

#### Plane Wave Imaging and Applications for Ultrafast Doppler, Elastography, and Contrast

#### **Mathias Fink & Mickael Tanter**

#### Short Course IEEE IUS, Dresden 2012

# **Ultrasound Technology Evolution**



#### How to obtain an ultrasonic image ?



#### Image formation using <u>sequential</u> transmit beams

## **Focusing in transmit/receive mode**



#### **Steering and Focusing**



$$\tau(x_i, \sin\theta_m, z_n) = \frac{-x_i \sin\theta_m}{c} + \frac{x_i^2 \cos^2\theta_m}{2z_n c}$$

## Focal spot dimension in transmit mode



### **Transmit Beam Forming**

- Time Delay Accuracy typically  $\lambda/32$
- Aperture Control determined by format
- Apodization primarily for depth of field
- Fixed focus multiple zone / frame rate

#### **Beam Forming in Receive Mode**





# In receive mode, Dynamical Focusing with variable focal depth



The focal depth is varying continuously with the time of arrival of the echoes

#### **Dynamical Apodization**



To get the same spatial resolution at all the depths F/D must stay constant on the whole depth of exploration

# Frame Rate with Sequential Imaging



#### 25 to 50 frames/sec

Typically, to get an image : 128 shots x 4 focal depths = 512 ultrasonic shots

**Time of flight – two ways:** 60 μs for 5 cm

**Time to get a full image:** 512 x 60 μs = 0,032 s **Frame rate:** 1/0,032 = 35 frames/ second

### How to go faster ?

Replace the focused transmit beams by one unfocused transmited beam that illuminated the whole field of view

## **Ultrafast Imaging**



#### Plane Wave Insonification One shot : One image

# The Time-Reversal approach : An elegant way to build the Acoustic Image of any source radiating ultrasound



# **Ultrafast Imaging with Time-Reversal**

3 Piezoelectric Transducer Arrays



M. Fink, "L'imagerie ultrasonore«, Revue de Physique Appliquée, 18, 1983, p.527-556

#### **The Dynamic Electronic Lens Approach**

446



Fig. 3 - Electronic lens with delay lines and 2 transducers arrays,

$$\frac{1}{f} = \frac{1}{z} - \frac{1}{z'} = \frac{2 z' - ct}{ctz'}.$$
(4)

$$\Delta \tau(x_{\rm n}, t) = \frac{-x_{\rm n}^2}{2 \ cf} = \frac{-x_{\rm n}^2}{c^2} \left(\frac{1}{t}\right) + \frac{x_{\rm n}^2}{2 \ cz'} \tag{5}$$

M. Fink "Principles and techniques of acoustical imaging", Imaging processes and coherence in physics" Springer, Lecture Notes in Physics, **1979**, p 438-452

# **The Computed Time-Reversal Approach**



### **Echoes and Images**

$$Echo_{i}(t) = \begin{cases} \sum_{n} \alpha_{n} e(\vec{r}_{i} - \vec{r}_{n}; t - \tau_{ni}) \\ 0 \end{cases} \qquad t \ge 0 \\ t < 0 \end{cases}$$

with 
$$\tau_{ni} = \left\{ z_n + \sqrt{z_n^2 + (x_i - x_n)^2} \right\} / C$$

**Time-reversal Imaging** 

$$\operatorname{Image}(\vec{r},t) = \sum_{i} Echo_{i} (T-t) \otimes G_{0} (\vec{r}-\vec{r}_{i};t) \quad \vec{r} = \{x,z\}$$

with  $G_0(\vec{r};t) = \delta(t - |\vec{r}|/c)/4\pi |\vec{r}|$  the Green's function

$$IMAGE(\vec{r}) = Image(\vec{r}, t = z/c)$$

#### Parallel beam forming

Image
$$(\vec{r}, T-t) = \sum_{i} Echo_{i}(t) \otimes \delta(T-t-|\vec{r}-\vec{r}_{i}|/c)$$



#### **Conventional Imaging / Ultrafast Imaging**



## **System Architecture**



# The Ancestors: A 20 transducers array For Ultrafast Imaging



Fig. 4 : Image of the heart

B. Delannoy, R. Torguet, C. Bruneel, E: Bridoux, J. M. Rouvaen, and H. Lasotaa Acoustical image reconstruction in parallel-processing analog electronic systems, J, Appl, Phys, 50(5), May 1979, 3153

B. Delannoy, R. Torguet, C. Bruneel, and E. Bridoux, **Ultrafast** electronical image reconstruction device, in Echocardiography, edited by C.T. Lancee (Nijhoff, The Hague, 1979), Vol.1, Chap. 3, pp. 447–450. 1273–1282 (1984).

### **The Explososcan**



FIG. 1. The Explososcan concept. For each oriented acoustic transmit burst, dashed line, information in four individual receive directions, solid lines, about the transmit direction is acquired simultaneously. Transmit beam response, dashed curve, extends beyond the four receive beam responses, solid curves.



FIG. 6. Schematic of receiver delay processing to achieve four to one parallelism in receive. Note that  $\Delta \tau_{tap}$  and the four summing amplifiers are the additional processing circuitry which was connected to the conventional phased array system.

1274 J. Acoust. Soc. Am., Vol. 75, No. 4, April 1984

#### D. Shattuck, M. Weinshenker, S. Smith, O. von Ramm, 1984

#### **Image Comparison**

#### Conventional 4 focal depths 512 beams

25 Frames/s



Ultrafast Imaging 1 unfocused beam : 1 Plane Wave 18 000 F/s



• Very High Frame Rate is reached by using plane wave transmissions and Time-reversal processing or parallel receive beamforming

• Loss of Transmit Focusing degrades image quality

#### Slightly Lower Resolution Much Lower Contrast

• How to reach High Frame Rate without compromising Image Quality ?

• Synthetic recombination of multiple angles plane wave transmissions – Coherent compounding

# **Coherent Plane Wave Compounding**

The coherent addition of plane waves with different incident angles allows to synthetize any focused wave



Fig. 4. (a) Individual plane waves send with the compound method. (b), (c), (d) The addition of the plane waves with the adequate delays enables focus at different depths and laterally. This focusing is performed synthetically. If this synthetic focusing is the same as in the standard focusing method, the final image must have the same quality in both methods.

