# Photoacoustic Imaging of Blood Vessels in Tissue

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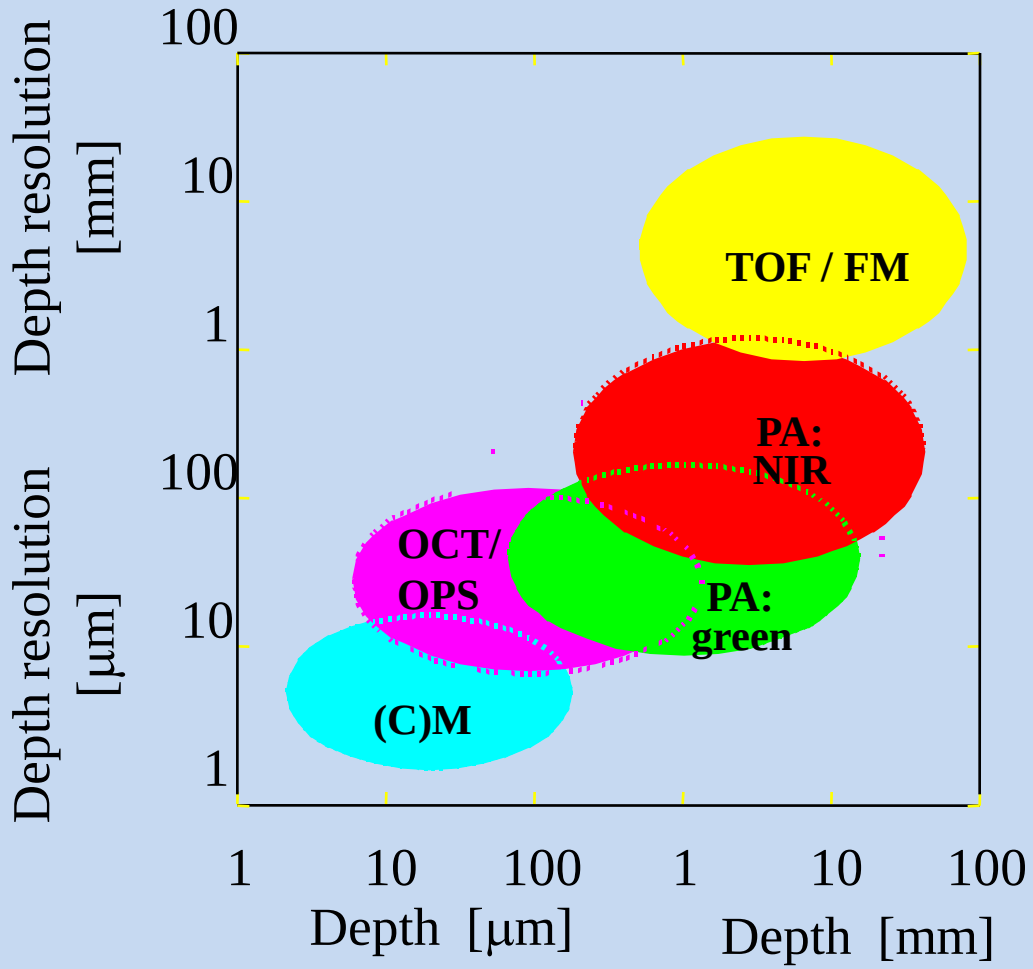
# Imaging methods for hidden structures in turbid media (tissue)




C(M) : (confocal) microscopy

OCT: optical coherence tomography

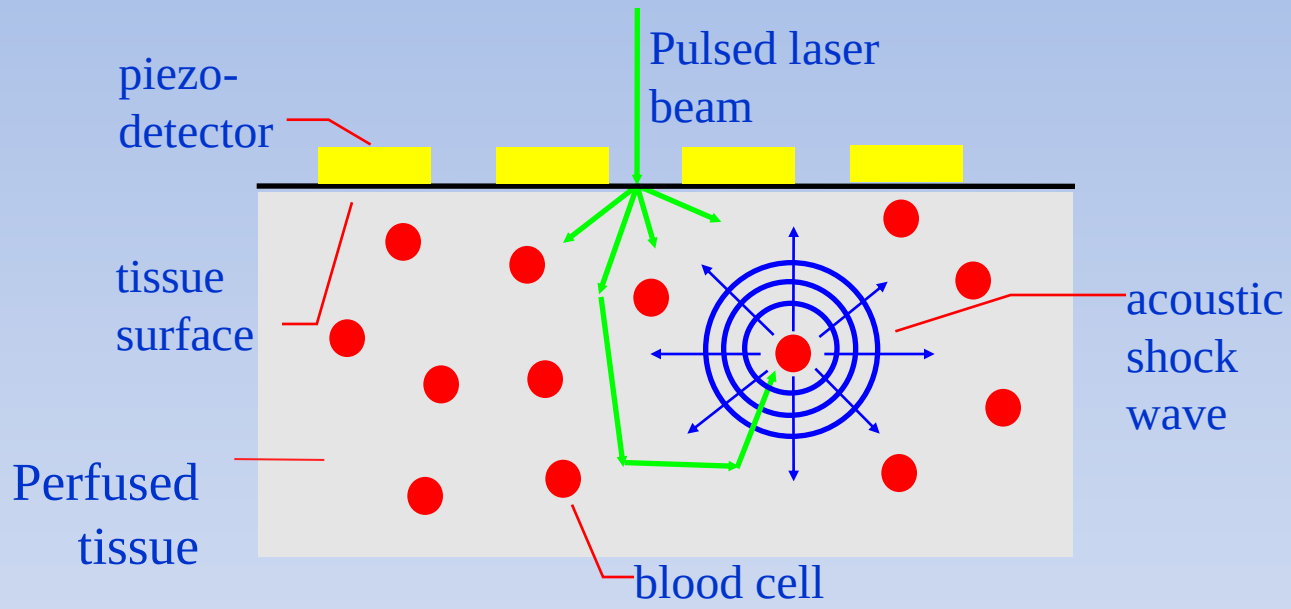
OPS: orthogonal polarization spectral imaging

