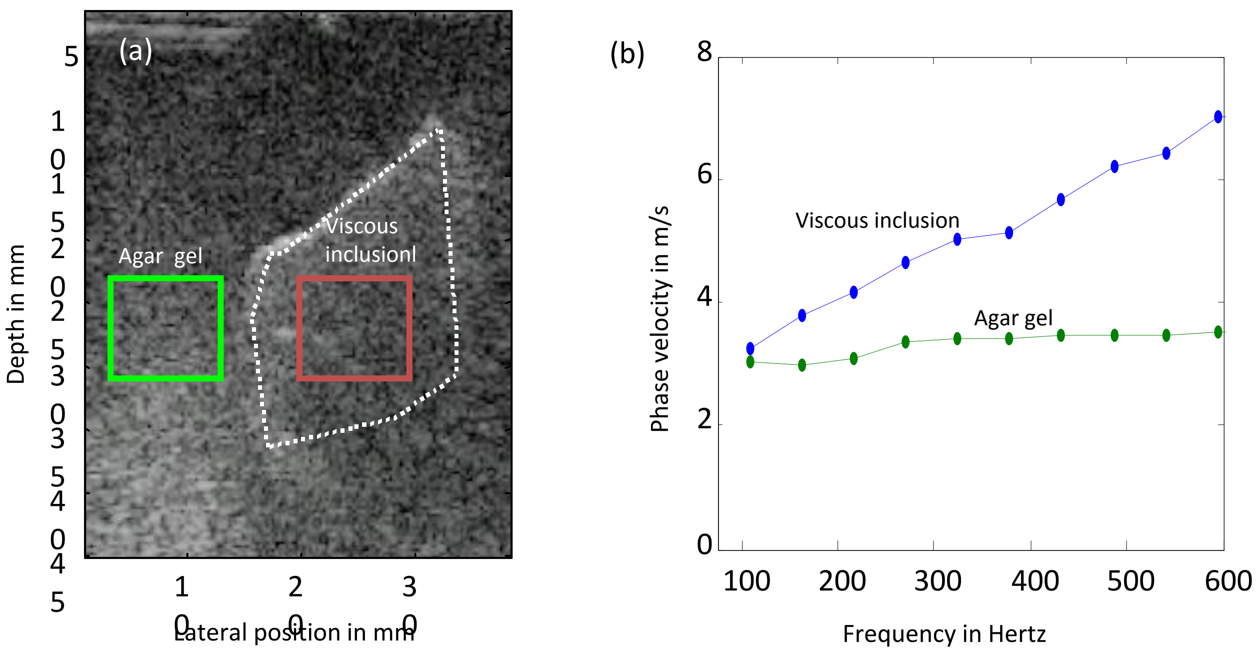




T. Deffieux, M. Tanter, G Montaldo, J. Bercoff. M. Fink

Shear Wave Spectroscopy : a broadband approach



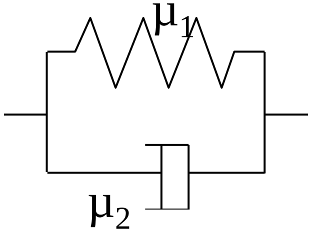


What Viscoelastic model ?

Isotropic, homogenous, linear, viscoelastic

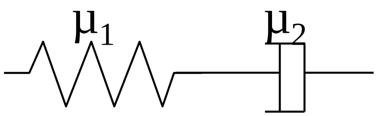
Voigt

(ex: Rubber)



Maxwell

(ex: Polymères)



Constitutive equation

Voigt:

$$\sigma = (\mu - \eta \frac{\partial}{\partial t}.)\varepsilon$$

Maxwell:

$$(\mu + \eta \frac{\partial}{\partial t}.)\sigma = \mu \eta \frac{\partial \varepsilon}{\partial t}$$

1D Helmoltz equation

Voigt:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\rho \omega^2}{(\mu + i\omega\eta)} U = 0$$

Maxwell:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\rho \omega^2 (\mu + i\omega\eta)}{i\omega\mu\eta} U = 0$$

