Acoustic (not only Ultrasonic) Medical Imaging

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Soft Tissues : an example of Soft Material

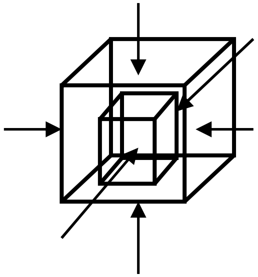
Isotropic assumption

Definition : **K >> μ**

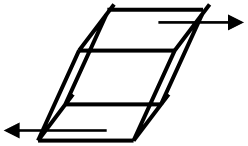
K constant, of the order of **10^9 Pa,** quasi incompressible

μ varies strongly with tissue pathology, between **10^2 to 10^7 Pa**

K



μ



K, μ

λ, μ

E, υ

$$E = \mu \frac{3\lambda + 2\mu}{\lambda + \mu} \approx 3\mu$$

$$K = \frac{3\lambda + 2\mu}{3} \approx \lambda$$

$$\upsilon = \frac{\lambda}{2(\lambda + \mu)} \approx \frac{1}{2}$$

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

$$\vec{u} = \nabla \wedge \vec{\Psi} - \vec{\nabla} \varphi$$

Elastic wave propagation in soft tissues

2 types of bulk elastic waves can propagate through tissues

- The compressional wave velocity V_l is nearly uniform in soft tissues (~1500 m/s with less than 5% fluctuations) observed at sonic and ultrasonic frequencies; at 5Mhz, wavelength = 0.3mm

- The shear wave velocity V_s (observed only at sonic frequencies < 5000 Hz) varies strongly in soft tissues from 1 to 40 m/s *(Sarvazian)*

  at 200 Hz, very large wavelength = 2cm

$$v_l = \sqrt{\frac{\lambda + 2\mu}{\rho}} \approx \sqrt{\frac{\lambda}{\rho}}$$

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

Shear modulus

Medical Ultrasound Imaging

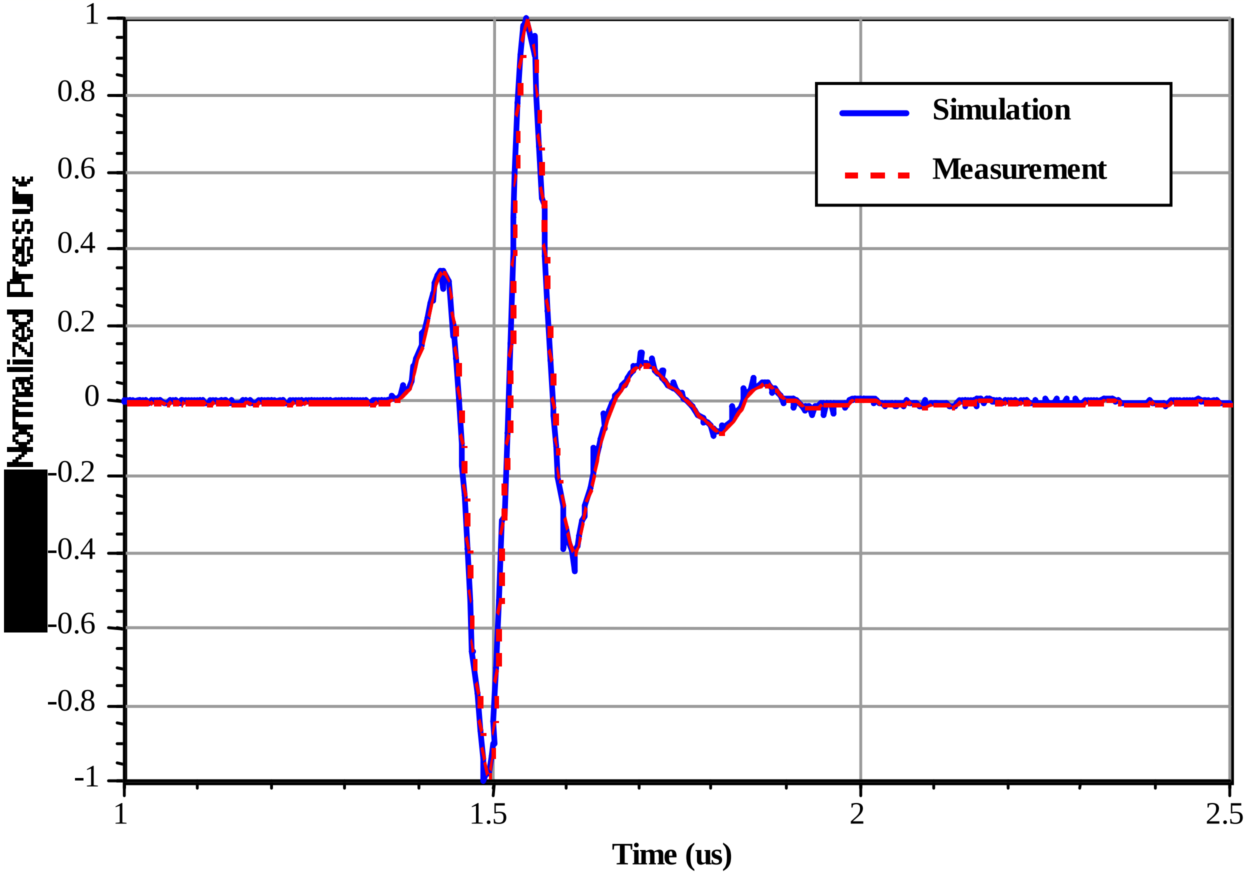
- At medical frequencies (3 to 50 MHz), only compressional waves
- Compressional modulus nearly uniform ~10^9 Pa
- Sound velocity around 1500 m/s at +-5 %.
- Weakly inhomogeneous medium : single scattering process – strong speckle noise .
- Typical wavelength : at 5 MHz, λ = 0.3 mm

How to transmit and receive ultrasound ?

- Piezoelectric reversible transducer array
- 1D array with 128 to 512 transducteurs (1.5 D and 2D), sampling pitch $\lambda/2$
- Large bandwidth transducer (100 % bandwidth at -6 dB).
- Transmission of very short pulses.
- Very good axial resolution.
- Electronic focusing to improve lateral resolution.
- Beam-forming in transmit- receive mode
- Acoustic lens synthesis

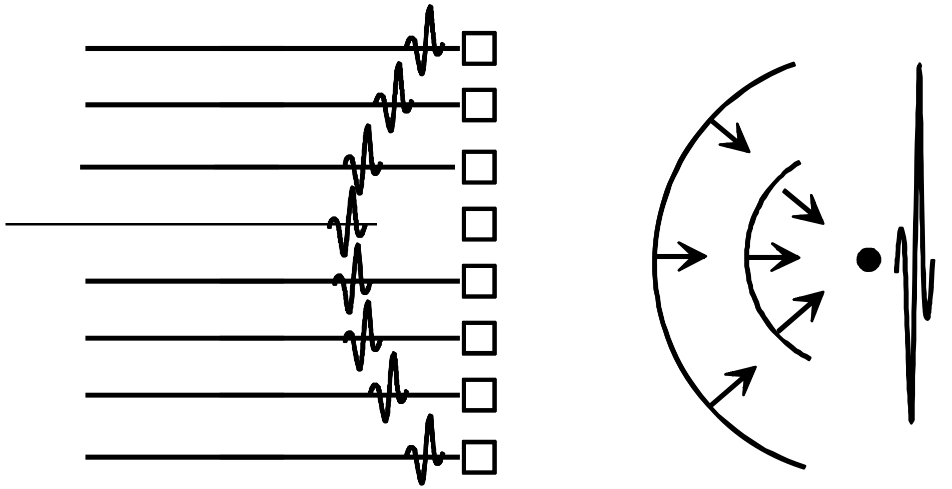
Linear transducer array

Typical waveform transmit by a transducer



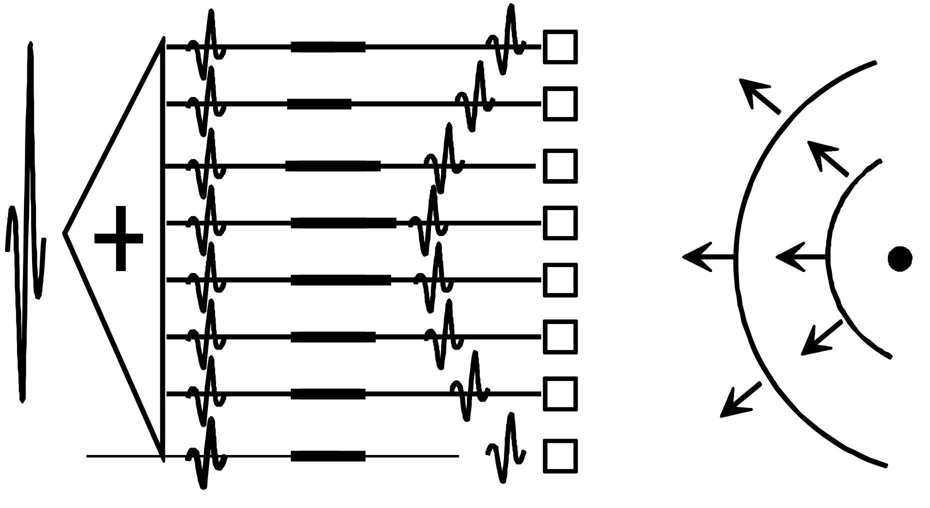
Beamforming in transmit/receive mode

Transmit focusing

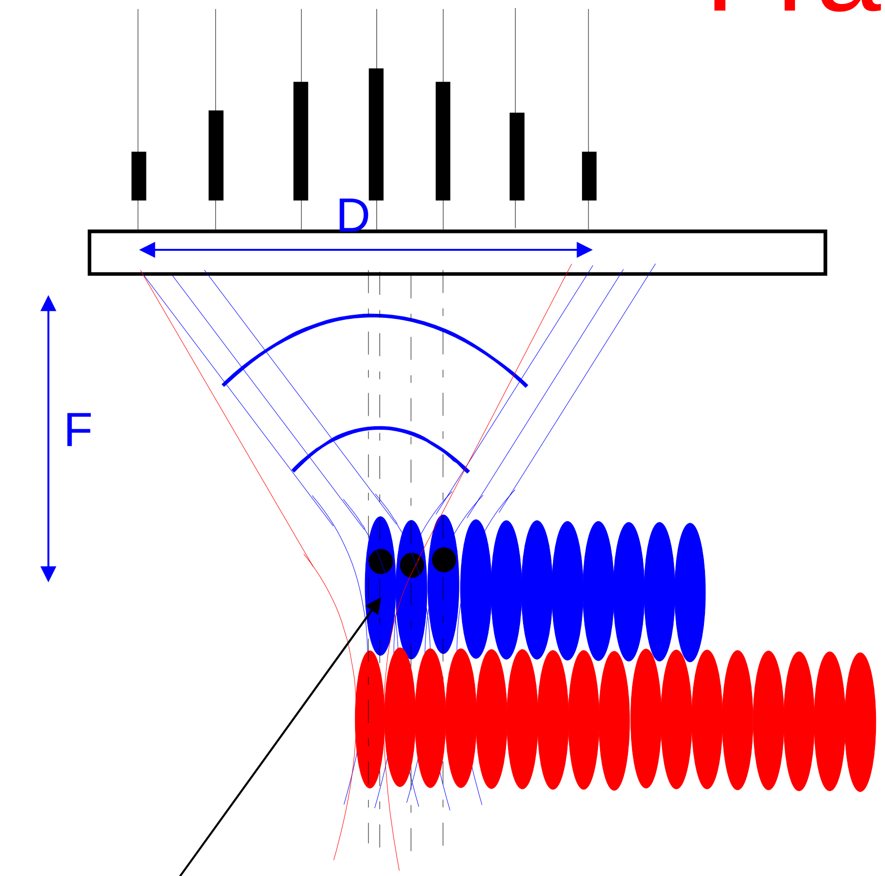


Homogeneous medium : c constant

Receive focusing



Frame Rate



$$\Delta x = \frac{\lambda F}{D} \qquad \Delta z = 7\lambda\left(\frac{F}{D}\right)^2$$

:

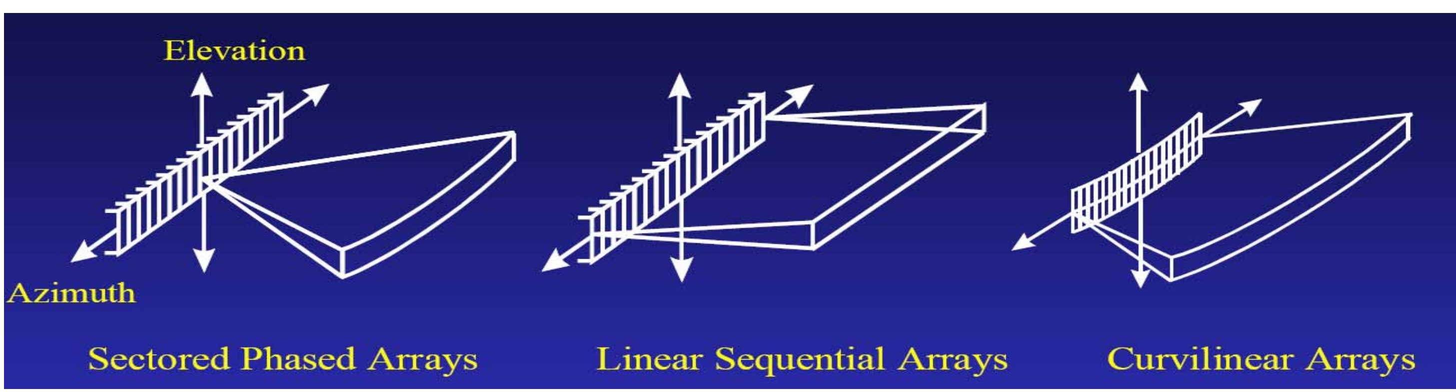
128 shots x 5 focal lengths = 640 transmited beams

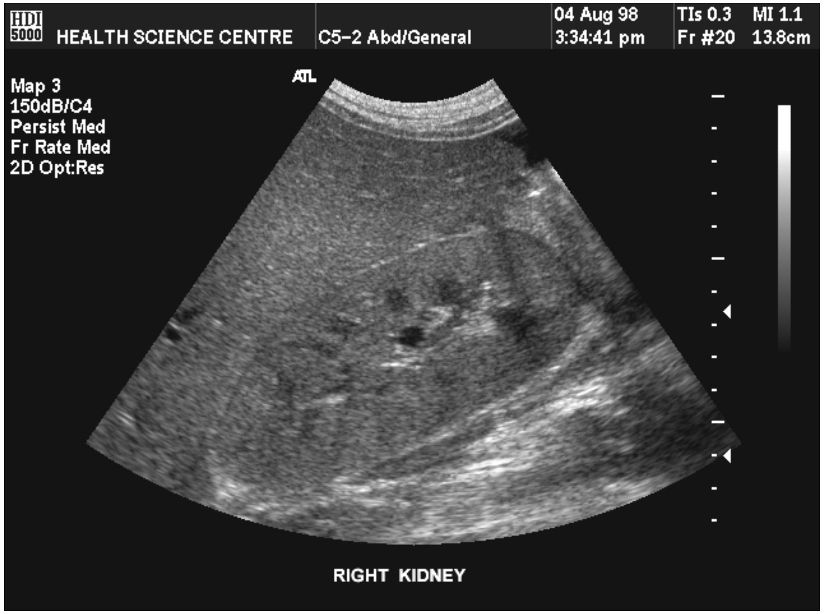
Back and fort time :

60 µs for 5 cm

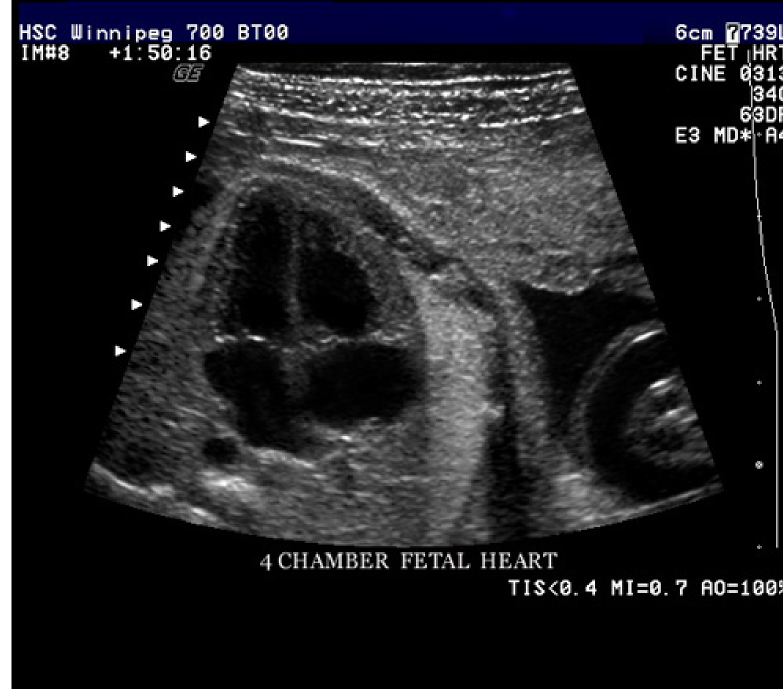
Frame rate :

