The future of ultrasound: Ultrafast Ultrasonic Imaging

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Ultrasound imaging success is related to the fact that the ultrasonic speed is quasi-uniform in soft tissues.

Ultrasonic speed uniformity (1520 m/s) makes focusing possible.

Piezoelectric transducer arrays

25 to 50 frames/sec
An ultrafast ultrasound scanner with a Time-Reversal processor

25 frames/second

1 shot for one image, 10,000 frames/s
Image quality with Ultrafast Imaging: Coherent Plane Wave compounding

Illumination with a set of Plane Waves with DIFFERENT ANGLES

Each plane wave gets a LOW QUALITY IMAGE

The coherent addition generates a HIGHER QUALITY IMAGE

Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography.
Trade-off between speed and quality

Conventional
4 focal depths
25 Frames/s

Ultrafast Compound
40 angles
350 F/s
17 angles
1000 F/s
1 angle
18 000 F/s
Is it interesting to get thousand images per second from the human body?

1- You can make a movie of the seismic activity of the body: Elasticity Imaging

Human body is mainly a soft solid, where two types of mechanical waves can propagate: P waves (compressional) and S waves (shear). There is a strong analogy with mechanical waves created by an earthquake.

2 - You can image ultra weak blood flow

Ultrafast Doppler: Functional Imaging
Elastic Properties of Soft Tissues

The mechanical properties sensed by palpation is the **Young modulus** $E$

$$E = \frac{\sigma}{\varepsilon}$$

2 other mechanical moduli are commonly used for defining the elasticity of a solid material:

**$K$** Bulk Compression Modulus, almost uniform in all tissues, of the order of $10^9 \text{ Pa}$, quasi incompressible medium

**$\mu$** Shear Modulus, strongly heterogeneous, varying between $10^2$ and $10^7 \text{ Pa}$,

$K \gg \mu$

$E \approx 3 \mu$
In Human Body, 2 different types of elastic waves can propagate

\( c_p \approx \sqrt{\frac{K}{\rho}} \)  
\( \approx 1500 \text{ m.s}^{-1} \)

\( c_s = \sqrt{\frac{\mu}{\rho}} \)  
\( \approx 1-10 \text{ m.s}^{-1} \)

Two kind of waves propagating at totally different speeds !!

Ultrasonic waves are only compressional waves with quasi uniform speed, (5MHz, small wavelength \( \lambda = 0.3 \text{ mm} \))

Shear waves propagate only at low frequencies < 1000 Hz (High Shear Viscosity). Large wavelength (typically centimetric)
How to Produce Shear Waves in Tissues?
Transient Elastography: Shear Wave Elastography

- One generate a transient strain that induced shear waves of low frequency (10 Hz to 1000 Hz)
- One follow the shear wave propagation with one ultrasonic transducer (Fibroscan) or with an array of transducers connected to an ultrafast ultrasonic scanner (Aixplorer)
- One deduce a map of the shear wave speed. Therefore a map the Young modulus is obtained from the relation:

\[ V_s = \sqrt{\frac{\mu}{\rho}} \approx \sqrt{\frac{E}{3\rho}} \]
Ultrafast Imaging to Image the full shear wave propagation

Typically 10,000 images/s

2D Method

1 mm

2 to 10 m/s
From Transient Elastography in a global mode to Shear Wave Imaging

**Fibroscan**
- Global Information on liver
- 1400 Fibroscan sold

**Aixplorer**
- 2D/3D stiffness mapping
- 450 Aixplorer sold

2 Technologies developed at Langevin Institute (LOA)
Transient Elastography and Ultrasonic Radiation Force

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
The Supersonic Push!!!!!!

Conventional US

Ultrafast US

A 30 ms Experiment!!
 Imaging a hard inclusion at 3000 Hz

Supersonic Shear Imaging: a new technique for soft tissue elasticity mapping.
The Evolution of Ultrafast Imaging Technology

**SuperSonic Imagine** is a company in medical imaging and therapy founded in September 2005 by Jacques Souquet, 120 employees, Aix en Provence and Seattle.

**Aixplorer sold**

Time Reversal Prototype

1996-2002

HDI 1000

2004-2005

Prototype V1

2006-2007

Aixplorer ©
Diagnostic impact in breast:
IDC Grade I, partially necrotic center proved by histology.

$E_{max} > 200\text{kPa}$ on surrounding tissue.

$E = 70\text{kPa}$ in the center.
Breast Chimiotherapy

\( \varnothing = 2.04 \text{ cm} \)
\( \varnothing \approx 1.80 \text{ cm} \)
\( \varnothing = 1.64 \text{ cm} \)
\( \varnothing \approx 0.1 \text{ cm} \)

June/2011
July/2011
August/2011
October/2011

(Collaboration A. Athanasiou, Curie Institute, Paris, France)
Quantitative Monitoring of Uterine Contraction during Pregnancy

O. Ami, J-L. Gennisson, M. Tanter
Coll. CHU Antoine Beclere, Service Pr. Friedman
Supersonic Shear Wave Imaging: Other Applications

Liver Cholangitis carcinoma

Transplanted Kidney

Carotid Plaque

Thyroid Nodule

Tendon Elasticity

Gastrocnemius and Soleus Contraction
Functional Imaging with Ultrafast Technology

Conventional Doppler

Ultrafast Doppler

Ultrasensitive blood flow imaging

20,000 frames/s
Sensitivity x 60

Rat Brain
*in vivo*

E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter
Functional Ultrasonic Imaging of Brain Activity, Nature Methods, July 2011
Ultrafast Ultrasound Imaging (20,000 images/s) allows to improve the sensitivity of blood flow imaging by a factor 100.

Cerebral Blood Volume Imaging

Spatial resolution: 100 x 100 microns
Temporal resolution: 200 milliseconds

Conventional Doppler Imaging

Ultrafast Doppler Imaging

Spatio-temporal dynamics of the blood volume during epileptic seizures

Spatial resolution: 100 x 100 microns
Temporal resolution: 200 milliseconds

CBV changes (%)

Whisker stimulation

imaging plane
barrel cortex

whisker stimulator

Propagation speed of epileptic seizures

EEG

Cortical “wave” speed 3.2 ± 0.3 mm/min
Ultrasensitive Doppler Brain Imaging on preterm neonate, < 32 weeks

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