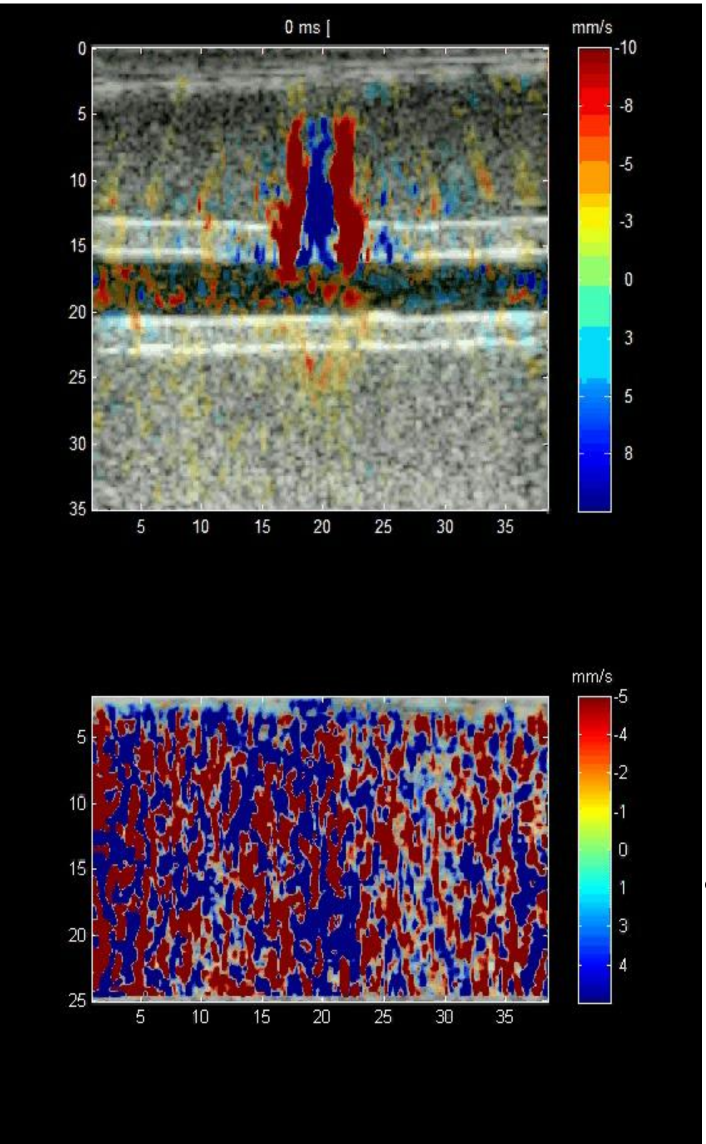
Voigt:

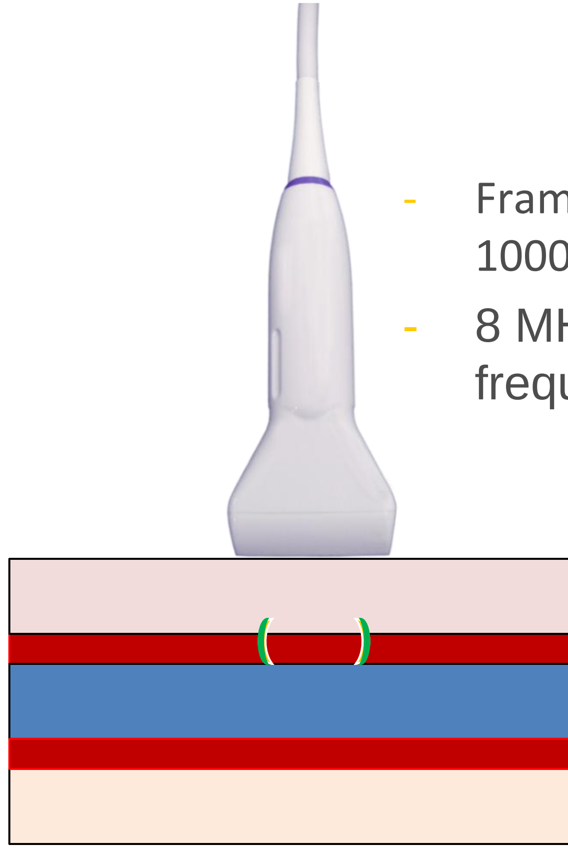
$$\begin{cases} C_T = \sqrt{\dfrac{2(\mu^2 + \omega^2\eta^2)}{\rho(\mu + \sqrt{\mu^2 + \omega^2\eta^2})}} \\ \alpha_T = \sqrt{\dfrac{\rho\omega^2(\sqrt{\mu^2 + \omega^2\eta^2} - \mu)}{2(\mu^2 + \omega^2\eta^2)}} \end{cases}$$