25 to 50 frames / second

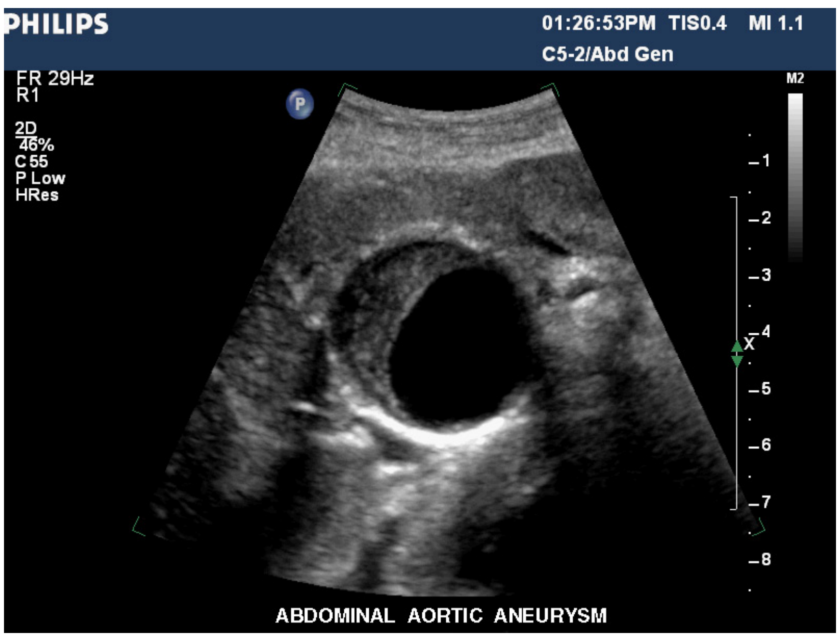




RIGHT KIDNEY



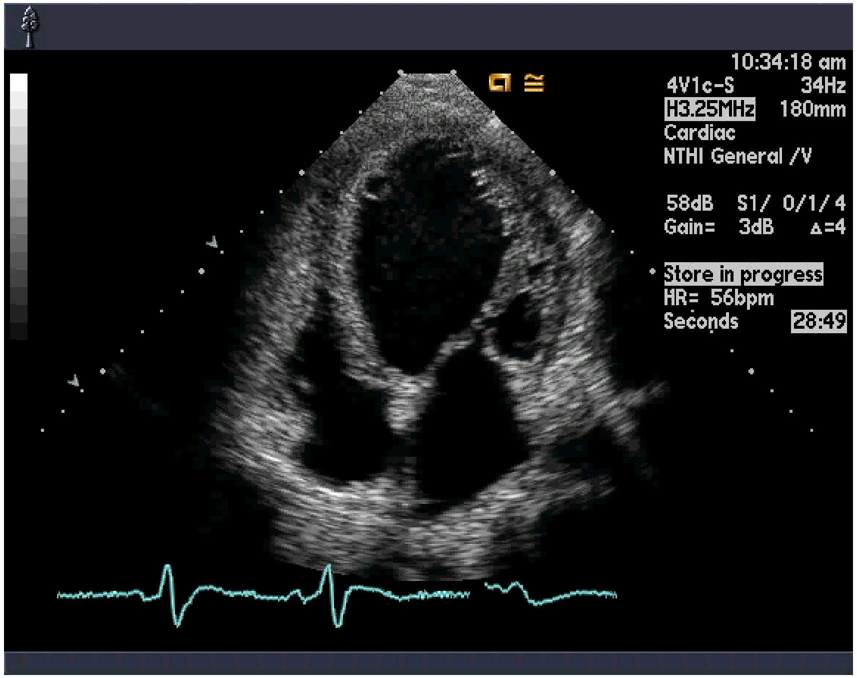
4 CHAMBER FETAL HEART

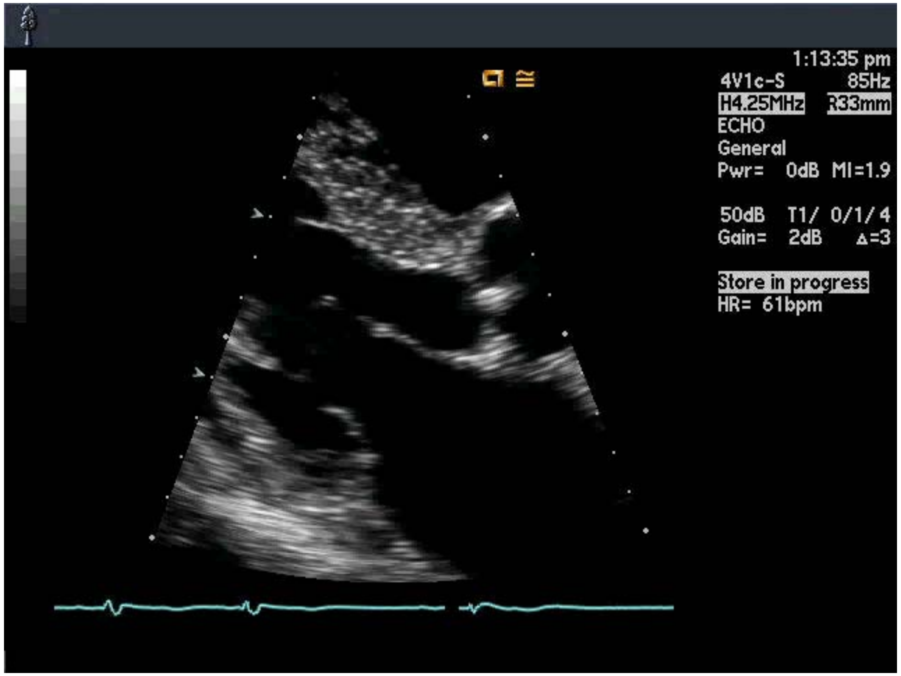


ABDOMINAL AORTIC ANEURYSM

17 - WEEK FETAL PROFILE

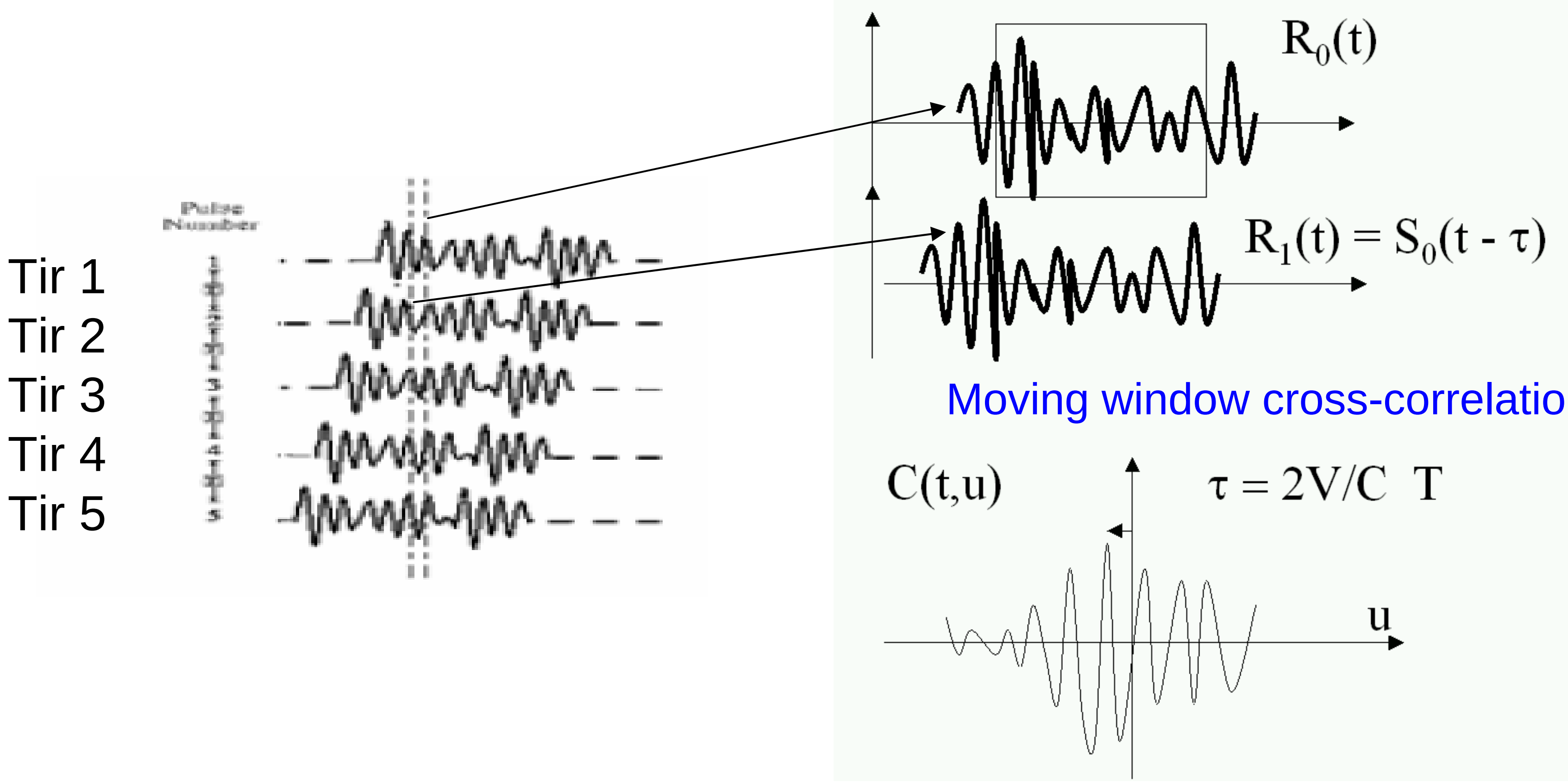
Cardiac Imaging



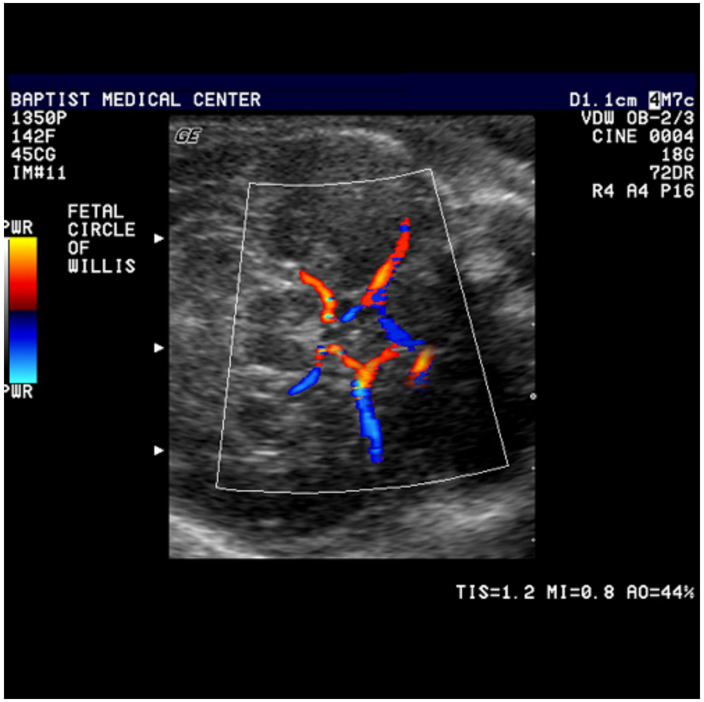


Flow imaging by cross-correlation techniques

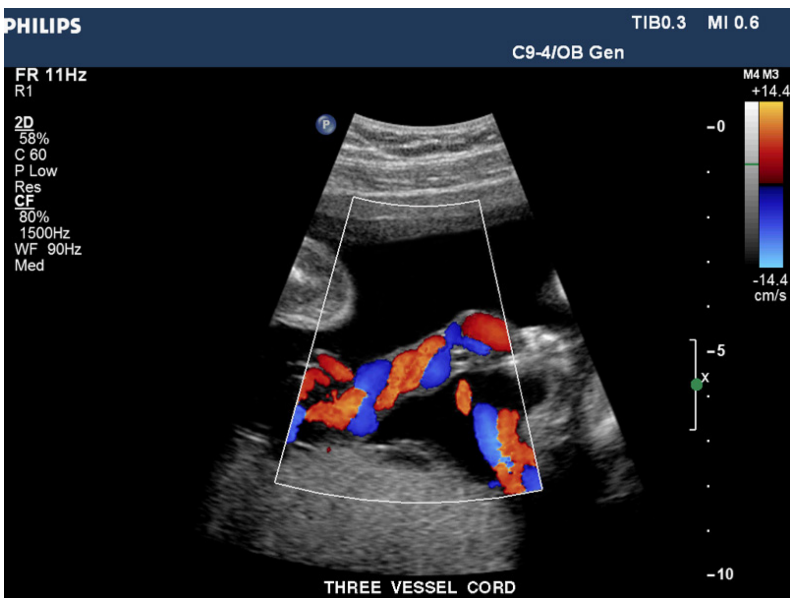
Red cells behave as random distributions of scatterers.
One repeat ultrasonic shots at high rate (less than 1 ms)

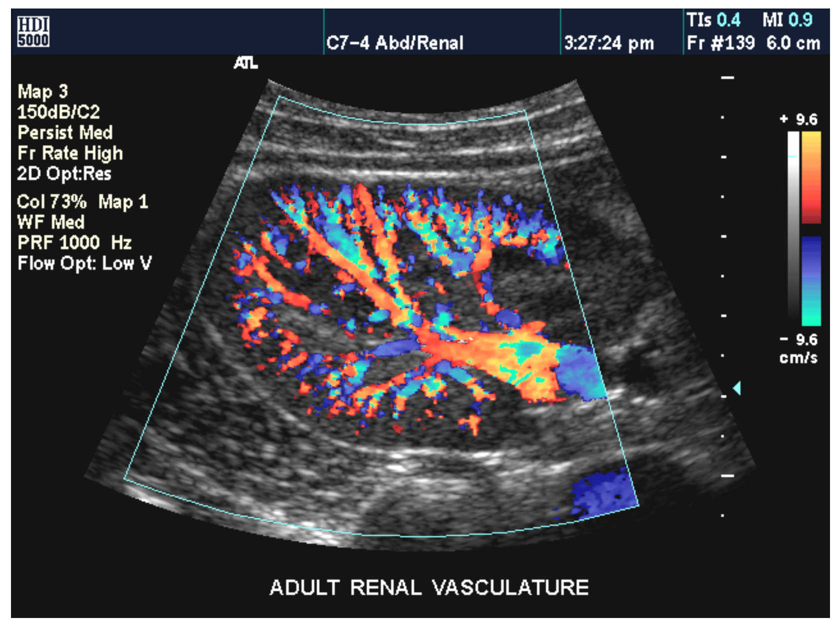


It is possible to measure between 2 shots (for example every ms)
displacements between 1 and 100 μ (particular velocity between 1 mm/s et 10 cm/s)


BAPTIST MEDICAL CENTER
1350P
142F
45CG
IM#11
D1.1cm 4M7c
VDW OB-2/3
CINE 0004
18G
72DR
R4 A4 P16
PWR
FETAL
CIRCLE
OF
WILLIS
PWR
TIS=1.2 MI=0.8 AO=44%

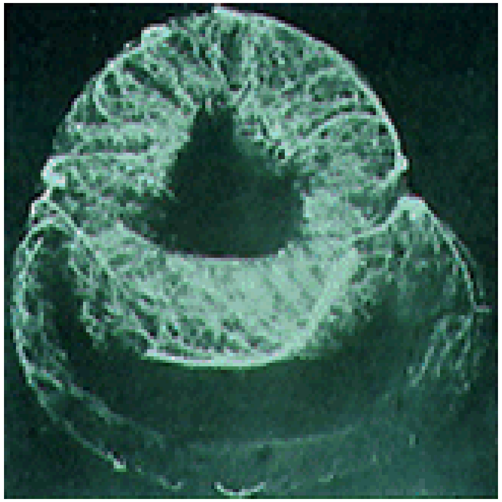

HEALTH SCIENCE CENTRE
2:52:30 pm
TIs 0.2
MI 0.8
14 Hz
4.2 cm
Map 2
Persist Low
Fr Rate High
2D Opt:Gen
WF Low
PRF 2500 Hz
Flow Opt: Low V
cm/s


PHILIPS
TIB0.3
MI 0.6
C9-4/OB Gen
FR 11Hz
R1
2D
58%
C 60
P Low
Res
CF
80%
1500Hz
WF 90Hz
Med
M4 M3
+14.4
-14.4
cm/s
-0
-5
-10
THREE VESSEL CORD

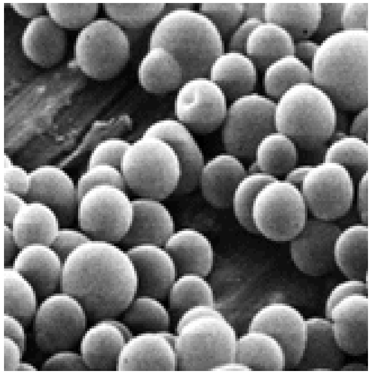

HDI 5000
C7-4 Abd/Renal
3:27:24 pm
TIs 0.4
MI 0.9
Fr #139
6.0 cm
ATL
Map 3
150dB/C2
Persist Med
Fr Rate High
2D Opt:Res
Col 73% Map 1
WF Med
PRF 1000 Hz
Flow Opt: Low V
+ 9.6
- 9.6
cm/s
ADULT RENAL VASCULATURE

Ultrasound contrast agents

- Tiny microbubbles sized to pass through the smallest capillaries

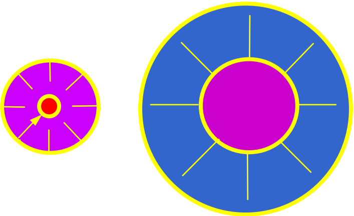


- **Designed to increase the strength of echoes**

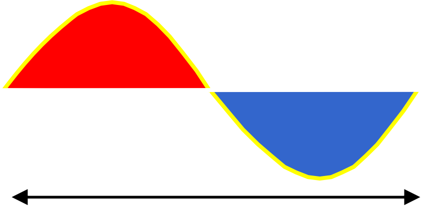


The bubble : a non linear oscillator

Easy dilation but diiificult to compress



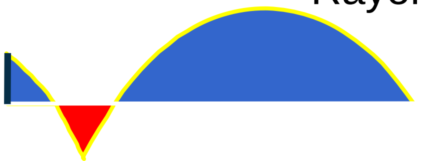
A sinusoidal acoustic pressure field :

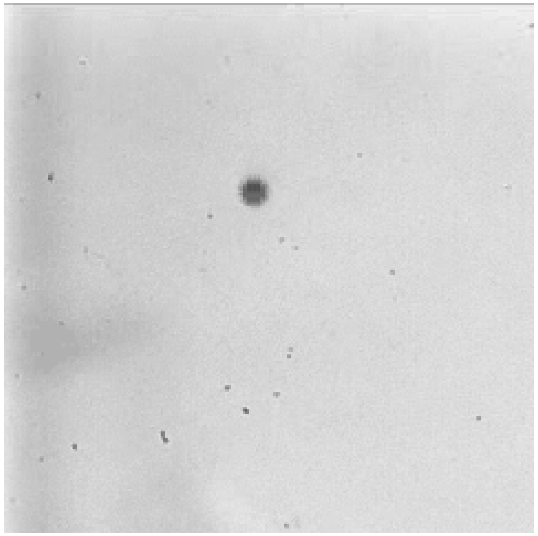


0.1 - 1 µsec

The radius of the bubble oscilates in a non linear way. Therefore the bubble behaves like a source of harmonic waves.