Coherent plane-wave compounding for very high frame rate ultrasonography and transient Elastography. G. Montaldo, M. Tanter, J. Bercoff, N. Benech, M. Fink IEEE Trans.UFFC, March 2009

# Ultrafast Imaging with 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 HIGER QUALITY IMAGE

Coherent plane-wave compounding for very high frame rate ultrasonography and transient Elastography. G. Montaldo, M. Tanter, J. Bercoff, N. Benech, M. Fink IEEE Trans.UFFC, March 2009

# Trade-off between speed and quality



#### **Quantitative Comparison: The PSF function**

The Point–Spread–Function is the image of a point-like object

We can measure: **RESOLUTION** and **CONTRAST** 



#### **Quantitative Comparison: CONTRAST**



Better CONTRAST using Plane Wave Coherent Compounding !

#### **Quantitative Comparison: RESOLUTION**

4 Mhz probe (linear Array 128 elements)



Better RESOLUTION using Plane Wave Coherent Compounding !

### **Quantitative Comparison: SNR**

SNR estimation:

- 1) acquisition of 10 images
- 2) for each pixel in the image
  - signal = mean of the 10 images
  - noise = standard deviation of the 10 images



Better SNR using Plane Wave Coherent Compounding

#### Implementation on Aixplorer<sup>®</sup> scanner (Supersonic Imagine)

11/12/2008 10:00:19

2D

Tissue Average SuperRes 5 Gen / Res Map 5 / 63 dB Gain 23 % Fr. 86 Hz SL15-4 / Breast MI1.1 TIb 0.0 TIS 0.0





FPS: 23.2 -- Arbitration : transition -- max echo id : 2/259, ssix : 5 new persistence 0.000000

#### Implementation on Aixplorer<sup>®</sup> scanner (Supersonic Imagine)

#### 11/12/2008 10:28:23

#### SL15-4 / Breast MI**1.1** TIb **0.0** TIs **0.0**

- 3

\*

#### 2D

Tissue Average SuperRes 5 Gen / Res Map 5 / 63 dB Gain 23 % Fr. 86 Hz



FPS : 0.0 -- Arbitration : transition -- max echo id : 1/259, ssix : 5 new persistence 0.000000

#### Ultrafast Frame Rates Give Access to New Information



#### **Ultrafast Doppler Imaging**

Full field imaging of complex flowsImaging of the micro-vascularization (tumor vasc., brain ischemia,...)Functional imaging of brain activation

# Quantitative Elasticity Imaging

# From Transient Elastography to Shear Wave imaging :

The multiwave approach

# What kind of mechanical waves can propagate in soft tissues ?

Two types of waves related to the two mechanical coefficients K and  $\mu$  used to define the elasticity of a solid material



K Bulk Modulus (Compression) almost constant, of the order of 10° Pa, Fluctuations  $\approx 5\%$  Quasi incompressible medium



 $\mu$  Shear Modulus, Strongly heterogeneous,<br/>varying between 10  $^2$  and 10  $^7$  Pa<br/>(A. Sarvazian)Young modulus<br/>E  $\approx$  3  $\mu$
#### Human Body Seismology : Mechanical waves in soft tissues

 $\begin{cases} \text{Compressional Waves propagate at } c_p \approx \sqrt{\frac{K}{\rho}} & (\approx 1500 \text{ m.s}^{-1}) \\ \text{Shear waves propagates at} & c_s = \sqrt{\frac{\mu}{\rho}} & (\approx 1-10 \text{ m.s}^{-1}) \end{cases} \end{cases}$ 

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 : Shear Wave Imaging - a Multiwave approach

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

$$\stackrel{1 \text{ mm}}{\frown} \stackrel{1 \text{ à 5 m.s}^{-1}}{\frown} 5.000 \text{ images.s}^{-1} \text{!}$$

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

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

## The Transient Elastography Technique

Shear wave generation + Ultrafast Imaging



## How to measure the axial displacement induced by shear waves ?



It is possible to measure between 2 shots (for example every 200  $\mu s$ ) displacements between 1 and 100  $\mu$  ( particular velocity between 1 mm/s et 10 cm/s)

#### Transient Elastography in Tissue Mimicking Phantoms



## Hard inclusion

Movie of Uz component





## A Simple Inversion Algorithm

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

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

#### - Assumptions:

- 1) The medium is considered as infinite, isotropic, purely elastic and locally homogeneous.
- 2)  $\lambda \gg \mu \Rightarrow$  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

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

### **Inverse Problem – Hard Inclusion**







#### Ultrafast Plane Wave Compound Imaging for Vector Tissue Motion Imaging



Fig. 3. Left and right subapertures performing two different left and right speckle images. The focal spot allowing one to perform a segment (at depth  $Z_0$ ) of the j<sup>th</sup> line of the image is presented: (a) for a classical transmit-receive beamforming, (b) for the left subaperture receive beamforming, (c) for the right subaperture receive beamforming.



Fig. 10. Dependence of the lateral and longitudinal displacements variance with the angle between subapertures (in degrees). For a 50- $\mu$ m displacement applied in both directions, the mean estimate of the lateral and longitudinal displacements are, respectively, 48 and 51  $\mu$ m.

*Ultrafast compound imaging for 2D motion vector estimation : Application to transient elastography"* M. Tanter, J. Bercoff, M. Fink, IEEE Ultr., Ferr. And Freq. Ctrl, 49 (10), pp 1363-1374, 2002.

#### Ultrafast Compound Imaging for Vector Tissue Motion Imaging Experimental Proof of concept for Transient Elastography



#### The extension to Ultrafast Vector Doppler was also proposed in the 2002 paper

Ultrafast compound imaging for 2D motion vector estimation : Application to transient elastography" M. Tanter, J. Bercoff, M. Fink, IEEE Ultr., Ferr. And Freq. Ctrl, 49 (10), pp 1363-1374, 2002.