Maxwell:

$$\begin{cases} C_T = \sqrt{\dfrac{2\mu}{\rho(1 + \sqrt{1 + \dfrac{\mu^2}{\omega^2\eta^2}})}} \\ \alpha_T = \sqrt{\dfrac{\rho\omega^2(\sqrt{1 + \dfrac{\mu^2}{\omega^2\eta^2}} - 1)}{2\mu}} \end{cases}$$

Wave Dispersion on arterial phantoms (agar-agar, gelatin)



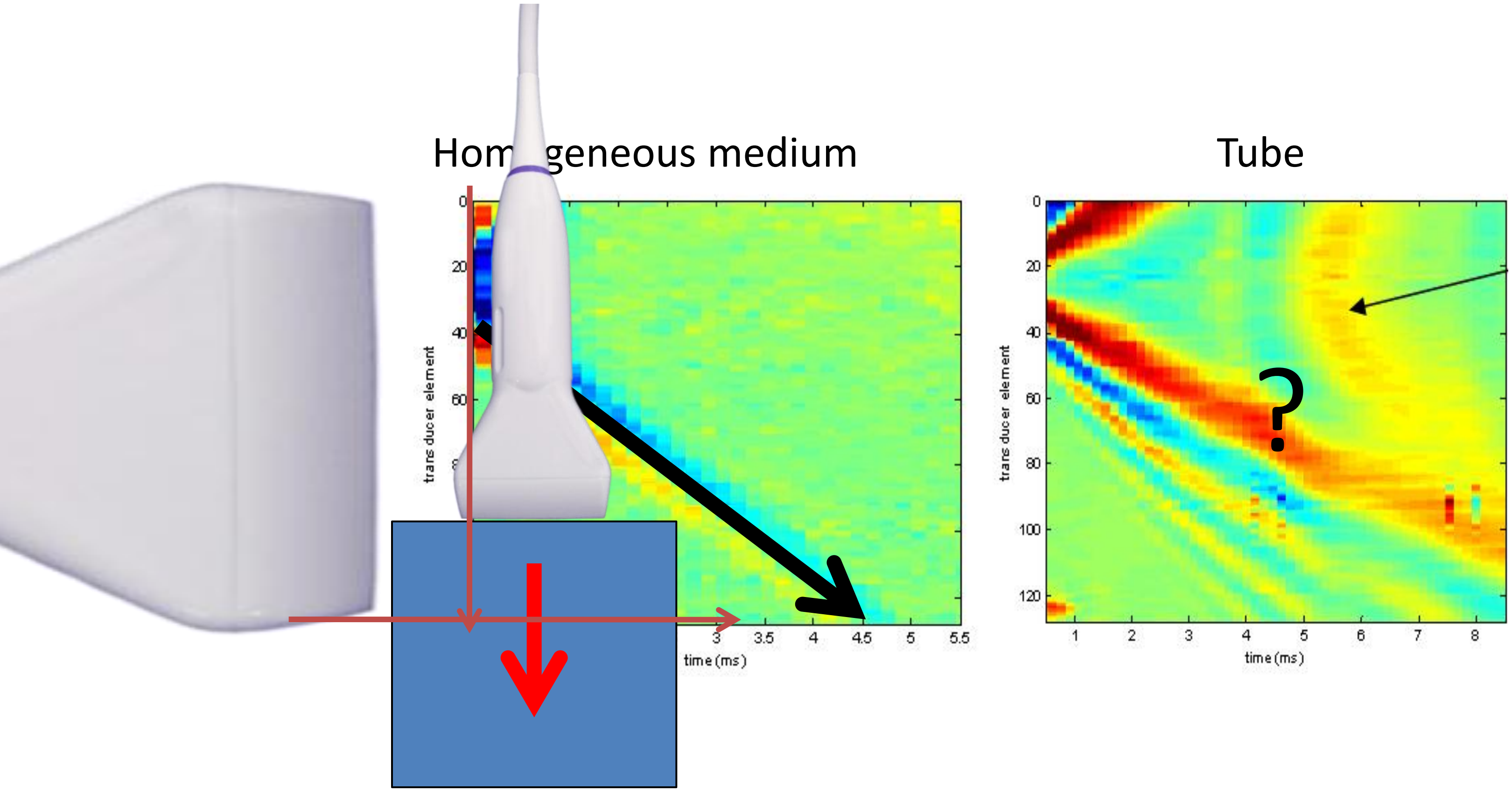


- Frame rate ~ 5000 to 10000 Hz
- 8 MHz central frequency

$$c = \sqrt{\frac{\mu}{\rho}}$$

- Wave velocity is strongly reduced when shear wave is generated in a thin layer : guided propagation