Rayon de la bulle





Destruction controlée

Harmonic generation

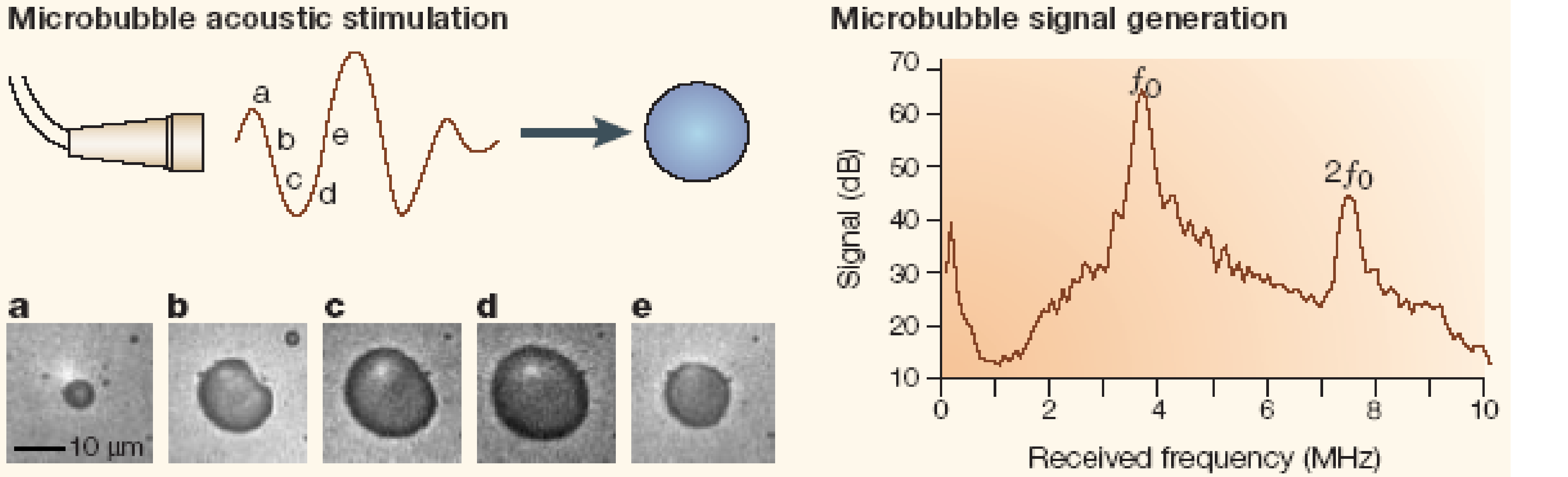


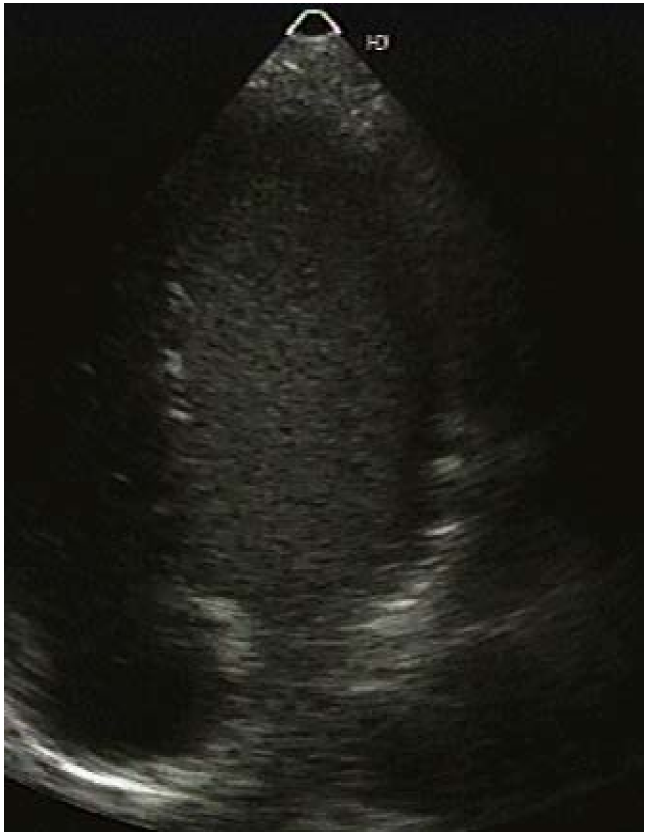
Figure 1 | **Schematic illustration of the acoustic properties of microbubbles.** The microscopy images obtained 330 ns apart demonstrate volumetric oscillation of a microbubble during exposure to ultrasound (500 KHz) that occurs during high- and low-pressure phases. Microbubble images were at a constant magnification and are courtesy of M. Postema, and N. de Jong, Erasmus University. Frequency versus amplitude data (revised, courtesy of P. Burns, University of Toronto) from microbubbles demonstrating returning signal both at the fundamental (f_0) and second harmonic ($2f_0$) frequencies.

Harmonic Imaging

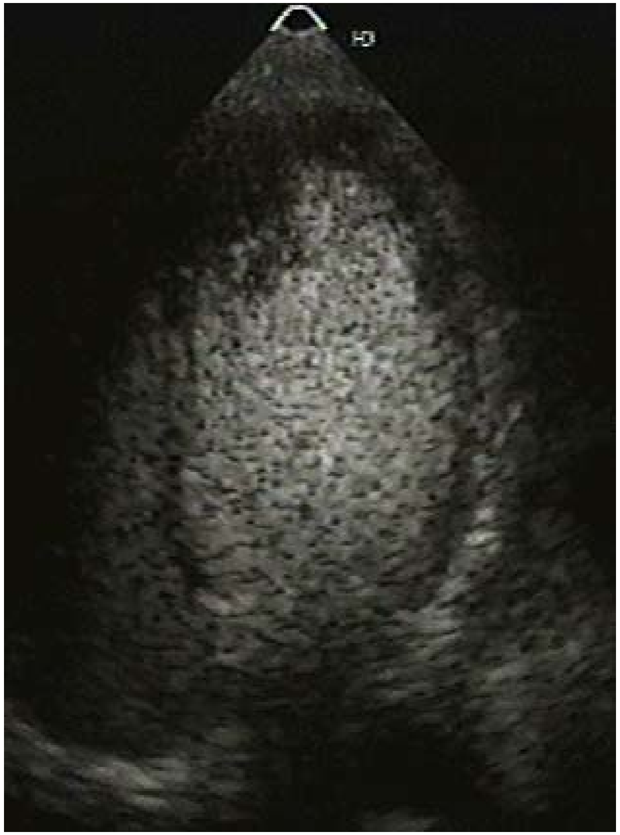
- Microbubbles resonate at diagnostic ultrasound frequencies
- They produce harmonics of transmit frequency
- The harmonic signal is the contrast signature
  - Transmit at f_o, receive at $2f_o$
- Greatly enhances contrast vs tissue

Harmonic B-mode

Albumex (MBI)

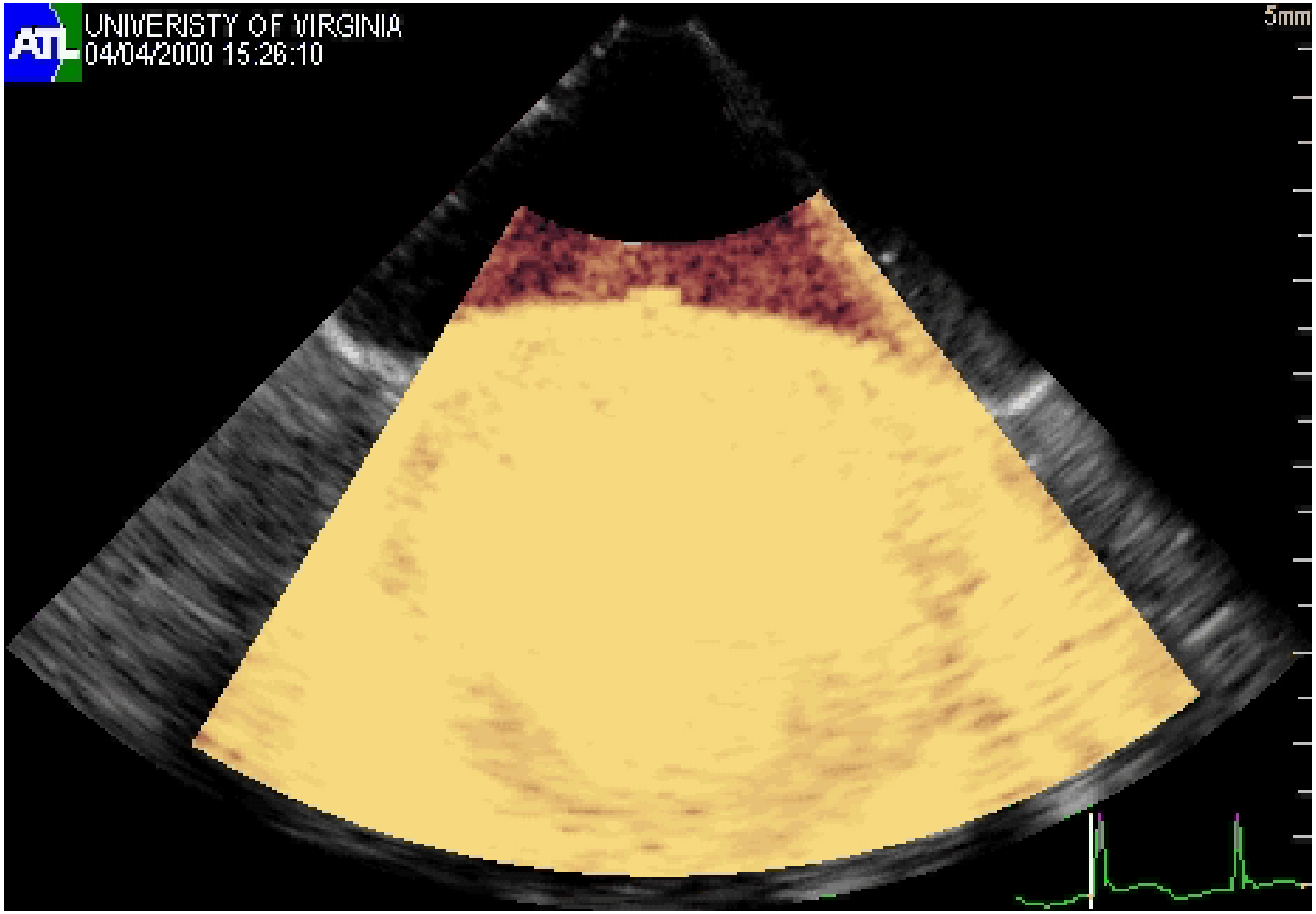


Linear

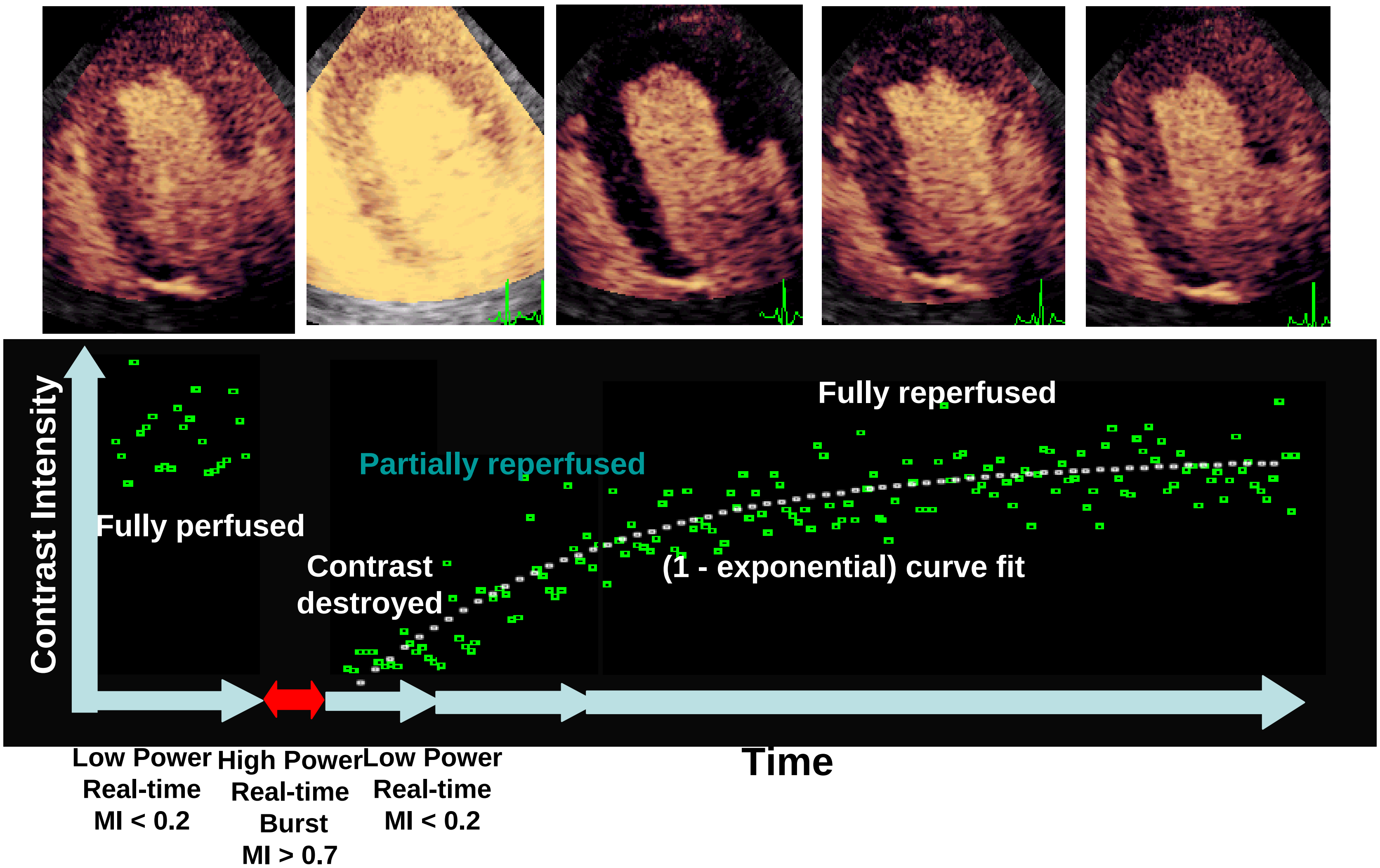


Harmonic

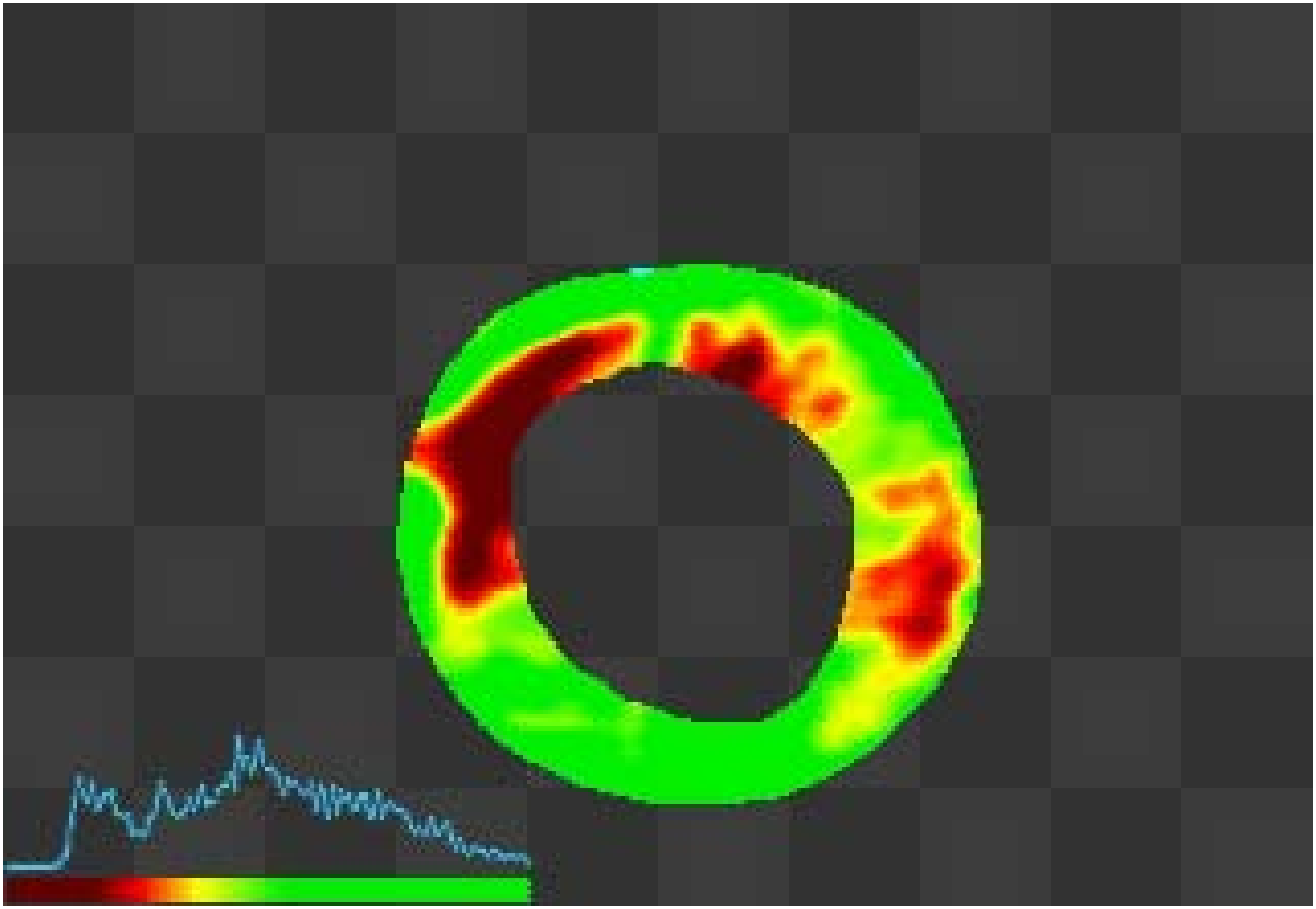
Cardiac Perfusion Imaging



Real Time Perfusion



Imaging perfusion time



Multi-Wave Imaging

Imaging Shear Elasticity with Ultrasound resolution :

TRANSIENT ELASTOGRAPHY

Imaging the shear modulus

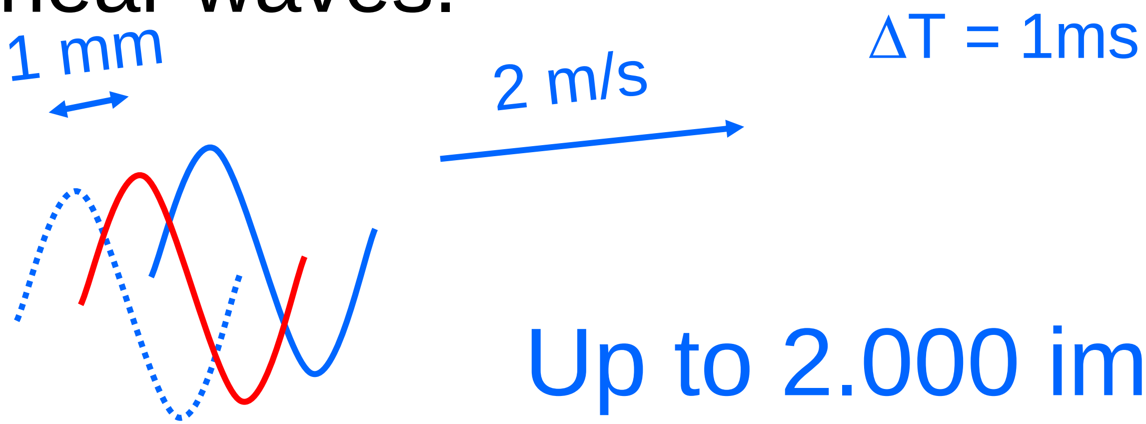
- **Transient Elastography**
  - Transmission of low frequency transient shear waves (30 Hz to 5000 Hz)
  - Following the shear wave propagation in a 2D or 3D zone of interest by comparing **successive ultrasonic images** of the random scatterers (speckle images) located in tissue.
  - Deducing the local shear velocity
  - Computing the shear modulus and the Young modulus in soft tissues from :

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

How to follow the shear wave propagation ?