### Ultrafast Plane Wave Compounding improves Motion estimation



*Ultrafast compound imaging for 2D motion vector estimation : Application to transient elastography"* M. Tanter, J. Bercoff, M. Fink, IEEE Ultr., Ferr. And Freq. Ctrl, 49 (10), pp 1363-1374, 2002.

## **Ultrafast imaging with Coherent Compounding**

Tradeoff between FRAME RATE and IMAGE QUALITY

Example in a 3cm depth image



**10dB contrast Improvement using Ultrafast Compound for SSI sequence** 

#### **Supersonic shear Imaging with Coherent compounding**

**Typical Experiment in Gelatin Phantoms** 



### In Vivo Breast Elasticity map using Coherent Compo

Medium: In Vivo Breast (healthy volunteer) 1 pushing line in the middle of the image

#### Shear wave velocity maps



#### Strong Increase of the quality of the shear velocity maps

## Transient Elastography and Ultrasonic Radiation Force



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

#### A. Sarvazyan, K Nigthingale, J Greenleaf, M. Fink, M Tanter

## **Ultrafast Imaging and Acoustic Radiation Force**



Plane wave insonification at 3000 Hz

## The Supersonic Push !!!!!!



# Shear beamforming with a supersonic moving source

Plane wave generation in a 2m/s phantom



Mach 3

Mach 10

#### Mapping Elasticity : Inverse problem of Shear Wave Propagation



#### Movie Duration 20 ms

La résolution des ultrasons Le contraste des ondes de cisaillement

## The goal of Elastography is to estimate tissue elasticity : Multiwave or not Multiwave ?

#### - Mechanical excitation

- Static (Ophir, Konofagou, Insana...)
- Dynamic / Harmonic (Parker, Sato, Greenleaf, Levinson,...)
- Transient (Fink, Tanter)
- Induced remotely by ultrasonic radiation force (Sarvazyan, Trahey, Nightingale (ARFI), Greenleaf, Fink, Tanter)

#### - Imaging tissue displacements

- Ultrasound Speckle motion (Sato, Parker, Levinson, Ophir, Fink...)
- Magnetic Resonance Imaging (Greenleaf,...)

## Static Elastography (J. Ophir)

One create a static stress that induces a static strain. On measure at all locations the strain (strain imaging)



#### Hitachi, Medison, Siemens, Ultrasonix, Zonare, Toshoba...

### Comparison between the Supersonic Shear Wave Imaging and Static Elastography (strain imaging)



## 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

M. Fink, M. Tanter, "Multiwave Imaging and Superresolution" Physics Today, 63(2), 28-33, Feb. 2010

#### Shear wavelength : typicaly 10 mm Spatial resolution on the shear modulus : 1 mm ( $\lambda_{us}$ )

**Ultrasonic Array** several hundreds of  $\lambda_{\rm US}$ Movie of the shear wave near-field Several tens of  $\lambda_{shear}$ closed to each heterogeneities **Multi-Wave Imaging allows to get the Contrast** of One Wave with the Resolution of the Second Wave

## The Evolution of our Ultrafast Imaging Technology



HDI 1000 2004-2005 Prototype V1

2006-2007



## Safety and Efficiency issues in Elastography

ondes et images

#### A Key difference between SSI and ARFI is ULTRAFAST IMAGING



## Medical applications

- Breast
- Tyroid
- Liver
- Kidney
- Muscle
- Vascular
- Cardiac
- Eye
- Prostate
- Monitoring HIFU

## Diagnostic impact in breast :







## **Breast Chimiotherapy**



June/2011

July/2011

August/2011

October/2011

(Collaboration A. Athanasiou, Curie Institute, Paris, France)

## Liver : Fibrosis and Cirrhosis



## Focal lesions in Liver : examples





**SWE Hepatocellular Carcinoma** 



## Prostate – multiwave imaging



## **Carotid Plaque Stifness**





#### ID: Aixplorer\_34333516

#### 02/02/2011 10:09:07 SL15-4 / Thyroid / vasculaire MI 1.2 TI 0.4

#### в

Pen/FR/H M 5/67 dB/Low T 1540 m/s SR 6 G 40 % Fr. 12 Hz

SWE™ Std/Med M 1/High S 5/O 50 % G 70 %

Z 100 %









#### **Dynamics of Muscle Contraction**



Shinohara S., Sabra K., Genisson J.-L., Fink M., Tanter M.

+100 kPa

80

60

40

20

0

"Real-time visualization of muscle stiffness distribution with ultrasound SWI during muscle contractions », Muscle and Nerve, June 2010


### Real Time Elasticity Changes of in vivo Cardiac Muscle (Sheep Model)







5000 fps



Pernot M, Matteo P., Couade M., Crozatier B., Fischmeister R., Tanter M. Journal of the American College of Cardiology , *2011* 

M. Couade, M. Pernot, P. Matteo, B. Crozatier, R. Fischmeister and M. Tanter Ultr. Med. Biol., Oct. 2010





### **Quantitative Monitoring of Uterin Contraction during Pregnancy**



# The arterial stiffness varies with blood pressure (diastole/systole) -Carotid

• 13 successive 20 ms experiment every 120 ms = 13 elasticity per cardiac cycle





# Ultrafast imaging of the pulse wave along the carotid

• Frame rate : 3.000 frames/second



# Local estimation of PWV using ultrafast imaging



Two estimations per cardiac cycle

≠ elasticity

# PWV measured by ultrafast imaging

### **PWV estimation using ultrafast scanner**

ondes et images



Couade, M.; Pernot, M.; Messas, E.; Emmerich, J.; Hagege, A.; Fink, M. & Tanter, M. (2011), 'Ultrafast imaging of the arterial pulse wave', *Irbm* 32(2), 106--108.



# Ultrafast Imaging of Intrinsic waves



# **Ultrafast Ultrasonic Imaging of Muscle fibers activation**



Our body is the ground of many transient phenomena at time scales of the order of milliseconds



### 2000 images/s

Can we use mechanical vibrations where electromagnetic waves are limited due to large wavelengths (cardiology, epilepsy,...) ?

Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A. 'Ultrafast imaging of in vivo muscle contraction using ultrasound', *Applied Physics Letters* 89(18), 2006

### 

# **Ultrafast Localization of activated muscle fiber bundles**



Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A. 'Ultrafast imaging of in vivo muscle contraction using ultrasound', *Applied Physics Letters* 89(18), 2006

Ultrafast Localization of activated muscle fiber bundles

#### Localization and time profile of contraction



Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A. 'Ultrafast imaging of in vivo muscle contraction using ultrasound', *Applied Physics Letters* 89(18), 2006

Effect of electro stimulation amplitude on the contraction



3.5 V

4.5 V

5.5 V

Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A.

'Ultrafast imaging of in vivo muscle contraction using ultrasound', Applied Physics Letters 89(18), 2006

Effect of electro stimulation amplitude on the contraction



Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A. 'Ultrafast imaging of in vivo muscle contraction using ultrasound', *Applied Physics Letters* 89(18), 2006

# 3D Ultrafast imaging of muscle electrostimulation

### 3D linear Scan with triggered acquisition/electrostimulation



22 translations with a 2 mm step

3D Scan volume : 35x35x44 mm<sup>3</sup>



Deffieux, T.; Gennisson, J.-L.; Tanter, M.; Fink, M. Nordez, A. 'Ultrafast imaging of in vivo muscle contraction using ultrasound', *Applied Physics Letters* 89(18), 2006



# **Electromechanical waves in the heart**

Myocardial rapid velocity distribution, Kanai, H; Koiwa, Y ULTRASOUND IN MEDICINE AND BIOLOGY, 27(4), 481-498, 2001

Left ventricular transmural systolic function by high-sensitivity velocity measurement "phased-tracking method" across the septum in doxorubicin cardiomyopathy, Koiwa, Y; Kanai, H; et al. ULTRASOUND IN MEDICINE AND BIOLOGY, 28, 11-12, 1395-1403, 2002

Electromechanical imaging of the myocardium at normal and pathological states Pernot, M; Konofagou, IEEE International Ultrasonics Symposium Location: Rotterdam, 2005

ECG-gated, mechanical and electromechanical wave imaging of cardiovascular tissues in vivo Pernot, Mathieu; Fujikura, Kana; Fung-Kee-Fung, Simon D.; et al., ULTRASOUND IN MEDICINE AND BIOLOGY, 33 (7), 1075-1085, 2007

Noninvasive electromechanical wave imaging and conduction velocity estimation in vivo Konofagou, Elisa; Luo, Jianwen; Saluja, Deepak; et al. IEEE ULTRASONICS SYMPOSIUM, 969-972,2007

Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A.; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.

H. Kanai: "Propagation of Vibration Caused by Electrical Excitation in the Normal Human Heart" *Ultrasound in Medicine & Biology* Vol. 35, No. 6, pp. 936-948 (June 2009)

Electromechanical Wave Imaging for Noninvasive Mapping of the 3D Electrical Activation Sequence in vivo, Provost, Jean; Lee, Wei-Ning; Fujikura, Kana; et al., CIRCULATION, 122(21), 2010

Physiologic Cardiovascular Strain and Intrinsic Wave Imaging, Konofagou, Elisa; Lee, Wei-Ning; Luo, Jianwen; et al., ANNUAL REVIEW OF BIOMEDICAL ENGINEERING, VOL 13 Book Series: Annual Review of Biomedical Engineering, 13,477-505, 2011

Imaging the electromechanical activity of the heart in vivo, Provost, Jean; Lee, Wei-Ning; Fujikura, Kana; et al., P.N.A.S., 108(21), 2011

Single-heartbeat electromechanical wave imaging using temporally unequispaced acquisition sequences, **Provost**, Jean; Thiebaut, Stephane; Luo, Jianwen; et al., Phys. Med. Biol., 57(4), 2012

First ultrasonic imaging of mechanical Waves

First US imaging of Electro- mechanical Waves (ECG Gated)

First ultrafast imaging of single heartbeat

ECG Gated US imaging Of Electromechanical waves

Ultrafast imaging of single hearbeat



### Use of circular waves to increase field of view

### Flat transmit



Circular transmit



#### Andresen et al. UFFC 2006 Symposium



Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A.; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009. Papadacci C., Pernot M., et al. IEEE IUS, Dresden, 2012



### Synthetic imaging with circular waves



Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A.; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.



# **Ultrafast Imaging of Heart Transient Vibrations**



Hiroshi Kanai: "Propagation of Vibration Caused by Electrical Excitation in the Normal Human Heart" *Ultrasound in Medicine & Biology* Vol. 35, No. 6, pp. 936-948 (June 2009)

Ultrafast Imaging of *in vivo* heart potentials (Wide field of view during a single cardiac cycle)

in vivo Sheep experiments Phased Array, fc = 3.3 MHz Field of View 8 cm 1600 frames per second



**Short Axis** 



Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A.; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.

Long Axis

Ultrafast Imaging the heart sound propagation

ondes et



Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A. ; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.



# Wall tracking with 2D speckle tracking combined with TDI

Wall tracking



#### TDI signal along the tracked wall



Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A. ; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.



# Aortic valve closure

- Long Axis View, signal along the septum
- FR = 1600 Hz, 800 frames



Couade M., «Application of ultrafast imaging in cardiology», PhD Thesis, Paris 7 University, 2011

Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays Couade M., Hagege, A.-A.; Fink, M. IEEE Ultrasonics Symposium, pp 515-518, 2009.



- FR = 1600 Hz, 800 frames
- Propagation of the heart sound from the aortic valve (short axis view)



Couade M., «Application of ultrafast imaging in cardiology», PhD Thesis, Paris 7 University, 2011



# Ultrafast Imaging of Acoustic Cavitation

Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events Induced by Short Pulses of High-Intensity Ultrasound', *leee Transactions On Ultrasonics Ferroelectrics and Frequency Control* 58(3), 517--532.