PA: photoacoustics

TOF: time-of-flight tomography

FM: frequency-modulated tomography

# Photoacoustic Imaging




- light pulse is absorbed in blood cell
- adiabatic heating
- pressure pulse emerging (≈ 1500 m/s)
- detection at tissue surface

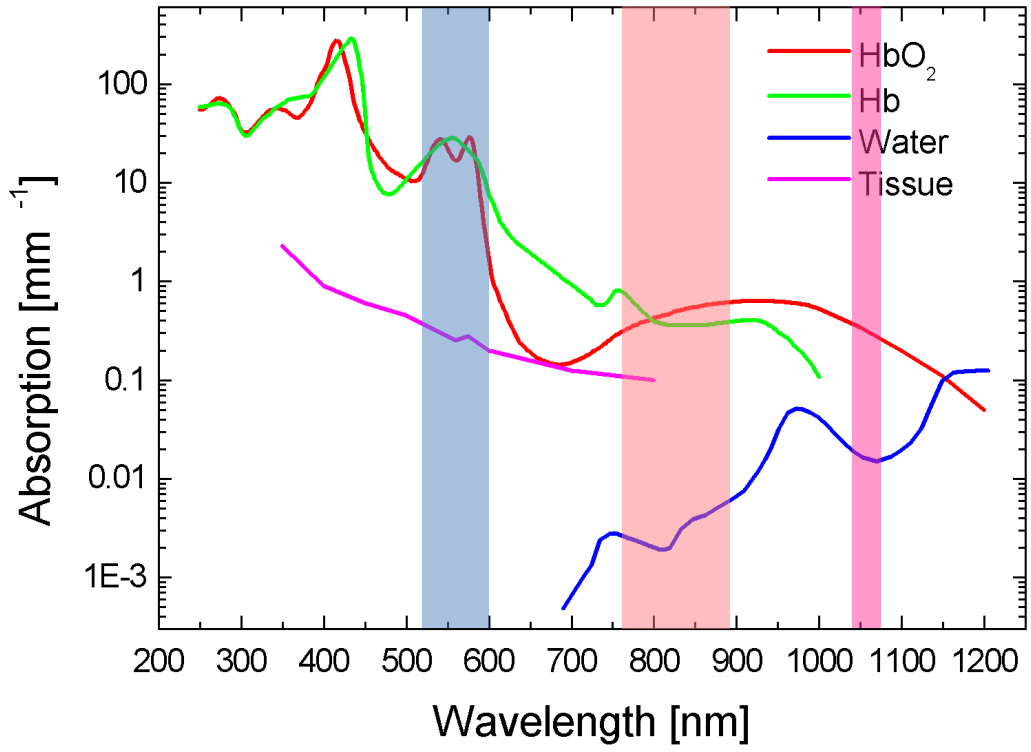
Depth:

- **Green light: ≈ 0 - 9 mm**
- Near-infrared: ≈ 0 – 30 mm

Depth resolution: ≈ 10 μm

# Optical properties of tissue and blood

## Scattering and absorption




(Reduced)
Scattering coefficient:

- λ = 580 nm:

  Dermis: 3 $mm^{-1}$

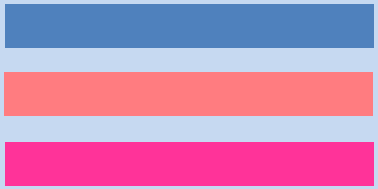
  Blood: 1 …

- λ = 850 nm:

  Dermis: 1 …

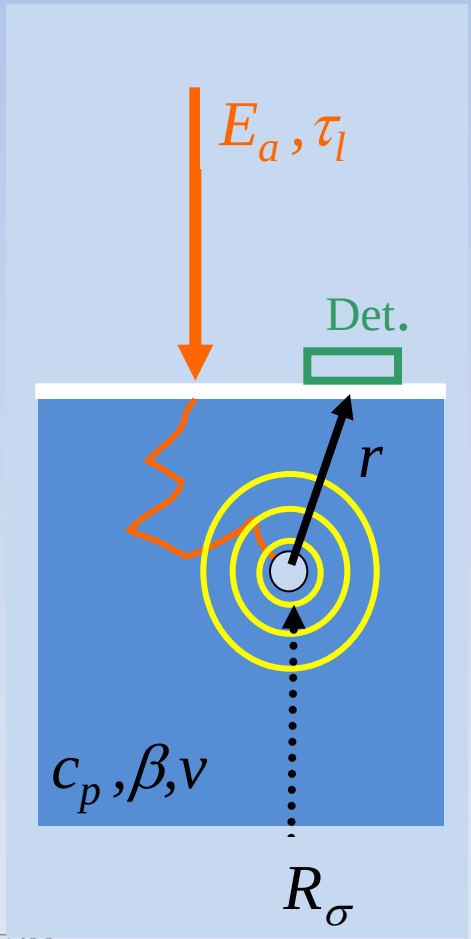
  Blood: 0.5 …

Available windows:



# Photoacoustic Signal Generation

Bipolar PA-signal generated by a spherical Gaussian Source

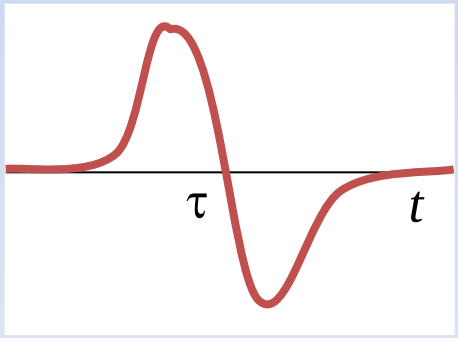



$$\tau_a = \frac{R_\sigma}{\nu} \qquad \tau_e = \sqrt{\tau_a{}^2 + \tau_l{}^2}$$

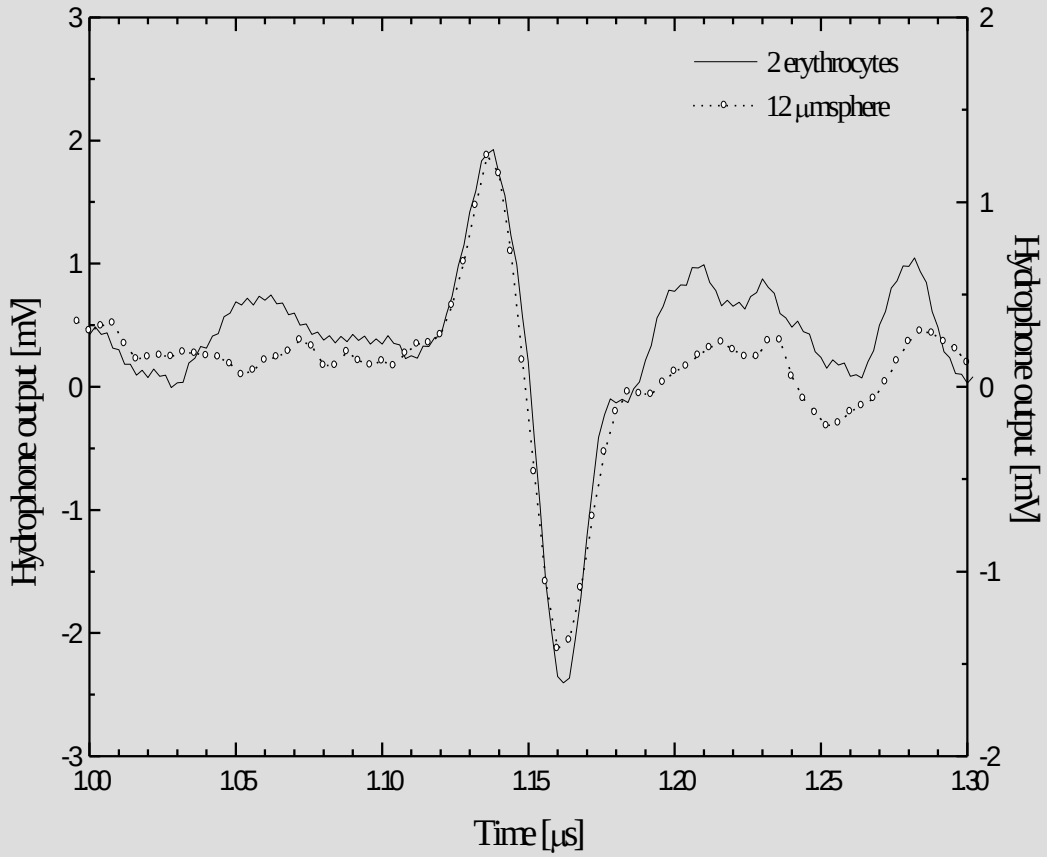
$$P(r,t) = -P_{\max}(r)\sqrt{e}\,\frac{t-\tau}{\tau_e}\exp\left\{-\tfrac{1}{2}\frac{(t-\tau)^2}{\tau_e{}^2}\right\}$$