: Ultrafast Imaging

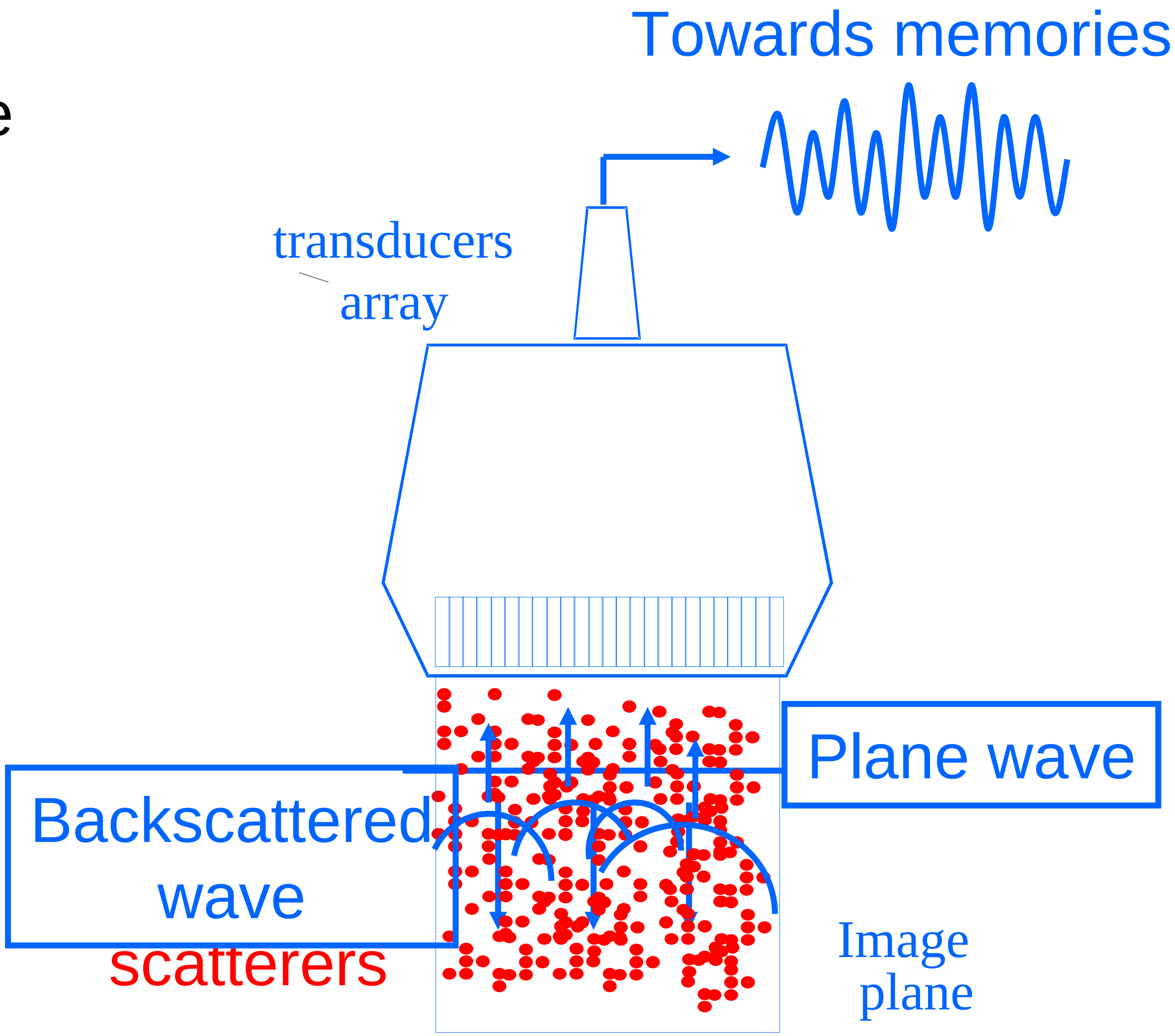
- Goal : Follow 2D propagation of LF shear waves.



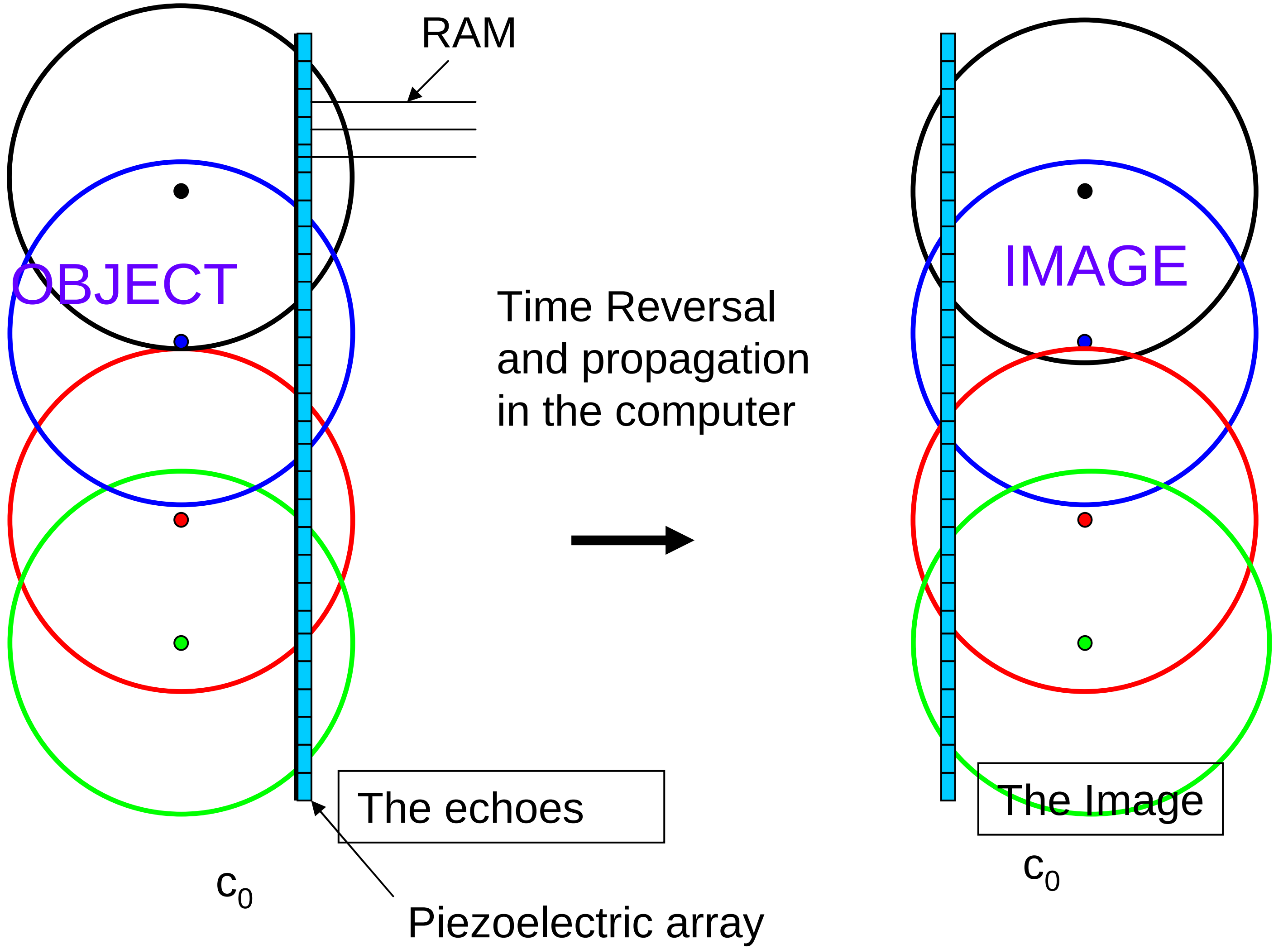
Up to 2.000 images/s !

Ultrafast Imaging

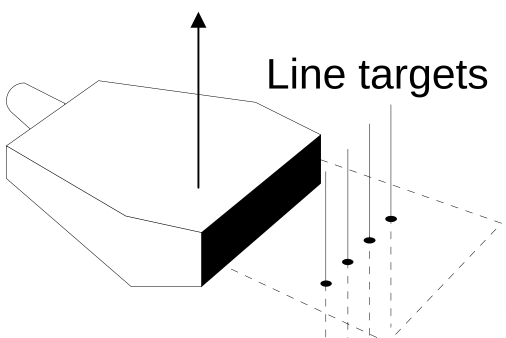
- Illumination by a plane wave
- recording all the RF signals in a large memory
- up to 5000 images/s
- Time reversal in the receive mode



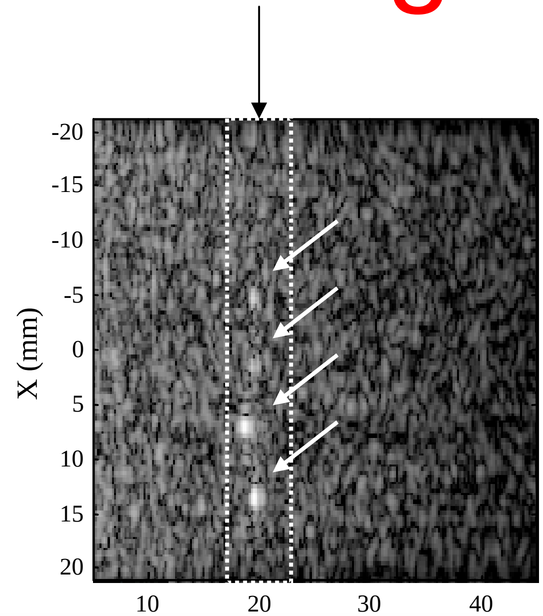
How to build an ultrafast image from pulsed echoes ? A time reversal operation in the computer with a sound velocity assumption c_0



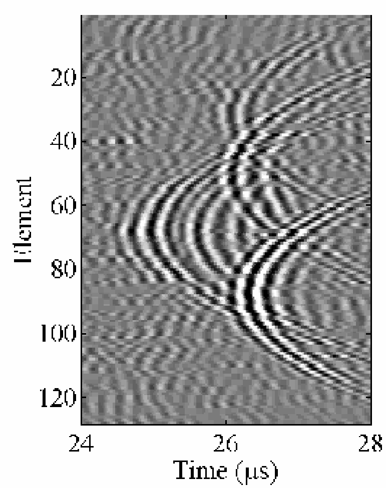
Ultrafast Ultrasonic imaging



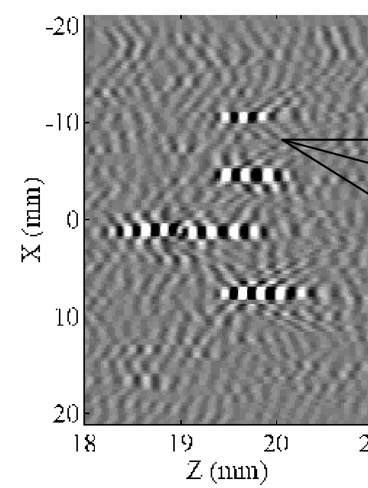
4.3 MHz Ultrasonic Array



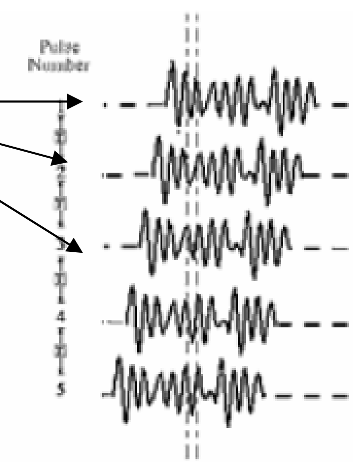
1 ms



The Echoes



The Images



Compute U_z

How to create LF shear waves

3 kind of shear wave sources:

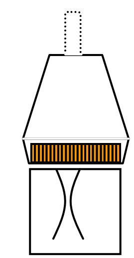
Natural

Heart

External

Punch

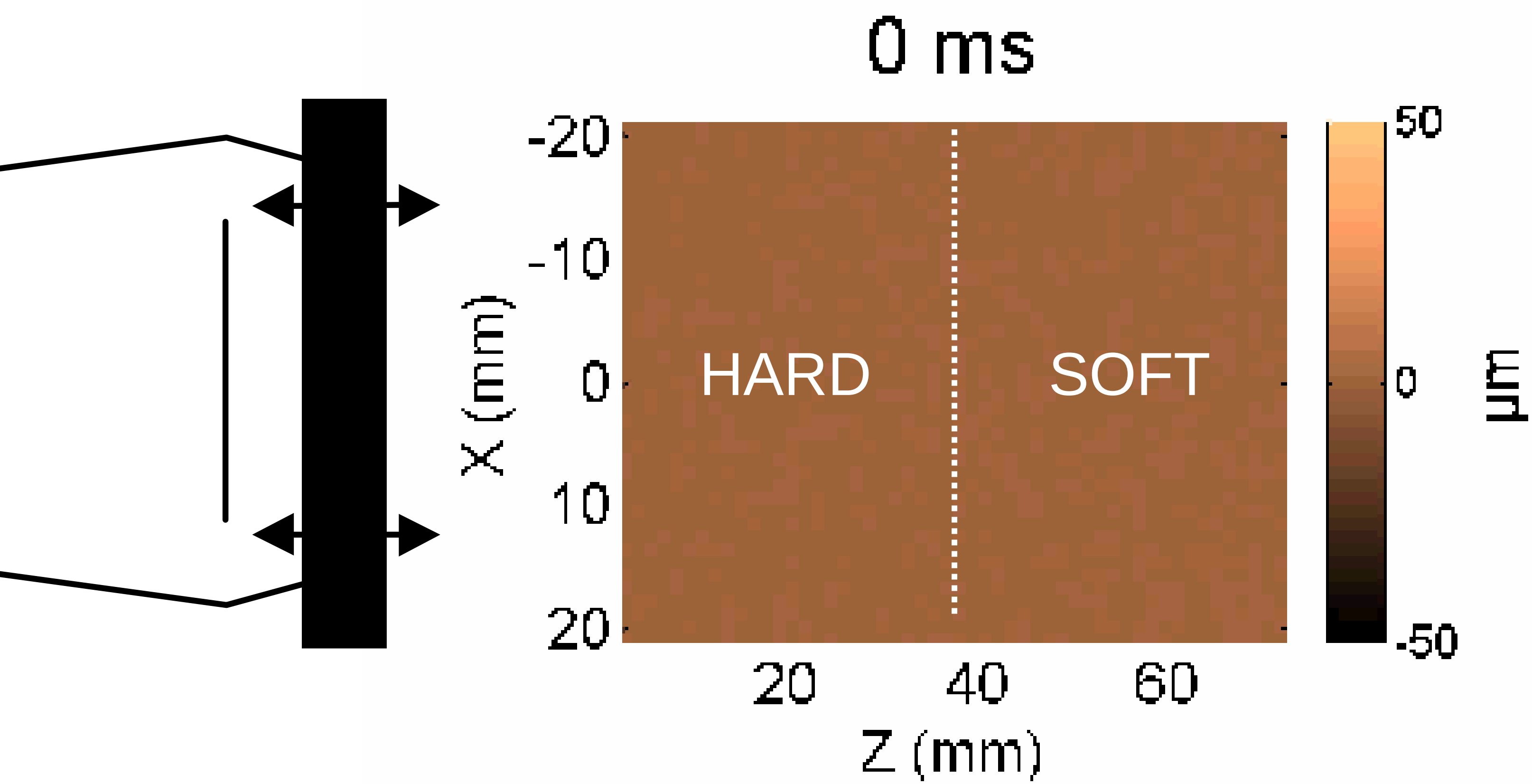
Remote



Ultrasound beams

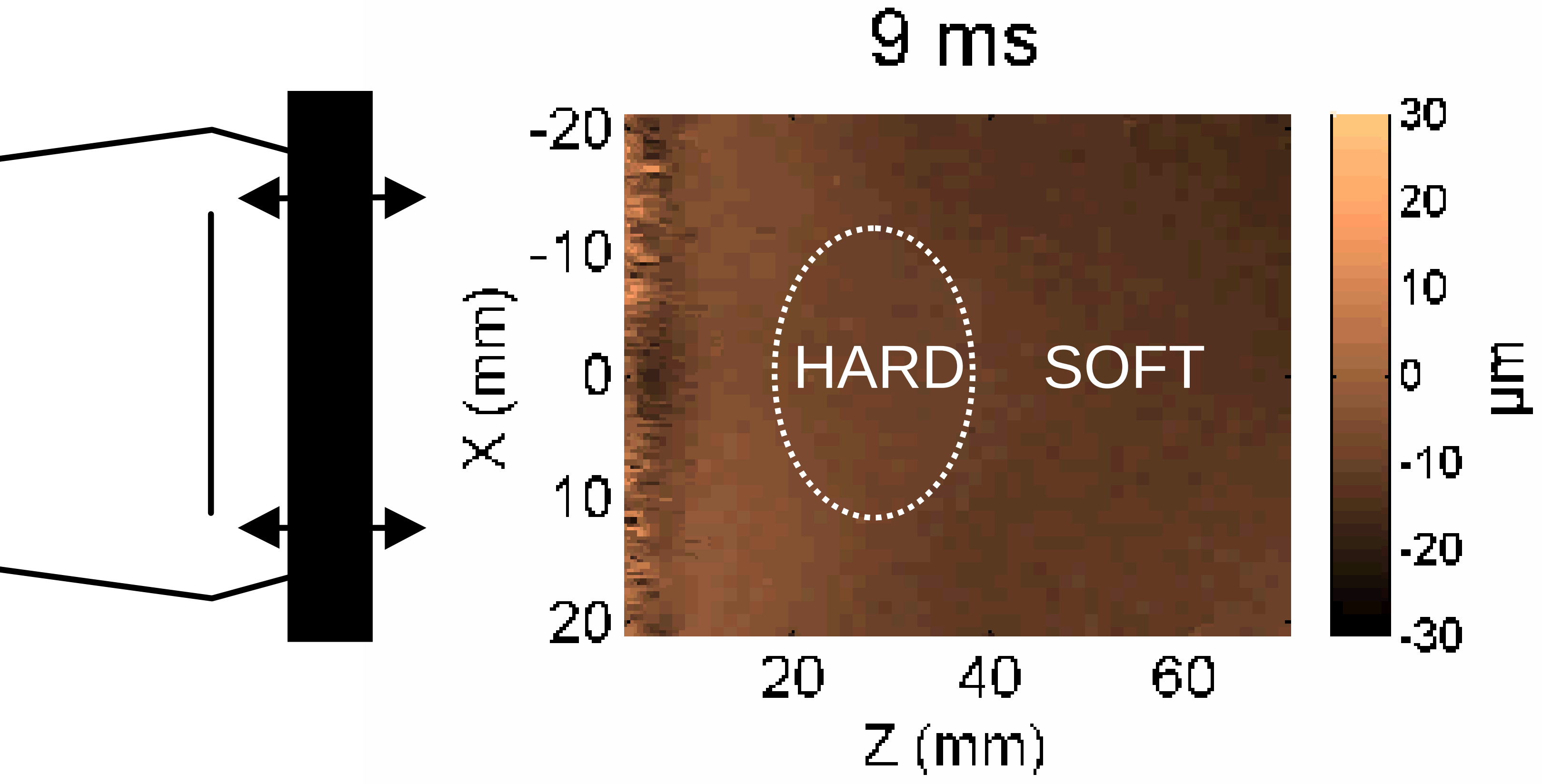
Bilayered phantom

Movie of U_z component



Hard inclusion

Movie of Uz component



A Simple Inversion Algorithm

- Motion Equation:

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

Compressional shear

- Assumptions:

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

2) λ>>μ => the bulk wave propagates instantaneously, and then:

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

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

No diffraction outside the image plane

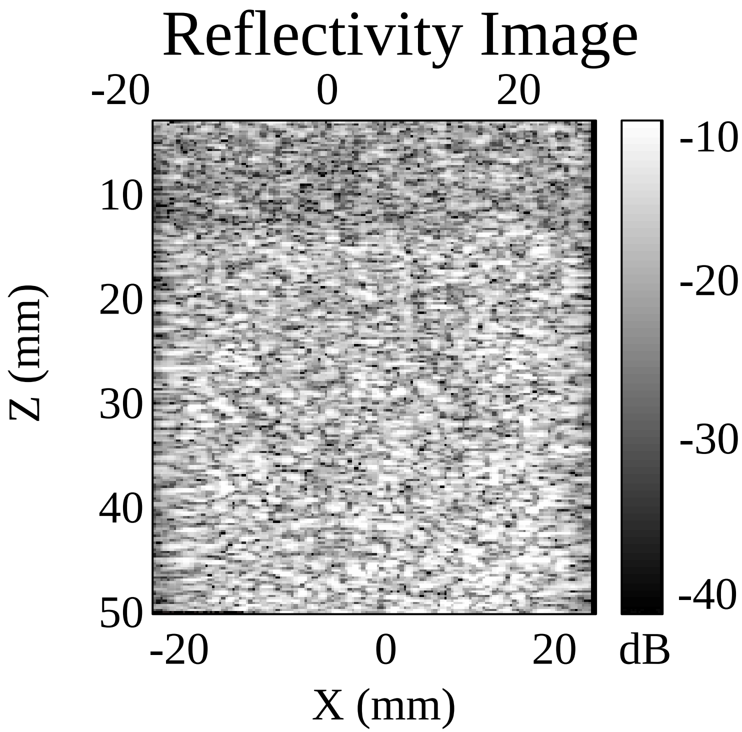
Inverse Problem

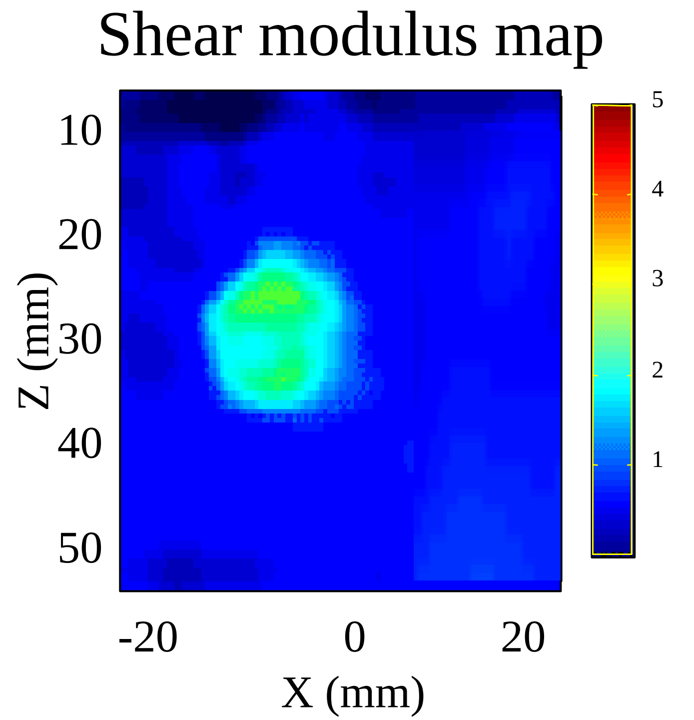
$$\rho \frac{\partial^2 u_z}{\partial t^2} = \mu \Delta u_z$$

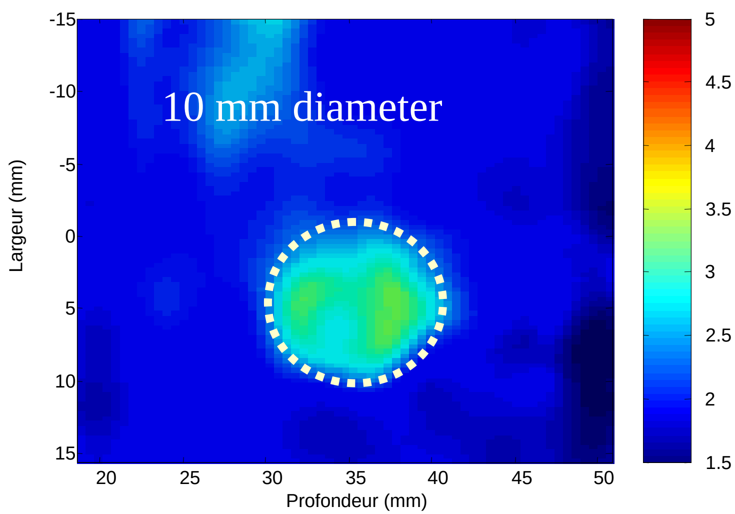
- Local inversion algorithm

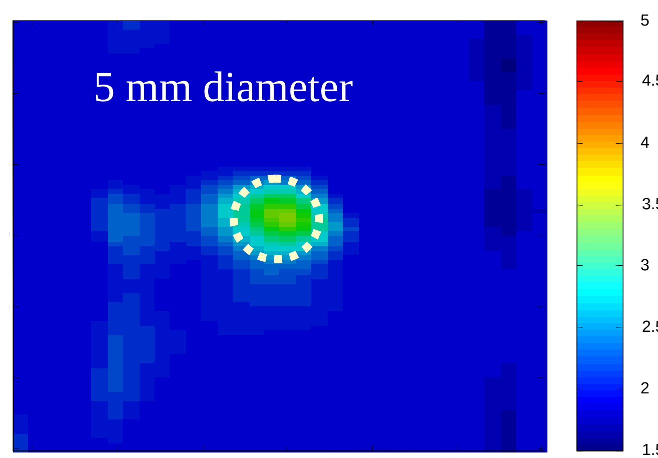
$$\mu(x,z) = \rho \frac{\left(\dfrac{\partial^2 u_z(x,z)}{\partial t^2} \right)}{\left(\dfrac{\partial^2 u_z(x,z)}{\partial x^2} + \dfrac{\partial^2 u_z(x,z)}{\partial z^2} \right)}$$

Inverse Problem – Hard Inclusion









Breast Cancer Detection : first *In Vivo* Results

- 20 Women with palpable tumors

- 10 minutes Data acquisitions

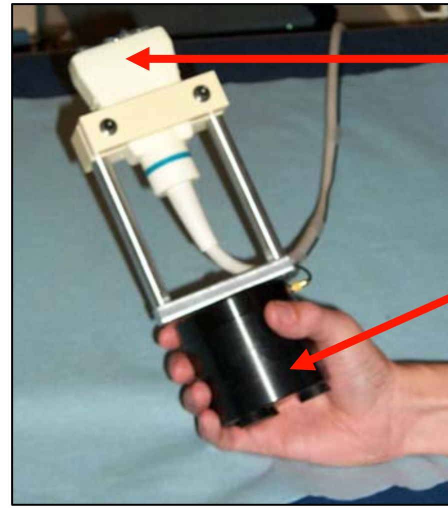
- Classical echographic exam

+ Transient elastography on the same system

- 200 speckles images (Frame rate : 2000 Hz)

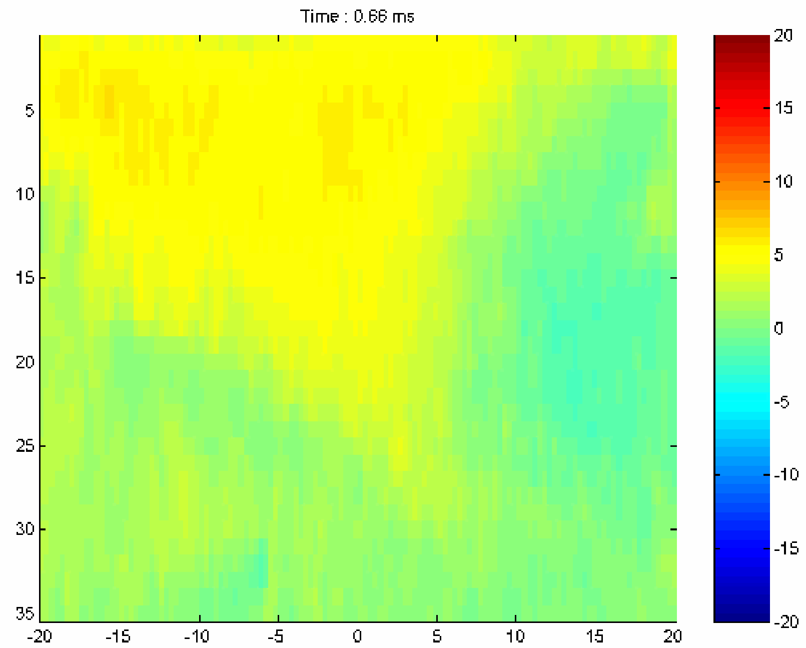
- Low frequency vibration : 50 Hz

Collaboration with Institut Curie

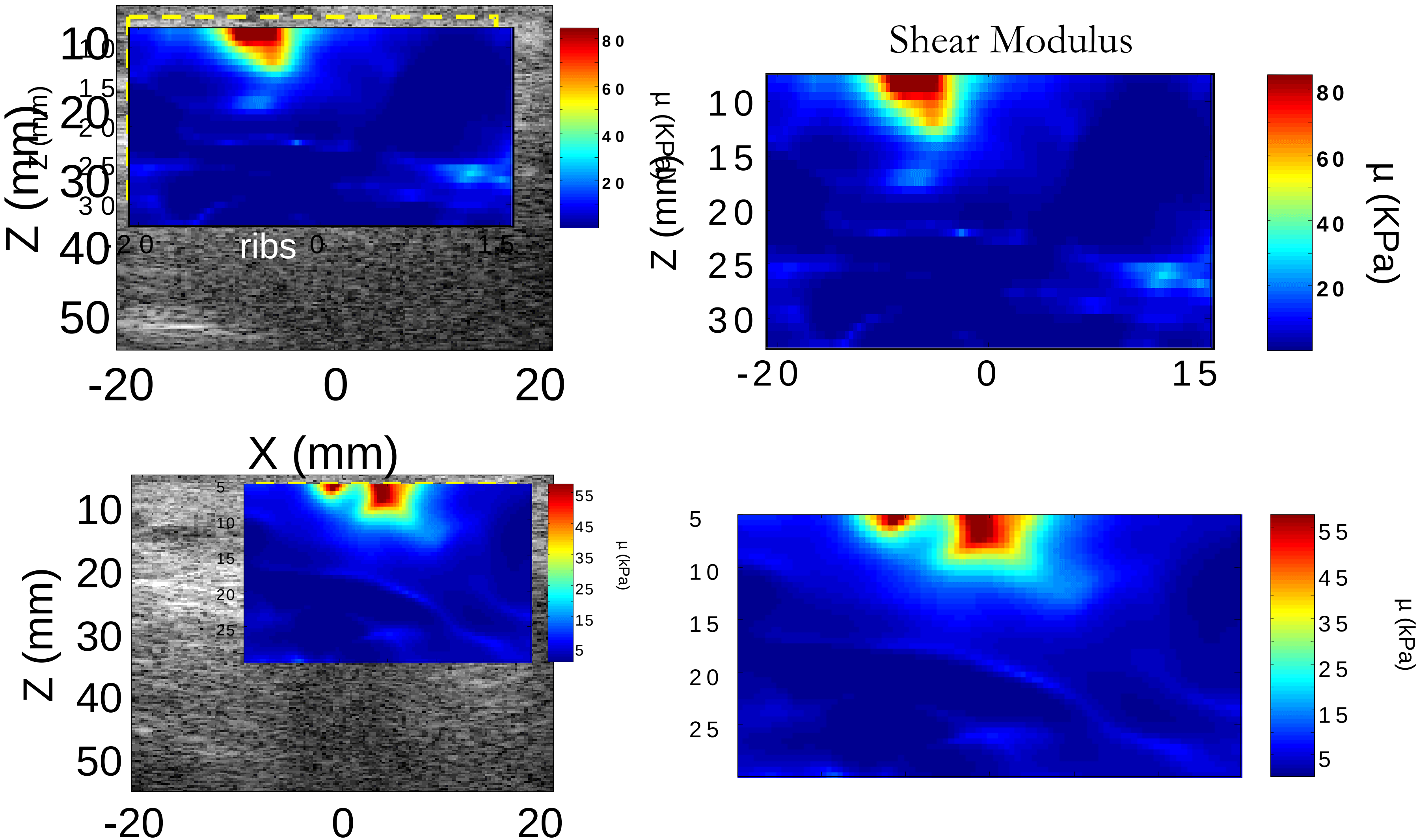


In Vivo Results : Shear propagation in breast

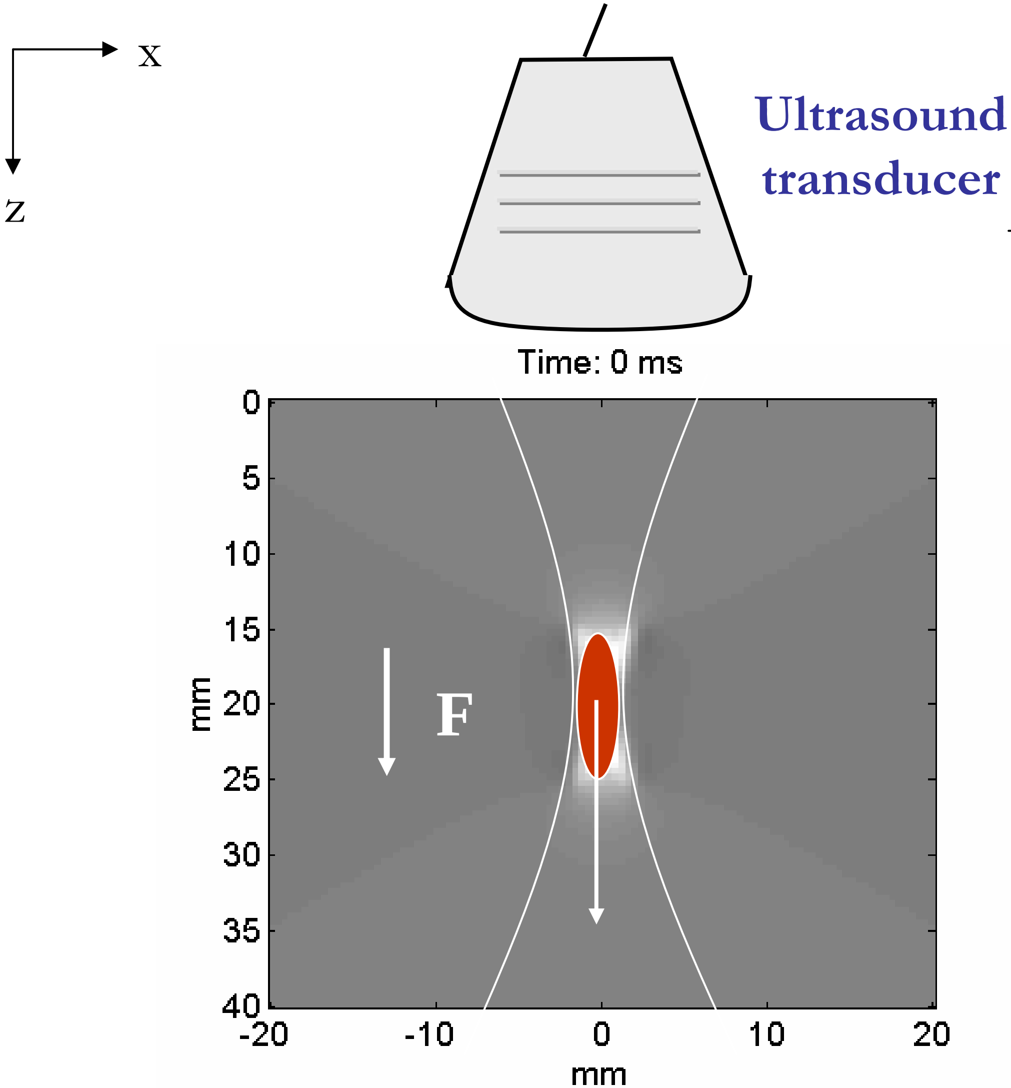
- 1D cross correlation Algorithm : Estimation of u_z



In Vivo Results : Shear Modulus reconstruction



The acoustic radiation force in soft tissues



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

Shear Speed = 1 to 10 m/s
in human tissues

Ultrasonic emission duration
~100 à 200 µs
(a few hundreds of periods)

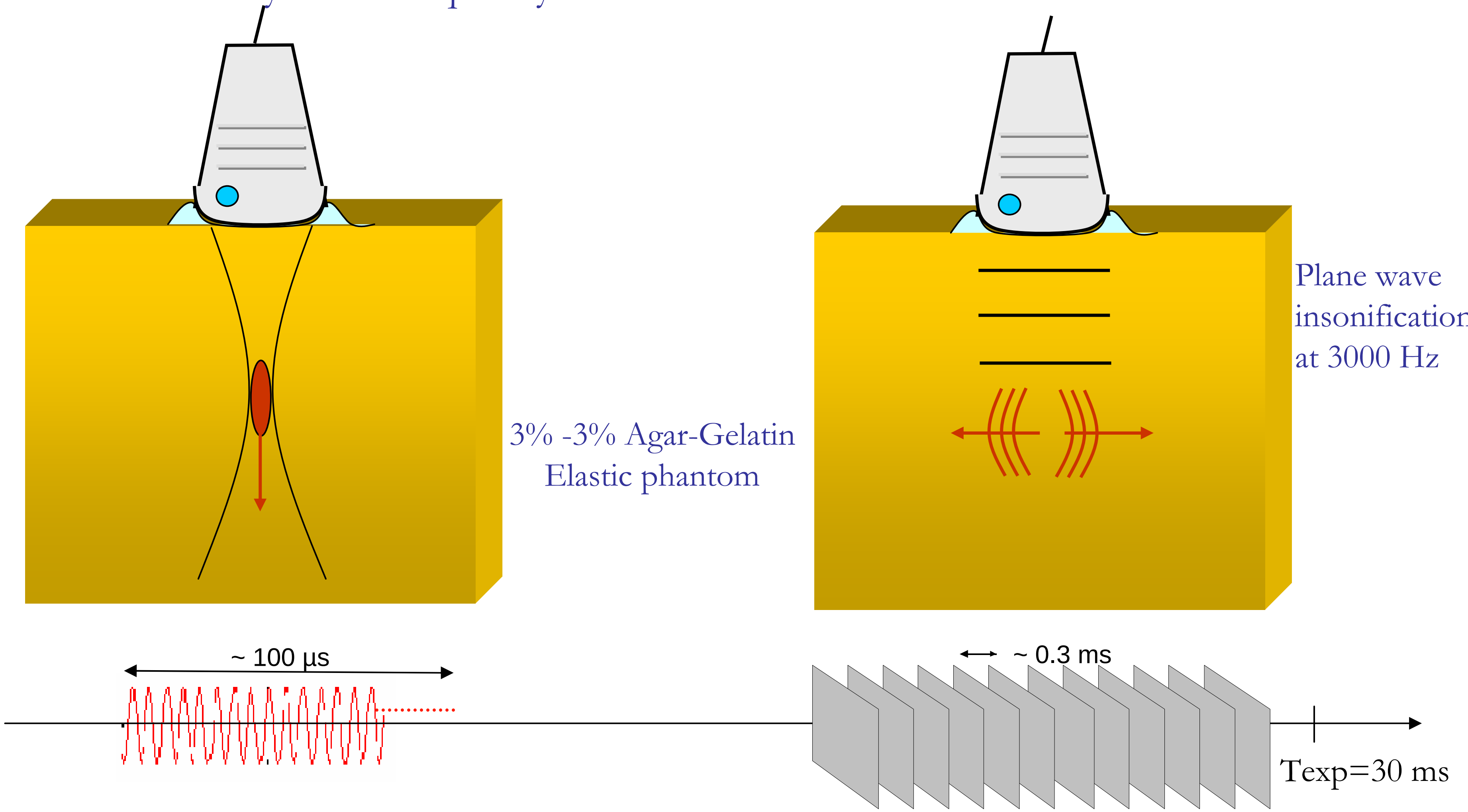
Displacements of a few µm !!