# **Active detection** of cavitation events in HIFU treatments

> Bubbles as scatterers

Conventional B-mode imaging :hyperechogenic region in the treated region



Acoustically induced bubbles

Roberts, WW; Hall, TL; Ives, K; et al. Journal of Urology, 175 (2): 734-738, 2006

(+) localization of the bubbles

(-) only large number of bubbles can be detected (bubble clouds)



# **Passive detection and localization of cavitation events in HIFU**

> Detection of the acoustic emission of the cavitation events



### Passive imaging in saline solution (520-kHz CW),

Passive cavitation imaging with ultrasound arrays, Vasant A. Salgaonkar, Saurabh Datta, Christy K. Holland, and T. Douglas Mast J. Acoust. Soc. Am., 2009



# **Passive detection and localization of cavitation events in HIFU**

### > Detection of the acoustic emission of the cavitation events

Passive mapping of two disjoint cavitation regions produced by insonifying an agar phantom with two talc suspensions



Passive Spatial Mapping of Inertial Cavitation During HIFU Exposure M. Gyongy and C. Coussios IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, 2010

(+) localization of the cavitation events(-) poor axial resolution



## Impact of Ultrafast Imaging in cavitation detection imaging

Why to study acoustic cavitation

using ultrafast ultrasound imaging ?

- *In Vivo* mapping of single cavitation events generated with high amplitude short ultrasonic excitation of tissue
- For monitoring early stages of therapeutic applications :
  - cavitation-enhanced heating
  - histotripsy
  - > location of the first bubbles leading to the initial cloud
- For evaluating the nucleation threshold in vivo (investigate safety in diagnostic applications)



# Impact of Ultrafast Imaging in cavitation detection imaging

### Potential in Therapeutic Ultrasound (HIFU, Histotripsy, RF ablation)

### Active Imaging with an ultrasonic array

• Not sensitive to single cavitation events (bubble clouds)

Improvement for single event detection : subtraction of a reference image+ ultrafast imaging technique (9KHz imaging rate)

#### Passive imaging with an ultrasonic array

Farny, CH; Holt, RG; Roy, RA, UMB , 35 (4): 603-615 APR 2009 Salgaonkar, VA; Datta, S; Holland, CK; et al, JASA 126 (6): 3071-3083 DEC 2009 Gyongy, M; Coussios, CC IEEE TBME, 57 (1): 48-56 JAN 2010

> no time origin, localization submitted to diffraction limit (both in lateral and axial dimension)

Improvement for single event detection : synchronized detection (no integration in time: improved axial resolution)



# **Ultrafast Cavitation Imaging**





HIFU single element transducer (Imasonic, France)

660kHz central frequency

Focal distance: 45 mm, f#=1

*driven by:* function generator + 300W or 5kW amplifier

Standard ultrasound imaging linear array (L7-4, Phillips)

128 transducers, pitch 0.3 mm, bandwidth: 4-7MHz

*driven by:* SuperSonic protoype programmable channels both in receive (64 channels) and transmit (128 channels)



# Passive Imaging In vitro experiment: gelatin phantom

<u>Phantom</u>: 5% (w/v) gelatin gel > free of scatterer

High amplitude excitation : 2cy. @ 660 kHz,

- 6.4 MPa negative peak

Synchronization with the emission:

passive recording starts 22  $\mu$ s after the transmit



# First case: one nucleated bubble



**Ultrafast Passive receive beamforming** 

Institut Langevin



Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *leee UFFC* 58(3), 517--532.



### Passive Imaging In vitro experiment: gelatin phantom



Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.



### Passive Imaging In vitro experiment: gelatin phantom



**Questions :** How many bubbles ? How accurate are the locations ?

Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *leee UFFC* 58(3), 517--532.



# Standard Active Cavitation Detection (ACD)

**B-mode imaging :** maximum frame rate 100Hz > possible dissolution of bubble before the 1st image

Improvement for single event detection : *ultra-fast imaging up to 9kHz* 

Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.



# Standard Active Cavitation Detection (ACD)

**B-mode imaging :** maximum frame rate 100Hz > possible dissolution of bubble before the 1st image



Improvement for single event detection :

ultra-fast imaging up to 9 kHz here



# Standard Active Cavitation Detection (ACD)

**B-mode imaging :** maximum frame rate 100Hz > possible dissolution of bubble before the 1st image



Improvement for single event detection : ultra-fast imaging up to 9 kHz here Plane wave : 1 cy., 6MHz 50 z (mm) 55 60 14 16 18 20 22 24 26 x (mm)330 µs after the high amplitude excitation



### First case : one nucleated bubble



 $330 \ \mu s$  after the high amplitude excitation

 $\Rightarrow$  Good spatial agreement between active and passive imaging

Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *leee UFFC* 58(3), 517--532.


# Second case : several nucleated bubbles



Only 2 bubbles in the active image and 1mm axial agreement :

- the assumptions for passive beamforming are not exact
- complex passive signature of nucleating bubble (rebound, collapse...)

> Passive images more complex, but qualitative agreement







Ultrafast Imaging is key for In vivo determination of the acoustic cavitation threshold

### Bmode image



## Skull base

Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.



# High amplitude excitation : 2cy. @ 660 kHz, up to - 20 MPa negative peak pressure



Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.



Active images 550 µs after the high amplitude excitation

No nucleation





Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.



# Active images 550 µs after the high amplitude excitation



Imaging of Cavitation Events', leee UFFC 58(3), 517--532.



# Active images 550 µs after the high amplitude excitation





Statistical study on 4 sheeps: 100 different sonications in the brain Experiments still ongoing Cavitation threshold : between -15MPa and -17.2MPa (660kHz)



Calibration of the 600kHz transducer with an heterodyne interferometer



Use of the high imaging frame rate to follow the bubble dynamics



Gateau, J.; Aubry, J.-F.; Pernot, M.; Fink, M. & Tanter, M. (2011), 'Combined Passive Detection and Ultrafast Active Imaging of Cavitation Events', *Ieee UFFC* 58(3), 517--532.

