Ultrasons : de la physique à la médecine

Pascal Laugier, Michael Tanter*

Laboratoire d 'Imagerie Paramétrique UMR CNRS 7623
15 rue de l'École de Médecine Paris 75006

*Laboratoire Ondes et Acoustique UMR CNRS
10 rue Vauquelin Paris 75005

Ultrasons en médecine

Applications diagnostiques

- Imagerie échographique
- Vélocimétrie
- Caractérisation tissulaire

Applications thérapeutiques

- Hyperthermie
- Lithotripsie

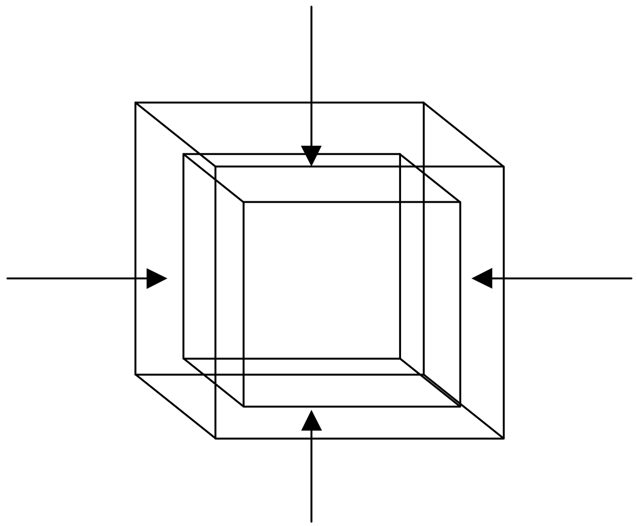
- Imagerie haute fréquence
- Focalisation dans les milieux hétérogènes
- Imagerie quantitative
- Elastographie
- Non linéaire, produits de contraste
- ...

Introduction :l'imagerie echographique

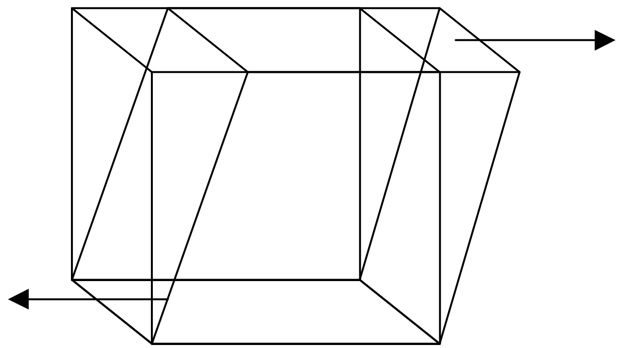
Caractéristiques du milieu de propagation
Solide élastique isotrope

- ❑ Densité r (kg/m ^{3})

- ❑ Modules de compression *K*, module de cisaillement m
  (Module d 'Young *E*, coefficient de Poisson s)



Compression uniforme K



Cisaillement λ

❑ Célérité *c* (m/s)

Onde longitudinale

$$c_l = \sqrt{\frac{3K + 4m}{3r}}$$

Onde de cisaillement

$$c_t = \sqrt{\frac{m}{r}}$$

Tissus mous μ (10^3-10^7 Pa) << K (10^9 Pa)

$$\Rightarrow \quad c_l \approx \sqrt{\frac{K}{\tilde{n}}} \qquad\qquad c_t = \sqrt{\frac{m}{r}}$$

c_l (environ 1500 m/s) >> c_t (qq. m/s à qq. 10 m/s)

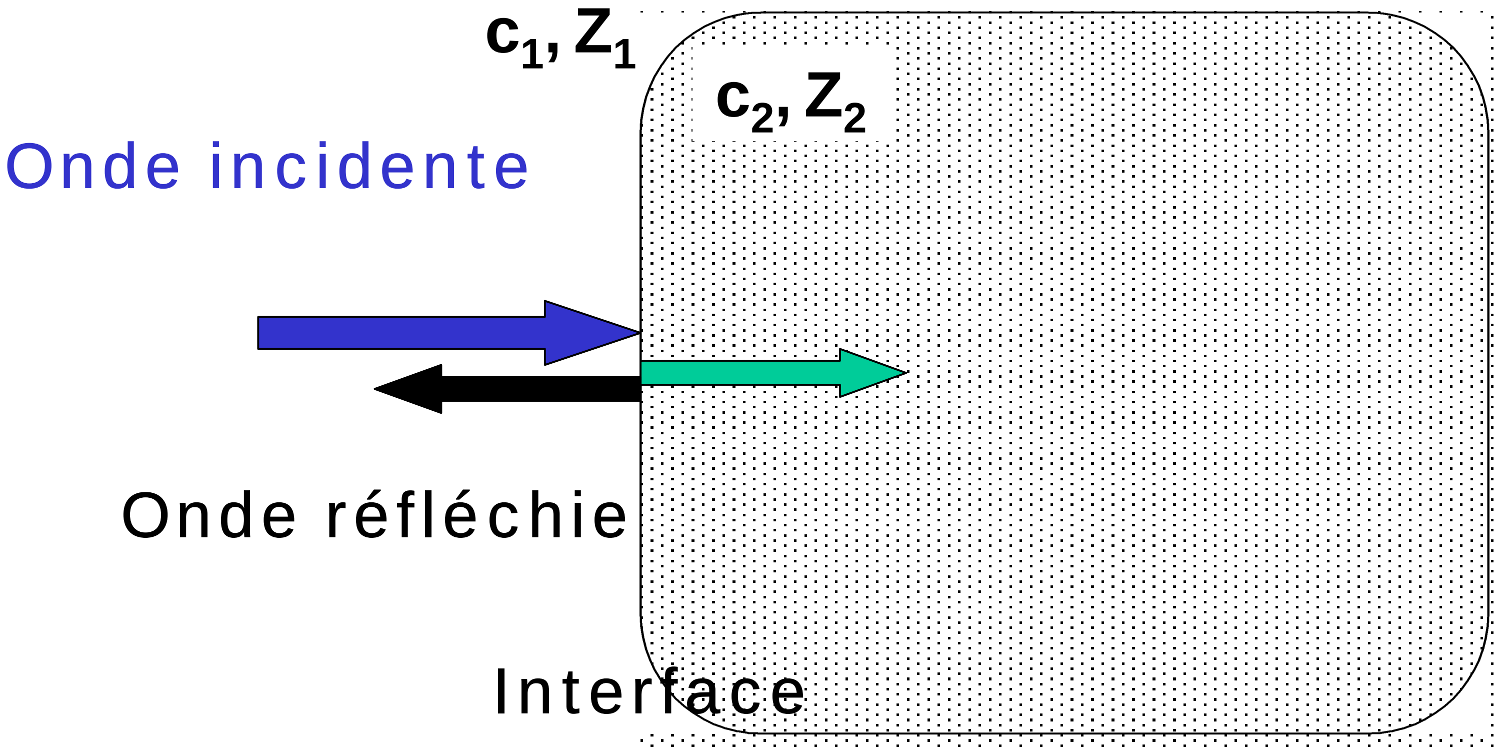
- Tissus mous biologiques

Aux fréquences ultrasonores, onde de cisaillement très rapidement atténuées. En première approximation, seules les ondes de compression se propagent (milieu équivalent fluide).

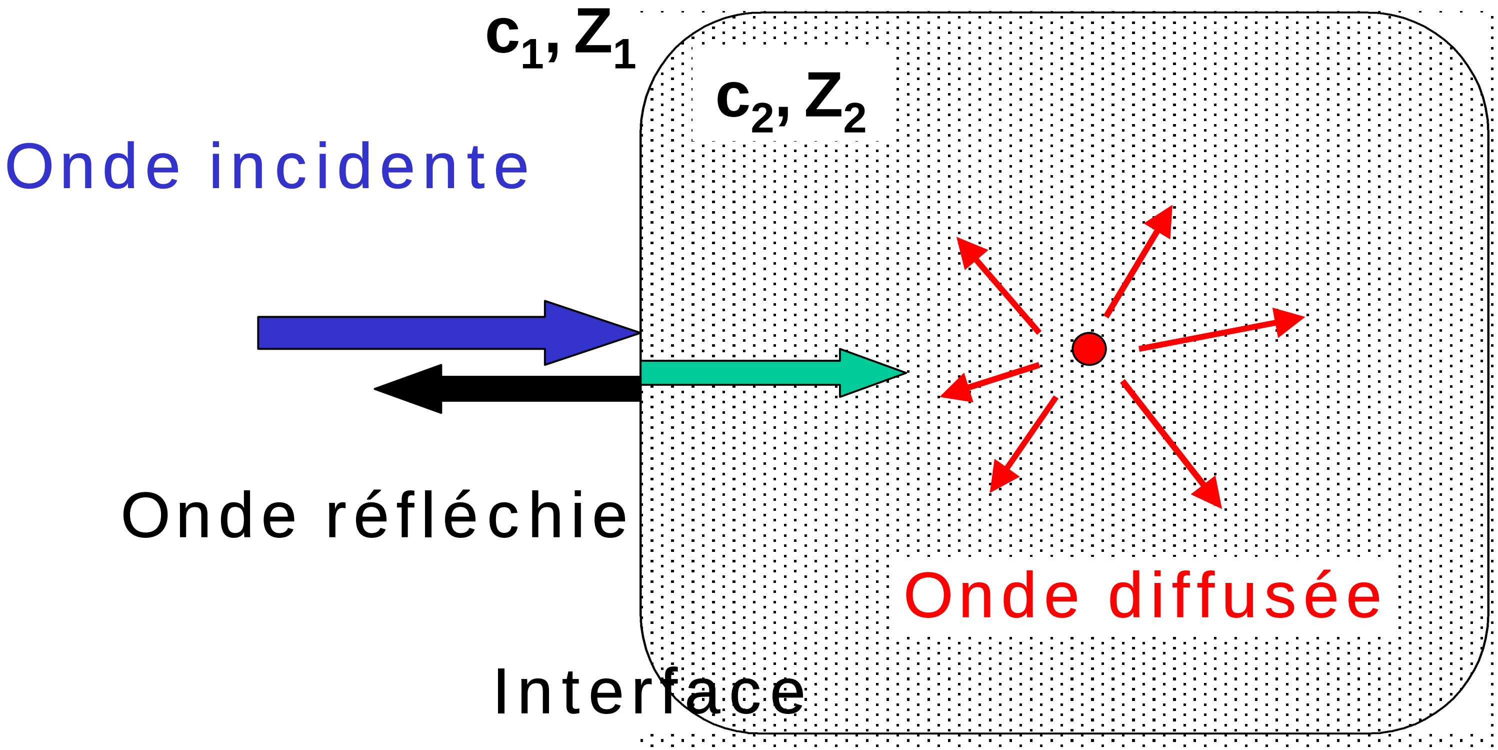
Tissus biologiques mous → HF → Modèle fluide

Tissus biologiques mous → BF → Modèle solide élastique

Interaction des ultrasons / milieu biologiques
Réflexion – Diffusion – Atténuation



Interaction des ultrasons / milieu biologiques
Réflexion – Diffusion – Atténuation



L'intensité incidente est réfléchie, diffusée ou atténuée

Caractéristiques du milieu de propagation

- Impédance acoustique $Z = rc_l$

$$\frac{I_r}{I_0} = R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

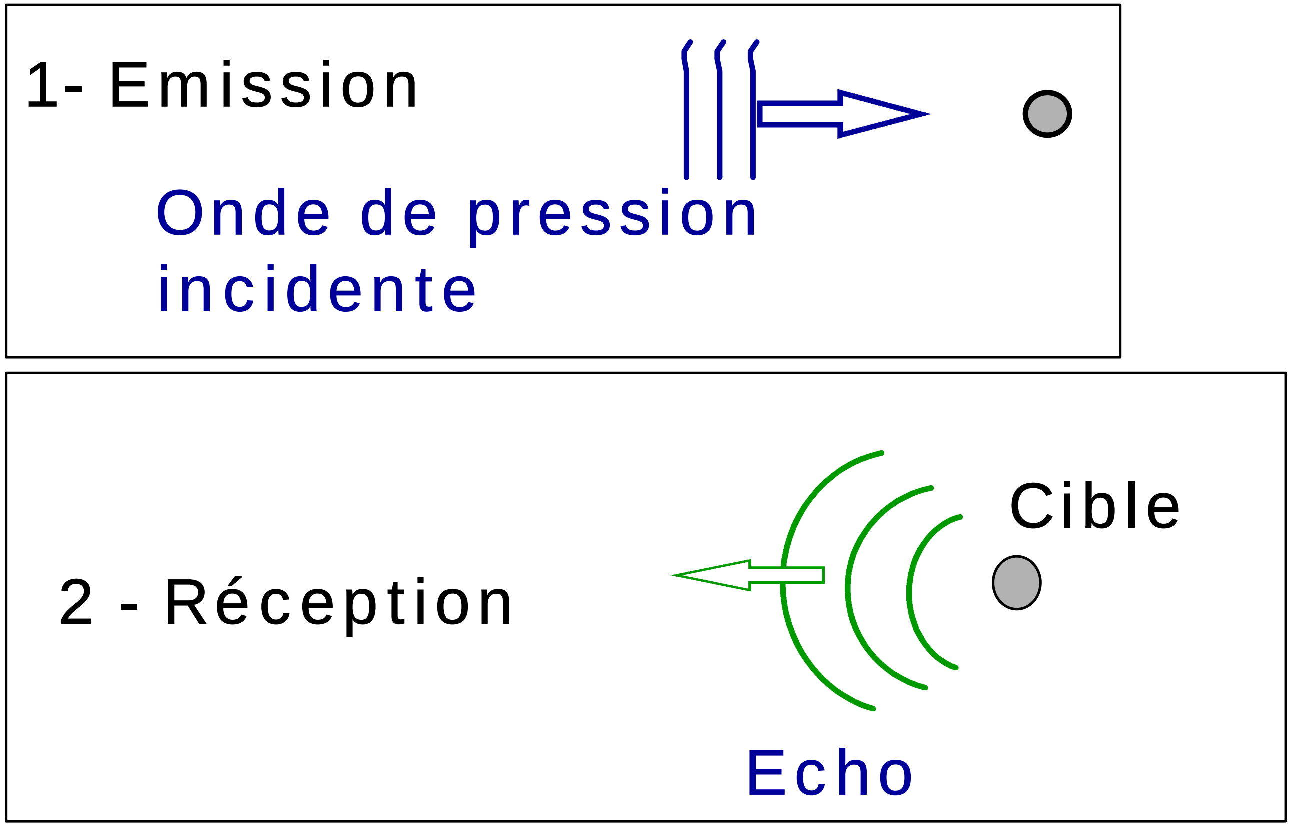
- Rétrodiffusion $\acute{o}_d \propto N V_d^2 k^4 . f(\ddot{a}K, \ddot{a}\tilde{n})$

- Atténuation

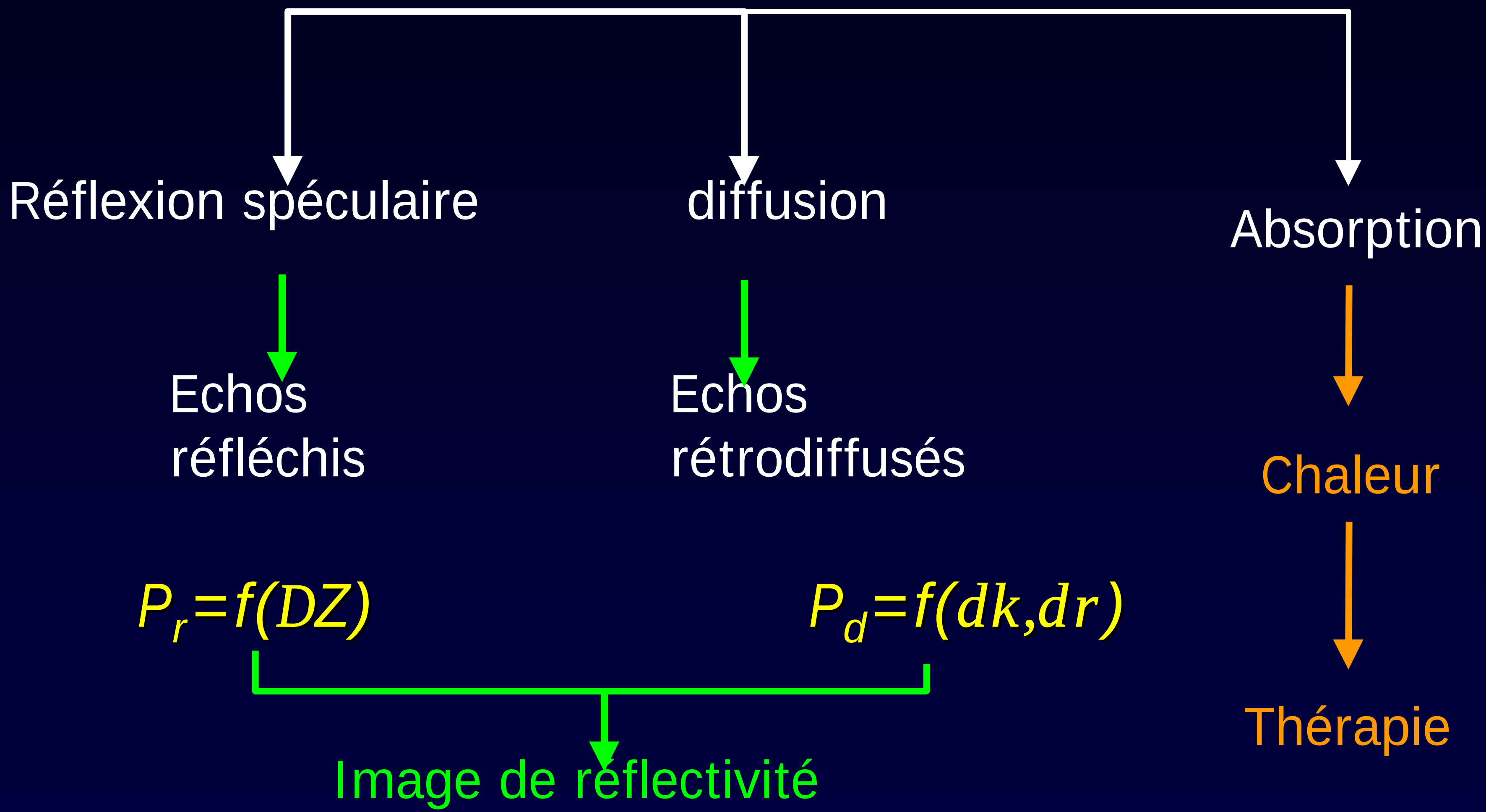
$$I(z) = I_0 e^{-\acute{a}(f)2z}$$

$$\acute{a}(f) = \hat{a}f$$

Principe général de l ’échographie



Energie ultrasonore incidente



Caractéristiques du milieu de propagation

- Atténuation

$$I(z) = I_0 e^{-á(f)2z}$$

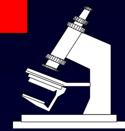
$$á(f) = âf$$

Lorsque la fréquence augmente

- la résolution augmente,
- la profondeur d'exploration diminue

Échelle de fréquence/longueur d'onde/ profondeur d’exploration

1MHz 10 MHz 20 MHz 100 MHz



1.5 mm<λ<150µm 150µm<λ<75µm 75µm<λ<15µm

Applications		
Abdomen Cou, pédiatrie Muscles/tendons (3.5-7.5 MHz)	Œil (10 MHz) Endocavitaire (7.5-12 MHz)	Peau (20 MHz) Endovasculaire (30-50 MHz) Œil (80 MHz)

- Imagerie haute fréquence
- Focalisation dans les milieux hétérogènes
- Elastographie
- Imagerie quantitative
- Non linéaire, produits de contraste
- ...