(*Sarvazian, Greenleaf, Fatemi, Nightingale*)

Ultrafast Imaging and Acoustic Radiation Force

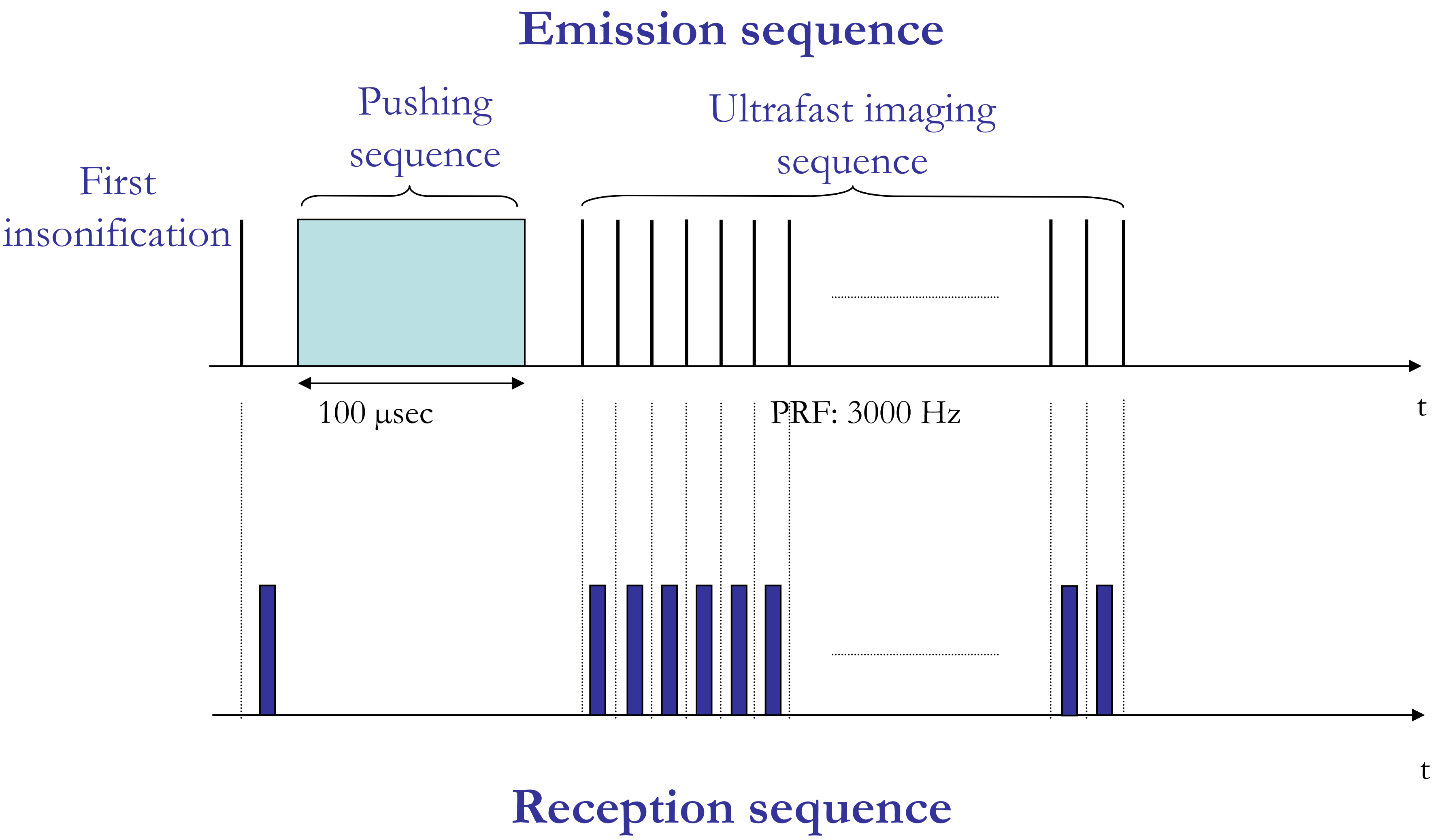
Step 1 : Creation of a LF volumic force by focusing an ultrasonic beam modulated by a low frequency

Step 2 : Ultrafast imaging of the shear displacement induced by the force

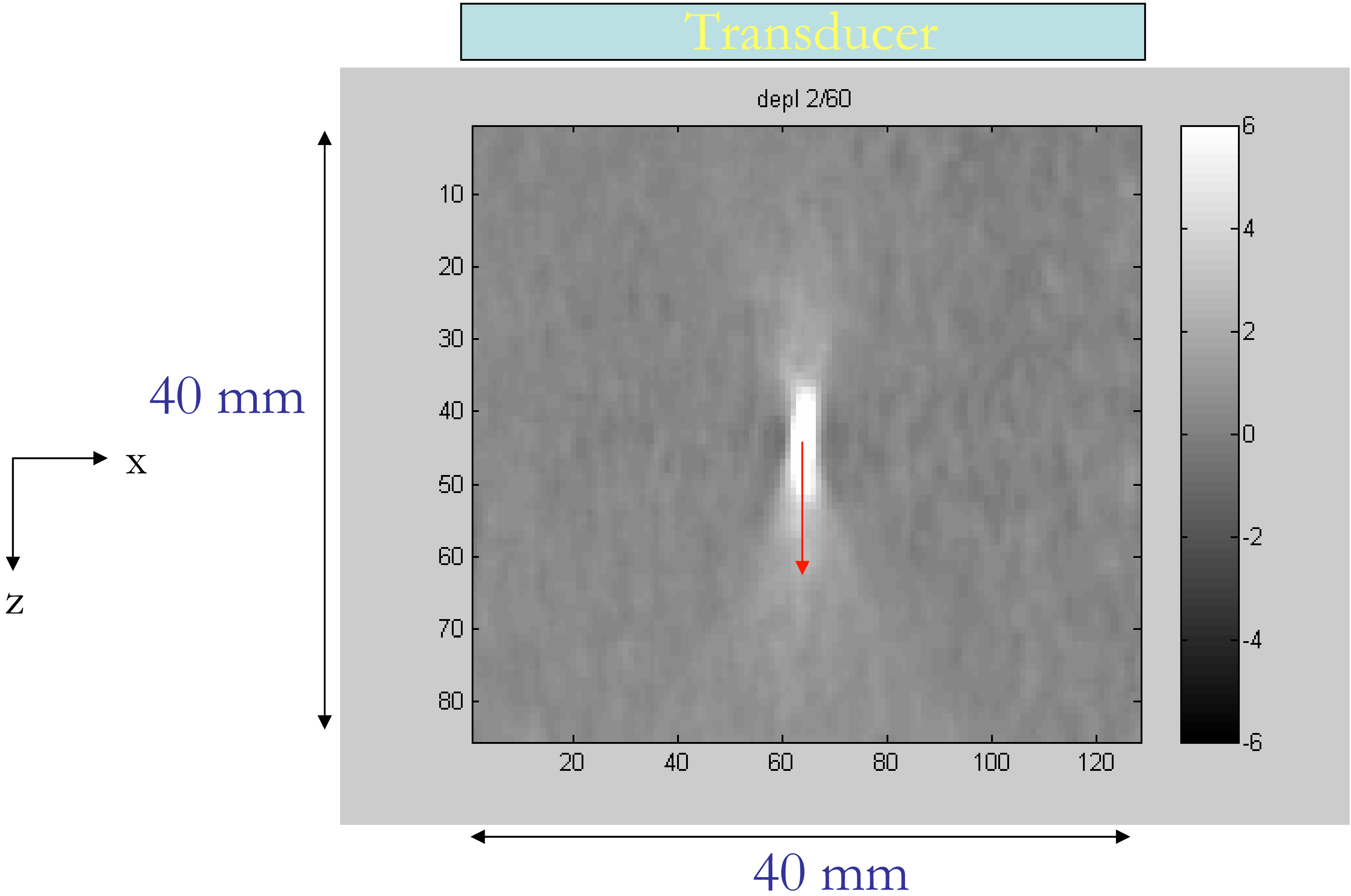


Radiation presure (*Sarvazian, Greenleaf, Nightingale*)

Acquisition Sequences

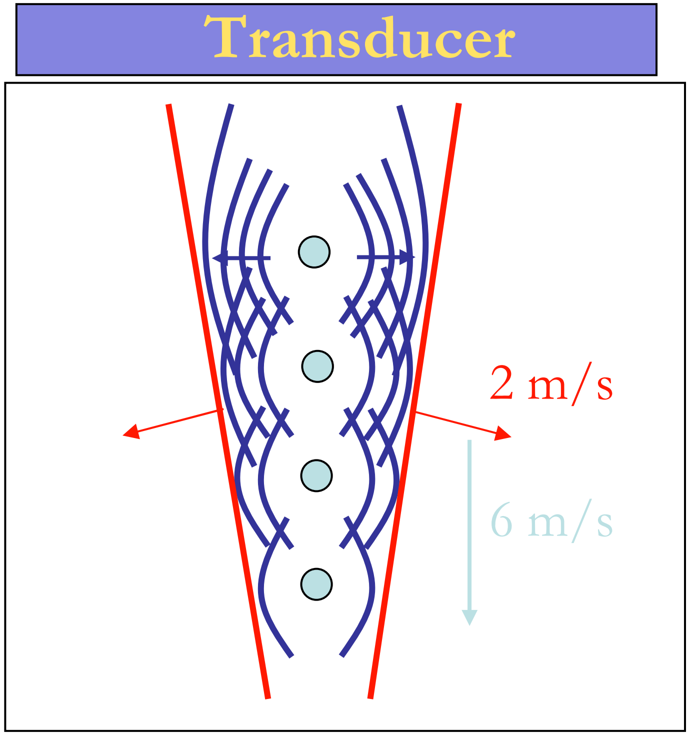


Experimental observation of the shear source



Total experience duration : 20 ms !

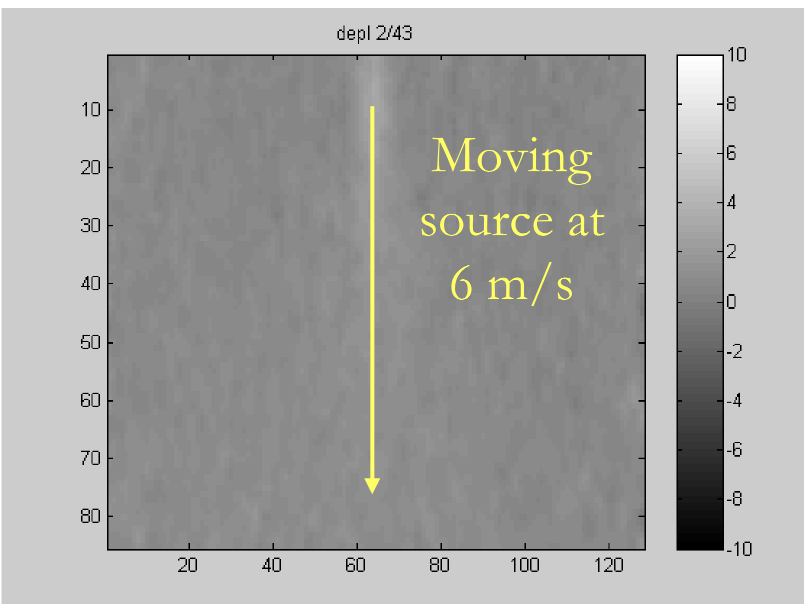
How to create a plane shear wave moving ? the shear source at a supersonic speed : The Mach Cone