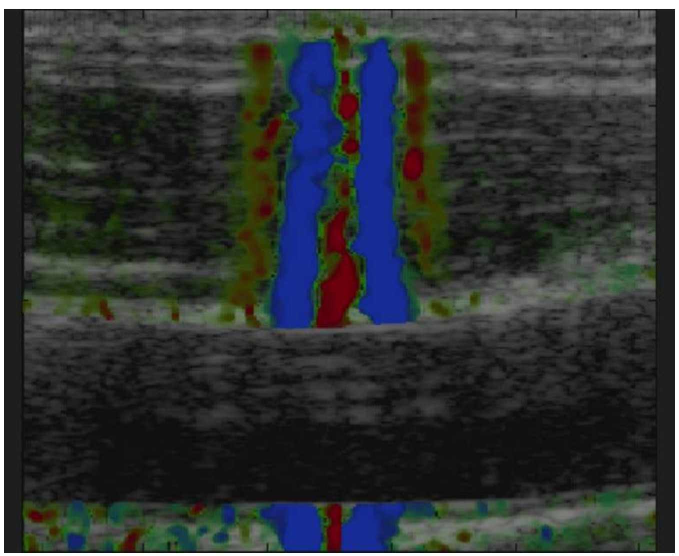
Guided shear wave along a tube

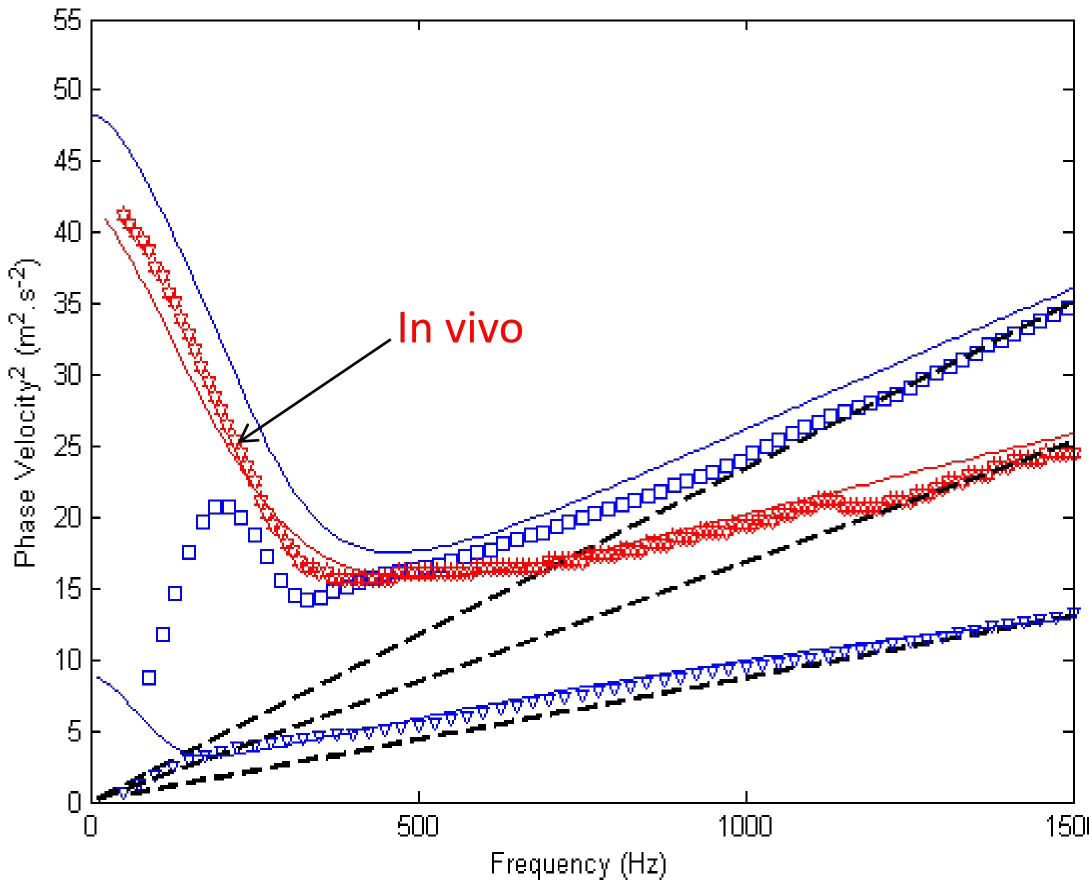


- Guided shear wave is dispersive : phase velocity is a function of the frequency

In vivo application

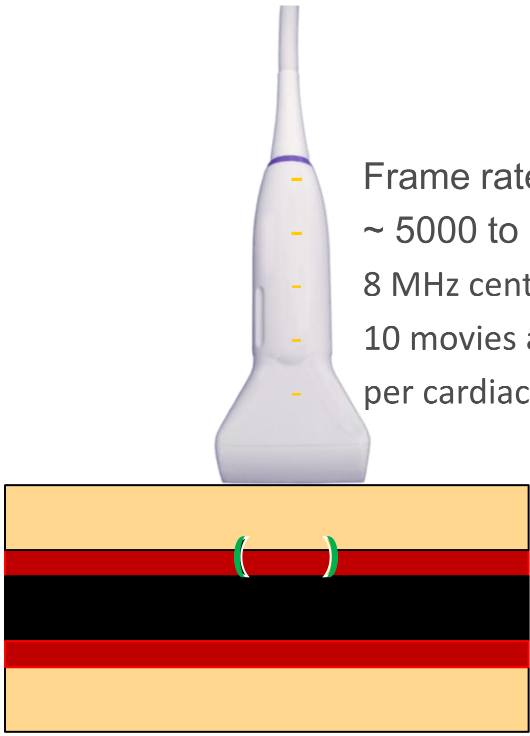
- In vivo experiment on healthy volonteers
- Dispersion curves behavior is similar to phantom
- Measured shear modulus : $\boldsymbol{\mu}$~ 90 kPa