Imagerie très haute résolution spatiale

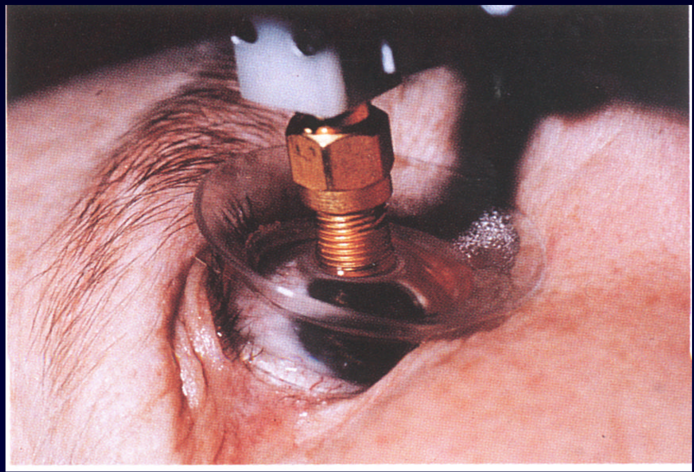
Biomicroscopie acoustique in vivo

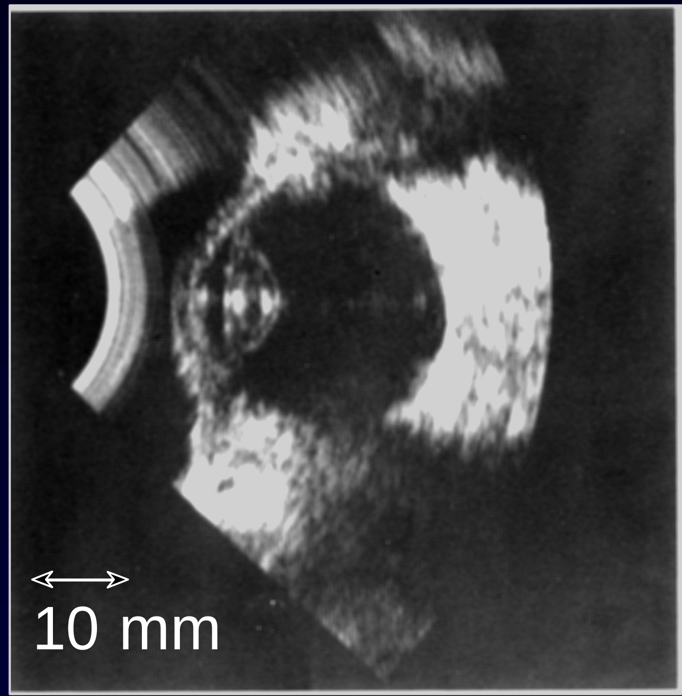
- Haute fréquence 20 - 80 MHz
- Résolution spatiale 30 - 75 µm
- faibles profondeurs d 'exploration
- Imagerie superficielle ou par voie endocavitaire

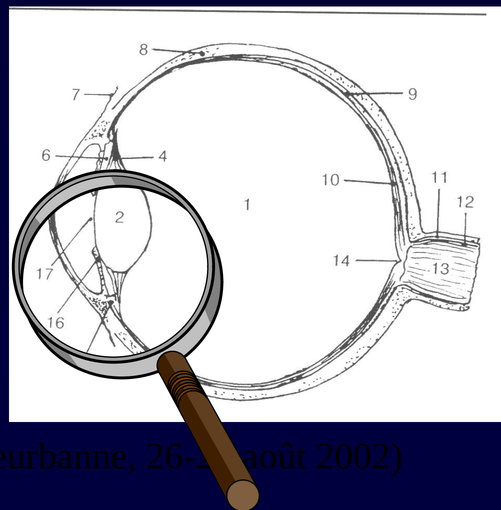
Imagerie très haute résolution spatiale

Un exemple : Ophtalmologie

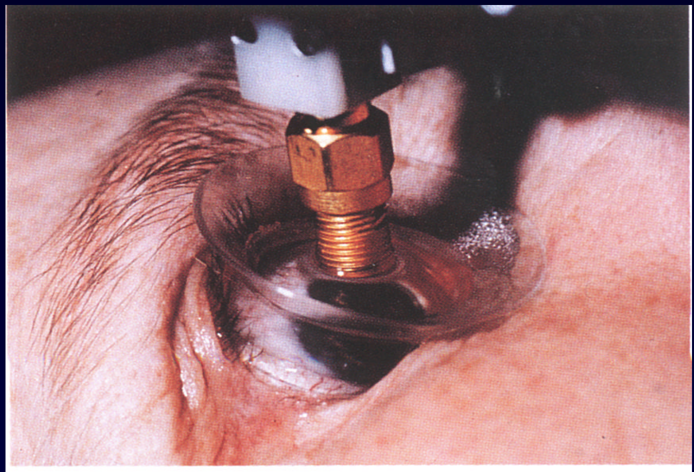
Echographie de l ’œil à 10 MHz
(basse fréquence)

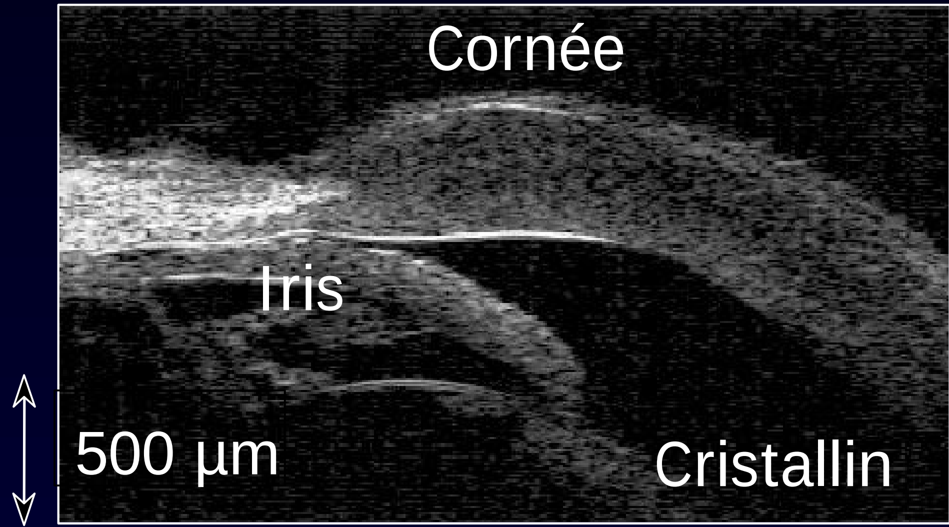


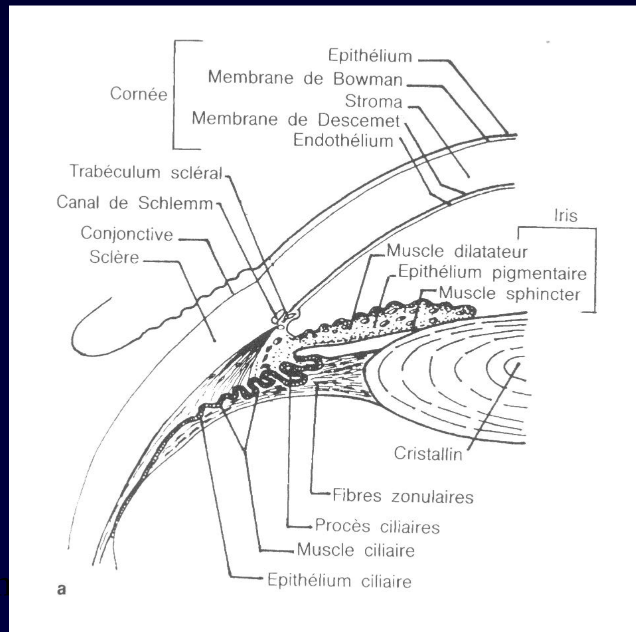




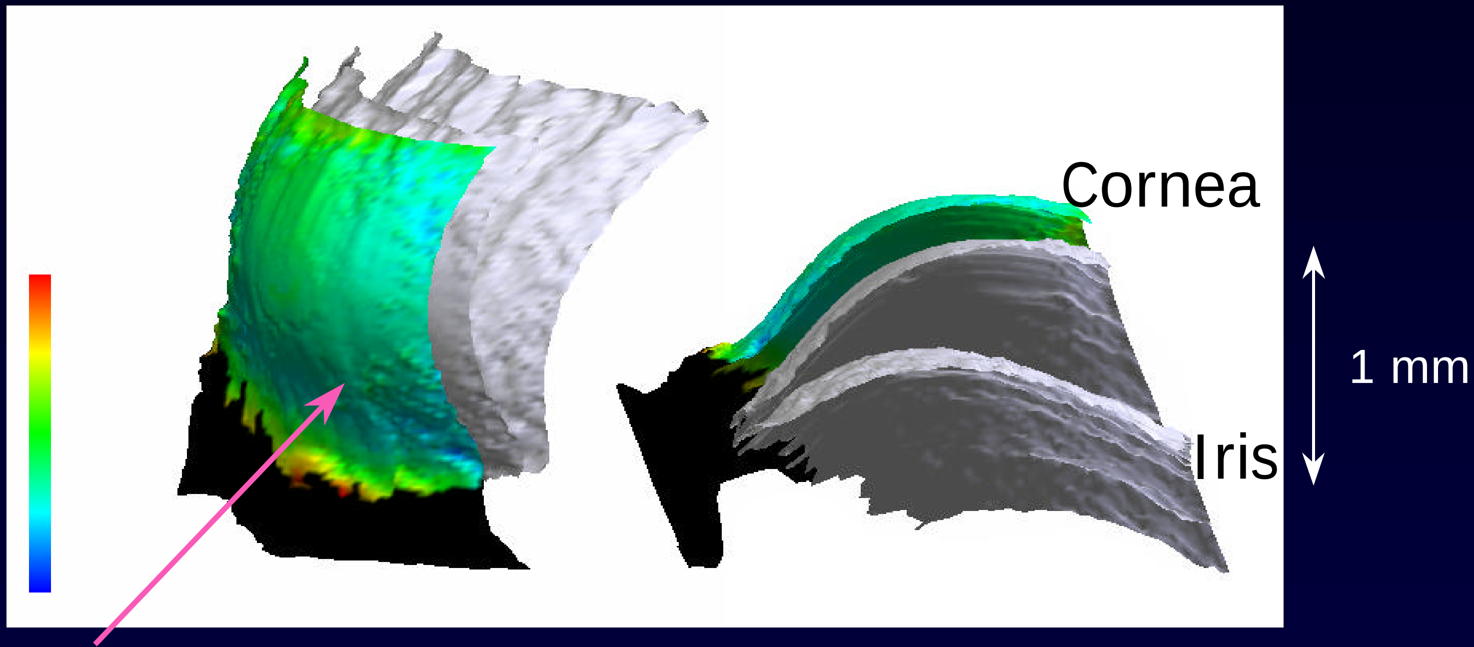
Echographie de l ’œil à 80 MHz
(haute fréquence)







3-D representation



Mapping of the cornea thickness

Saied, LIP

Imagerie très haute résolution spatiale

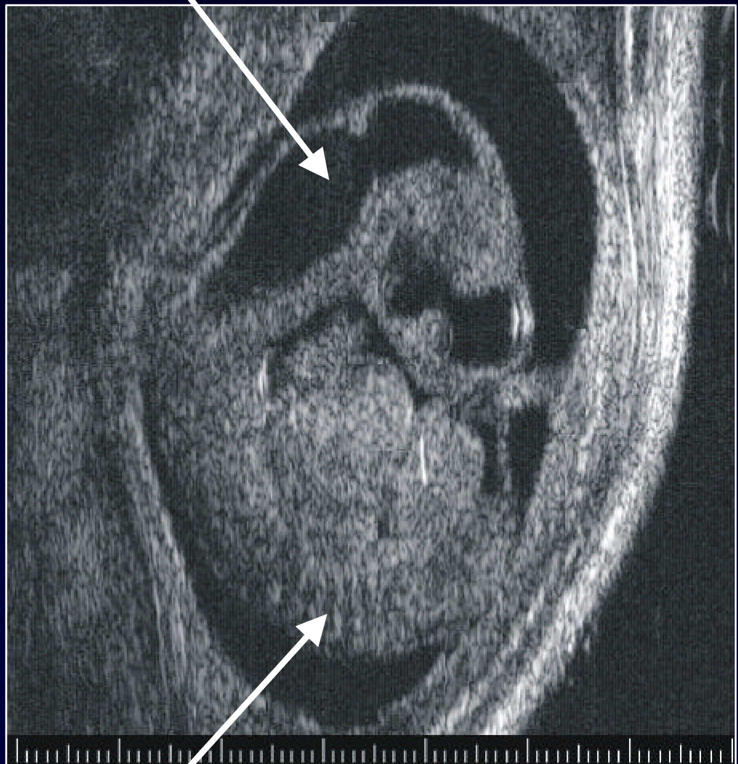
De l 'Homme à la Souris

Embryonic Development

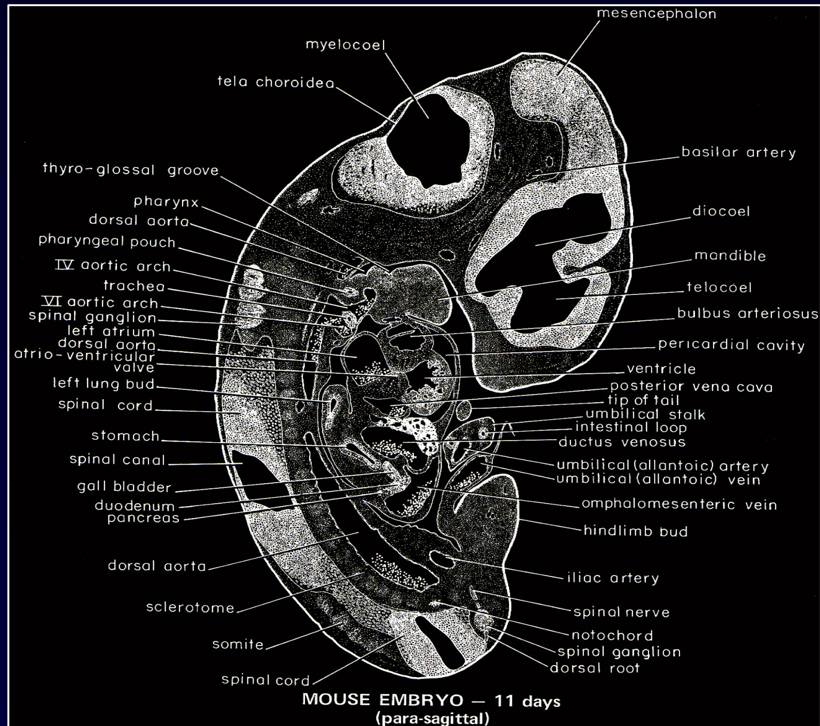
Embryonic day 11.5

Neural Tube

1 mm



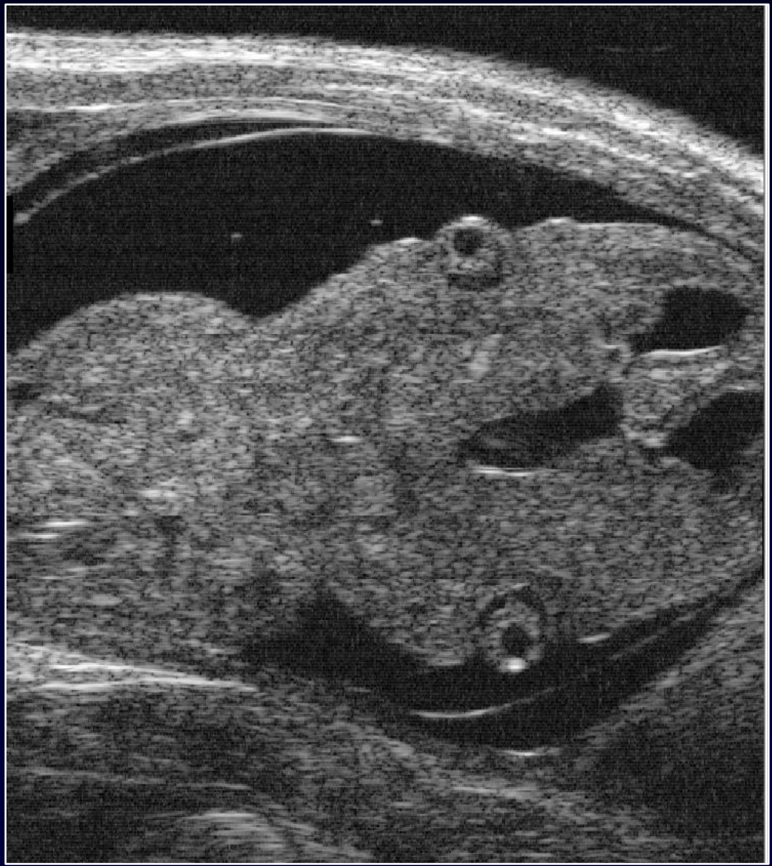
Somites



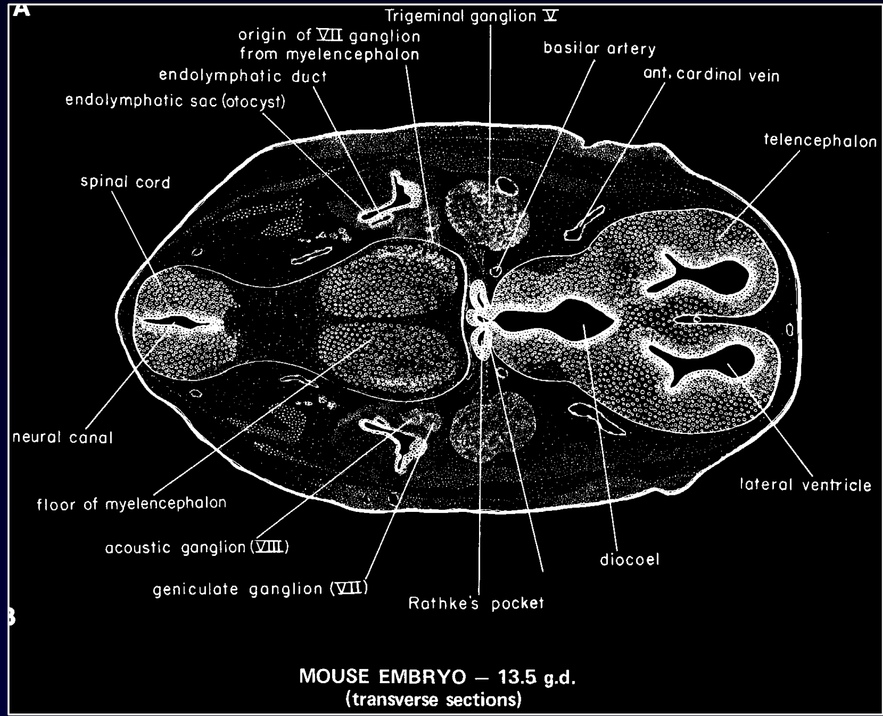
Rugh, 1994. The Mouse: Its reproduction and Development. Oxford Science Publications.

