Functional ultrasound imaging of the brain

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Final presentation
Principles of Medical Imaging System
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Outline

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History of ultrasonic imaging

- Build in 1950s, 1970s extensively used

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Outline

Review

What affects ultrasound imaging

- Wave length

Review

What affects ultrasound imaging

- Wave length
- Focus size

Review

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- Wave length
- Focus size
- Signal attenuation

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What affects ultrasound imaging

- Wave length
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- Balance of spatial and temporal resolution

Review

What affects ultrasound imaging

- Wave length
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Plane scanning

Principles

Functional ultrasound imaging of the brain

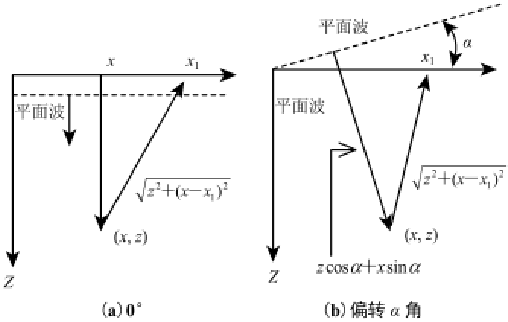


Figure: Time delays for plane wave insonification

$$t_1(x_i, x, z) = z/c + \sqrt{(z^2 + (x - x_i)^2)}/c \quad (1)$$

$$t_2(x_i, x, z) = (zcos\alpha + xsin\alpha)/c + \sqrt{(z^2 + (x - x_i)^2)}/c \quad (2)$$

Principles

Functional ultrasound imaging of the brain

$$t_2(x_i, x, z) = (zcos\alpha + xsin\alpha)/c + \sqrt{(z^2 + (x - x_i)^2)}/c$$

$$S(x, z, \alpha) = \int RF[x_1, t(x, z, \alpha)]dx_1 \tag{3}$$

$$CI(x, z) = \sum_{i=1}^{n} S(x, z, \alpha_i) \tag{4}$$

or

$$CI = \frac{1}{N} \sum_{i=1}^{N} S_B^2(t_i) \tag{5}$$

where α is the angle of deflection.
CI represent final combined images.

Principles

Frame frequency comparison

The velocity of ultrasound in brain is about 1540m/s.
Assume the imaging depth is 5cm
If there are 15 angle of deflection

Multi-angle plane wave coherent composite imaging algorithm:
$F_{flat} = 15400Hz$, $F_{compound} = 1026Hz$

Traditional 128 - line focused ultrasound frame frequency: 120Hz

Principles

Image of the brain

Principles

Activation map

Basically - Pearson's correlation coefficient

$$\rho_{XY} = \frac{Cov(X,Y)}{\sqrt{D(X)}\sqrt{D(Y)}}$$

Principles

Activation map

Basically - Pearson's correlation coefficient

$$\rho_{XY} = \frac{Cov(X,Y)}{\sqrt{D(X)}\sqrt{D(Y)}}$$

$$r = \frac{\sum_{i=1}^{N_t}\left(s_B(t_i) - \hat{s}_B\right)\left(A(t_i) - \hat{A}\right)}{\sqrt{\sum_{i=1}^{N_t}\left(s_B(t_i) - \hat{s}_B\right)^2}\sqrt{\sum_{i=1}^{N_t}\left(A(t_i) - \hat{A}\right)^2}}$$

$$\begin{bmatrix} 1 \\ 4 \\ 7 \end{bmatrix} \begin{bmatrix} 1 \\ 8 \\ 7 \end{bmatrix} = 0.7924$$

Principles

Video for Comparison

Play/Pause

Media Caption

Outline

Optical super-resolution microscopy

Inspiration from optical imaging

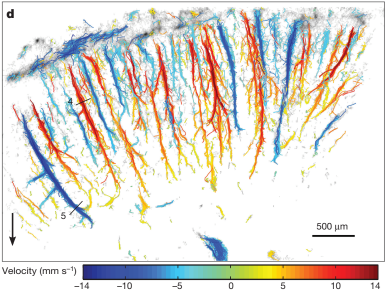
Figure: Winner of the 2014 Nobel Prize in Chemistry:
(left) Eric Betzig, (middle) Stefan W. Hell, (right) W.E. Mona.

PALM, STED, Photoactivation

Super-resolution ultrasound microscopy

Tanter and his work

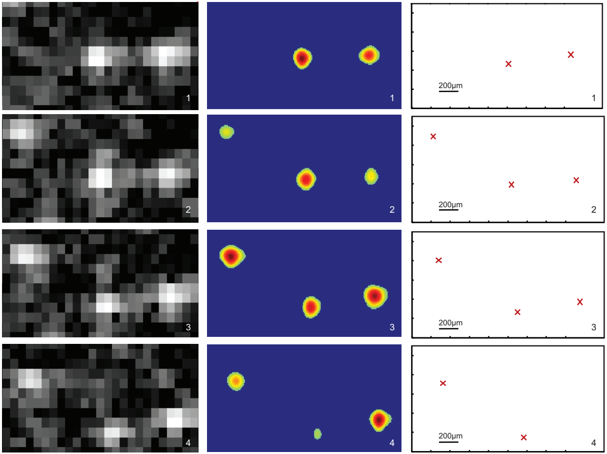
(a) Mickael Tanter



(b) Images of blood flow in the brain of rats by using superresolution ultrasound imaging method