# Summary - Ultrafast Imaging of Acoustic Cavitation

- Single bubble nucleation events were detected and localized <u>passively</u> and <u>actively</u> with an axial resolution of less than 0.3 mm
- Active detection is performed even in scattering media
- Small number of events can be separated
- Combination of passive and active detection provides information on the nucleation event and the induced bubbles Cavitation threshold in vivo in brain: between -15MPa and -17.2MPa (660kHz) (still ongoing)
- Active high frame rate :

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- reach PRF in the kHz range > step by step formation a bubble cloud
  - follow the dynamics of the induced bubble

<u>Applications :</u> study the nuclei population *in vivo* and monitor the initiation phase of bubble cloud formation for cavitation therapies







# Ultrafast Imaging of contrast agents disruption



### **Context – Conventional ultrasonic imaging of Blood Perfusion**





Conventional imaging is too slow to image dissolution over an entire image



Bouakaz et al. 2009



# Plane wave compounding increases SNR and reduces frame rate to 500 Hz

### Pulse sequence used for contrast agents dissolution imaging









The process of dissolution in the wall-less vessel is observable over 100 ms





The dissolution curves in 2D are similar to those measured with single transducers





The dissolution curves depends on disruption pulse length and amplitude





Distinguishing bound and unspecific microbubbles is a challenge in molecular imaging with ultrasound





# Tumor-targeted Microbubbles

Control microbubbles

# (StBx Shiga Toxin)



Bound and unspecific microbubbles are distinguished through their clearance time in the tumor



Couture, O.; Bannouf, S.; Montaldo, G.; Aubry, J.-F.; Fink, M. & Tanter, M. (2009), 'Ultrafast Imaging of Ultrasound Contrast Agents', *Ultrasound In Medicine and Biology* 35(11), 1908--1916.



The physical environment affects the acoustic response of microbubbles

<u>Hypothesis</u>: The dissolution time after disruption changes in the "bound state".



### **Free Bubbles**

### **Targeted microbubbles**



Dissolution imaging is performed with an elastography apparatus on two parallel setup





### The process of dissolution is also observable on a dot of targeted microbubbles





Targeted microbubbles dissolve faster than freely moving microbubbles.



Couture, O.; Bannouf, S.; Montaldo, G.; Aubry, J.-F.; Fink, M. & Tanter, M. (2009), 'Ultrafast Imaging of Ultrasound Contrast Agents', *Ultrasound In Medicine and Biology* 35(11), 1908--1916.

Couture, O.; Dransart, E.; Dehay, S.; Nemati, F.; Decaudin, D.; Johannes, L. & Tanter, M. (2011), 'Tumor Delivery of Ultrasound Contrast Agents Using Shiga Toxin B Subunit', *Molecular Imaging* 10(2), 135--143.



Dissolution imaging gives access to new types of contrast enhancement

# Impact of ultrafast imaging for contrast agents imaging



- Differentiate bound from unspecific microbubbles

- Fast events are dependent on the geometry of the environment

- Pulses schemes (PI, AM, ...) can be applied to entire frames

- Frame rate accelerates with calculations capacity

Couture, O.; Bannouf, S.; Montaldo, G.; Aubry, J.-F.; Fink, M. & Tanter, M. (2009), 'Ultrafast Imaging of Ultrasound Contrast Agents', *Ultrasound In Medicine and Biology* 35(11), 1908--1916.

Couture, O.; Dransart, E.; Dehay, S.; Nemati, F.; Decaudin, D.; Johannes, L. & Tanter, M. (2011), 'Tumor Delivery of Ultrasound Contrast Agents Using Shiga Toxin B Subunit', *Molecular Imaging* 10(2), 135--143.



# **Ultrafast Contrast Imaging**

'Ultrasound Contrast Plane Wave Imaging' O. Couture, M. Fink, M. Tanter, IEEE Trans. Ultr. Ferr. Freq. Ctrl., in press, 2012



# Microbubbles are used to image vascularization and measure perfusion





#### **Ultrafast Contrast Plane Wave Imaging produces a much better contrast**







Images obtained for a similar disruption ratio of microbubbles (25 % disruption after 100 images or focused: 55 kPa peak-negative pressure and Plane waves = 40 kPa).

'Ultrasound Contrast Plane Wave Imaging' O. Couture, M. Fink, M. Tanter, IEEE Trans. Ultr. Ferr. Freq. Ctrl., in press, 2012



0.25

0.00

0.5

 $I_{SPTA}$  (mW/cm<sup>2</sup>)

5

0.05

Disruption ratio obtained after 100 images. The ratio is calculated from the intensity of the microbubble echo before and after the full sequence. In plane-wave imaging, each pixel is insonified 121 times rather than a single time in focused imaging.

\_Hence, at the same peak-negative pressure, plane-wave imaging disrupts slightly more bubbles.

0.6

Conventional Focused imaging

0.4

Peak-Negative Pressure (MPa)

• Plane wave imaging

0.2

0.25

0.00

But Plane-wave imaging spread the energy over more pulses at lower pressure. Microbubbles being sensitive to the peak-negative pressure, rather than the total energy, the 50% disruption point is only observed at 0.47 mW/cm2 for plane-wave imaging as compared to 0.02 mW/cm2 for focused pulses.

Less acoustic energy can be emitted with focused pulses before microbubbles disruption occurs.







# Ultrafast Ultrasound for Contrast Superresolution Imaging



Ultrasound imaging is still limited by the trade-off between resolution and penetration



Mouse embryo at 40 MHz Penetration ≈ 1 cm



Human fœtus at 5 MHz Penetration ≈ 10 cm



# Imaging resolution is limited by the wavelength



# Two distincts sources

**Rayleigh criterion** 

Two indistinguishable sources



Sources become distinguishable when they are activated separately







P-FPALM image of a fixed fibroblast (scale bar = 1  $\mu$ m). Gould et al. Nat Methods 2008. (Hess group)



# Ultrafast (plane-wave) imaging shows distinct events in-vivo



Frame Rate: 5000 kHz



'Microbubbles Ultrasonic Super Localization Imaging » O. Couture, M. Fink, M. Tanter, Proc. IEEE, Orlando, 2011



## A bubble is an ideal punctual source



'Microbubbles Ultrasonic Super Localization Imaging » O. Couture, M. Fink, M. Tanter, Proc. IEEE, Orlando, 2011



A punctual source defines the classical resolution limit after the beamforming process



'Microbubbles Ultrasonic Super Localization Imaging » O. Couture, M. Fink, M. Tanter, Proc. IEEE, Orlando, 2011



### A punctual source generates a parabola on the RF signals (Bscan)





'Ultrasound Contrast Plane Wave Imaging' O. Couture, M. Fink, M. Tanter, IEEE Trans. Ultr. Ferr. Freq. Ctrl., in press, 2012