Courtesy of S Foster et al, University of Toronto, Canada

Embryonic day 13.5



1 mm



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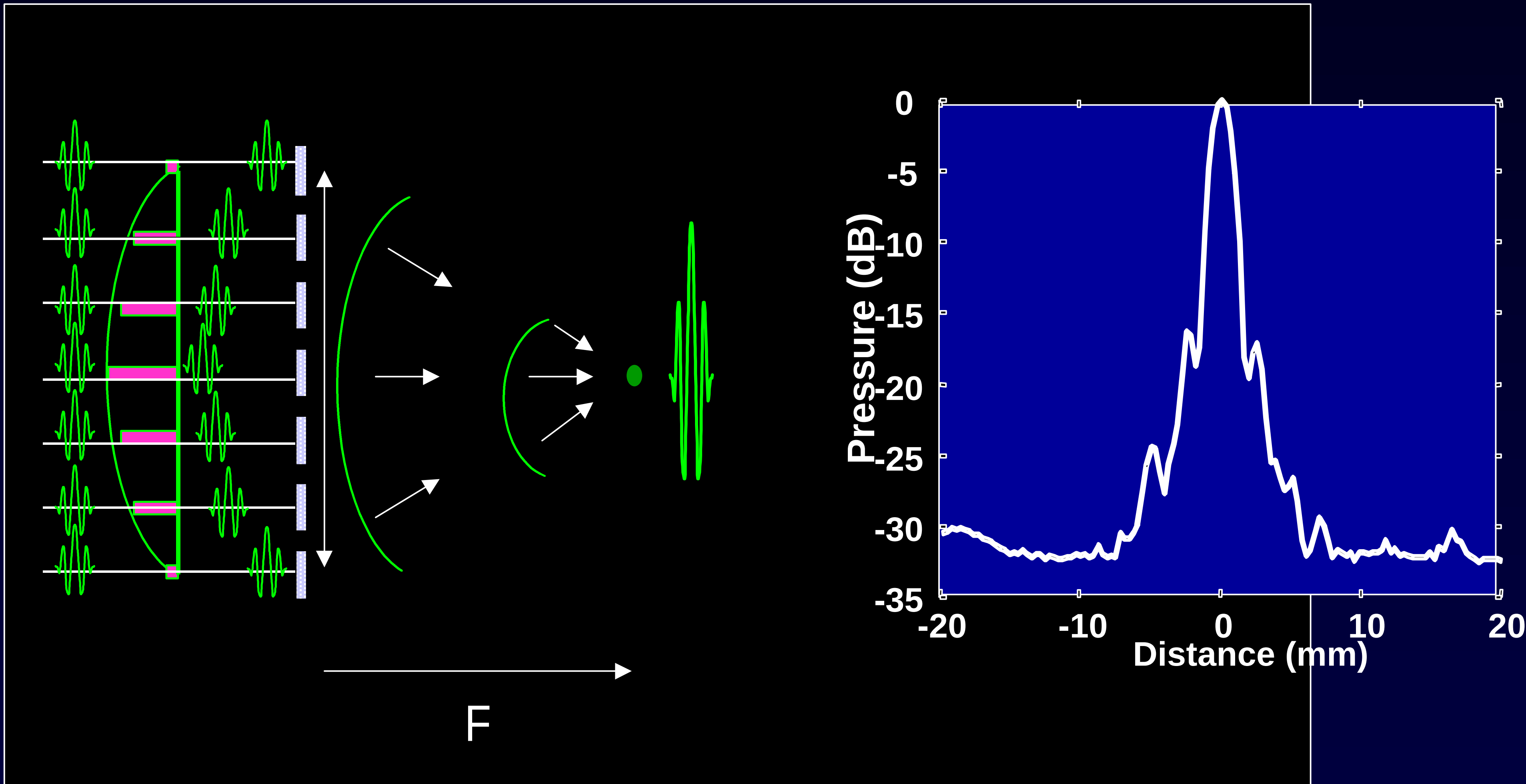
P. Laugier, LIP & M. Tanter, LOA - e2phy 2002 (Villeurbanne, 26-29 août 2002)

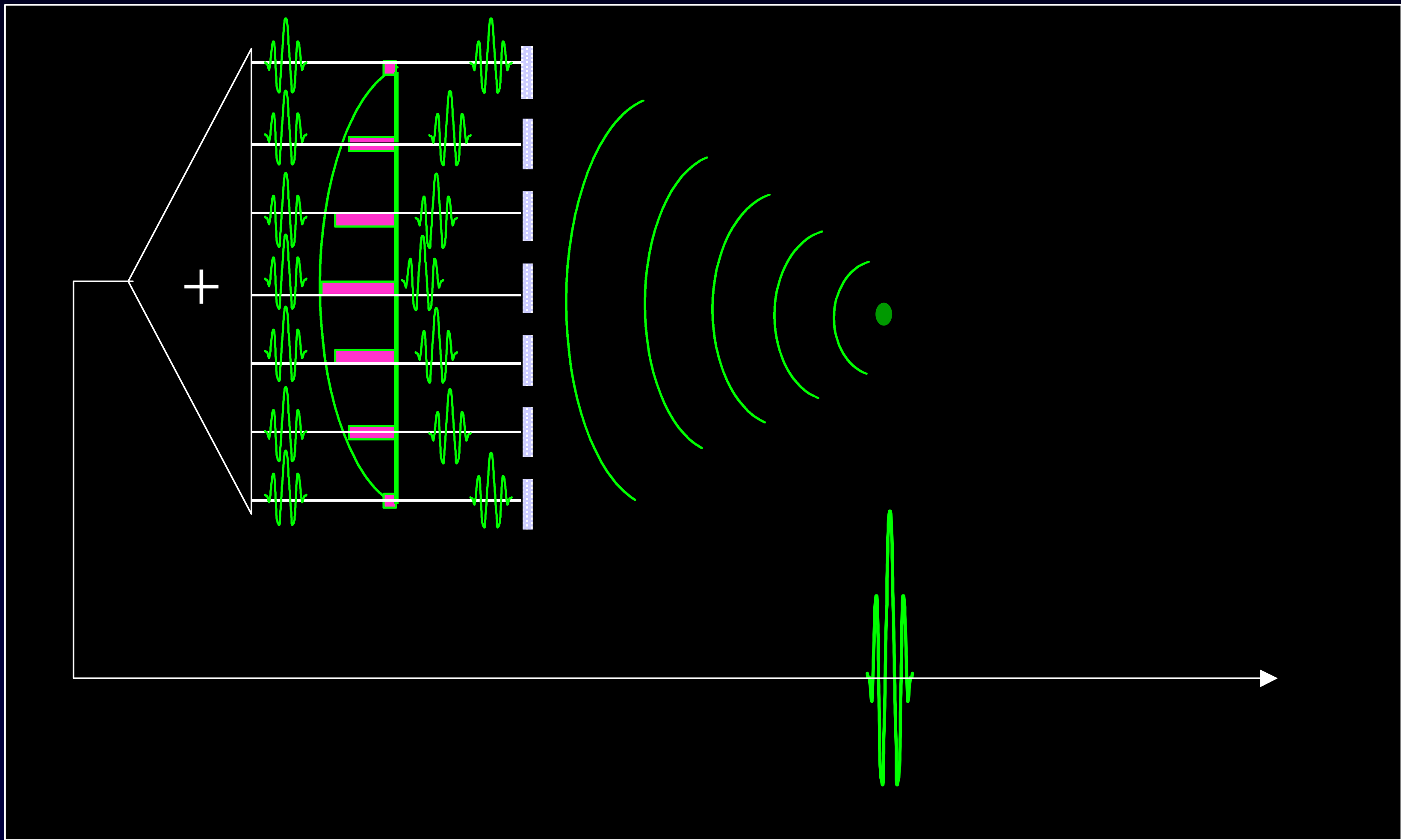
- Imagerie haute fréquence
- **Focalisation dans les milieux hétérogènes**
- Imagerie quantitative
- Elastographie
- Non linéaire, produits de contraste
- ...

Focalisation l 'émission



Focalisation par retards analogiques ou numériques

Focalisation dynamique en réception



Focalisation par retards analogiques ou numériques

Surface mode of the fetal face and both hands at 22 weeks

Vitesse de propagation dans les tissus biologiques

Milieu	célérité (m/s)
Eau	1480
Air	340
Sang	1566
Graisse	1460
Foie	1560
Muscle	1600
Peau	1700
Os cortical	4000

M. Tanter, J.L. Thomas, J.F. Aubry, LOA

Focusing through the skull

Experimental setup

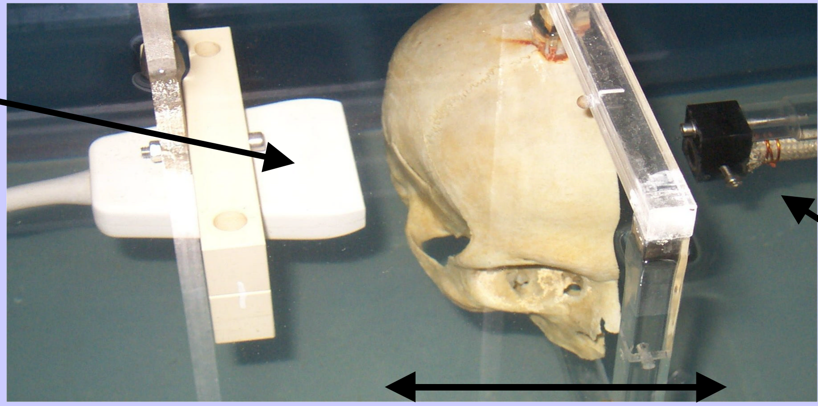
Linear array of transducers:

128 elements

λ/2 array pitch

central frequency: 1.5MHz

70 mm total aperture



Hydrophone

10cm

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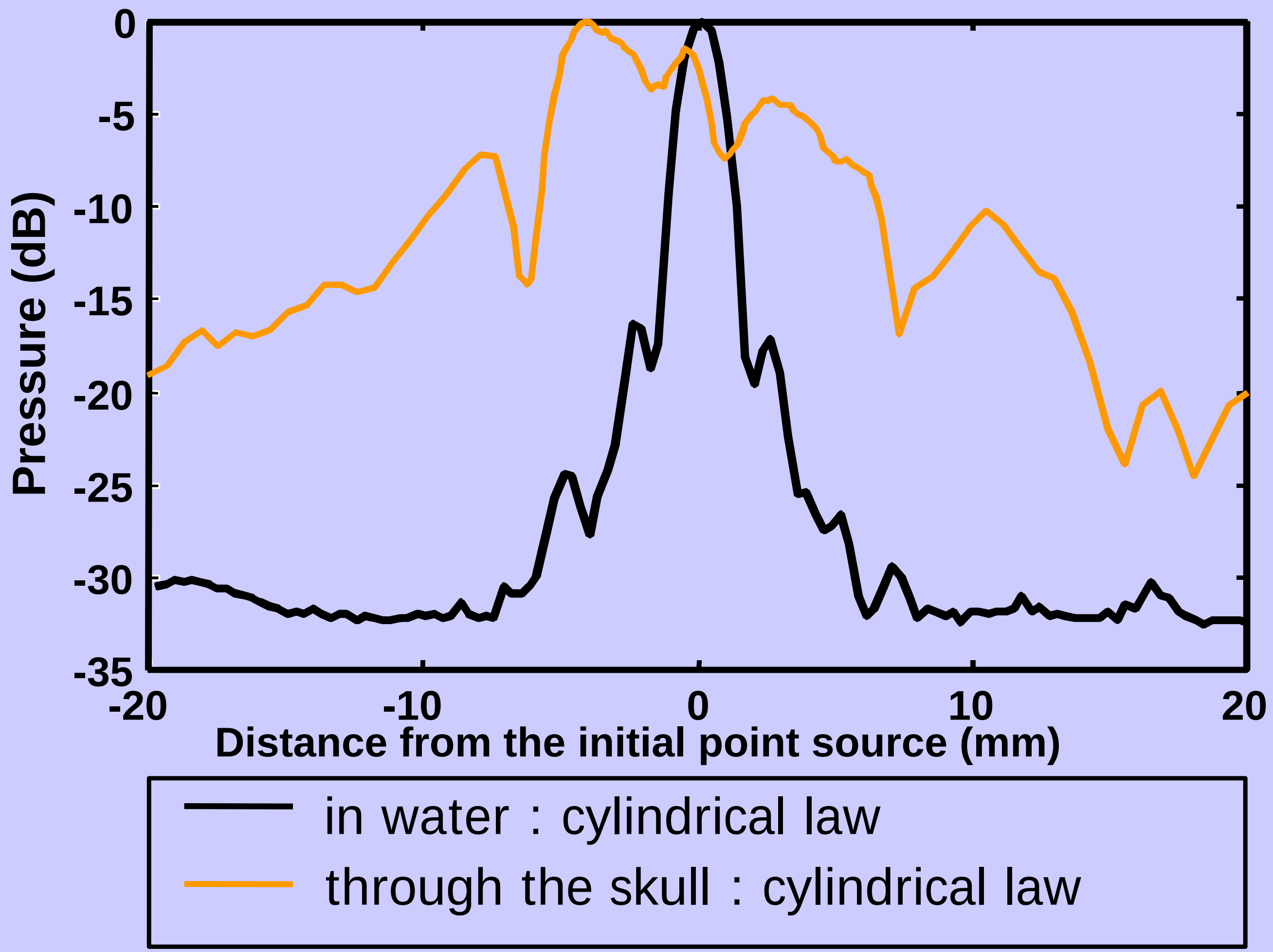
Focusing through the skull : cylindrical law

Experimental results



Time reversal in non dissipative fluid

$\boldsymbol{p}(\vec{\boldsymbol{r}},\boldsymbol{t})$ acoustic pressure field (scalar)

$r(\vec{\boldsymbol{r}})$ is the density and $\boldsymbol{c}(\vec{\boldsymbol{r}})$ is the sound velocity

In linear acoustic $\rightarrow$

$$\boxed{r(\vec{\boldsymbol{r}})\,\boldsymbol{div}\left(\frac{\boldsymbol{grad}(\boldsymbol{p})}{r(\vec{\boldsymbol{r}})}\right)-\frac{1}{\boldsymbol{c}^2(\vec{\boldsymbol{r}})}\frac{\partial^2\boldsymbol{p}}{\partial\boldsymbol{t}^2}=0}$$

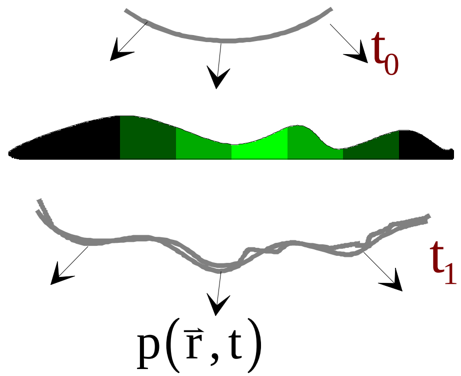
Spatial reciprocity Time reversal invariance

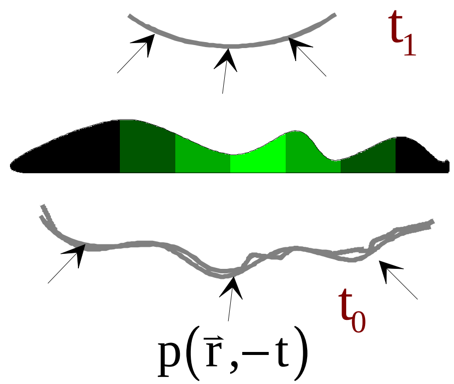
This equation contains only $\dfrac{\partial^2\boldsymbol{p}(\vec{\boldsymbol{r}},\boldsymbol{t})}{\partial\boldsymbol{t}^2}$

Then if $\boldsymbol{p}(\vec{\boldsymbol{r}},\boldsymbol{t})$ is a solution

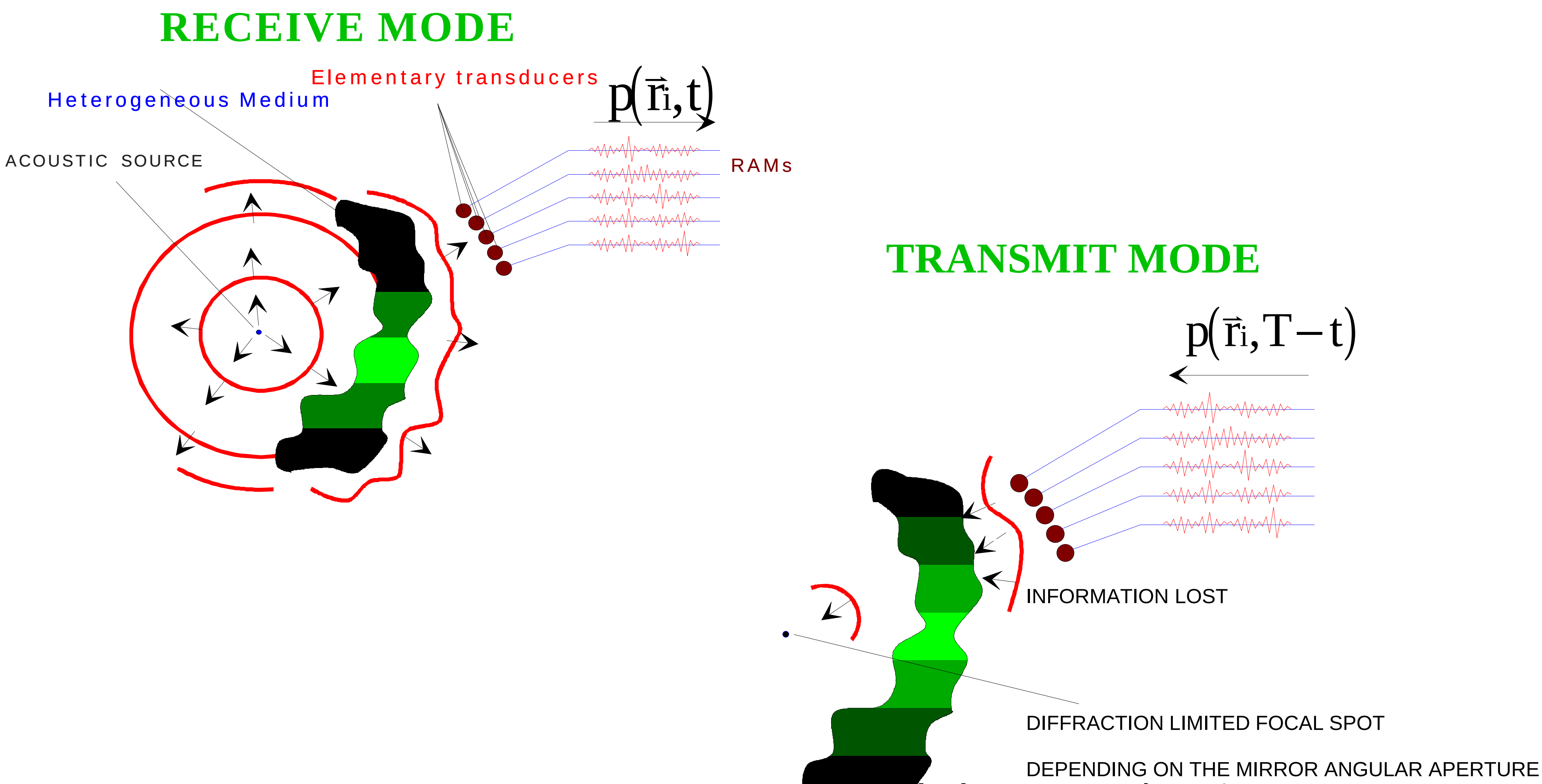
$\boldsymbol{p}(\vec{\boldsymbol{r}},-\boldsymbol{t})$ is also a solution

because $$\frac{\partial^2\boldsymbol{p}(\vec{\boldsymbol{r}},\boldsymbol{t})}{\partial\boldsymbol{t}^2}=\frac{\partial^2\boldsymbol{p}(\vec{\boldsymbol{r}},-\boldsymbol{t})}{\partial\boldsymbol{t}^2}$$