$$\tau = \frac{r}{\nu}$$

$$P_{\max}(r) = \frac{\beta\, E_a}{2\sqrt{e}(2\pi)^{3/2} c_p \tau_e{}^2 r}$$



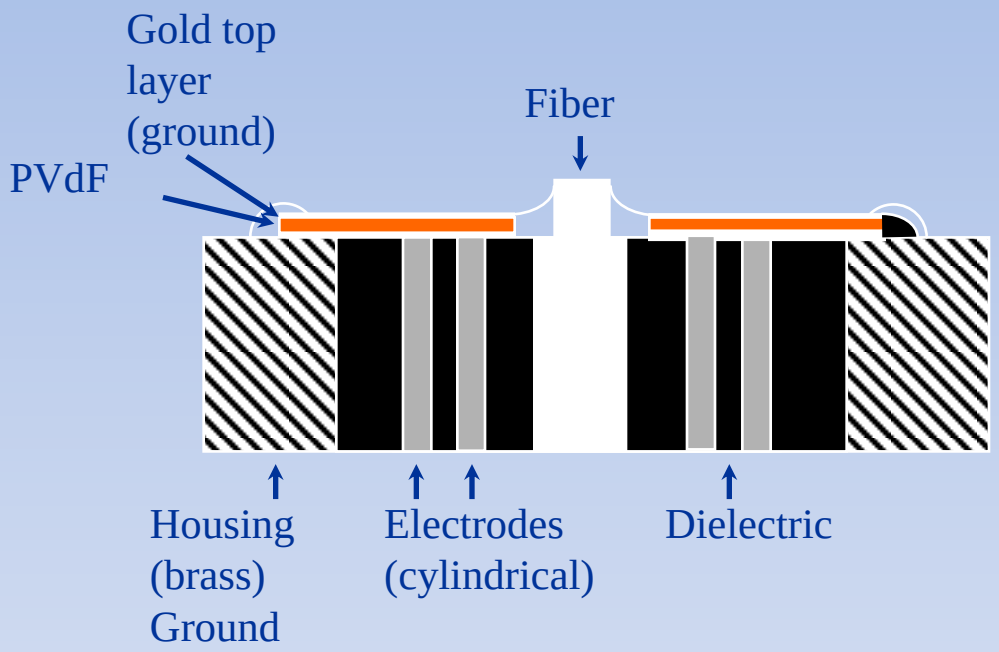
# Photoacoustic Imaging



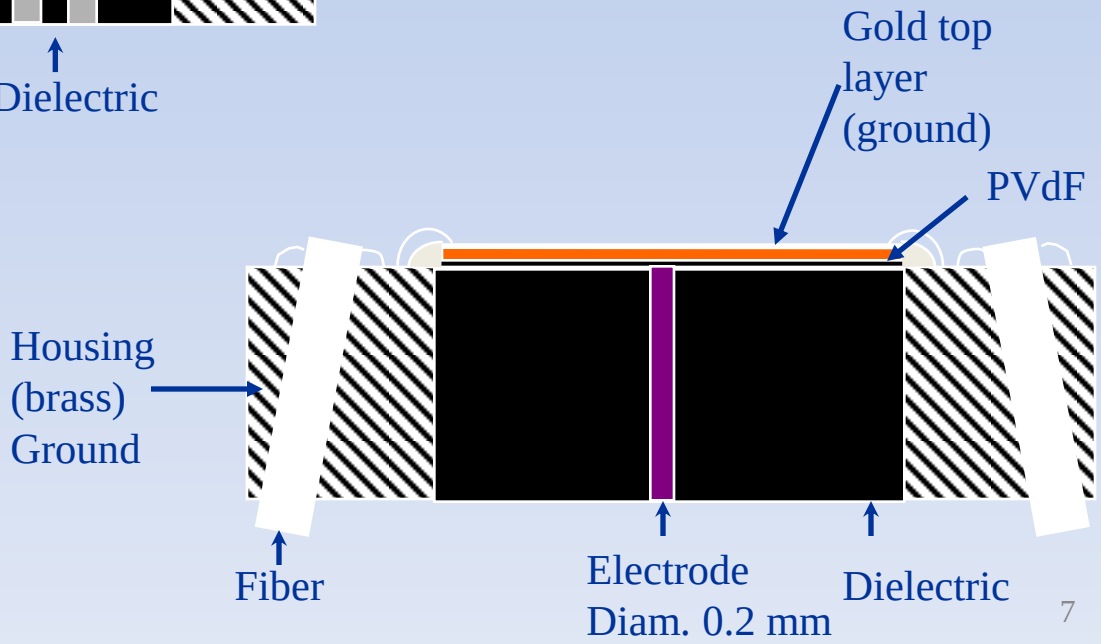

Two erythrocytes

Diameter: ≈ 10 µm (compared with a 12 µm blue polystyrene sphere)
detection distance: ≈ 1.7 mm ( = 1.15 µs x 1500 m/s)
medium: water/PBS