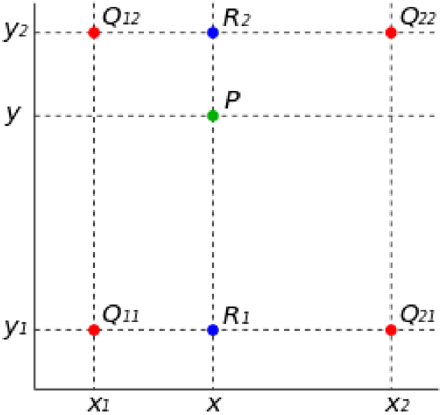
Principles

Airy disk



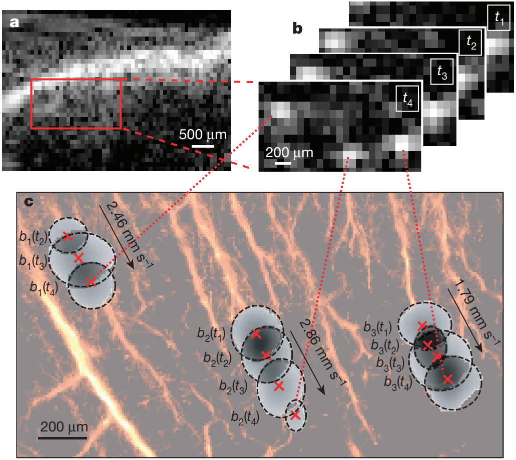
Principles

Bilinear interpolation



Principles

Deep super-resolution vascular imaging



Outline

Comparison

Functional ultrasound imaging

- Resolution ratio & SNR

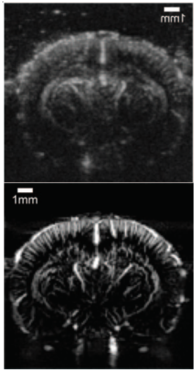


TABLE I. EXPERIMENTAL PARAMETERS USED FOR A TIME-EQUIVALENT COMPARISON OF THE FOCUSED METHOD AND THE ULTRAFAST COMPOUND METHOD.

Parameter	Focused	Compound
Ultrasound frequency	15 MHz	15 MHz
Pulse width	3 cycles	3 cycles
Aperture	4 mm	12 mm
Focal depth	10 mm	—
Maximal depth	20 mm	20 mm
Pulse repetition frequency, PRF	16 kHz	16 kHz
Sampling frequency, f_{samp}	1 kHz	1 kHz
Number of angles	—	16
Lines in a block	16	—
Number of blocks	8	—
Number of firings	5120	5120
Acquisition time	0.32 s	0.32 s
Number of frames, n_{imag}	40	320

The main difference is the number of images (8 times greater in the ultrafast compound method) for the same number of firings and the same acquisition time.

Achievement

Functional ultrasound imaging

- High temporal and spatial resolution
- Good penetration depth

Functional imaging in mobile small animal

Ultralight probes monitor brain activity in small animals

Application and prospect

Neonatal pediatric neurology

- Preterm infants seizures
- Take the place of fMRI

Application and prospect

Neonatal pediatric neurology

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Functional ultrasound imaging in adults

- Spatial localization of the activated area
- Take the place of electrocortical stimulation mapping (ESM)

Outline

Comparison

Question: capillary thickness

May be a valuable tool for basic understanding and diagnosis of disease processes that alter microvascular blood flow

Achievement

Ultrafast ultrasound localization microscopy (uULM)

- High temporal and spatial resolution
- The diffraction limit was broken ($\lambda/10$)

Application and prospect

Ultrafast ultrasound localization microscopy (uULM)

Tumor

- Find tumor
- Know the growth of the tumor

Application and prospect

Ultrafast ultrasound localization microscopy (uULM)

Tumor

- Find tumor
- Know the growth of the tumor

Coronary microvascular disease

- Difficult to visually detect the disease
- Therapeutic effects cannot be directly quantified

For Further Reading I

- Mace, E., Tanter, M., et al.
  Functional Ultrasound Imaging of the Brain: Theory and Basic Principles
  IEEE Transactions On Ultrasonics, Ferroelectrics And Frequency Control, 60(3), 492-506. doi: 10.1109/tuffc.2013.2592

- Errico, C., Tanter, M., et al.
  Ultrafast ultrasound localization microscopy for deep super-resolution vascular imaging
  Nature, 527(7579), 499-502. doi: 10.1038/nature16066

For Further Reading II

- Mace, E., Tanter, M., et al.
  Functional Ultrasound Imaging of the Brain
  Nature Methods, 8(8), 662-664. doi: 10.1038/nmeth.1641
- Imbault, M., Tanter, M., et al.
  Intraoperative Functional Ultrasound Imaging of Human Brain Activity.
  Scientific Reports, 7(1). doi: 10.1038/s41598-017-06474-8