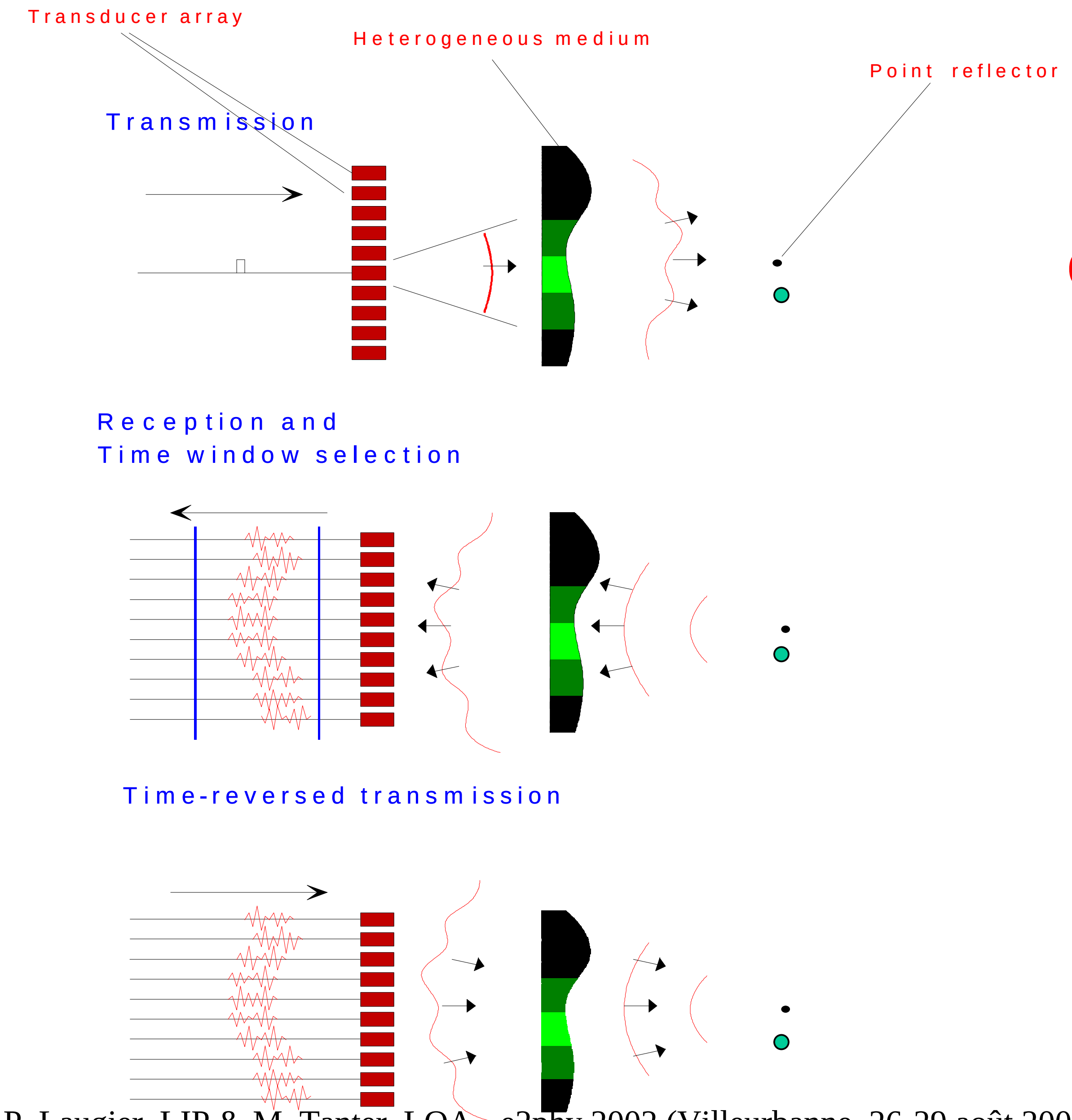


TIME REVERSAL MIRROR



Theory by D. Cassereau, D. Jackson, D.R. Dowling

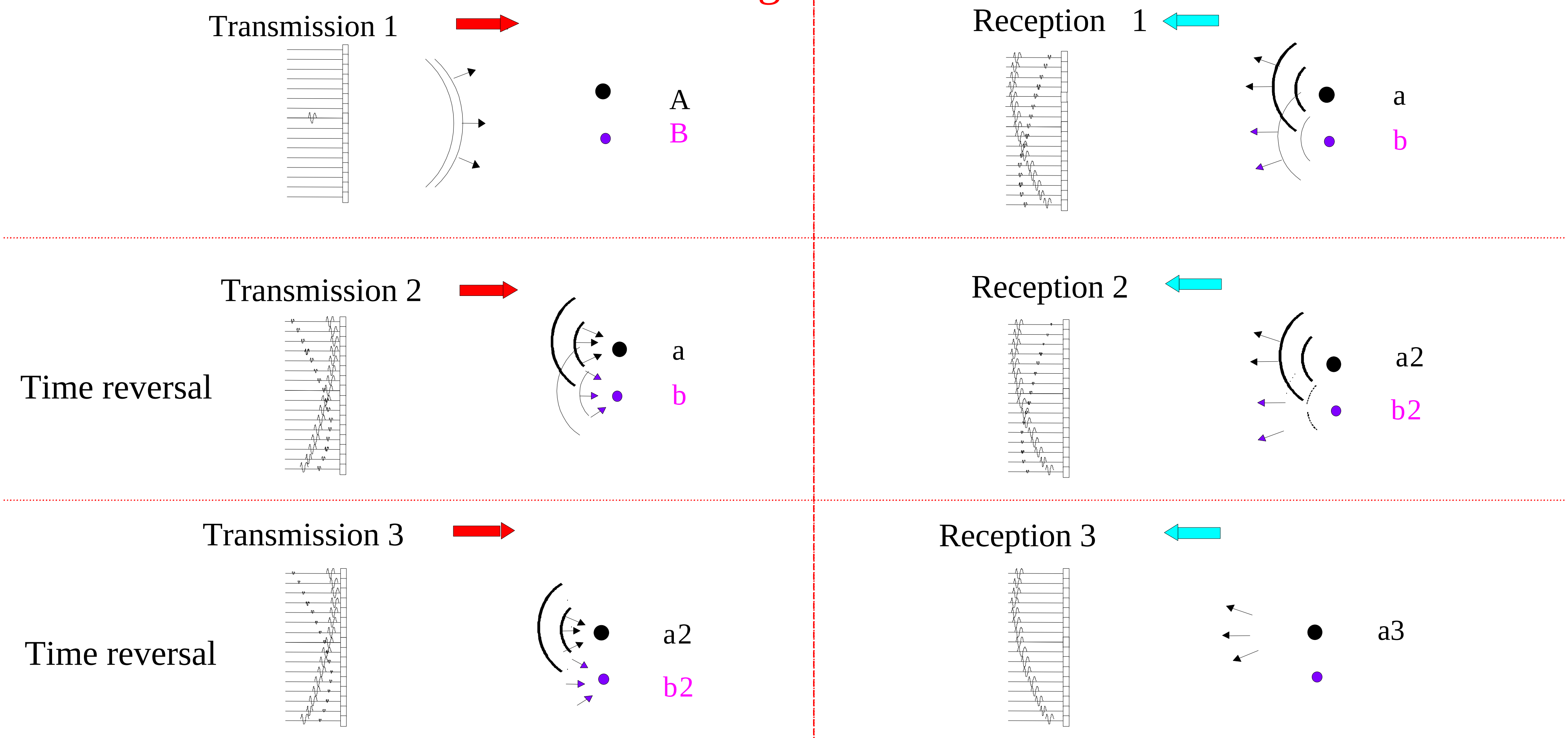
AUTOFOCUS IN PULSE ECHO MODE



One target

The Iterative Time Reversal Process

Multi target medium



C.Prada

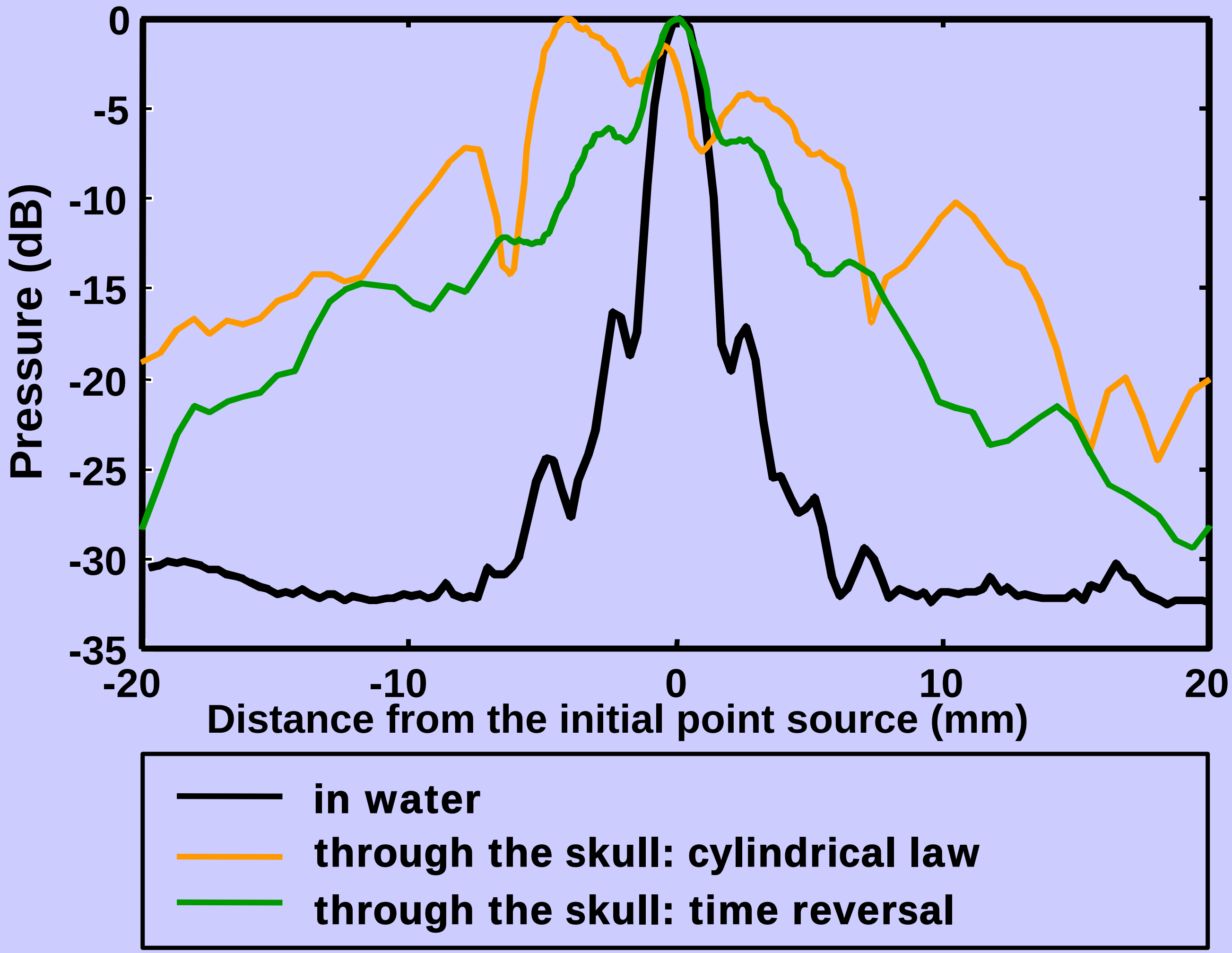
Application of TRM to Lithotripsy

J.L. Thomas, F. Wu, LOA

M. Tanter, J.L. Thomas, J.F. Aubry, LOA

Time reversal through the skull

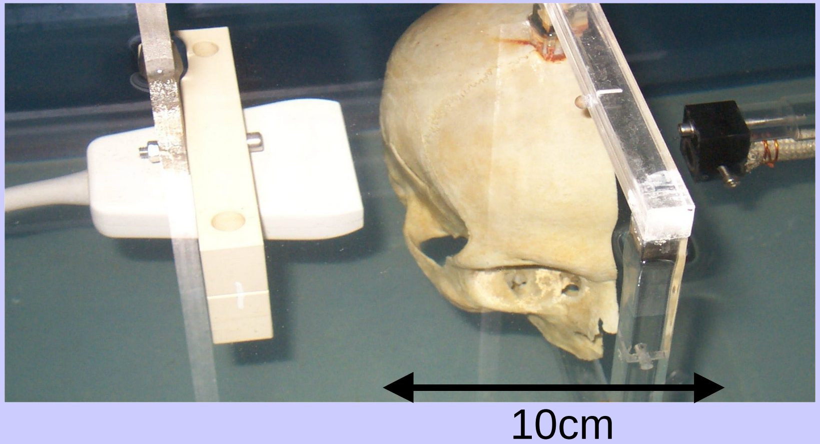
Experimental results



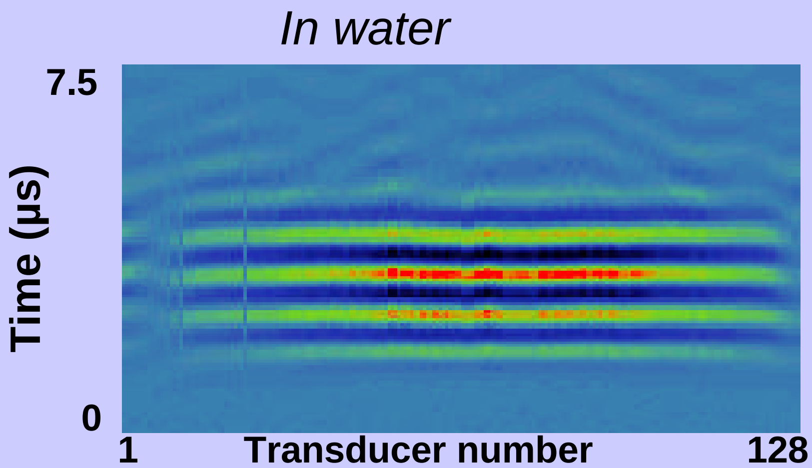
M. Tanter, J.L. Thomas, J.F. Aubry, LOA

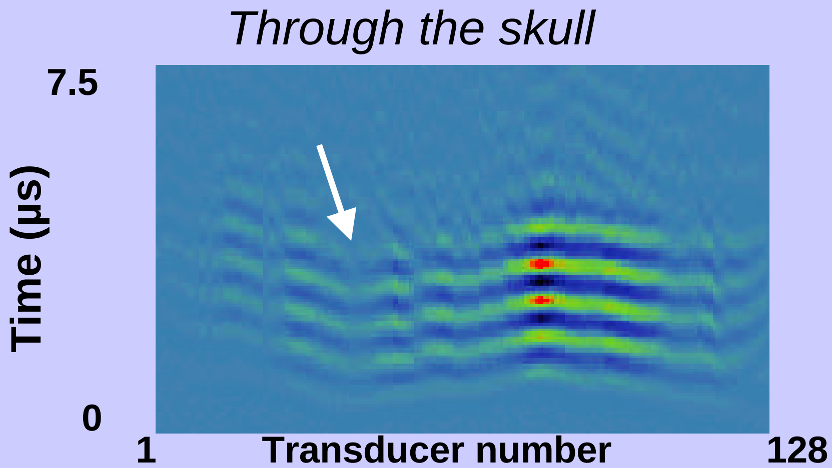
Time reversal through the skull

Experimental setup

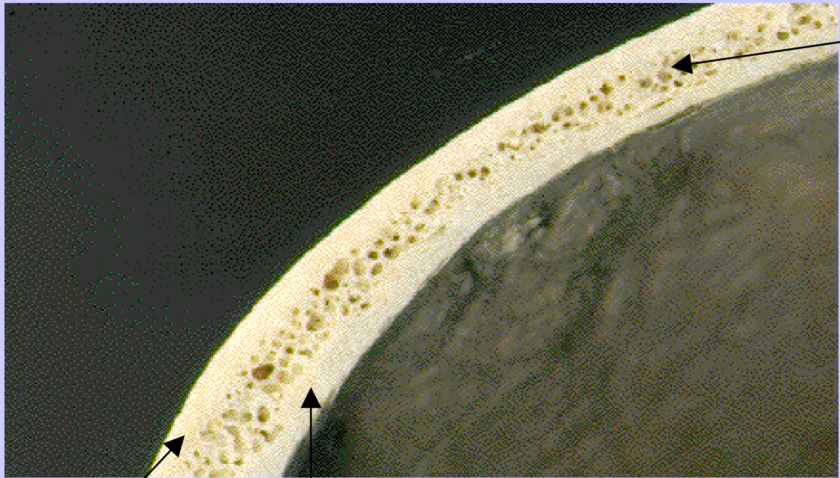


Effects of the skull on the wave front





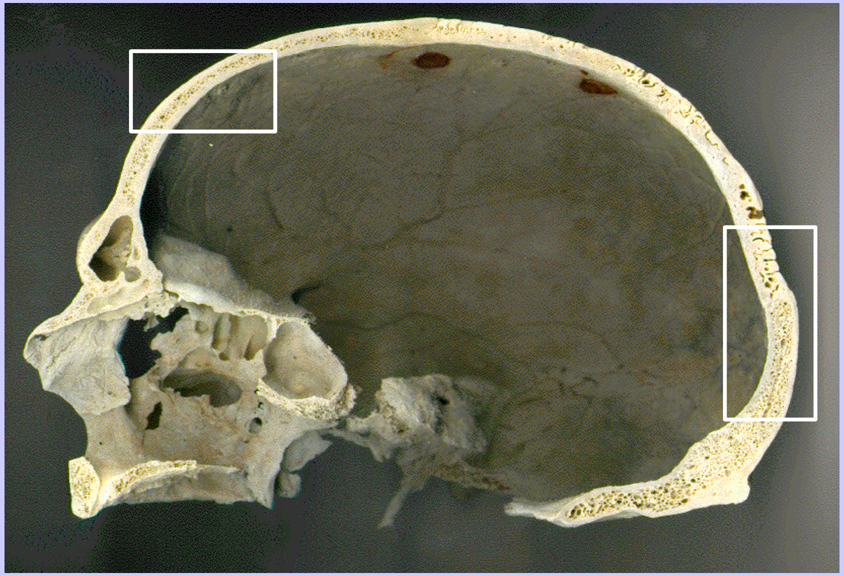
Influence of the trabecular bone on the acoustic propagation



Diploë :Porous zone
(c = 2700 m.s^{-1})

External wall
(c = 3000 m.s^{-1})

Internal wall
(c = 3000 m.s^{-1})



P. Laugier, LIP & M. Tanter, LOA - e2phy 2002 (Villeurbanne, 26-29 août 2002)

M. Tanter, J.L. Thomas, J.F. Aubry, LOA

Time reversal in an heterogeneous absorbing medium

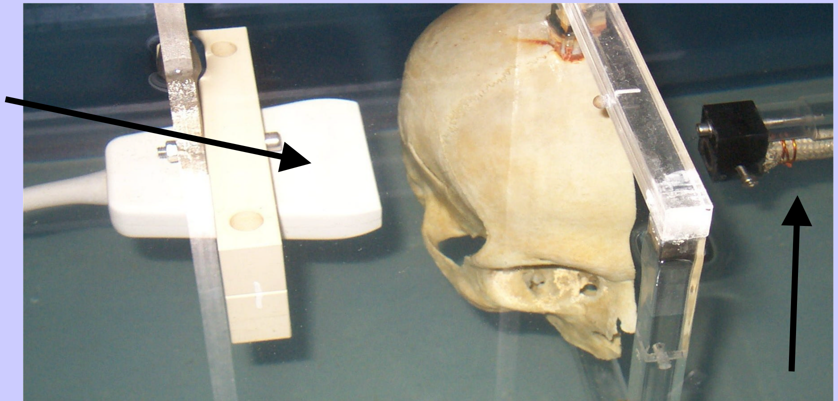
Theory

Wave equation in fluids :

$$\left(1+t(\vec{r})\frac{\partial}{\partial t}\right)r(\vec{r})\,div\left(\frac{\overrightarrow{gradp}(\vec{r},t)}{r(\vec{r})}\right)-\frac{1}{c^2(\vec{r})}\frac{\partial^2 p(\vec{r},t)}{\partial t^2}=0$$