# Photoacoustic Imaging

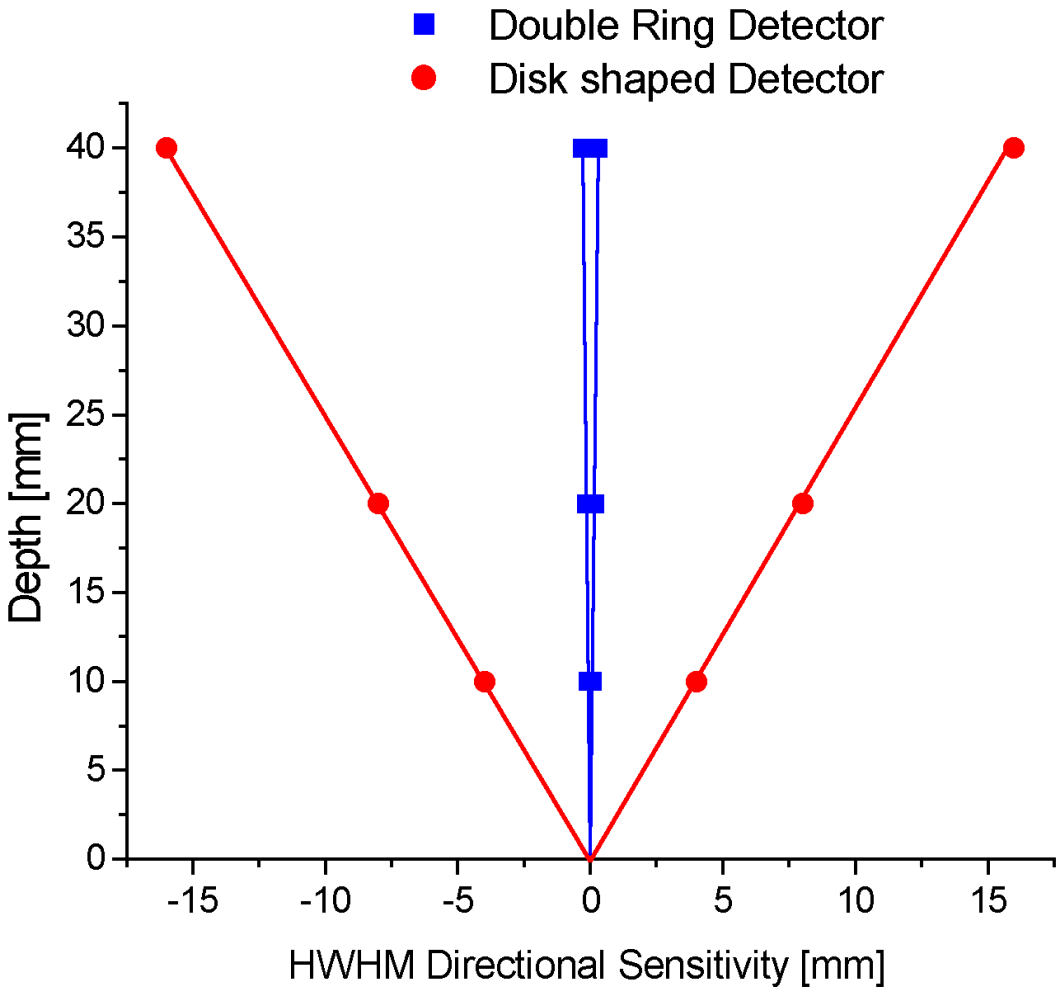



Double-Ring Detector
One-fiber illumination




Disk-shaped Detector
Ring illuminator

# Photoacoustic Imaging

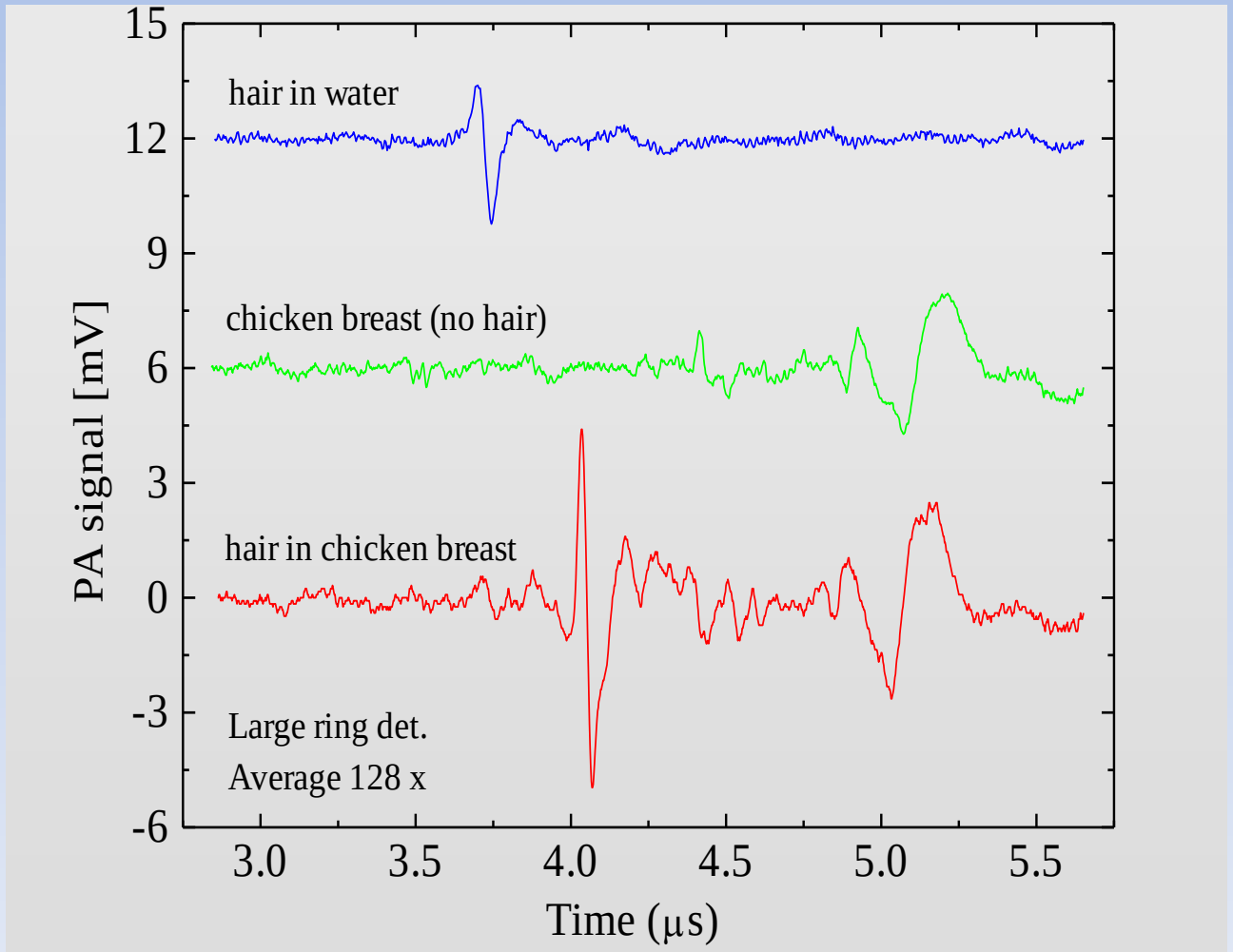