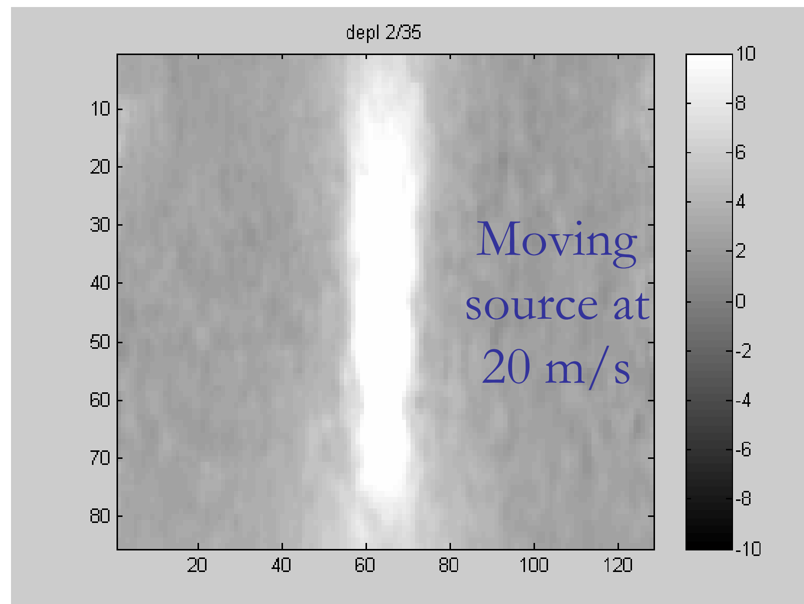
Displacements up to 100 µm

Multiple shear sources: shear beamforming with a supersonic moving source

Plane wave generation in a 2m/s phantom



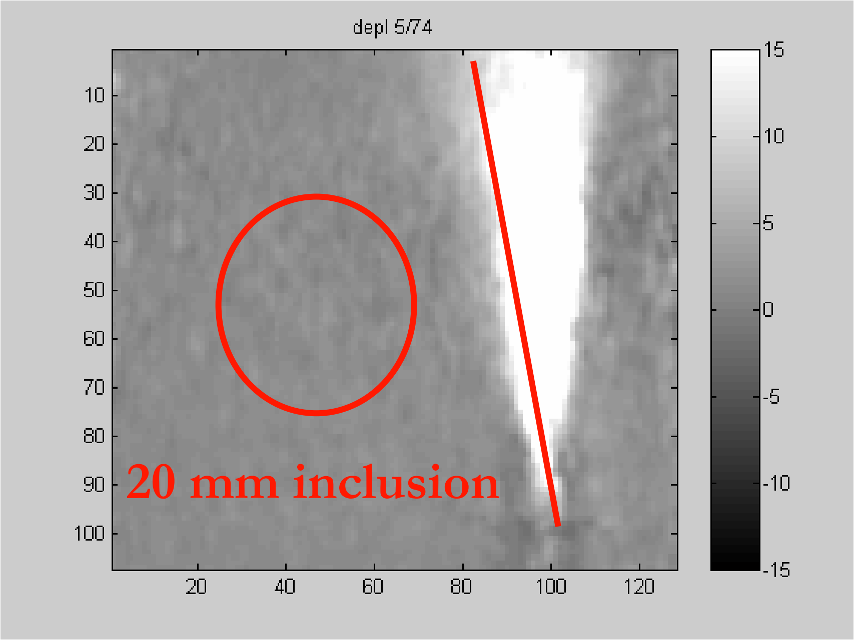
Mach 3

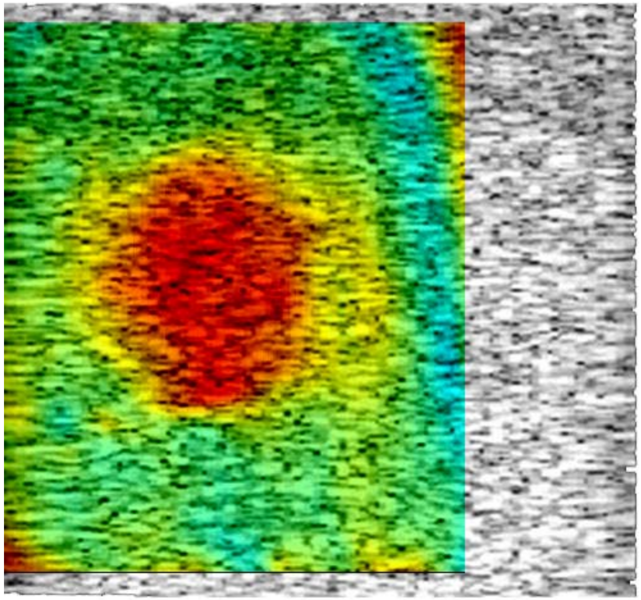


Mach 10

Supersonic's elastography mode

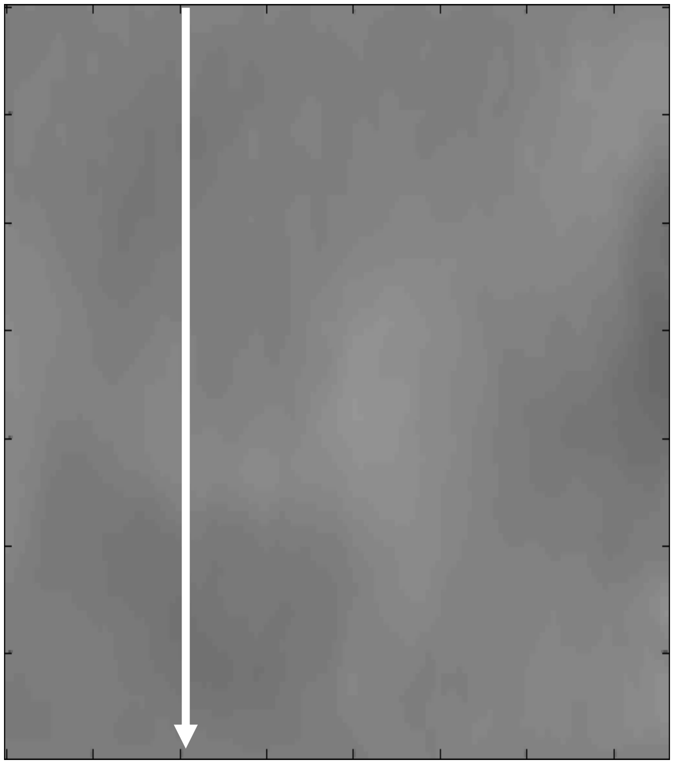
Imaging an inclusion at 3000 Hz

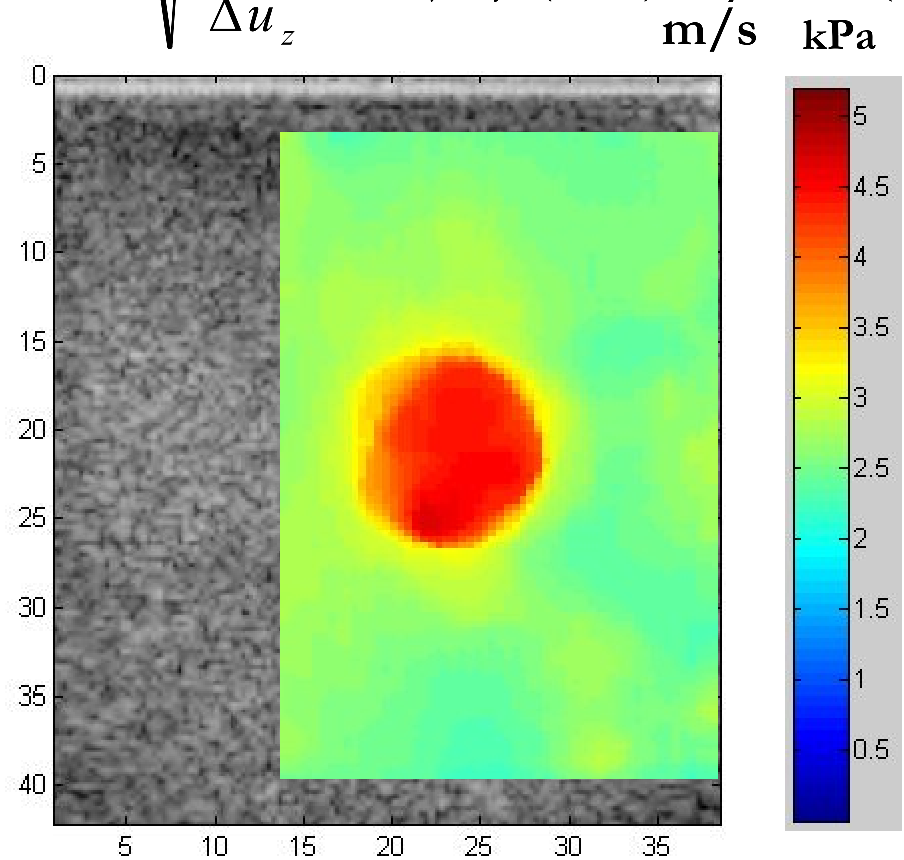




Supersonic Shear Imaging

$$\frac{\partial^2 u_z}{\partial t^2} - c^2 \Delta u_z = 0 \quad \Rightarrow \quad c(x,z) = \sqrt{\frac{\dfrac{\partial^2 u_z}{\partial t^2}}{\Delta u_z}} \quad \Rightarrow \quad \mu(x,z) = \rho \times c^2(x,z)$$





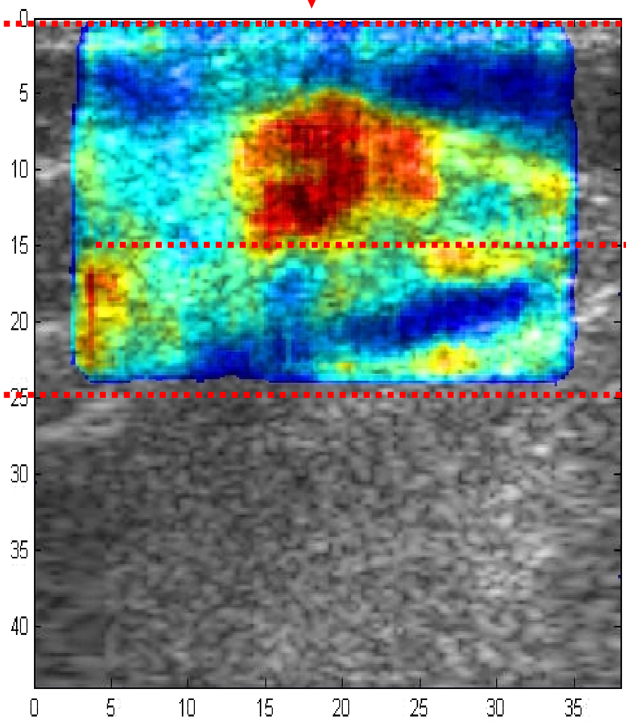
<u>Ref:</u> *Supersonic Shear Imaging: a new technique for soft tissue elasticity mapping.* J. Bercoff, M. Tanter and M. Fink, IEEE Trans., April 2004

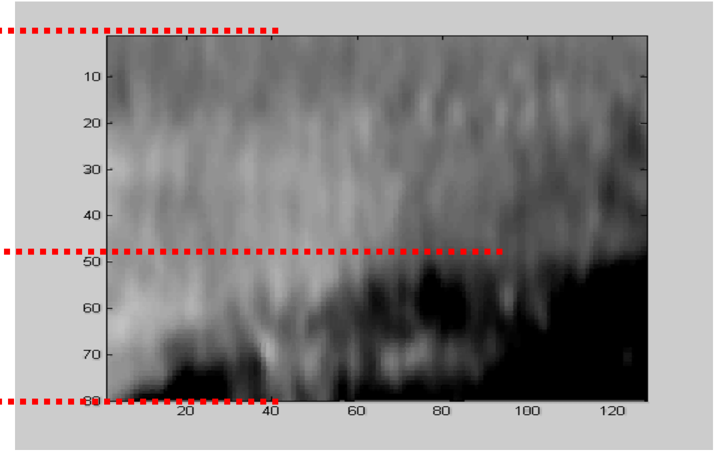
Case 1

9800375

Age: 72 years old

Elasticity map



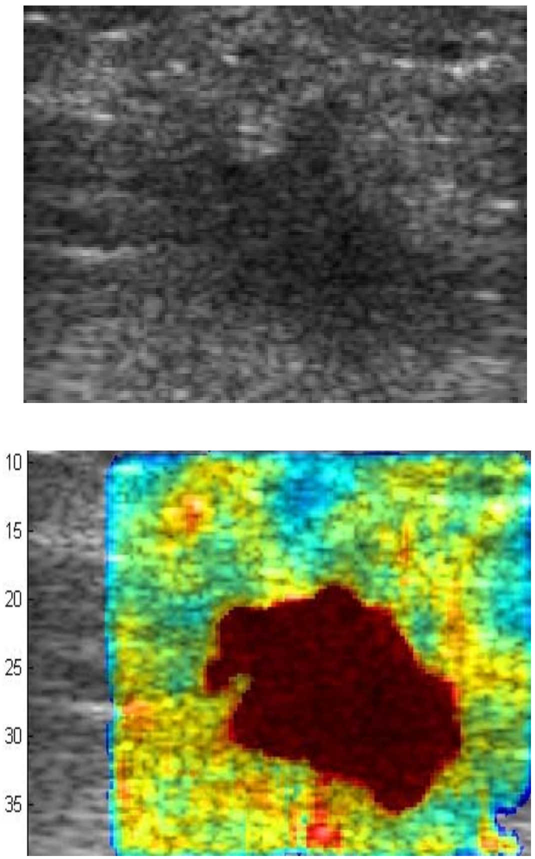


Hystology: Invasive ductal carcinoma, grade III (trabecular architecture)

Preliminary clinical Investigation

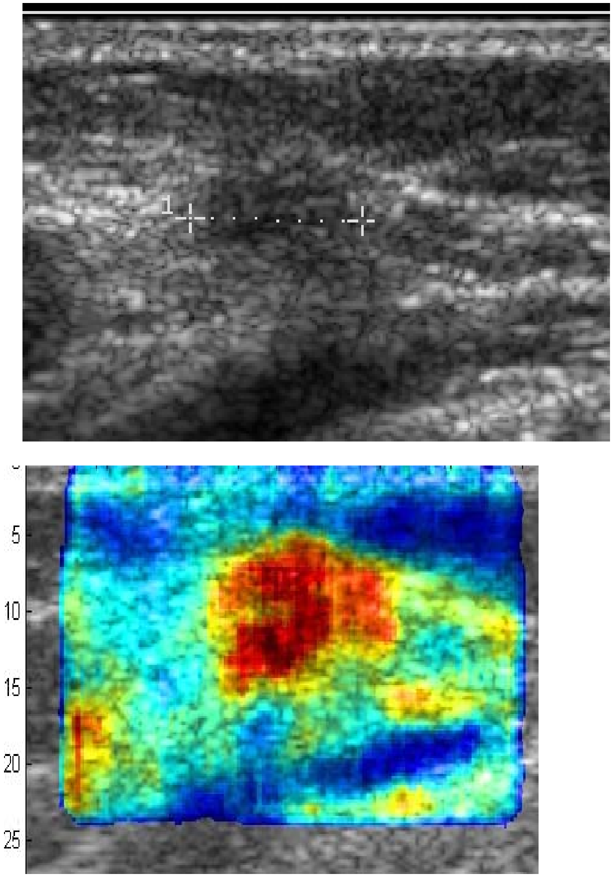
Malignant cases

20 mm, ACR5, palpable

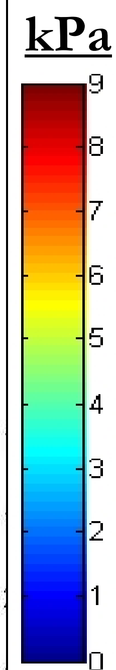


Invasive ductal carcinoma grade III

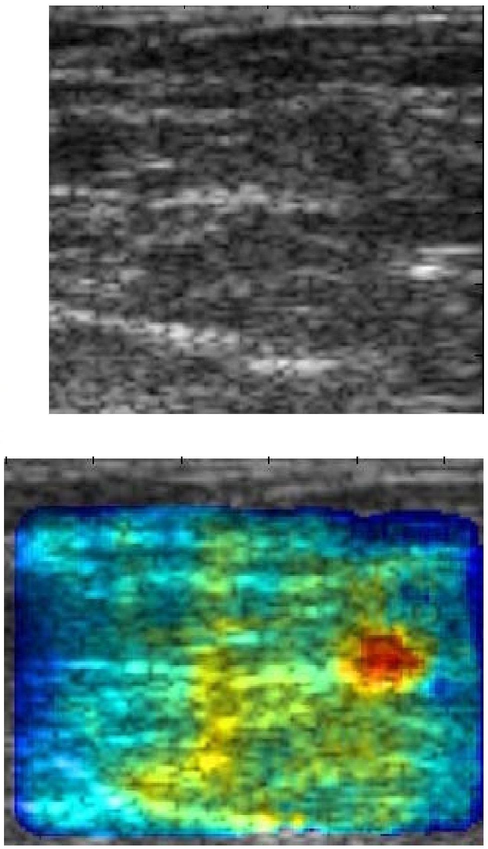
15 mm, ACR5, palpable



Invasive ductal carcinoma grade III

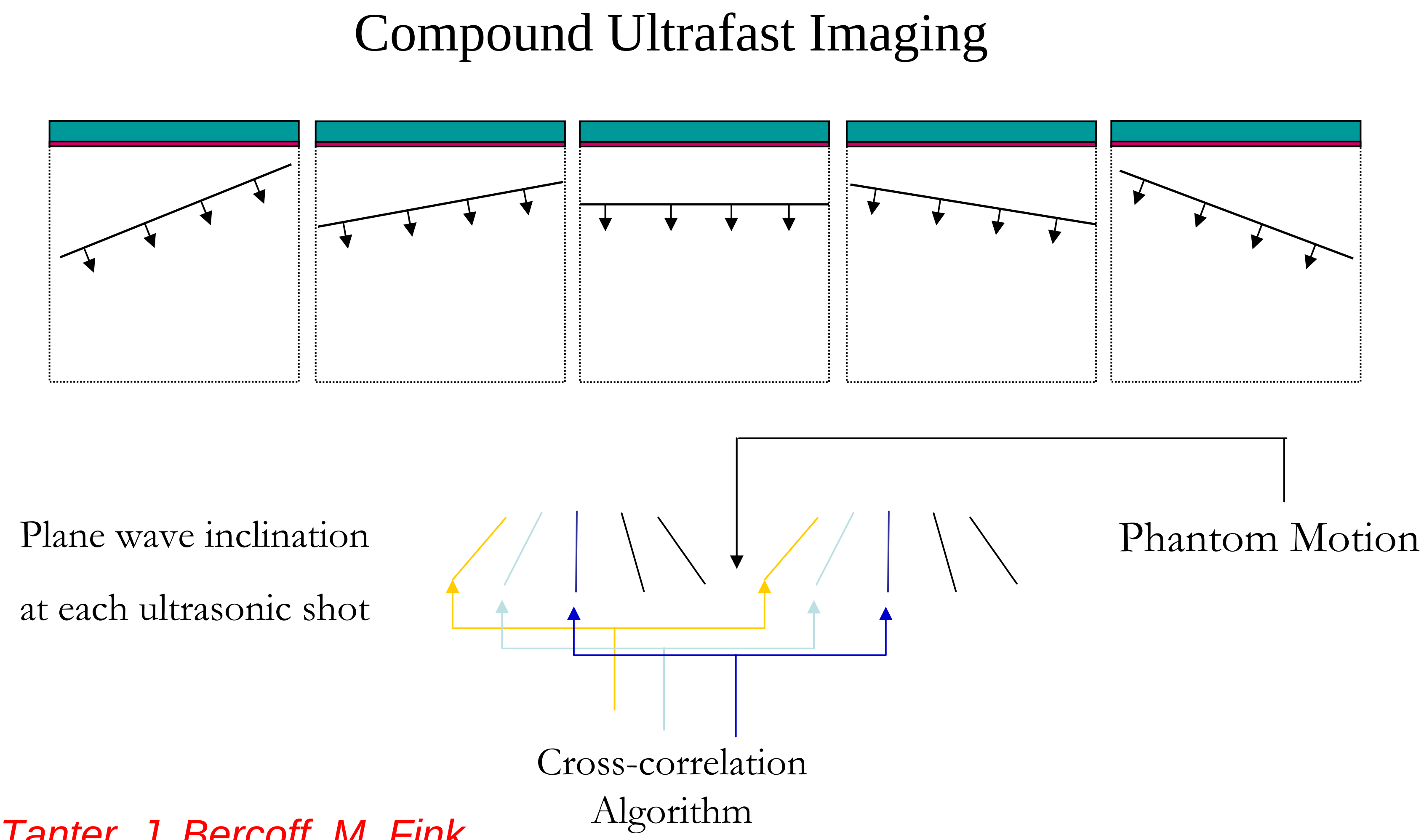


8 mm, ACR5



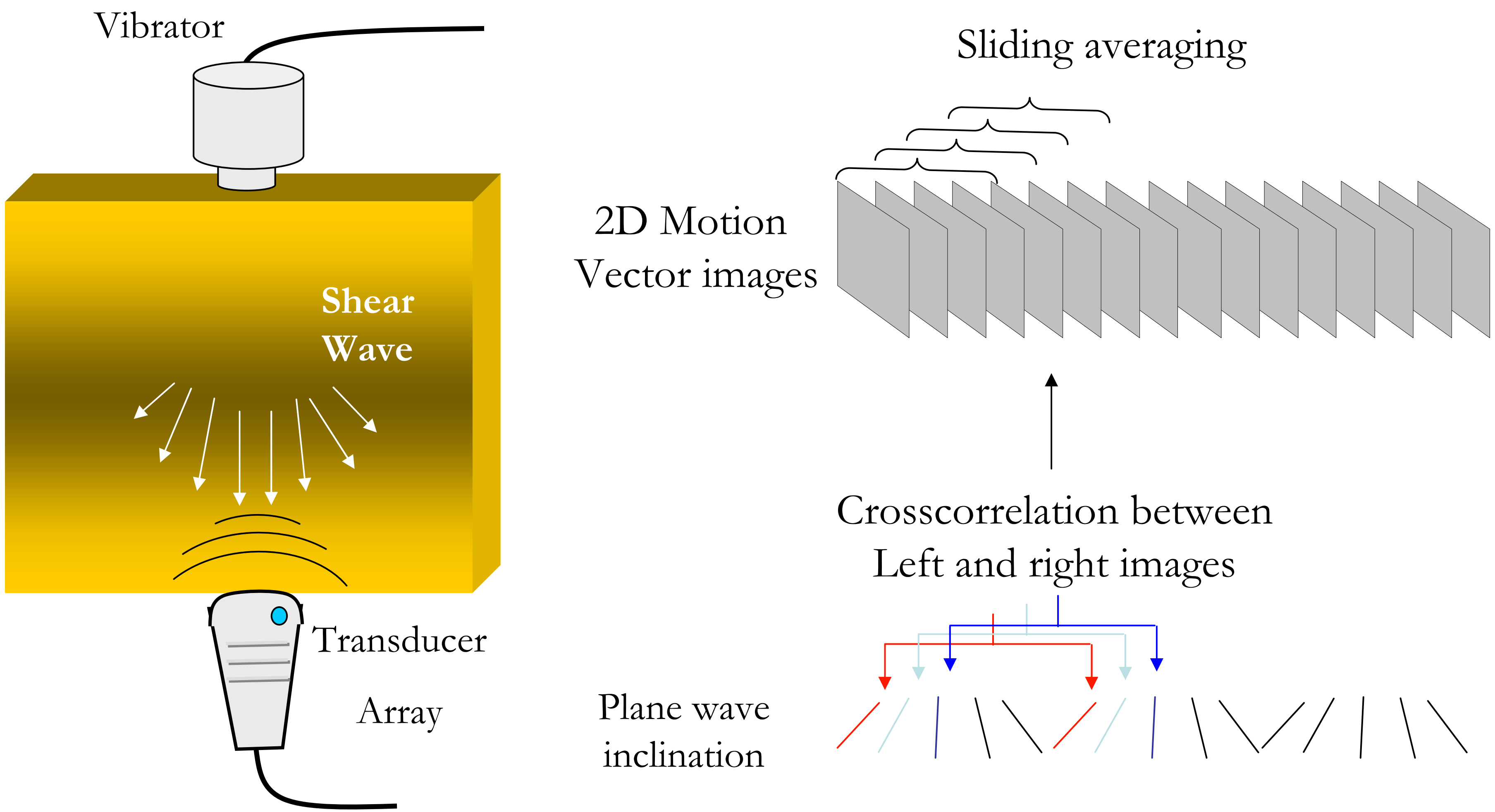
Invasive lobular carcinoma grade III

How to measure both axial and transverse motion induced by shear sources ? Needed for full 3D,