Breaking the time reversal invariance

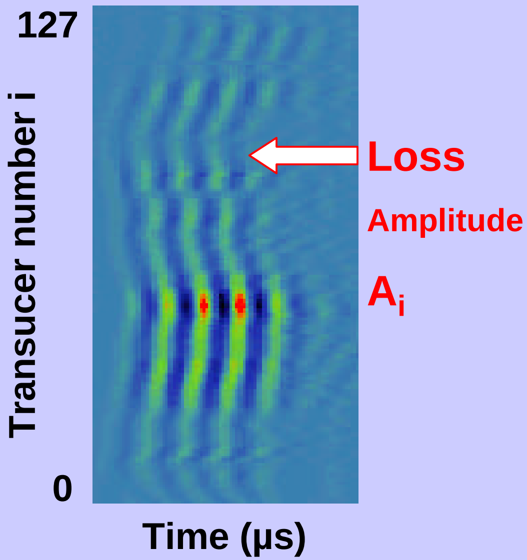
Experimental setup



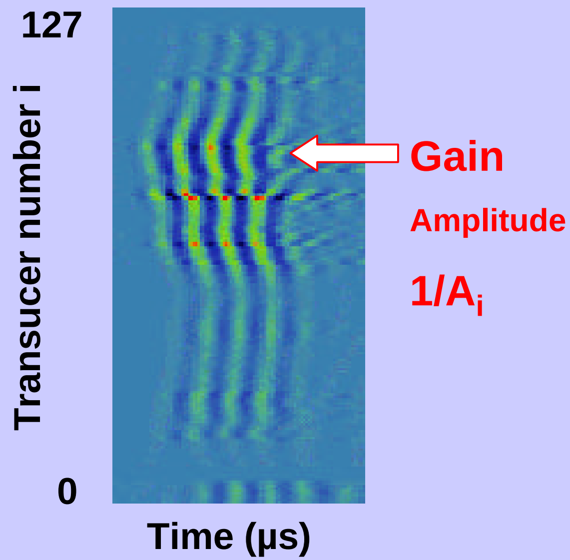
Hydrophone

Amplitude compensation

Received wave front



Corrected wave front



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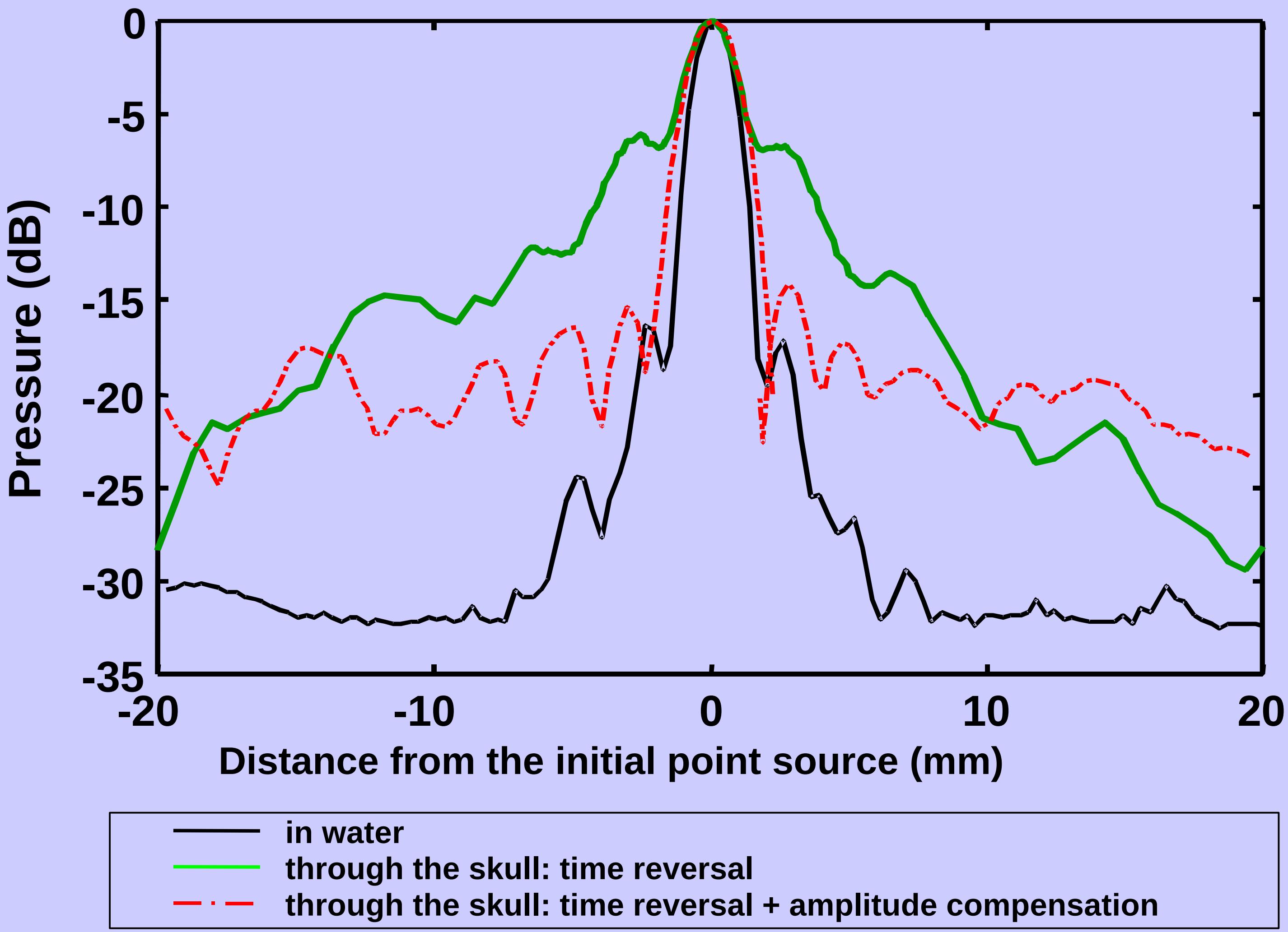
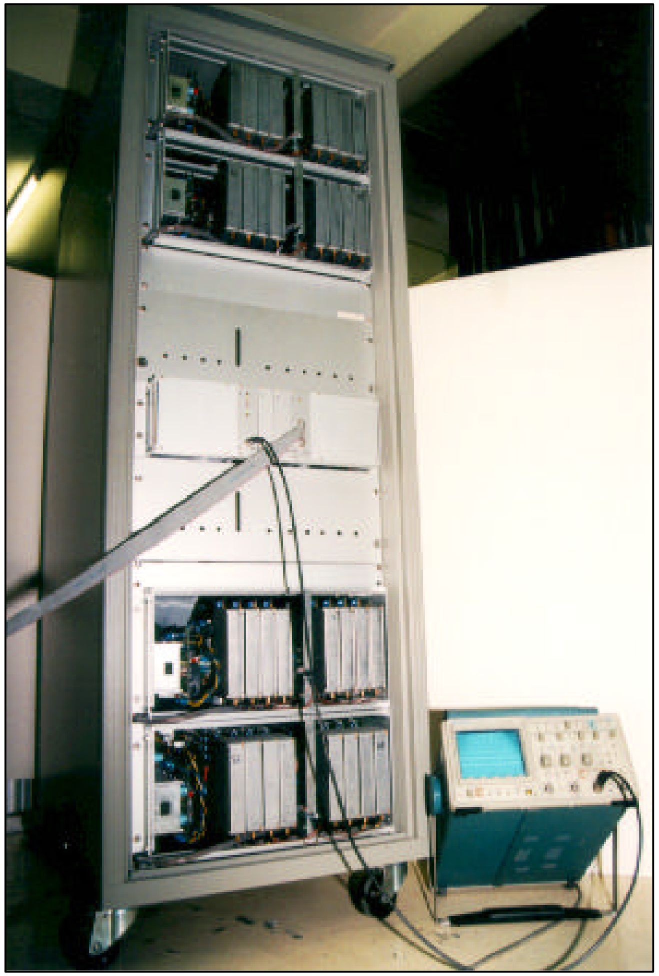
Time reversal in heterogeneous absorbing media

Experimental results

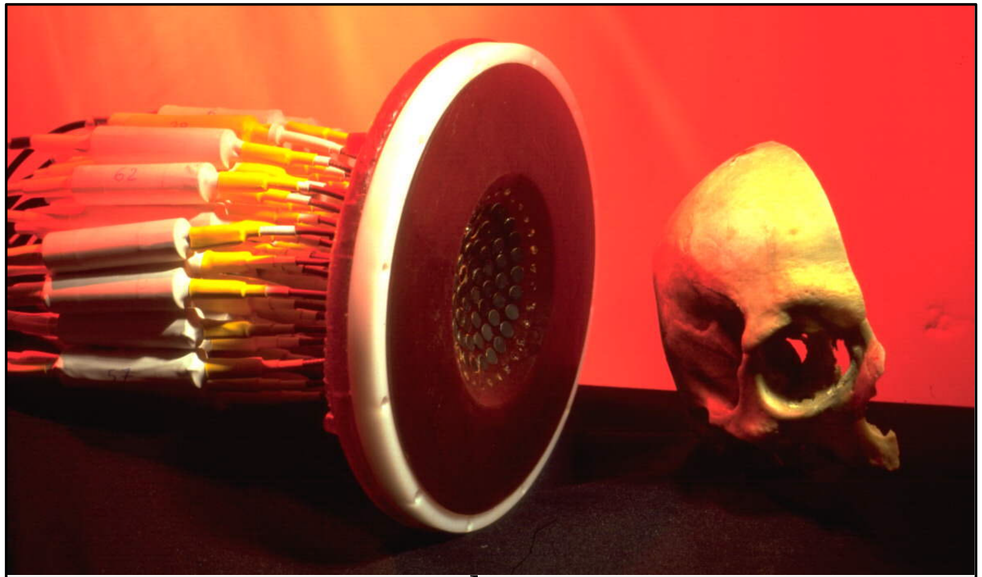


High Power Time Reversal Mirror for Hyperthermia



Electronic

- ❒ 64 Channels T/R 18 W
- ❒ 64 Transducers (1 MHz, 7 bars)
- ❒ Geometrical focus 100 mm
- ❒ Acoustic Power at the focus 6000 W.cm^{-2}



Transducers array

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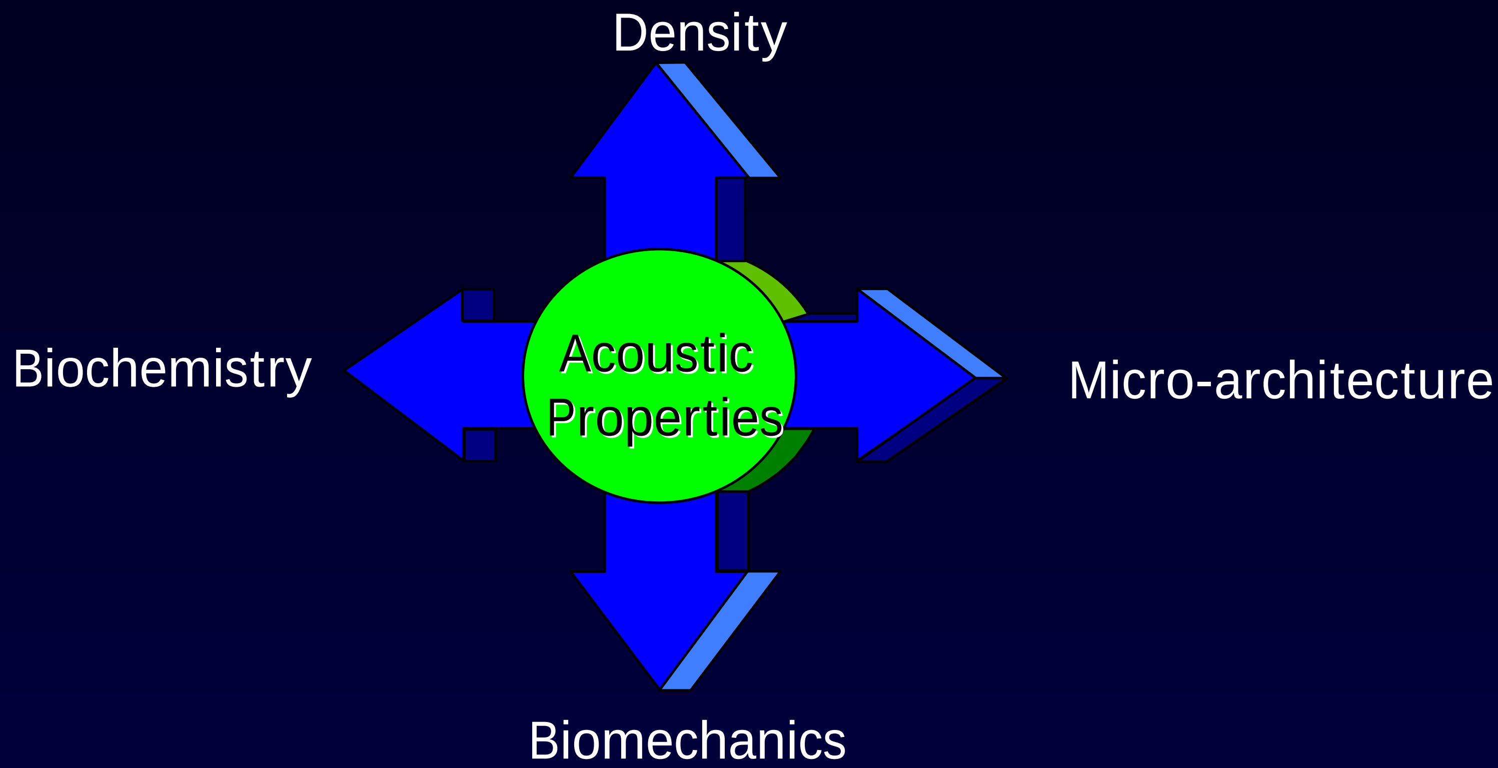
- Imagerie haute fréquence
- Focalisation dans les milieux hétérogènes
- **Imagerie quantitative**
- Elastographie
- Non linéaire, produits de contraste
- ...

ULTRASOUND TISSUE CHARACTERIZATION



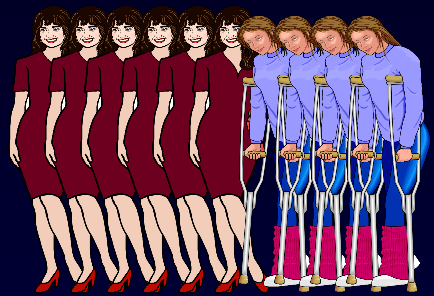
Notion d 'information complémentaire

Méthodes ultrasonores d'évaluation des propriétés osseuses: principes et techniques

Osteoporosis : A Major Public Health Problem

q Most common metabolic bone disease in women

Postmenopausal women



~35% Fractures

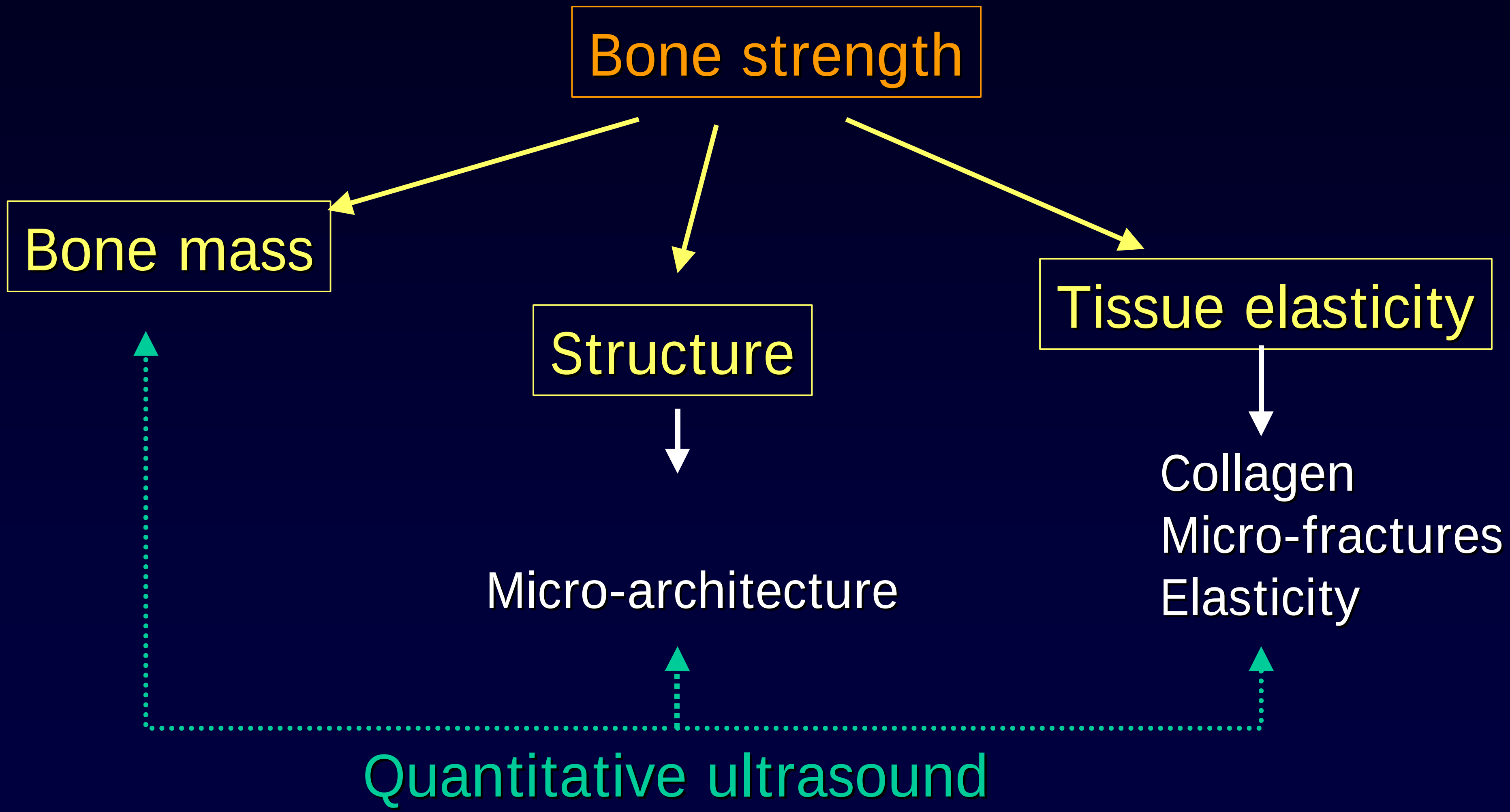
Hip 18%
Spine 17%
Others 5% (Wrist…)

q Drugs to reduce fracture risk

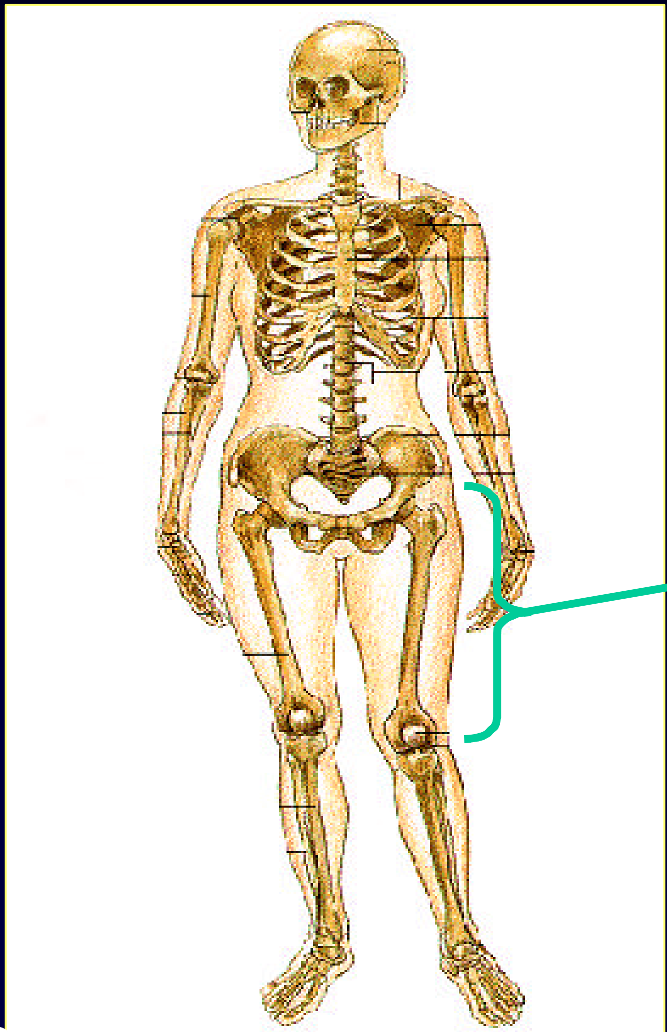
Prevention : evaluate the factors of fracture risk