Depth (axial)
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### Fitting the arrival times parabola localizes the bubble

 $delay = \frac{\sqrt{depth_of_bubble^2 + (x - lateral_position)^2}}{speed_of\_sound}$ 



### Spatial Localization precision is much better than conventional imaging

'Ultrasound Contrast Plane Wave Imaging' O. Couture, M. Fink, M. Tanter, IEEE Trans. Ultr. Ferr. Freq. Ctrl., in press, 2012







Microbubble ultrasound super-localization imaging (MUSLI) improves resolution 100-fold

1.5 MHz	λ/2	EXP.	Simulation
AXIAL	500 µm	6 µm	4.5 µm
LATERAL		40 µm	11 µm



### **Experimental proof of concept in 2D with microchannels**



MUSLI can resolve a microchannel carrying microbubbles





Microbubbles ultrasound super-localization imaging could resolve capillaries at low frequencies





# **Ultrafast Doppler Imaging**



- ShearWave Elastography (SWE) provides an additional information to the user: tissue stiffness
- SWE completes the information circle of ultrasound devices
- **B-mode** 
  - $\rightarrow$  $\rightarrow$ **Doppler**

Elastography  $\rightarrow$ 

ANATOMY FLOW **STIFFNESS**  (1970s - 1980s)(1980s - 1990s)(2000s - 2010s)



- SWE has key advantages compared to other elastography techniques
  - Automated stress generation •
  - Quantitative imaging (2D/3D)
  - Real time



# Can we reinvent conventional ultrasound modes with an Ultrafast imaging system ?



Bercoff<sub>5</sub>J.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), 'Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl*; 58(1)

# Doppler imaging today: two separate modes

### 1) Color Flow Imaging

- Real time imaging of flow
- Display the mean velocity per pixel in a color coded representation
- Used for detection of flow or localization of flow abnormalities



Imaging

### 2) Spectral Doppler

- Full quantification of flow velocity per
  Fourier analysis
- Available at on given location

#### velocities



# Conventional vs Ultrafast Doppler sequences

Conventional CFI

Conventional PW



# **Leveraging Ultrafast Doppler Data**

Ultrafast Doppler



1) Increase color flow imaging performances

- + Sensitivity: improve slow flow detection
- + Frame rate: finer flow dynamics analysis
- + Consistency: All pixels shown are synchroneous.

2) Quantification => PW (spectral analysis) everywhere

Bercoff<sub>55</sub>J.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl;* 58(1)



### A Trade-off between Speed and Sensitivity

### FASTER



### Ultrafast Doppler mode presentation Workflow



Bercoff, J.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), 'Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl,* 58(1)



# Ultrafast Doppler: Full Retrospective analysis



Bercoff<sub>15</sub>J.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl*; 58(1)

## **Ultrafast Doppler: Quantitative Validation**

Ultrafast PW vs Conventional PW













All images are courtesy of J.P. Henry

# Improving visualisation of hemodynamics

**STANDARD CFI** 

Bercoff<sub>162</sub>.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl*; 58(1)

# Improving visualisation of hemodynamics

ULTRAFAST DOPPLER

Bercoff<sub>65</sub>J.; Montaldo, G.; Loupas, T.; Savery, D.; Meziere, F.; Fink, M. & Tanter, M. (2011), Ultrafast Compound Doppler Imaging: Providing Full Blood Flow Characterization', *leee Trans. Ultr. Ferr. Frq. Ctrl*, 58(1)

## **Full flow Characterization**







Fr: 9/166



Fr: 59/166





# **Ultrafast Vector Doppler Imaging**

Courtesy of Jørgen Arendt Jensen

Center for Fast Ultrasound Imaging Department of Electrical Engineering Technical University of Denmark



Transducer

### Fast plane wave imaging

- Single plane wave emitted
- Full image reconstructed from single emission
- Very fast imaging can be attained with thousand of image per second
- Flow imaging with excellent temporal resolution
- Vector flow imaging possible
- Implemented on the RASMUS experimental scanner
- Frame rate of more than 100 Hz

Udesen et al: 'High Frame-Rate Blood Vector Velocity Imaging Using Plane Waves: Simulations and Preliminary Experiments', IEEE UFFC, vol 55, no. 8, pp. 1729-1743, 2008.



Center for Fast Ultrasound Imaging Technical University of Denmark Carnegie Mellon University Next Generation Medical Imaging

### Frame rate : 100 Hz, Common carotid artery



From Hansen et al: *In-vivo Examples of Flow Patterns With The Fast Vector Velocity Ultrasound Method* Ultraschall in der Medizin, vol 30, no. 5, pp. 471-477, 2009

Center for Fast Ultrasound Imaging Technical University of Denmark Carnegie Mellon University Next Generation Medical Imaging DTU



1 0.88 -0.75 -0.63 0.5 0.38 0.25 0.13 DTU

Truncus brachiocephalic a, a. subclavia and a. carotis com.

versity dical Imaging



### Truncus brachiocephalica

DTU



Center for Fast Ultrasound Imaging Technical University of Denmark Carnegie Mellon University Next Generation Medical Imaging



The jugular vein and carotid artery

Center for Fast Ultrasound Imaging Technical University of Denmark Carnegie Mellon University Next Generation Medical Imaging





The jugular vein and carotid artery arnegie Mellon University

Center for Fast Ultrasound Imaging Technical University of Denmark

Next Generation Medical Imaging



Center for Fast Ultrasound Imaging Technical University of Denmark Carnegie Mellon University Next Generation Medical Imaging



# A more complex case : the Myocardium

# Ultrafast Doppler Imaging of small flows in a fast moving organ ?

Ultrafast Doppler imaging of blood flow dynamics in the myocardium. Osmanski BF, Pernot M, Montaldo G, Bel A, Messas E, Tanter M, IEEE Trans Med Imaging. 2012