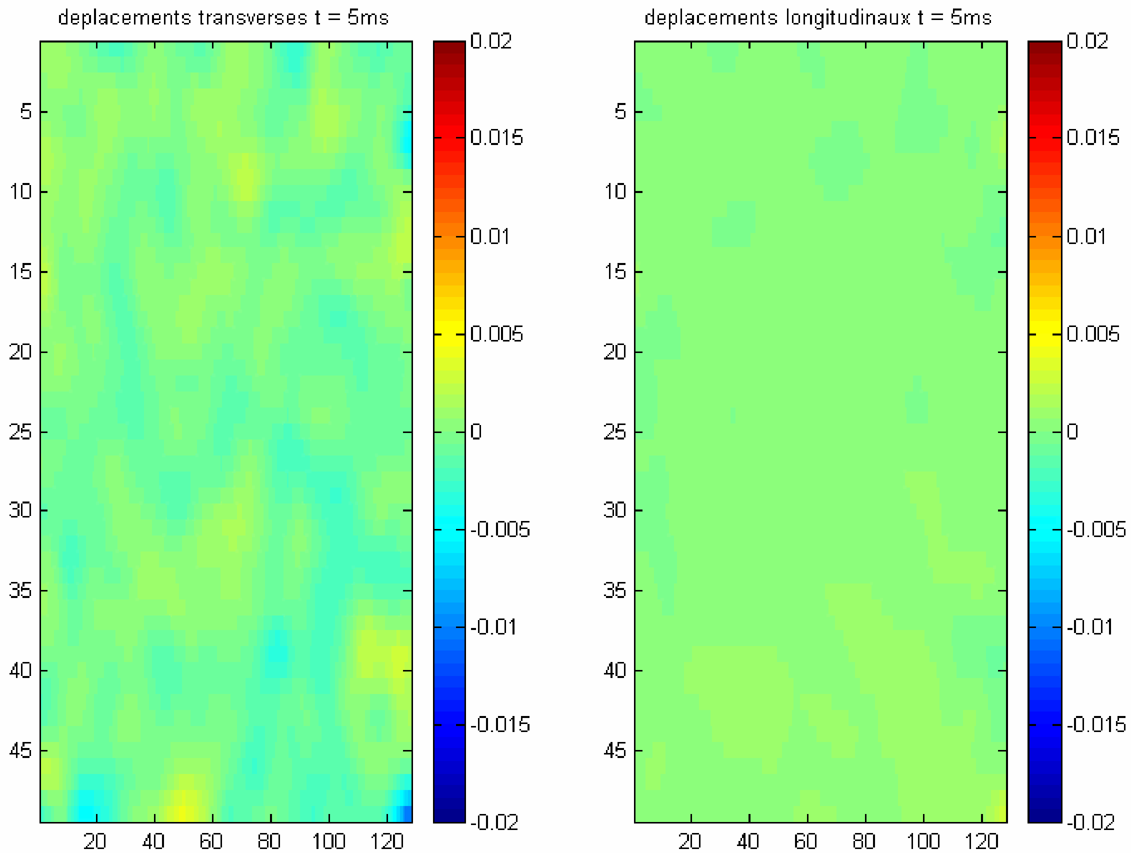
M. Tanter, J. Bercoff, M. Fink

Real Time Experiment : Shear Wave Imaging



Real Time Experiment : Phantoms Results

Transverse Displacements | *Longitudinal Displacements*

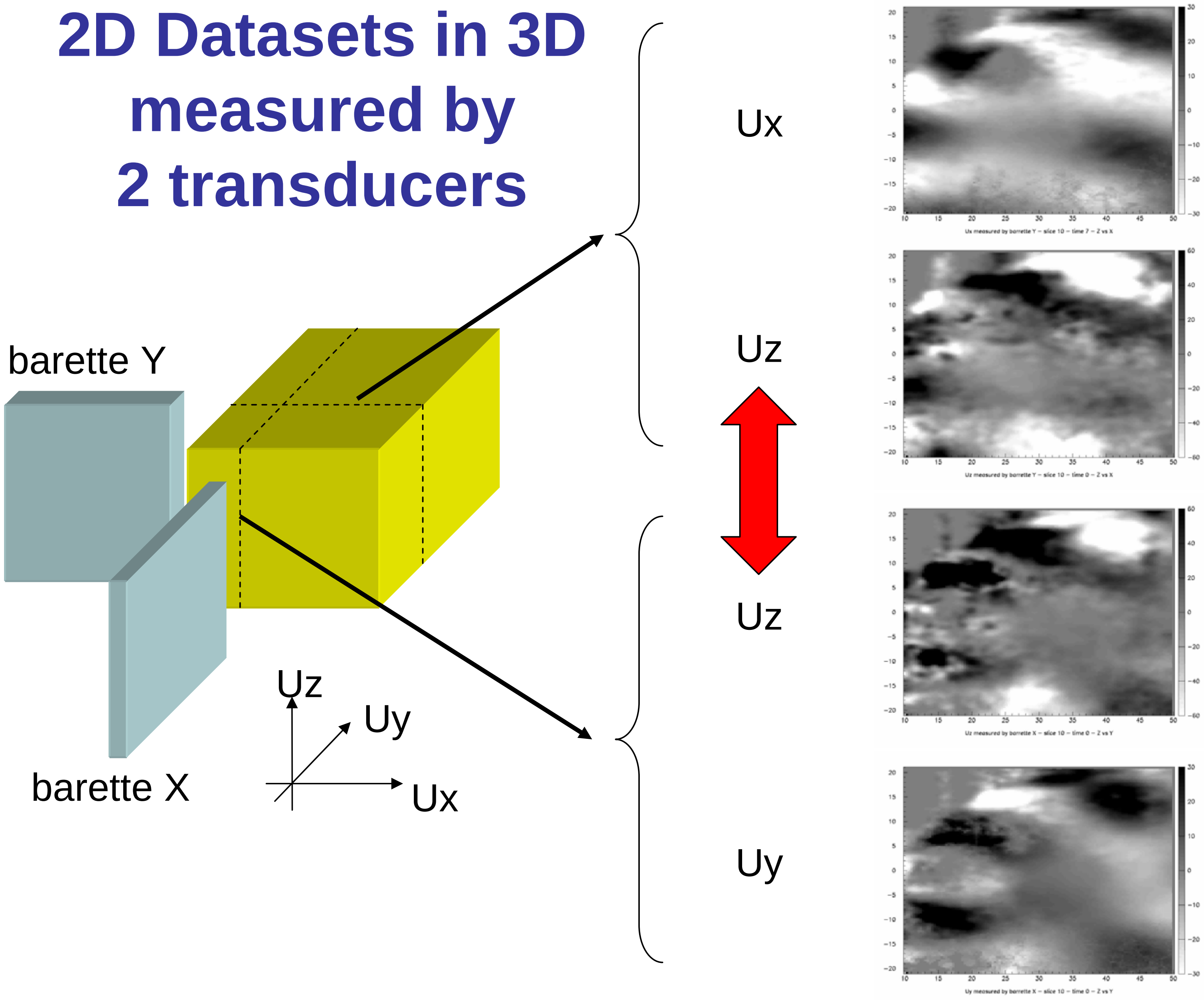


Width : 50 mm

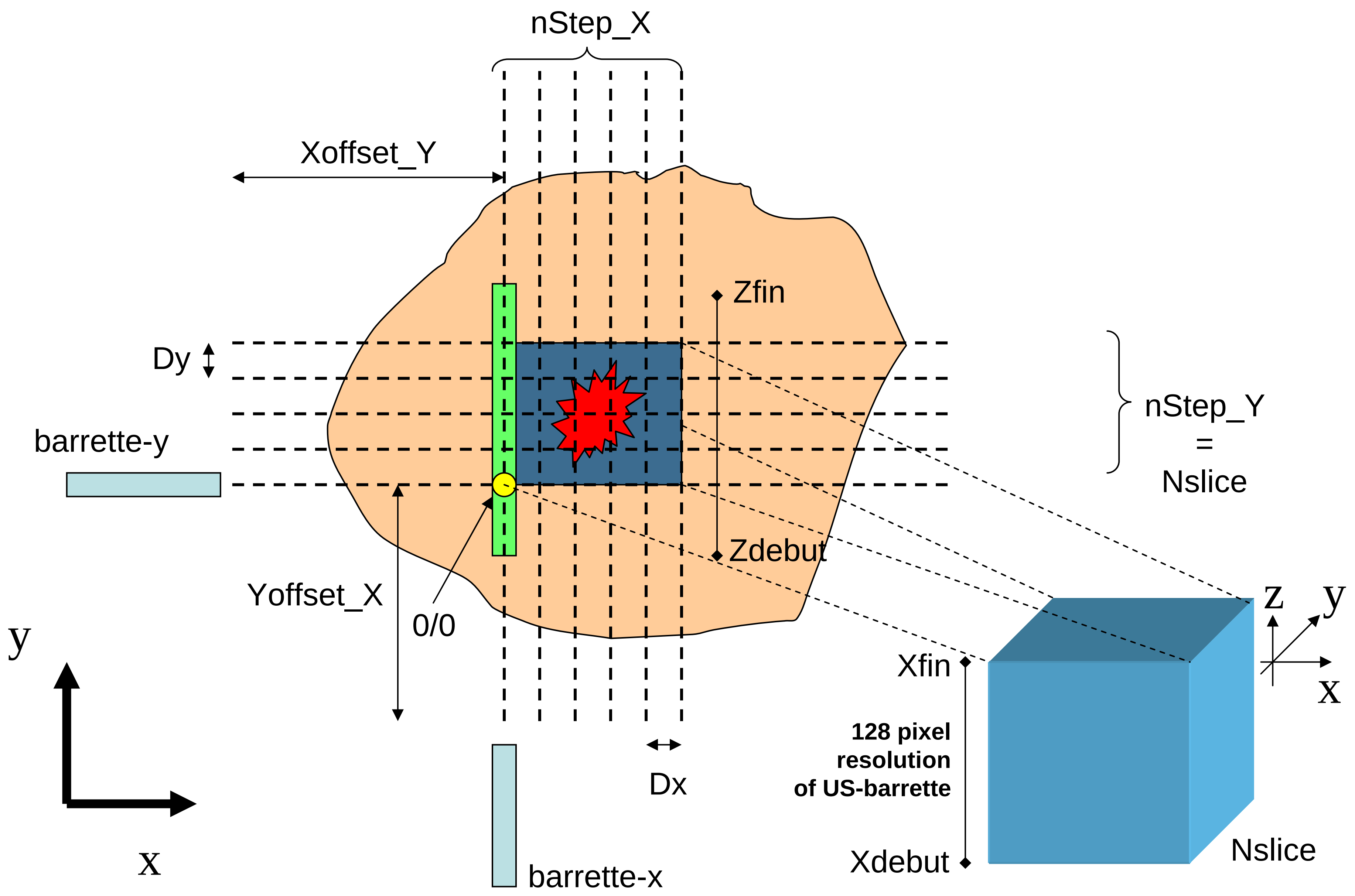
Frame rate : 5000 Hz

Experiment Duration : 25 ms

2D Datasets in 3D measured by 2 transducers



Data Fusion

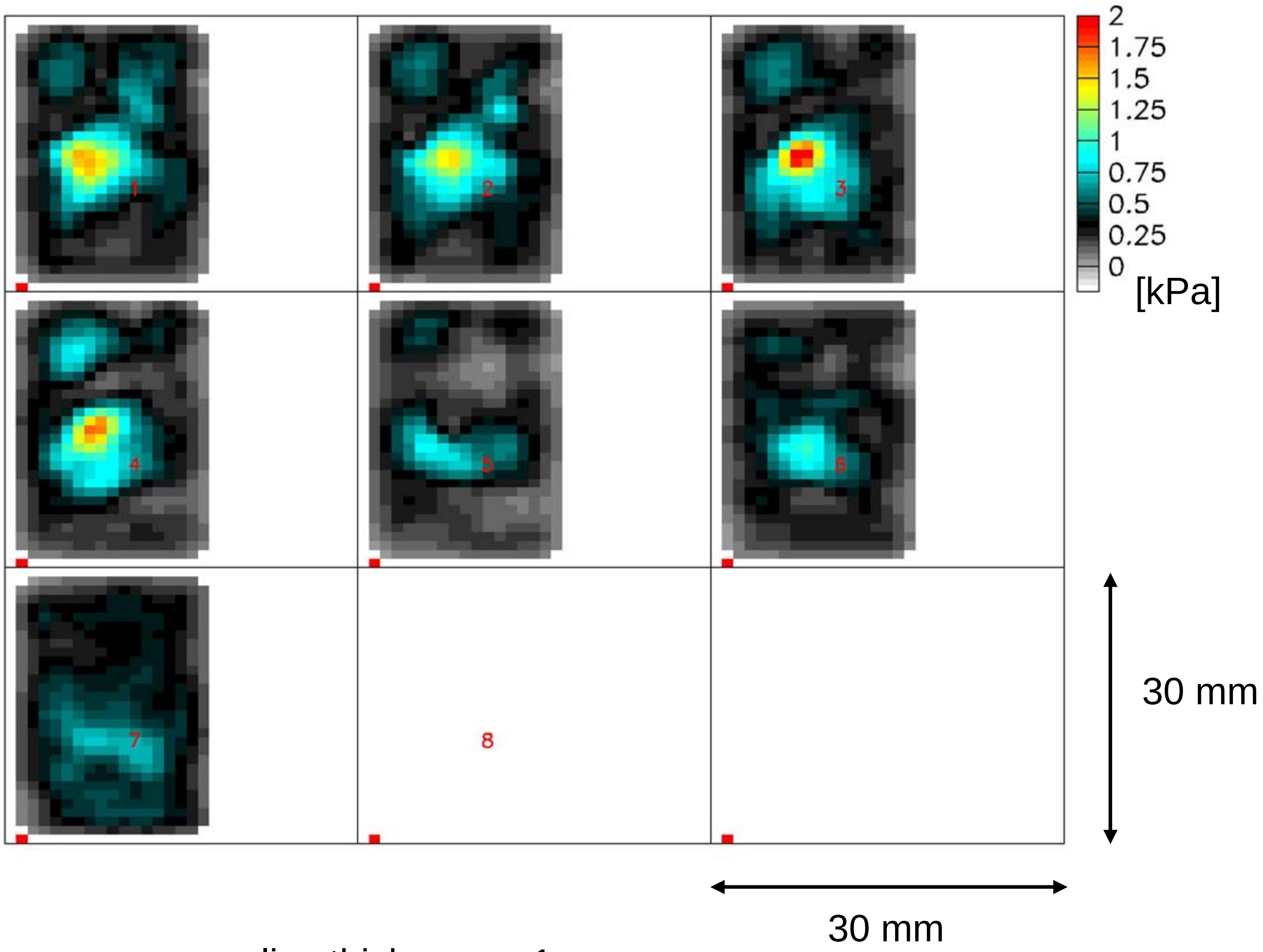


nStep_X
Xoffset_Y
Zfin
Dy
nStep_Y
=
Nslice
barrette-y
Zdebut
Yoffset_X
0/0
z
y
y
Xfin
x
128 pixel
resolution
of US-barrette
Dx
x
Xdebut
Nslice
barrette-x

Reconstructed Shear Modulus

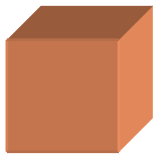
slice at centre of inclusion

slice just out of inclusion



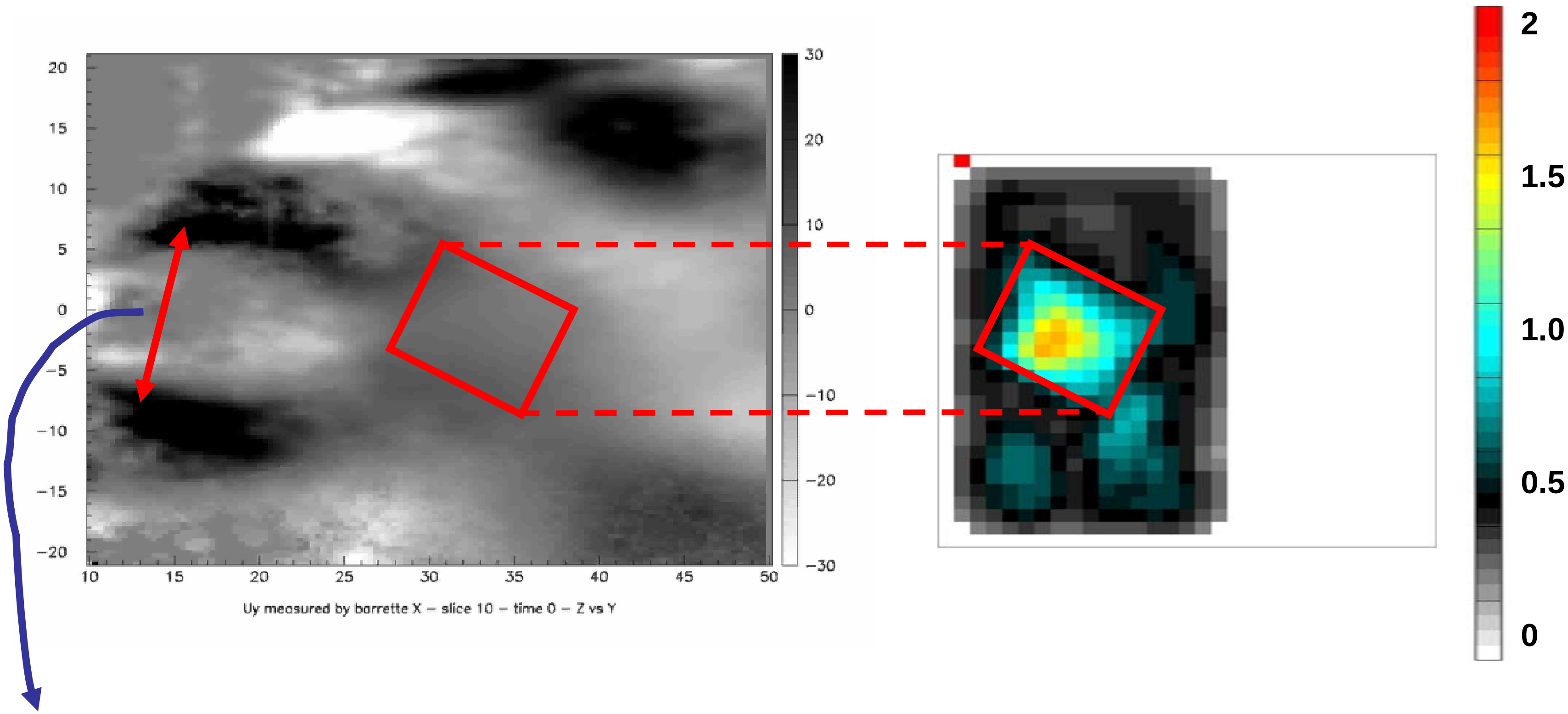
slice thickness = 1mm

inclusion



10 x 10 x 10 mm^3

Reconstructed Shear Modulus



$\lambda \approx 1$ cm $\Rightarrow$ $\mu \approx 0.5$ kPa for background

lesion about 2-3 times stiffer

2D or 3D ?

Supersonic shear imaging

- Control on shear wave generation
- Quantitative
- Not dependant on boundary conditions or motion artefacts
- Natural decoupling of shear and compressional waves
- User independant and Freehand
- Applicable to other organs (heart, liver, prostate,…)

SuperSonic Imagine
Startup created in 2005

3D Ultrasound based elastography

- Robust
- Anisotropy and viscosity mapping
- Cheaper, faster and better resolved than MRE
- Heavy and dedicated protocol