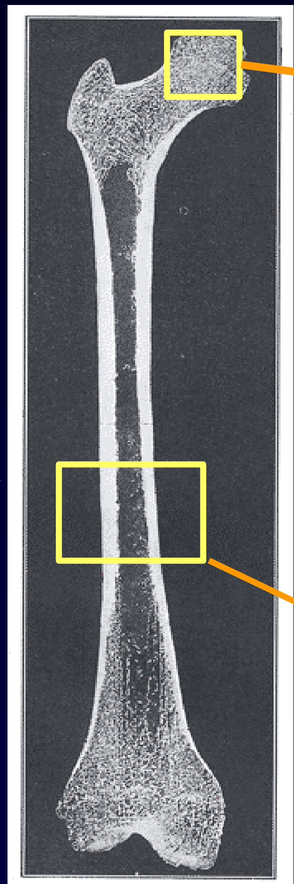
L I P

Skeletal factors of fracture risk

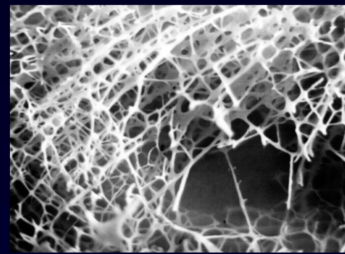


Architecture of bone





Cancellous bone

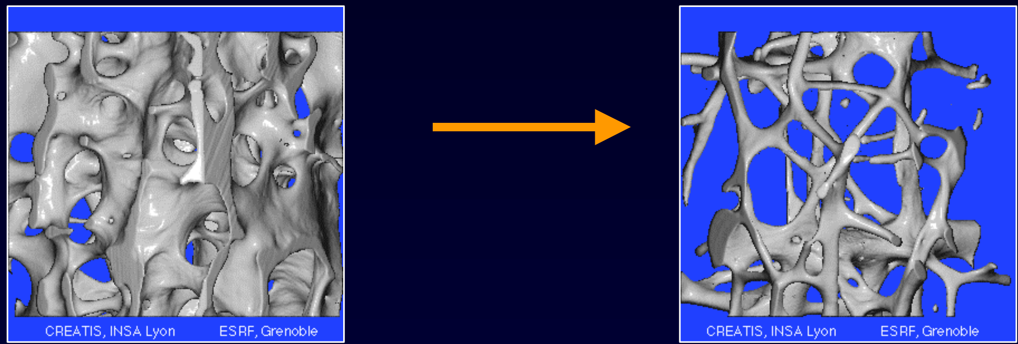


Cortical bone

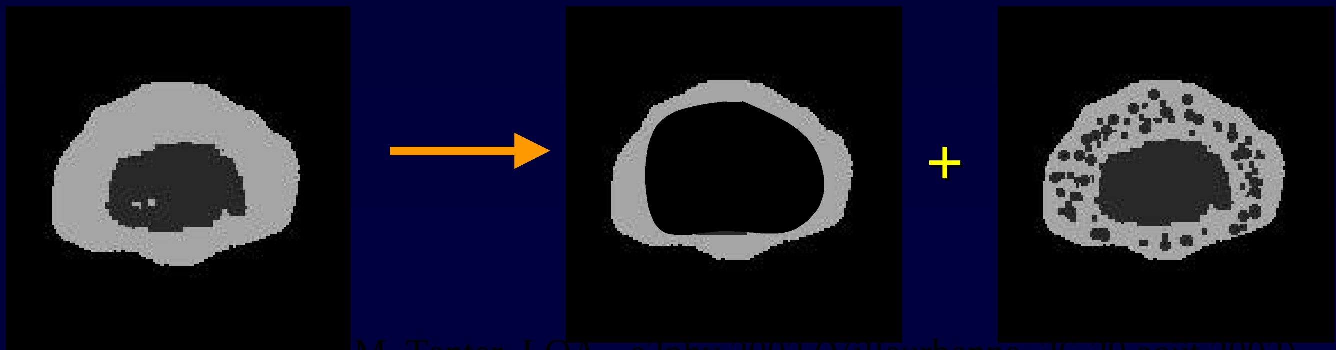
L I P

Mechanisms of bone loss

Cancellous bone : thinning of trabeculae and disruption of connectivity



Cortical bone endosteal resorption +increased porosity



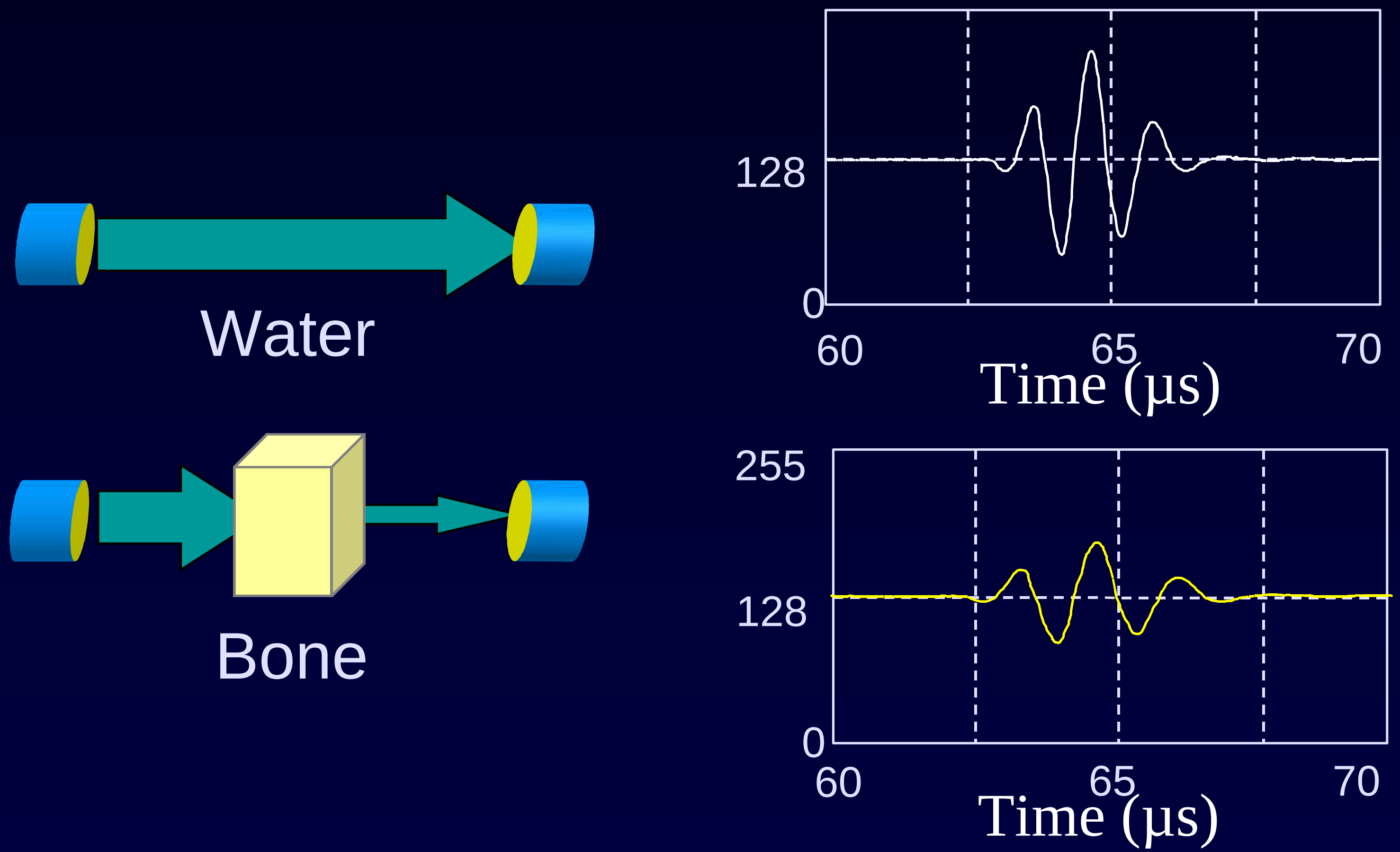
Transverse transmission

Skeletal site :	Calcaneus (heel)	Finger phalanges
Type of bone	90% Cancellous bone	Integral bone
Frequency :	500 kHz	1.25 MHz

Typical range of values

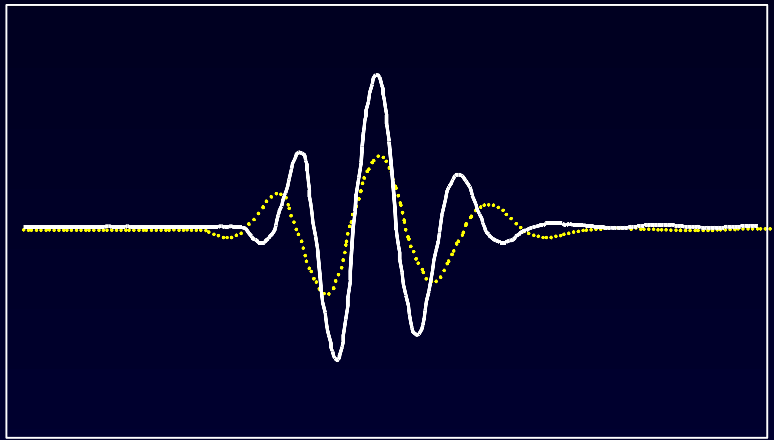
Attenuation	2-40 dB.cm $^{-1}$.MHz^{-1}	
Speed of sound	1475-1650 m.s $^{-1}$	1800-2200 m/s

Méthode par substitution



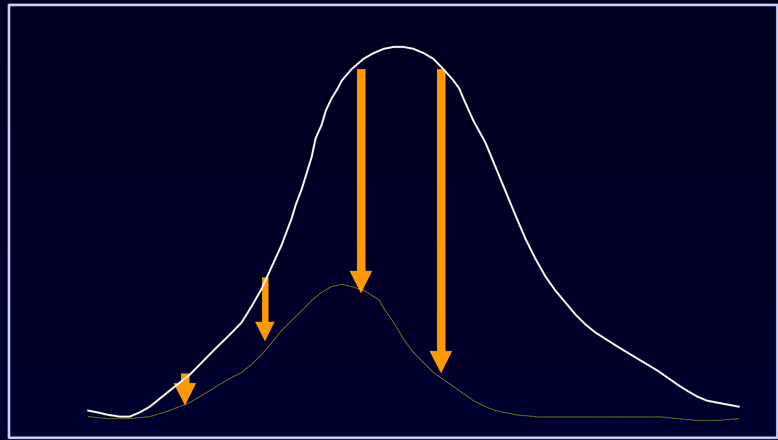
Attenuation measurements using FFT

Rf waveforms



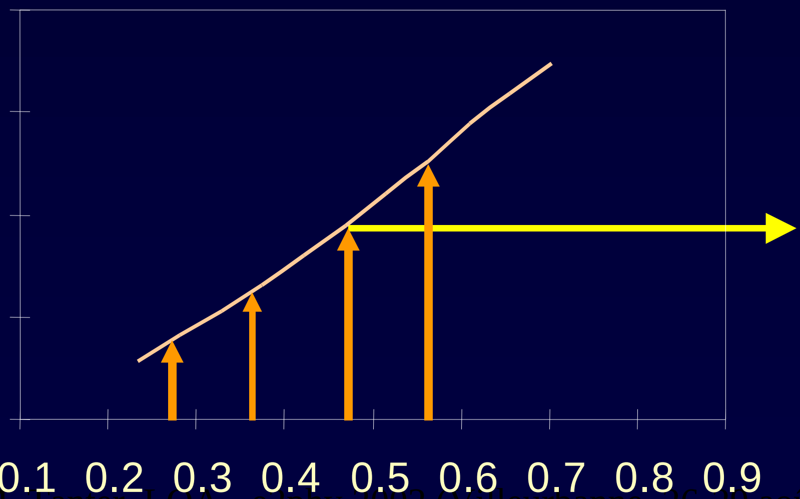
TIME (µs)

Power spectra



FREQUENCY (MHz)

Attenuation curve vs. frequency

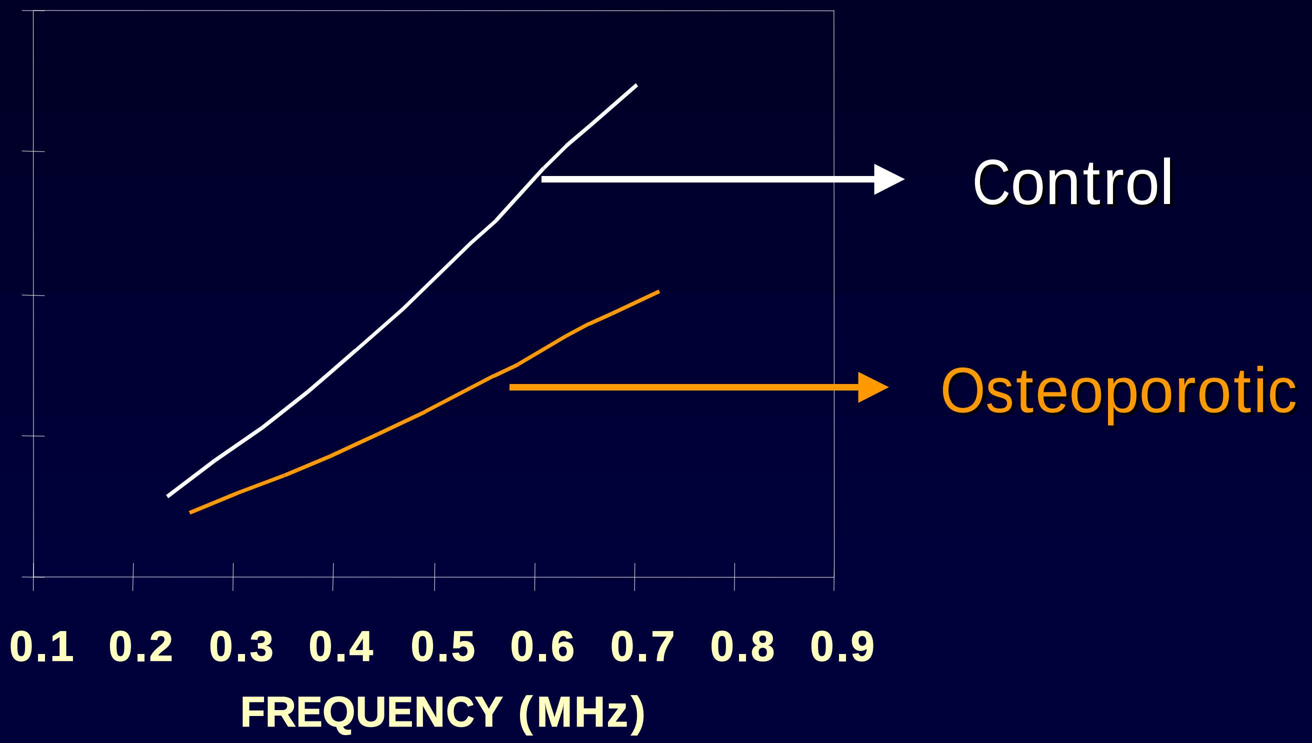


FREQUENCY (MHz)

Slope
BUA dB/MHz

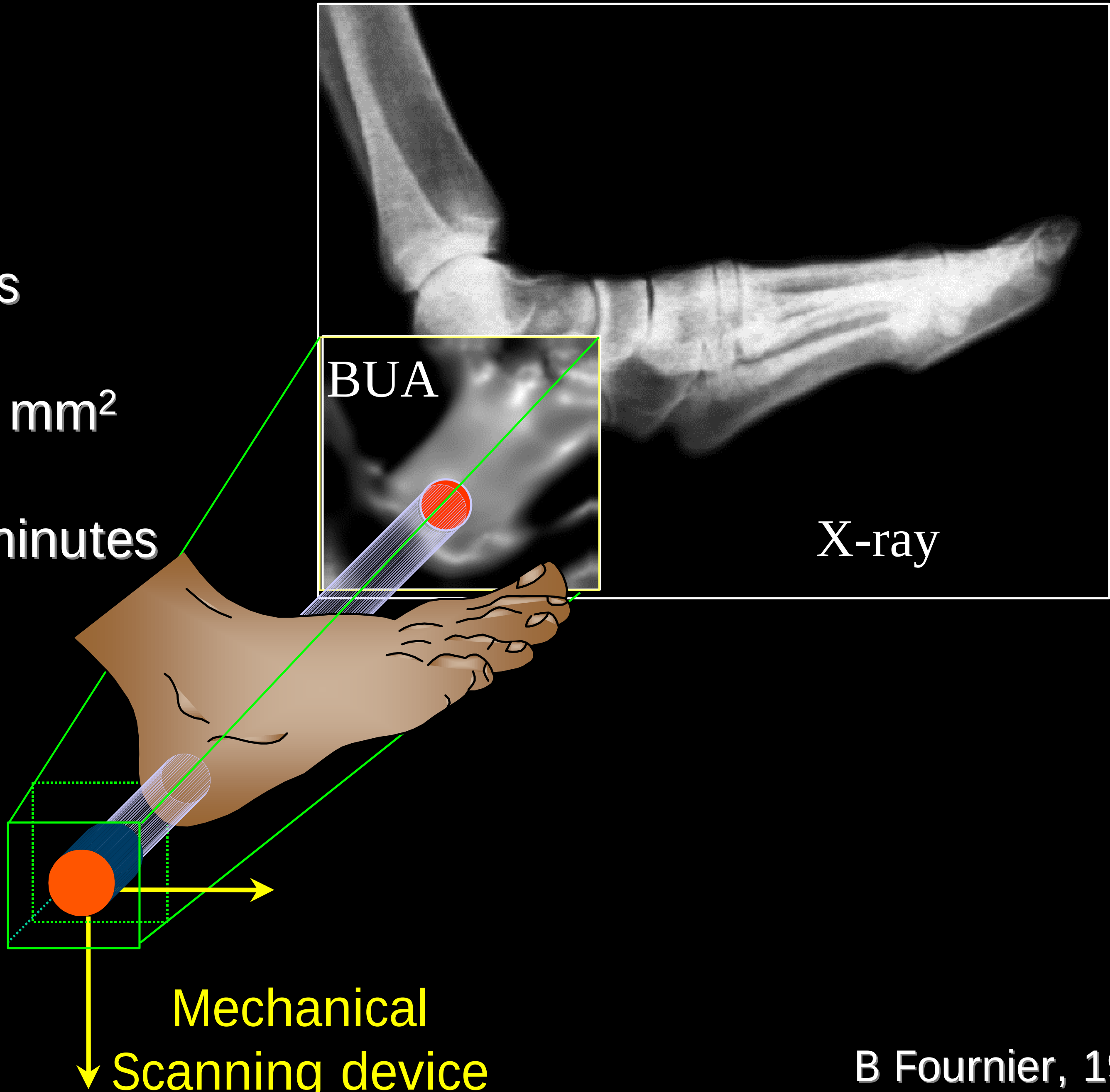
L I P

Attenuation curve vs. frequency



QUS Imaging

Immersion
Focused transducers
500kHz
Field of view 60x60 mm²
Pixel size 1mm²
Acquisition time 2 minutes



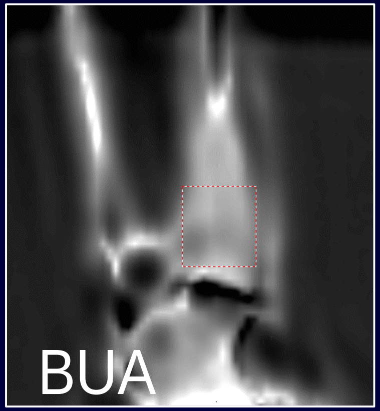
L I P

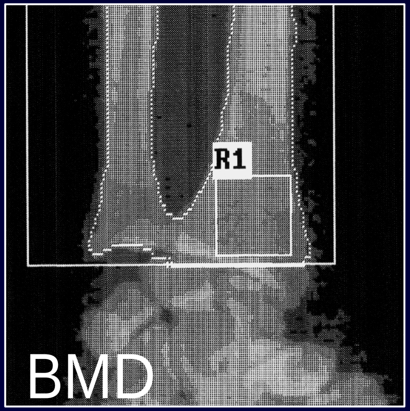
B Fournier, 1997

QUS Imaging in progress...