Directional Sensitivity:

Disk Detector:
FWHM : Depth
1 : 5

Ring Detector:
FWHM : Depth
1 : 70

# Photoacoustic Imaging

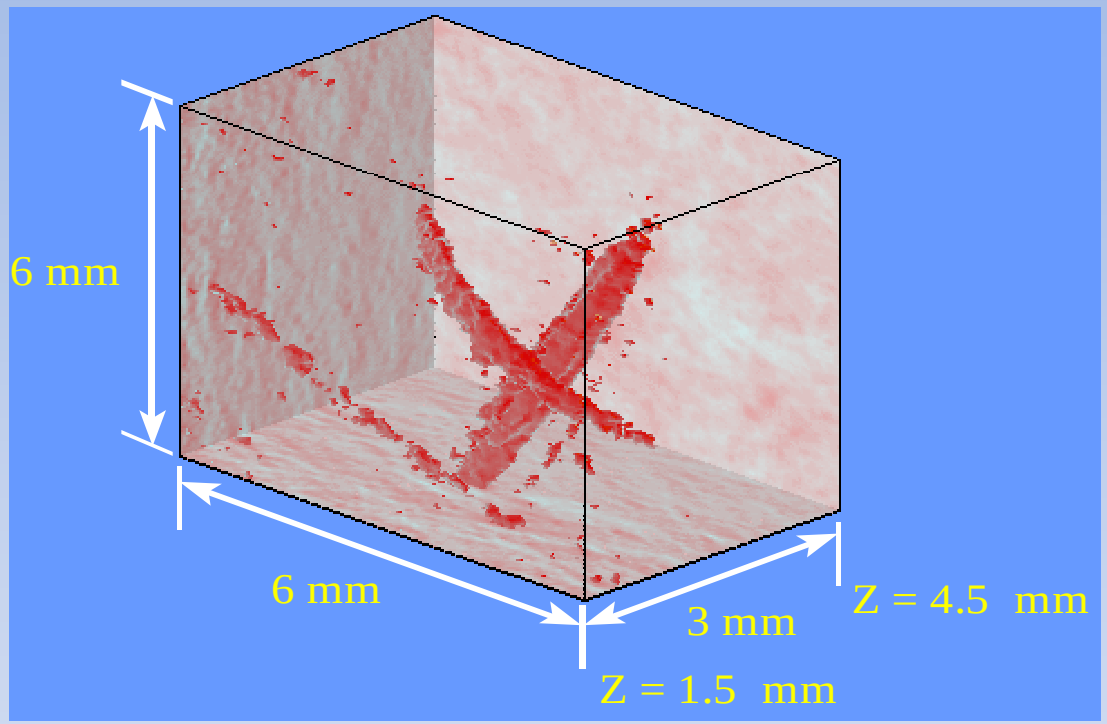


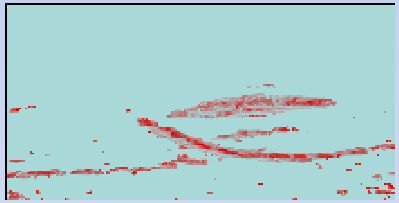

A human hair in chicken breast tissue.