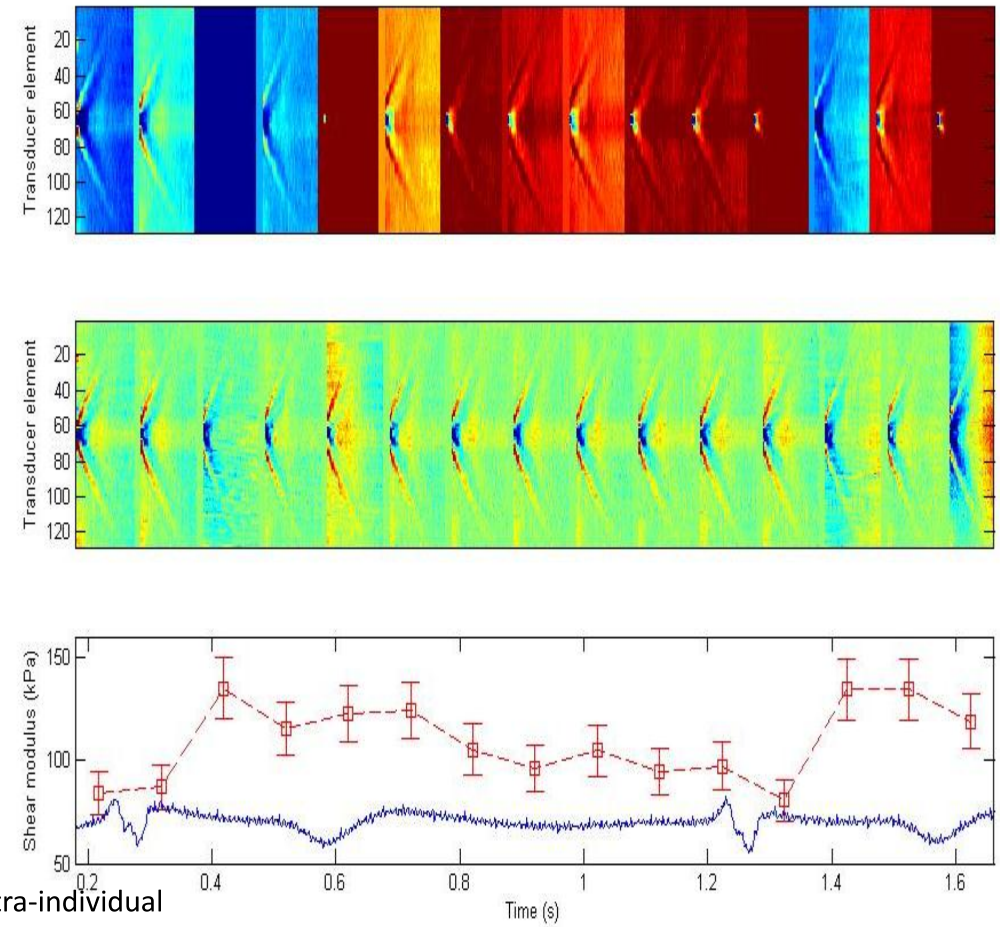


Real Time Elasticity of the carotid during one single cardiac cycle

Generating a « pushing beam » at the surface of the arterial wall
enables the precise estimation of local visco-elastic properties of arterial wall



Frame rate
~ 5000 to 10000 Hz
8 MHz central freq.
10 movies acquired
per cardiac cycle