Significant techological advances with contact imaging using 2D Arrays of transducers (24x24 elements) 500 kHz
M Defontaine
LUSSI/GIP Tours France

QUS Imaging of the wrist
C Chappard, 2000





Axial transmission

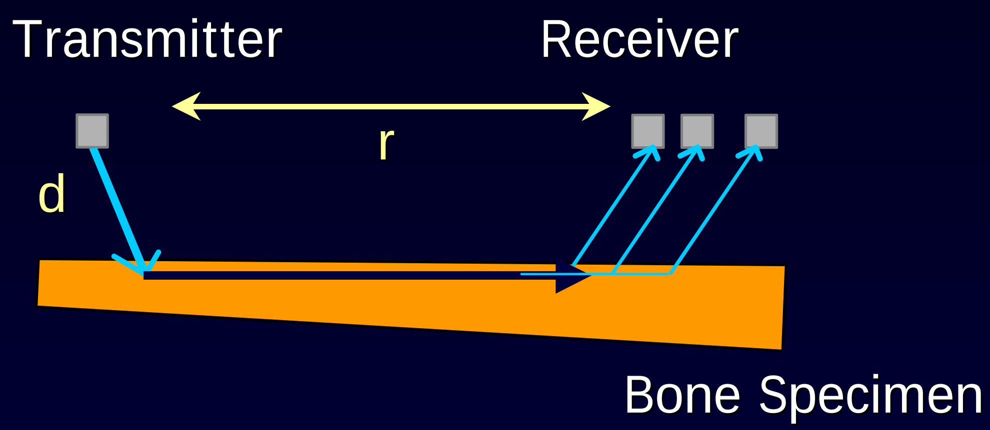
Skeletal site :	Tibia	Multi-site
Type of bone	Cortical bone	Cortical bone
Frequency :	250 kHz	1 MHz
Parameter :	SOS	SOS

Typical range of values

SOS : 3500-4200 $m.s^{-1}$

L I P

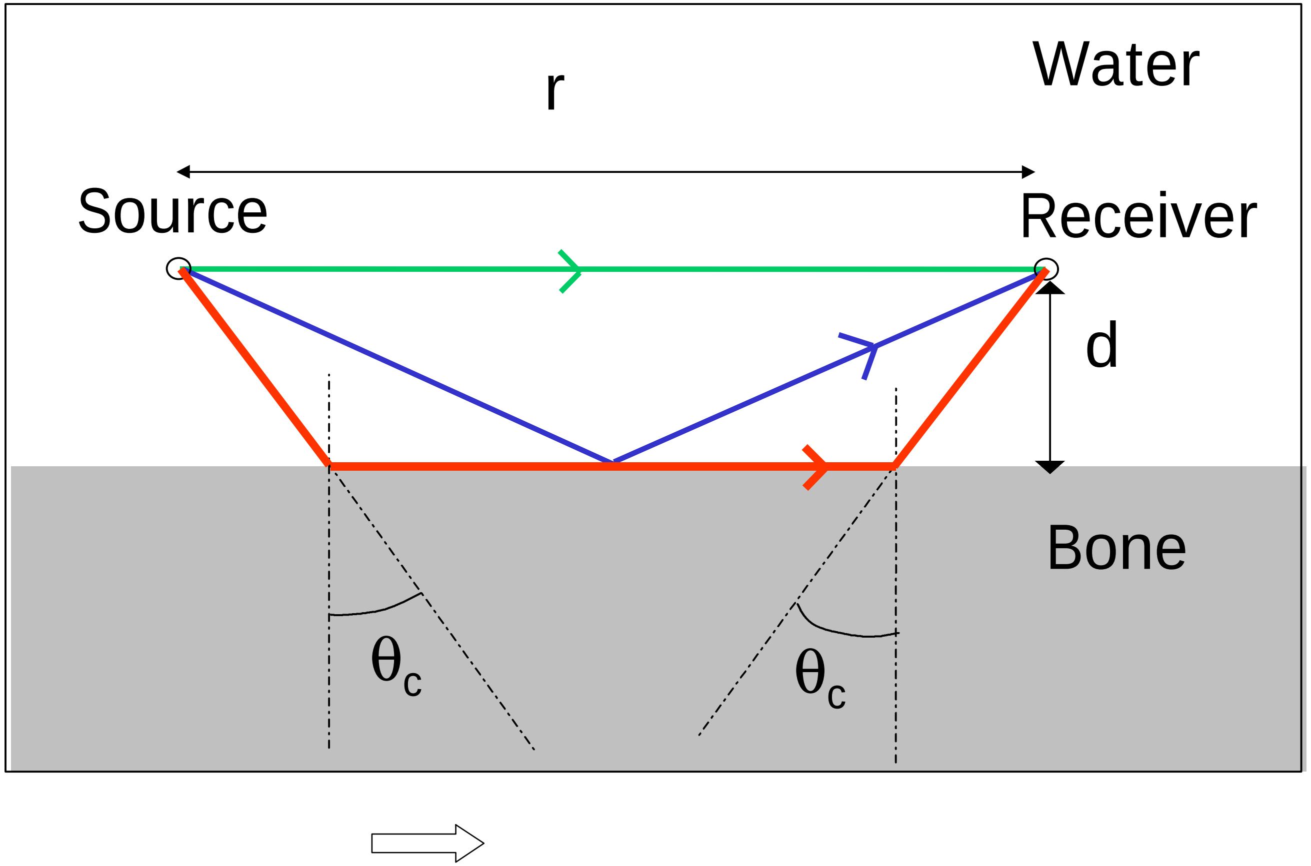
Axial transmission



Transmission at the critical angle
Lateral wave propagating along the sample surface at the longitudinal velocity

E Camus, LIP

Theoretical Background : lateral wave in case of an interface between two semi infinite media
Time-of-Flight



Clinical applications

Independent predictor of fracture risk — Yes

Secondary osteoporosis — Yes

- Endocrinal, renal and genetic disorders
- Drug-induced osteoporosis (gluco-corticoid)
- Loco-regional osteoporosis associated with arthritis
- Chronic and inherited disorders in children
- Pregnancy and lactation
- Immobilization and space applications

- Imagerie haute fréquence
- Focalisation dans les milieux hétérogènes
- Imagerie quantitative
- Elastographie
- Non linéaire, produits de contraste
- ...

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Elastographie

Nombreuses pathologies associées à une modification de l 'élasticité

Exemple : tumeur cancéreuse (palpation $\longrightarrow$ sein, prostate, foie)

Palpation = évaluation module d'Young

solide élastique isotrope (K, m)

tissus mous $m << K$

$$\boxed{E = \frac{9Km}{3K+m} \approx 3m}$$

$$\longrightarrow \quad c_l = \sqrt{\frac{3K+4m}{3r}} \approx \sqrt{\frac{K}{r}} \qquad\qquad c_t = \sqrt{\frac{ì}{ñ}}$$

Limites de l'échographie classique : sensible aux variations de K seulement

AUCUNE INFORMATION SUR μ

Techniques Elastographiques

Couplage entre une sollicitation mécanique (BF)
à un système de mesure des déplacements des tissus
destiné à l'évaluation quantitative du module d'Young
des tissus

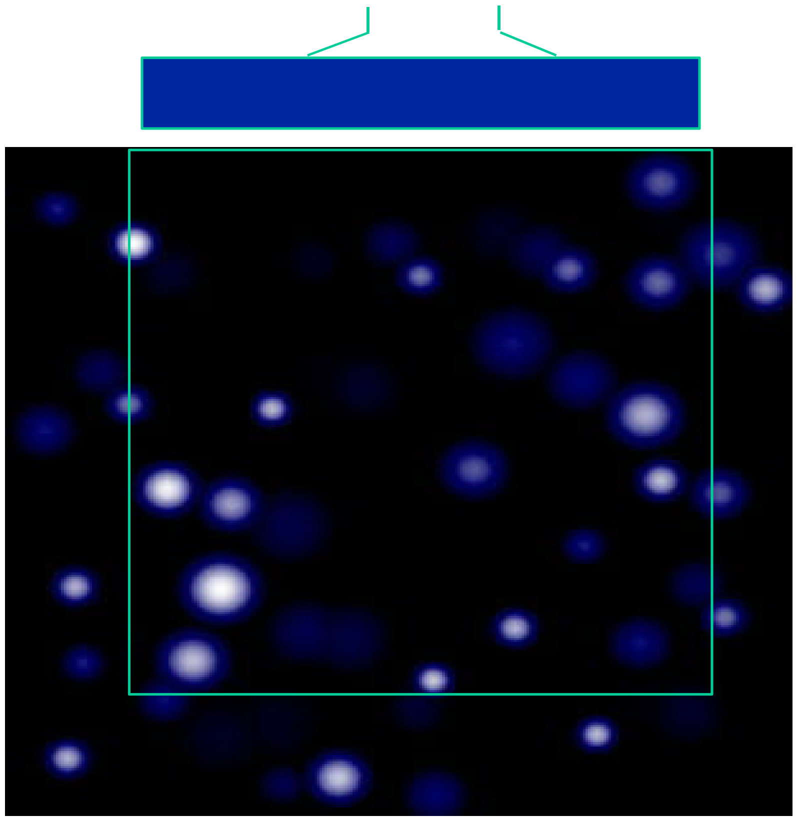
Sollicitation

- Statique
- Vibration BF (onde de cisaillement)
- Impulsionnelle (onde de cisaillement)

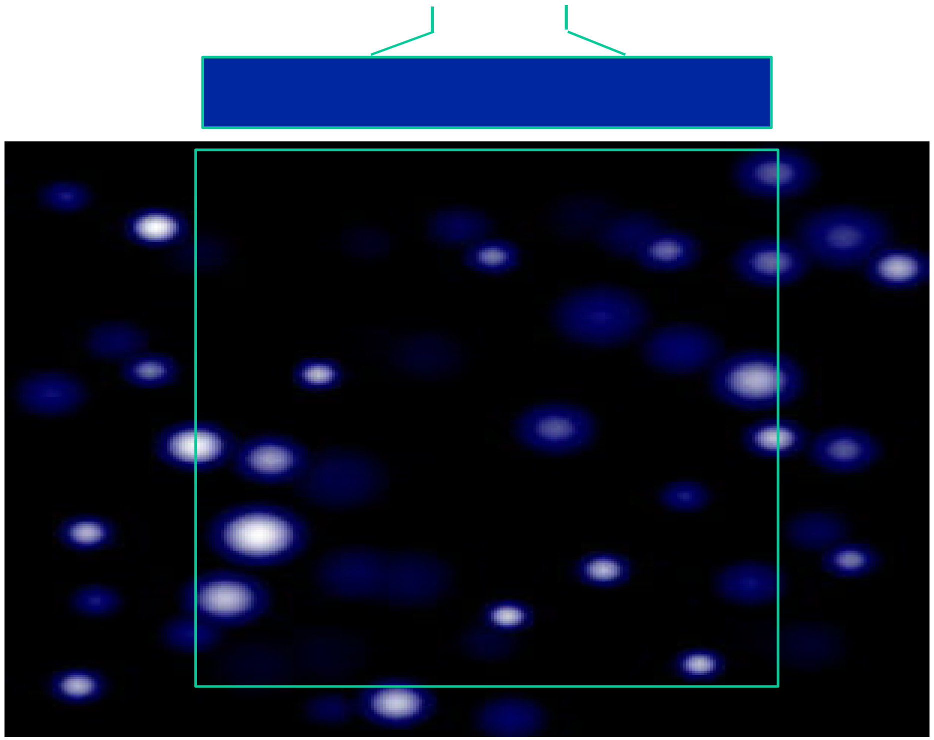
Mesure déplacements

- Ultrasons : Interférométrie speckle

2. L’élastographie Statique : Principe (*Pr. J. Ophir)*



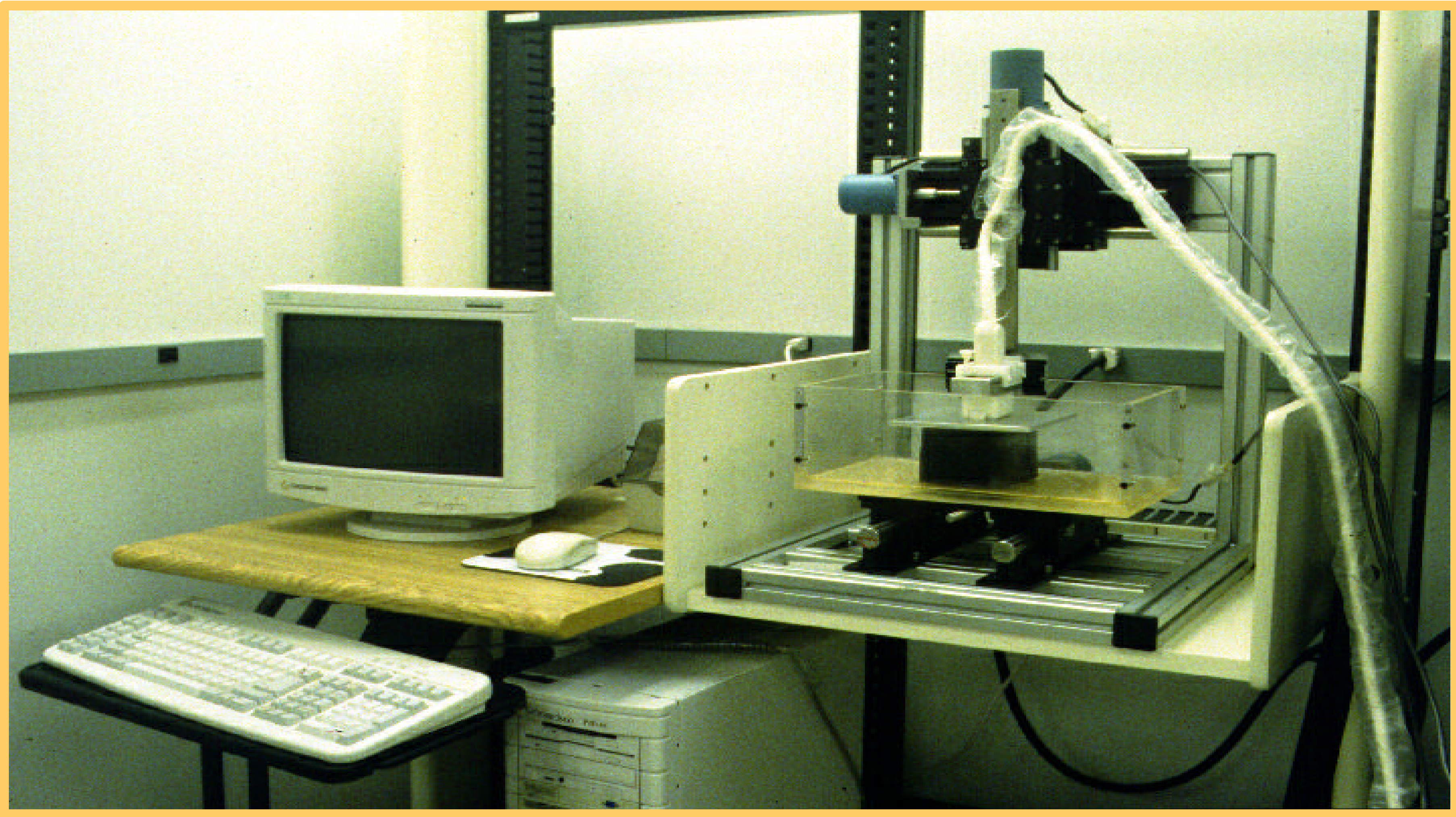
Avant compression



Après compression

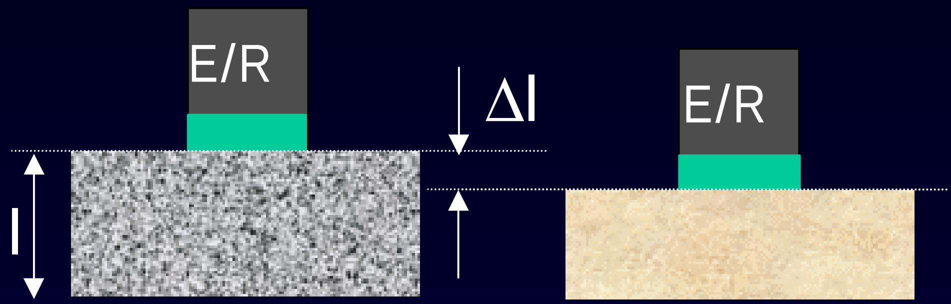
2. L’élastographie Statique : système d ’acquisition (*Pr. J. Ophir)*

Un échographe standard + Un système de compression statique

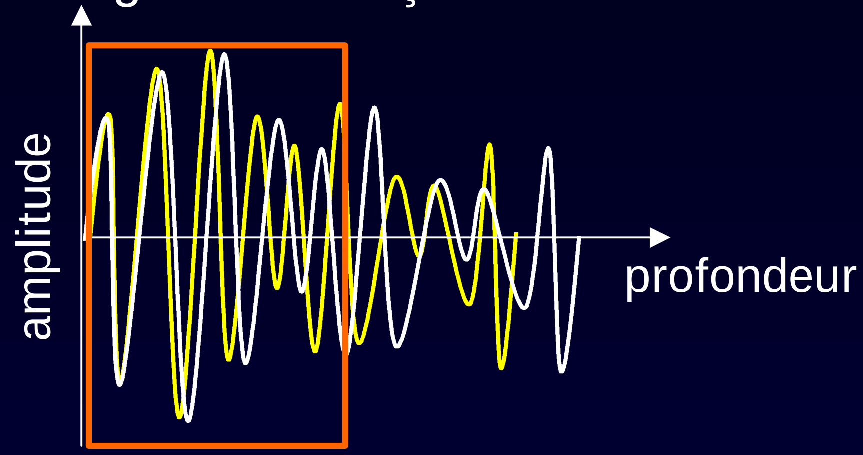


- I - Elastographie statique

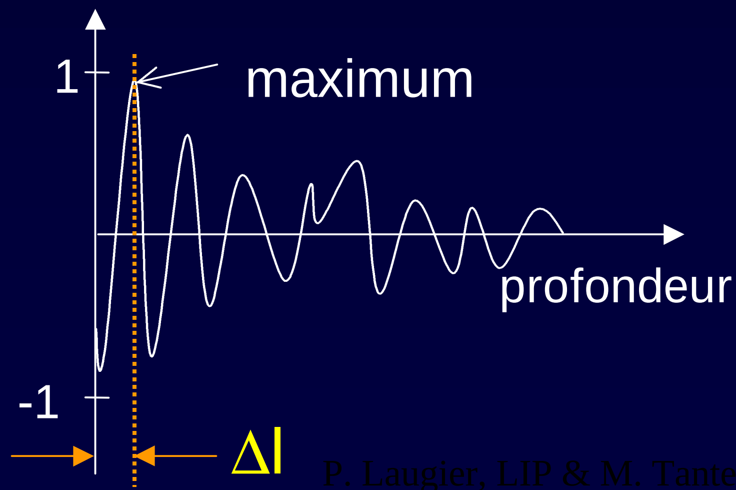
Principe



Signaux RF reçus



Intercorrélation des deux signaux RF

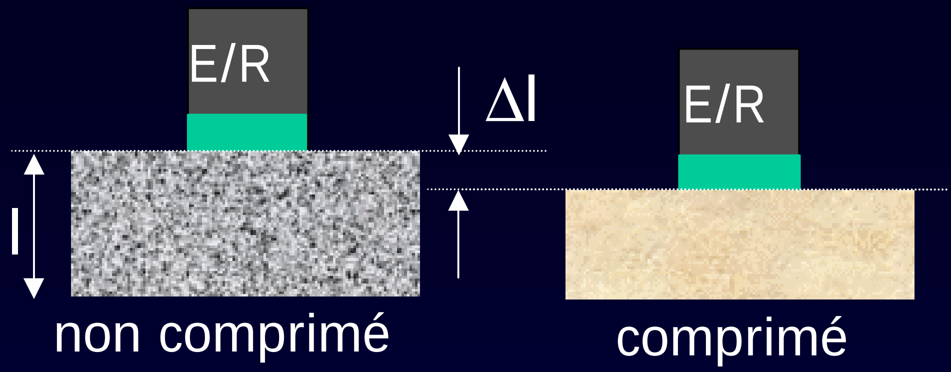


→ cartographie des déformations locales

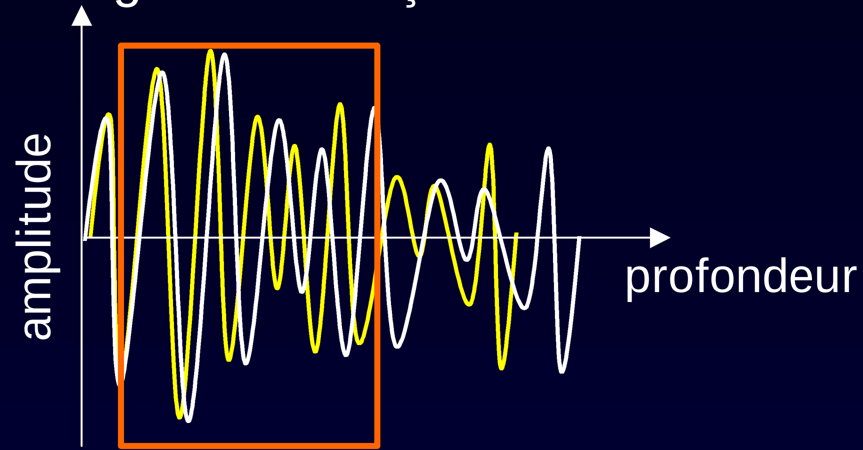
module d'Young $E = \frac{\acute{o}}{\ddot{A}l/l}$