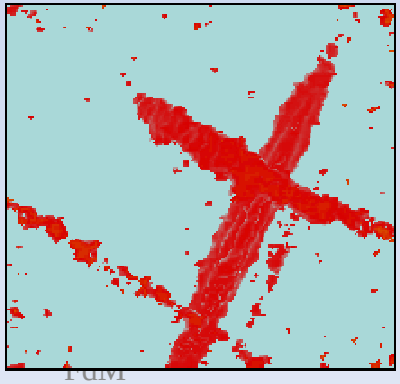
Depth: ≈ 6 mm (≈ 4 μs x 1500 m/s)

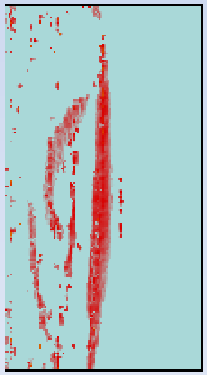
# Photoacoustic Imaging

Vessels in chicken breast tissue



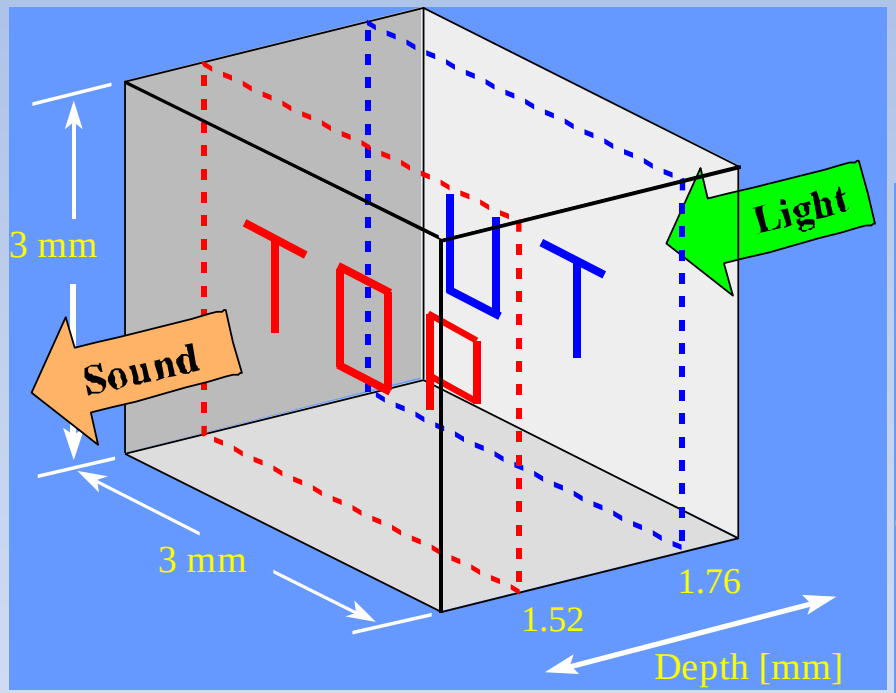





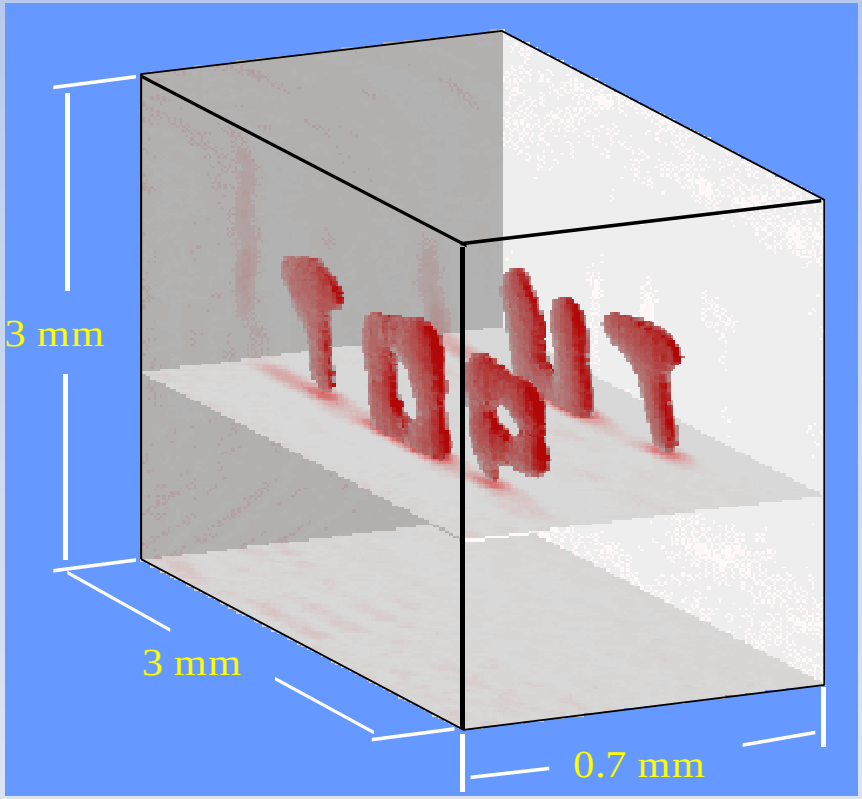


Sample : 5 mm thick chicken breast tissue in water