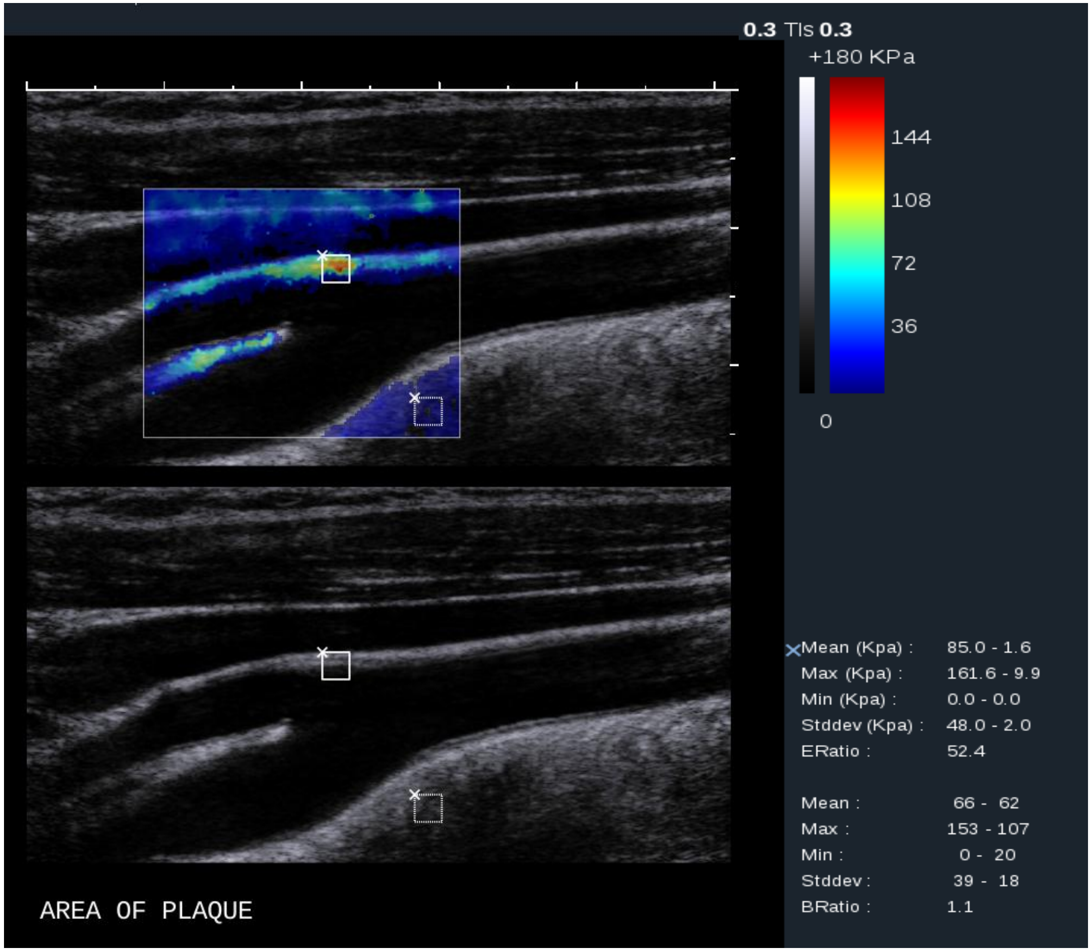


Athérosclérosis, fibrodysplasia, myocardial fibrosis…

N=70 Healthy Volunteers	Mean	Intra-individual Reproducibility (s.d)	Intra-individual Reproducibility (relative error)
local PWV (m/s)	5,45	0,68	**12%**
Shear wave velocity (m/s) @ 900 Hz	5,68	0,2	**4%**