## **Myocardial Blood Flow Dynamics**

Intramyocardial Blood Flow Dynamics

-> Early diagnosis of cardio-vascular diseases

### State of the Art

#### X ray coronarography



#### Ultrasound imaging



### Left Anterior Descending Coronary Artery (LAD)

### C. Caiati, Circulation (1999)

### Institut Langevin ondes et images

### Ultrafast Imaging of the myocardium : Experimental Set-Up



# Ultrafast Imaging of the myocardium : acquisition sequence







### **Solution = Frequency Demodulation**

Ultrafast Doppler imaging of blood flow dynamics in the myocardium. Osmanski BF, Pernot M, Montaldo G, Bel A, Messas E, Tanter M, IEEE Trans Med Imaging. 2012
## Ultrafast Imaging of the myocardium : demodulation process



Ultrafast Doppler imaging of blood flow dynamics in the myocardium. Osmanski BF, Pernot M, Montaldo G, Bel A, Messas E, Tanter M, IEEE Trans Med Imaging. 2012

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#### **Signed Power Doppler: discriminate arteries and Veins**





#### Ultrafast Imaging of the myocardium : systole ejection



Osmanski BF, Pernot M, Montaldo G, Bel A, Messas E, Tanter M, IEEE Trans Med Imaging. 2012



#### **Ultrafast Imaging of the myocardium : Diastole**





#### **Transition between Arterial and Venous Flow**





Occlusion of two main epicardial coronary arteries upstream the imaging plane



**Before Ischemia** 

#### After Ischemia



Systole (Venous Flow)

Diastole (Arterial Flow)





Ultrafast Doppler imaging of blood flow dynamics in the myocardium. Osmanski BF, Pernot M, Montaldo G, Bel A, Messas E, Tanter M, IEEE Trans Med Imaging. 2012



## **Ultrafast Doppler for** *fUltrasound* **:**

## Functional Ultrasound Imaging of brain Activity



## How to image the brain in action?



#### Blood changes → Indirect image of brain activation



### **Functional imaging techniques**



Functional ultrasound (fUS) overcomes the poor sensitivity of Doppler ultrasound



## A classical model of brain activation: whisker stimulation



## The concept of µDoppler based on Ultrafast Imaging



E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter Functional Ultrasonic Imaging of Brain Activity, *Nature Methods*, July 2011

#### Impact of the number of time samples on Ultrafast Doppler sensitivity



200 compound



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400 compound





What is really measured by I?

1/I is proportional to the number of scatterers (red blood cells) in the voxel

2/ Only a range of velocity is detected

Doppler frequencies > cutoff frequency (70 Hz)

3/ The effect of the vessel angle can be neglected



I measures the volume of blood flowing at a velocity higher than 4 mm/s (vessels >30  $\mu$ m) in the voxel



## What is the sensitivity of Power Doppler Imaging?



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## **Theoretical Sensitivity Gain : Conventional/ Ultrafast Doppler**



Functional ultrasound imaging of the brain: theory and basic principles. E. Mace, G. Montaldo, B.-F. Osmanski, I. Cohen, M. Fink, M. Tanter, IEEE UFFC, under review



## 3D µDoppler Scan of rat Cerebral Blood Flow



E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter Functional Ultrasonic Imaging of Brain Activity, *Nature Methods*, July 2011



## Mapping the direction of the flow





## 3D µDoppler Scan of rat CBV : Sagittal orientation











E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter, Nature Methods, July 2011





0.8

0.4

0

Correlation map r

#### Activated pixels (t-test, p>0.001)



#### Superposition



Identification



E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink and M. Tanter. Nature Methods, 8, 662-664 (2011)

# Can we detect smaller activated areas?



E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink and M. Tanter. Nature Methods, 8, 662-664 (2011)

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## **Epilepsy: A Challenge for neuroimaging techniques**

#### SEIZURE

#### **IMAGING MODALITY**



	<b>EEG-fMRI</b>		PET	Optics
Penetration/fie ld of view	*		~	*
Spatial resolution	only few points	~	*	~
Temporal resolution		*	*	✓
Sensitivity (SNR)	~	*	<b>v</b>	<b>v</b>





E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter, Nature Methods, July 2011

# Correlated with neuronal activity?



E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink and M. Tanter. Nature Methods, 8, 662-664 (2011)





## Propagation speed of epileptic seizures



664 (2011)

E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink and M.



## Spatial extension of synchronous activity

**Reference points** 





#### **Correlation maps**

Point 1







- Large synchronous areas matching with anatomical features
- Areas of independent seizing patterns







#### Other functional sensorial activity : following the olfactory track





Piriform cortex and olfactory bulb

Olfactory bulb

B. Osmanski, H. Gurden, G.Montaldo, F. Pain, M. Fink, M. Tanter

Piriform cortex



#### Ongoing work (II) : Development of Chronic and awake fUltrasound





#### Thinned-skull surgical procedure



#### Thinned skull ≈ 50 µm

hinned-skull

Craniotomy

μDoppler

Day 0

Day 7





**Minimally invasive Quick recovery** No sign of bone regrowth Low attenuation Smaller field of view



ImplementationFirst clinical st









### Ongoing work (III) : Proof of concept of clinical fUS

#### First in vivo data on preterm infants (transfontanel imaging)





# Coronal view Sagittal view Pulsatility on one single cardiac cycle

R Debré Hospital C. Demene, M. Pernot, V. Biran, M. Alison, O. Baud, M. Fink, M. Tanter



- Ultrafast ultrasound imaging is linked to the concept of Holography in Optics
- Ultrafast imaging using the concept of plane or circular waves paves the way to tremendous applications for medical ultrasound
- Ultrafast plane wave imaging was initially introduced for Transient Elastography
- Ultrafast imaging is the key for quantitative and real time Elastography
- Ultrafast imaging technology has emerged thanks to video game industry
- Supersonic Shear Wave Elastography was the first clinical application of ultrafast imaging and led to the first ultrafast imaging commercial device
- Beyond Elastography, new modalities are already emerging today :
  - Ultrafast Doppler for complex flows or small vessels imaging
  - Conventional Bmode will be replaced by Coherent plane wave compounding
  - Ultrafast Cavitation Imaging
  - Ultrafast Contrast imaging
  - fUltrasound : functional ultrasound imaging of brain activation



## **Thank You very much !**



At Institute Langevin, Paris