- I - Elastographie statique

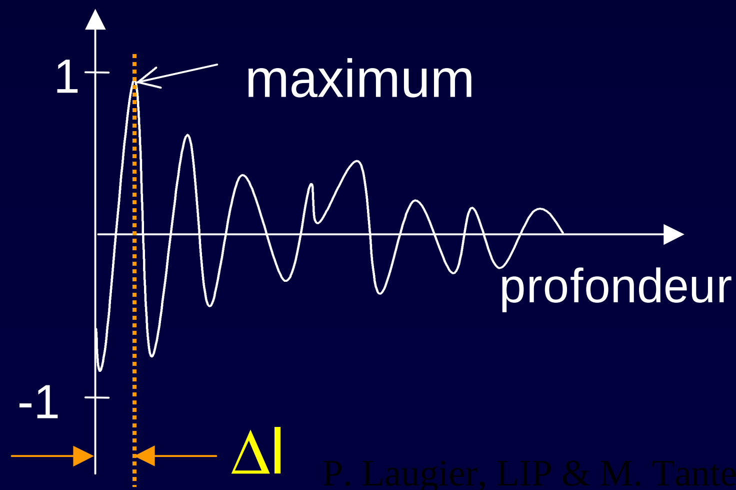
Principe



Signaux RF reçus



Intercorrélation des deux signaux RF



→ cartographie des déformations locales

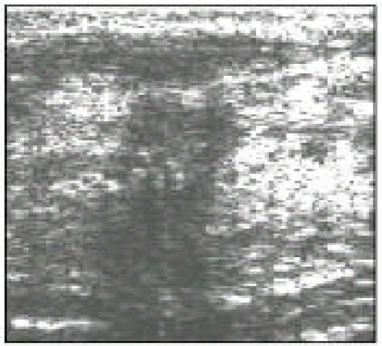
module d'Young $E = \frac{\text{ó}}{\text{Äl}/\text{l}}$

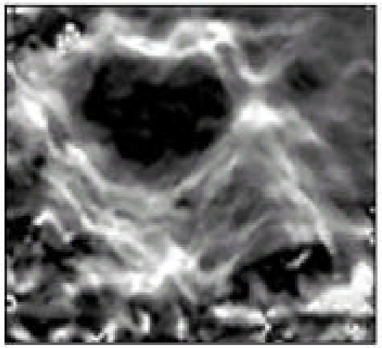
(*Pr. J. Ophir*)

Quelques résultats...

Malignant in vivo breast tumor

sonogram Elastogram





- II - Elastographie impulsionnelle

- Générer une onde de cisaillement dans le corps
- Méthode ultrarapide d 'imagerie (10 000 i/s)
- Enregistrement de la propagation de l 'onde de cisaillement
- Mesure du déplacement en chaque par méthode d'intercorrélation
- u(r,t) est connu à chaque instant et en chaque point de l 'espace

Problème inverse $c_t^2 = \frac{\partial^2 u(r,t)/\partial t^2}{\Delta u(r,t)}$ → Cartographie µ

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

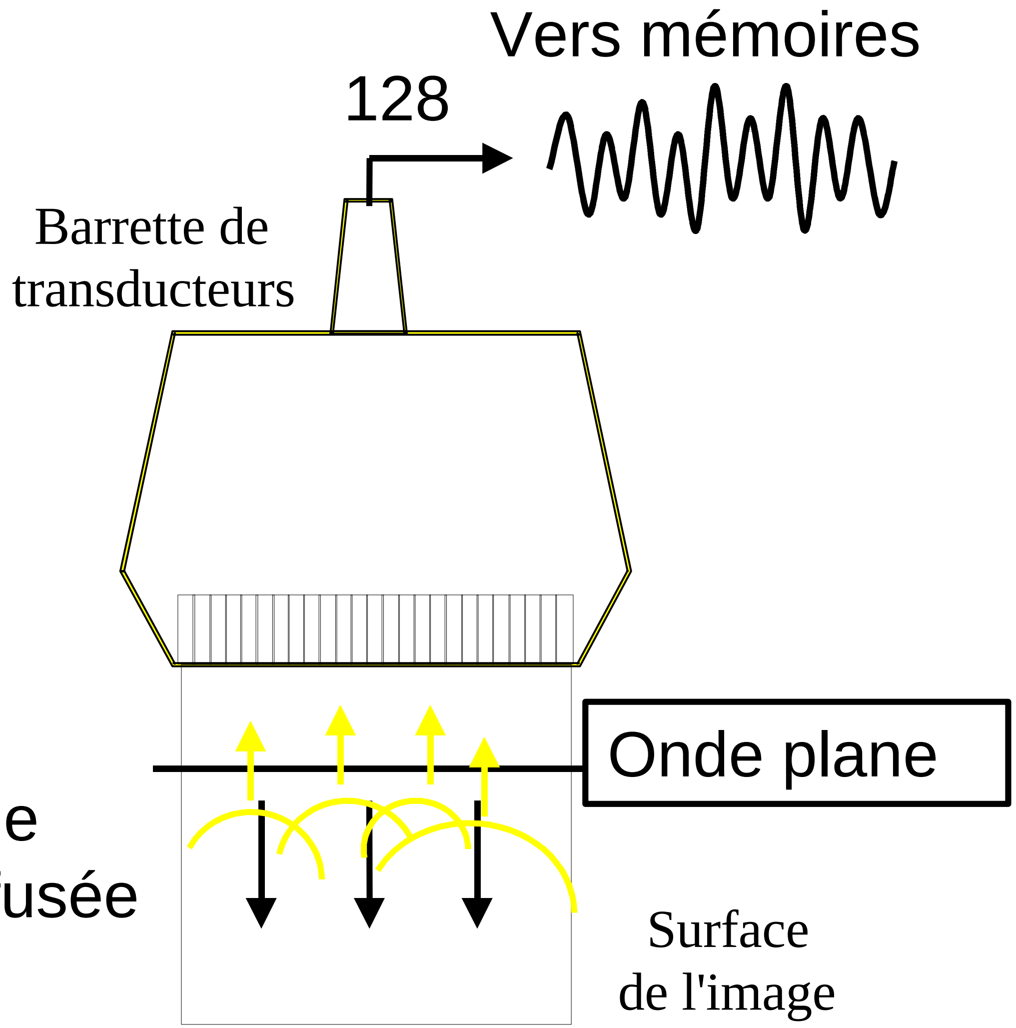
4. Principe de l’ Ultrafast imaging

– Illumination à l’aide d’une onde plane

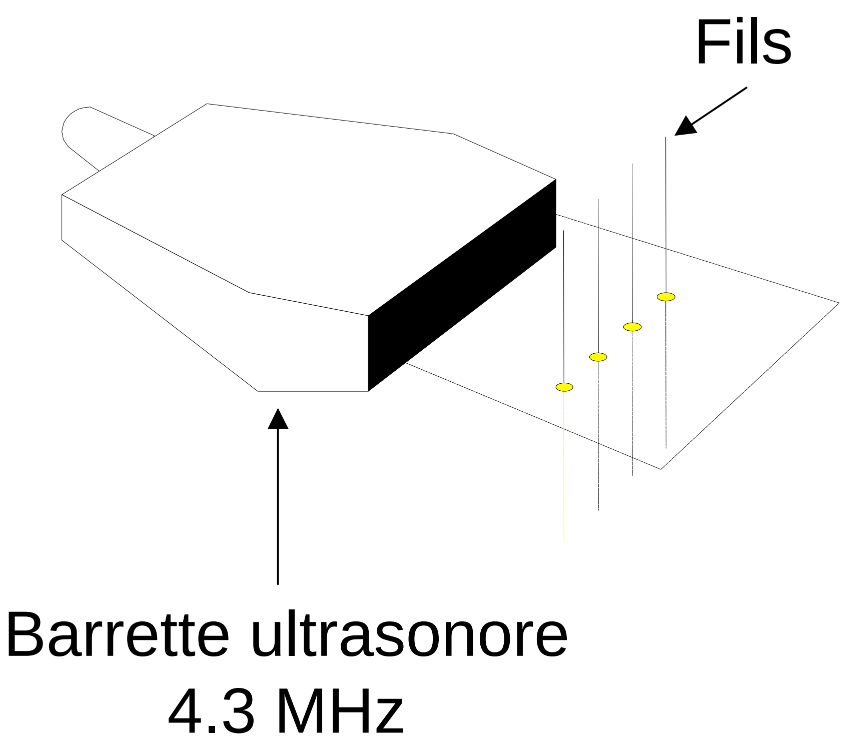
– Stockage des signaux ultrasonores

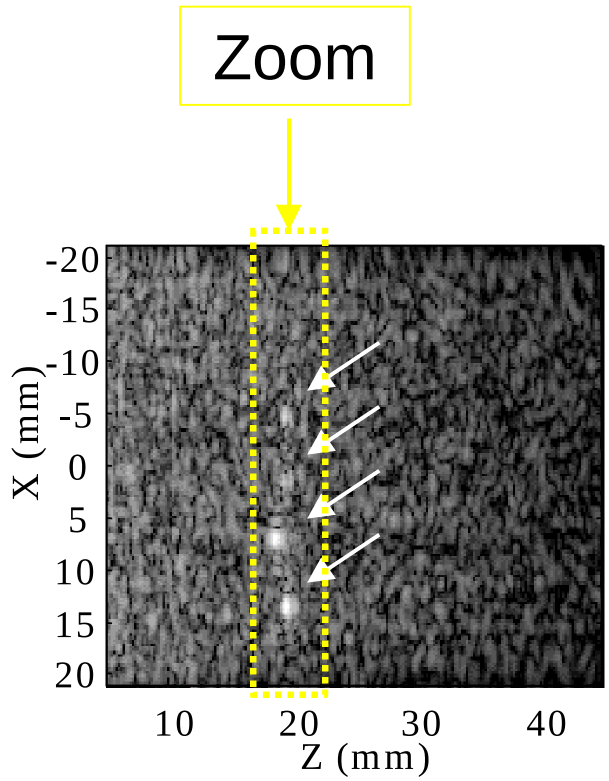
– 10000 images/s

– Focalisation simple à la réception



4. Image d'un fantôme de test



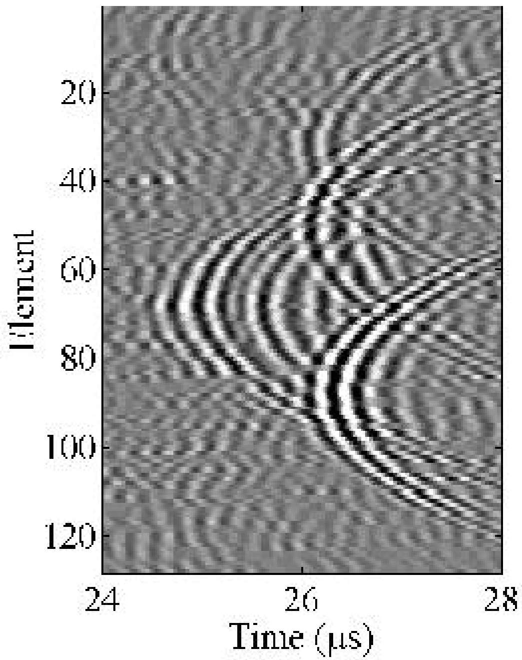


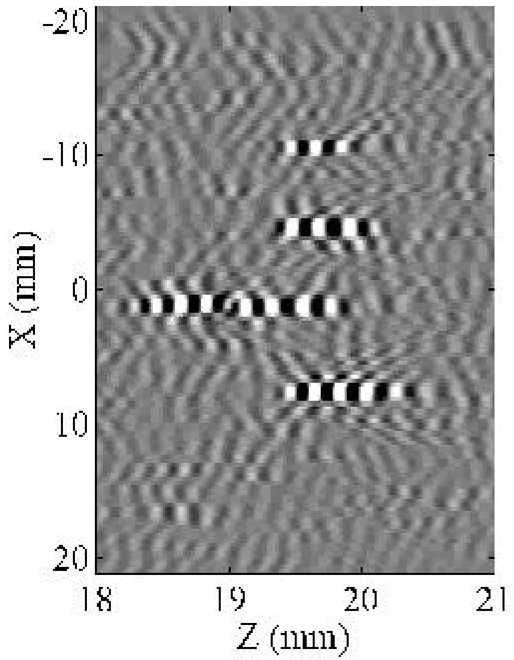
4. Acquisition en dynamique

- Agitation mécanique
- 1000 images par seconde

1 ms

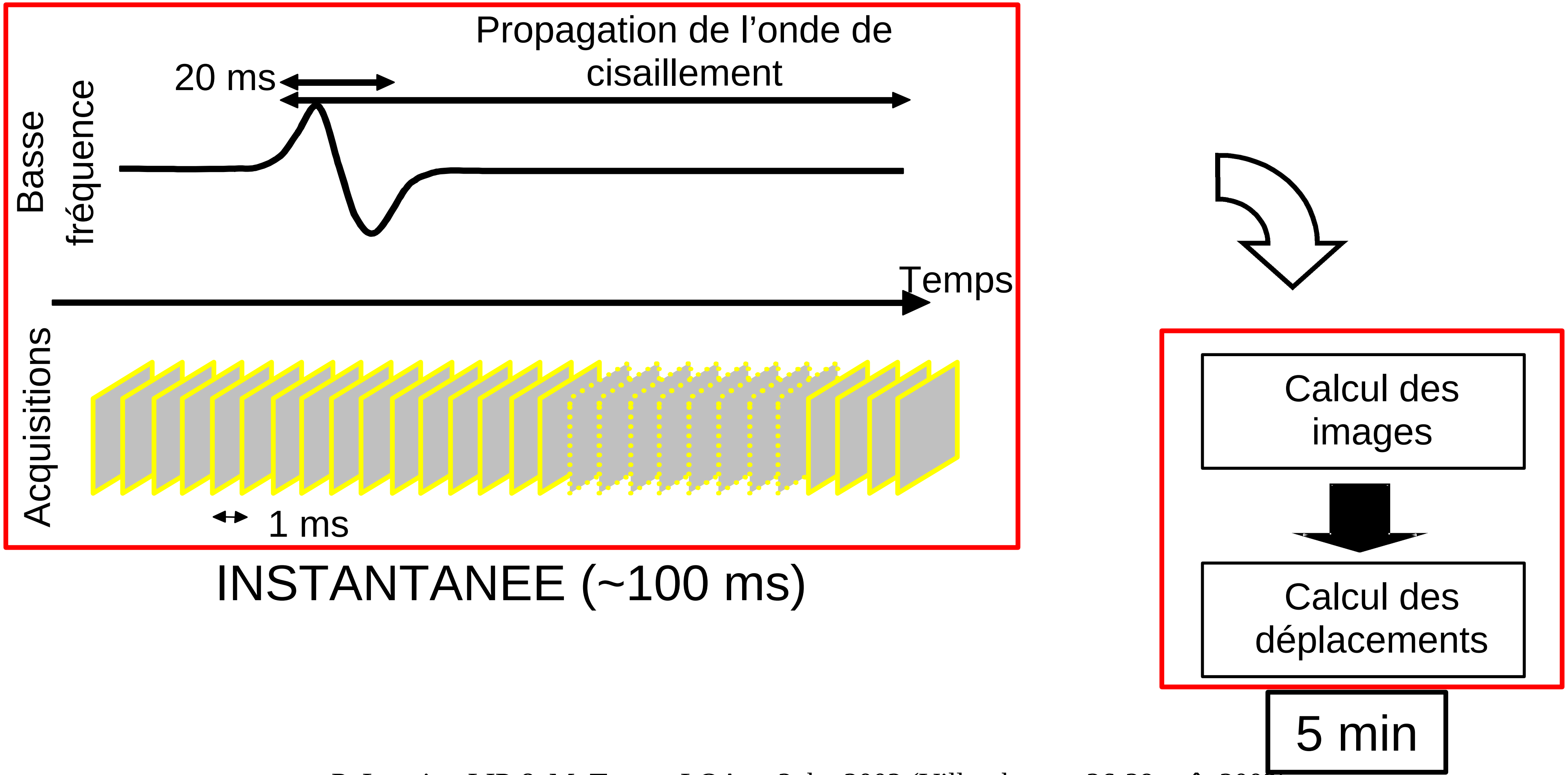
Signaux ultrasonores



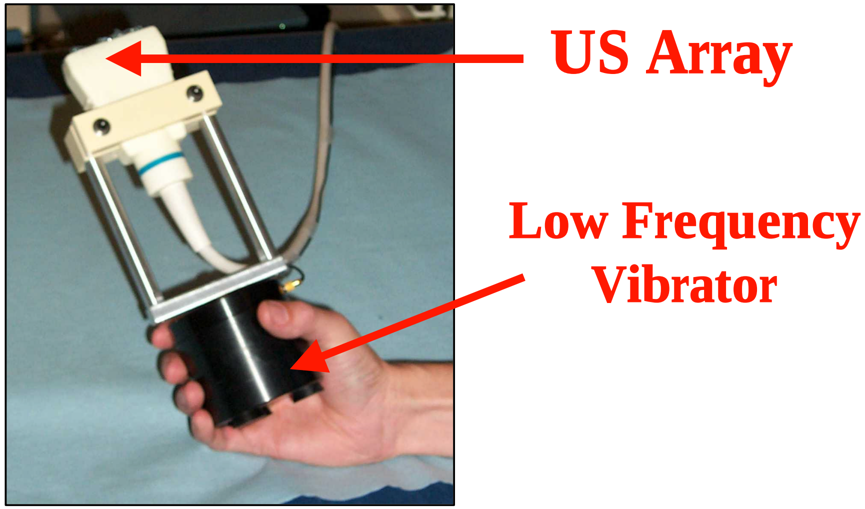


Images ultrasonores

4. Séquence d’acquisition et traitements



5. 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

ECHO: Nymphe des forêts,
personnification de l'écho.

LIP