Arterial stiffness estimation

Propagation of shear wave (Lamb wave) in the arterial wall



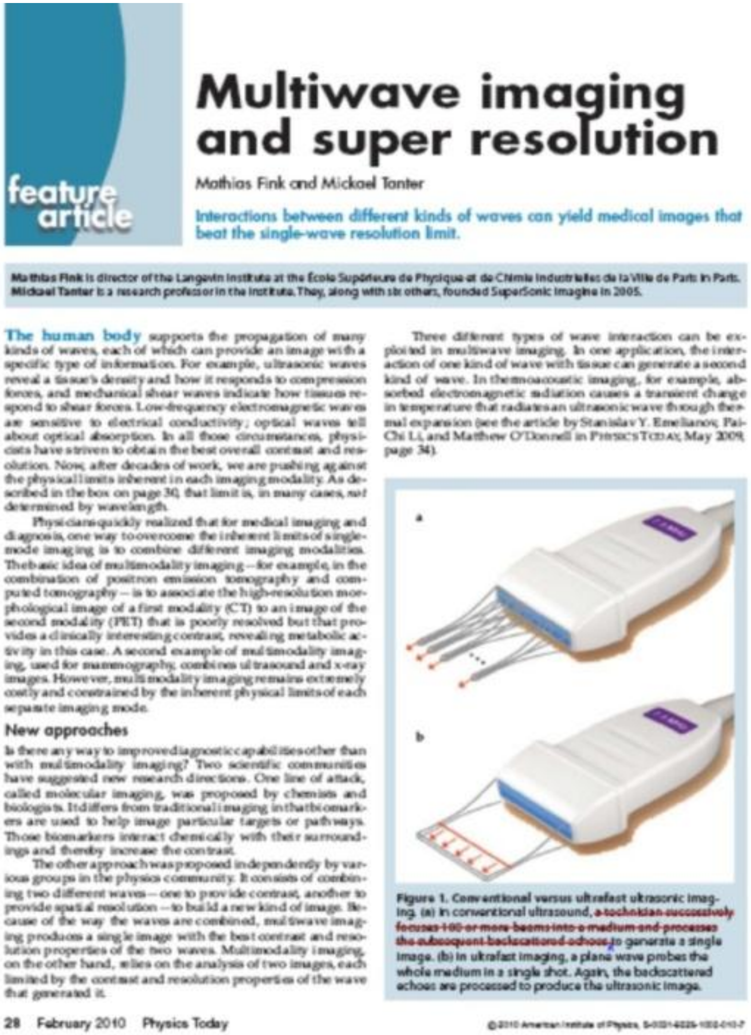
Exemple of a hard plaque

MultiWave Imaging

One wave gives the contrast.
The other wave gives the spatial resolution.

- Ultrasound based Shear Wave imaging
- MRI based Shear Wave imaging
- Shear Wave AcoustoOptics
- AcoustoOptics
- PhotoAcoustics
- Electric Impedance / Ultrasound Imaging
- Current Density / Ultrasound Imaging
- US Imaging of mechanical contraction

  due to Action potentials
- MR Imaging of Ultrasonic Radiation force
- Transient Shear Waves / OCT
- …



feature article

Multiwave imaging and super resolution

Mathias Fink and Mickael Tanter

Interactions between different kinds of waves can yield medical images that beat the single-wave resolution limit.

Mathias Fink is director of the Langevin Institute at the École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris in Paris. Mickael Tanter is a research professor in the Institute. They, along with six others, founded SuperSonic Imagine in 2005.

The human body supports the propagation of many kinds of waves, each of which can provide an image with a specific type of information. For example, ultrasonic waves reveal a tissue's density and how it responds to compression forces, and mechanical shear waves indicate how tissues respond to shear forces. Low-frequency electromagnetic waves are sensitive to electrical conductivity; optical waves tell about optical absorption. In all those circumstances, physicists have striven to obtain the best overall contrast and resolution. Now, after decades of work, we are pushing against the physical limits inherent in each imaging modality. As described in the box on page 30, that limit is, in many cases, not determined by wavelength.

Physicians quickly realized that for medical imaging and diagnosis, one way to overcome the inherent limits of single-mode imaging is to combine different imaging modalities. The basic idea of multimodality imaging—for example, in the combination of positron emission tomography and computed tomography—is to associate the high-resolution morphological image of a first modality (CT) to an image of the second modality (PET) that is poorly resolved but that provides a clinically interesting contrast, revealing metabolic activity in this case. A second example of multimodality imaging, used for mammography, combines ultrasound and x-ray images. However, multimodality imaging remains extremely costly and constrained by the inherent physical limits of each separate imaging mode.

New approaches

Is there any way to improve diagnostic capabilities other than with multimodality imaging? Two scientific communities have suggested new research directions. One line of attack, called molecular imaging, was proposed by chemists and biologists. It differs from traditional imaging in that biomarkers are used to help image particular targets or pathways. Those biomarkers interact chemically with their surroundings and thereby increase the contrast.

The other approach was proposed independently by various groups in the physics community. It consists of combining two different waves—one to provide contrast, another to provide spatial resolution—to build a new kind of image. Because of the way the waves are combined, multiwave imaging produces a single image with the best contrast and resolution properties of the two waves. Multimodality imaging, on the other hand, relies on the analysis of two images, each limited by the contrast and resolution properties of the wave that generated it.

Three different types of wave interaction can be exploited in multiwave imaging. In one application, the interaction of one kind of wave with tissue can generate a second kind of wave. In thermoacoustic imaging, for example, absorbed electromagnetic radiation causes a transient change in temperature that radiates an ultrasonic wave through thermal expansion (see the article by Stanislav Y. Emelianov, Pai-Chi Li, and Matthew O'Donnell in PHYSICS TODAY, May 2009, page 34).

Figure 1. Conventional versus ultrafast ultrasonic imaging. (a) In conventional ultrasound, ~~a technician successively focuses 100 or more beams into a medium and processes the subsequent backscattered echoes~~ to generate a single image. (b) In ultrafast imaging, a plane wave probes the whole medium in a single shot. Again, the backscattered echoes are processed to produce the ultrasonic image.

28 February 2010 Physics Today