Image : 663 mm, inside sample, 35 % isosurface threshold
Vessels : 3 Nylon capillaries, 0.28 0.40 mm diameter
Absorber : Evans Blue, flowing, a = 300 cm-1
Detection : at Z = 0 mm, 51 51 points, 0.15 mm spacing

# Photoacoustic Imaging



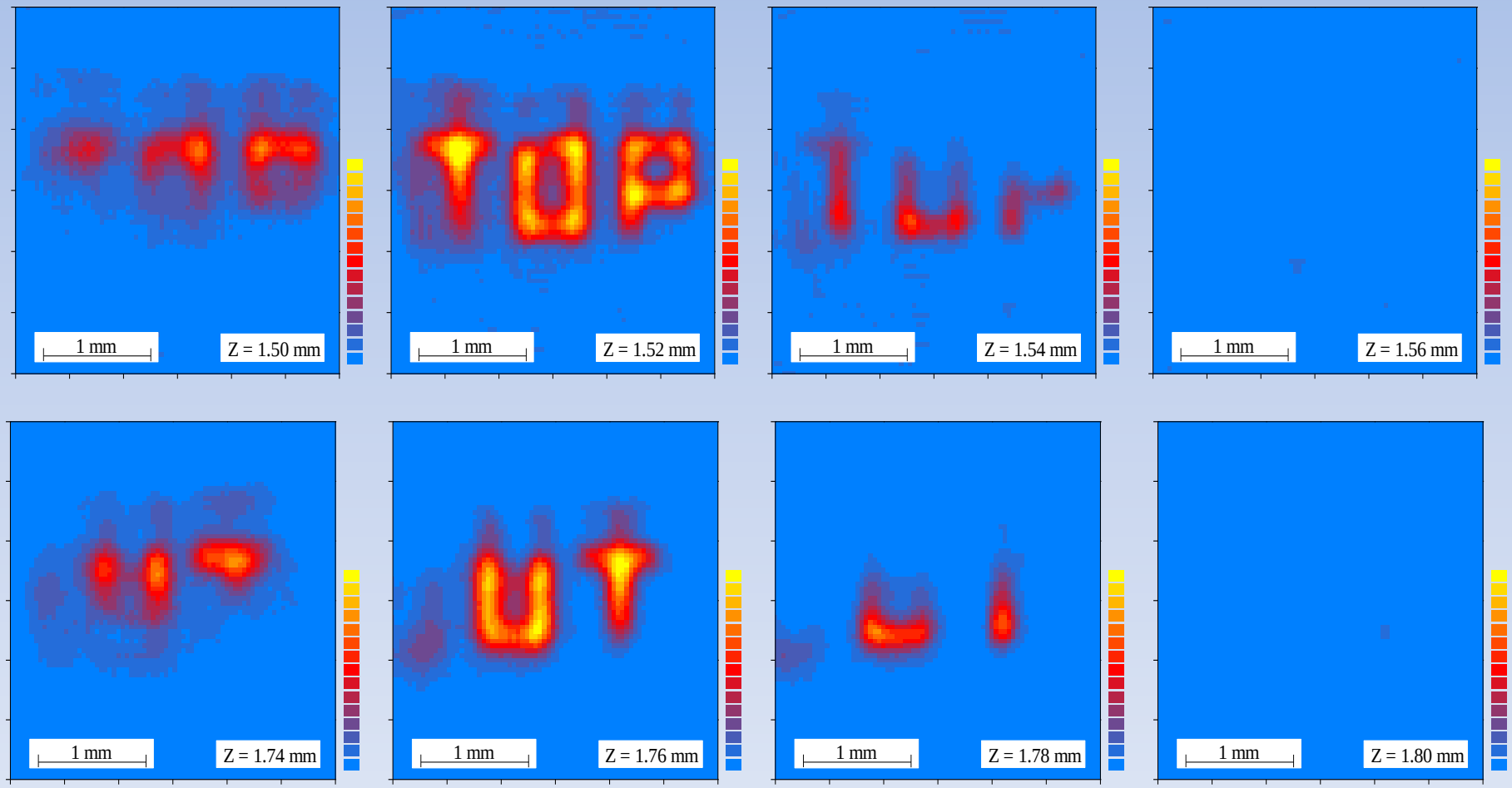

Reconstruction of hidden objects



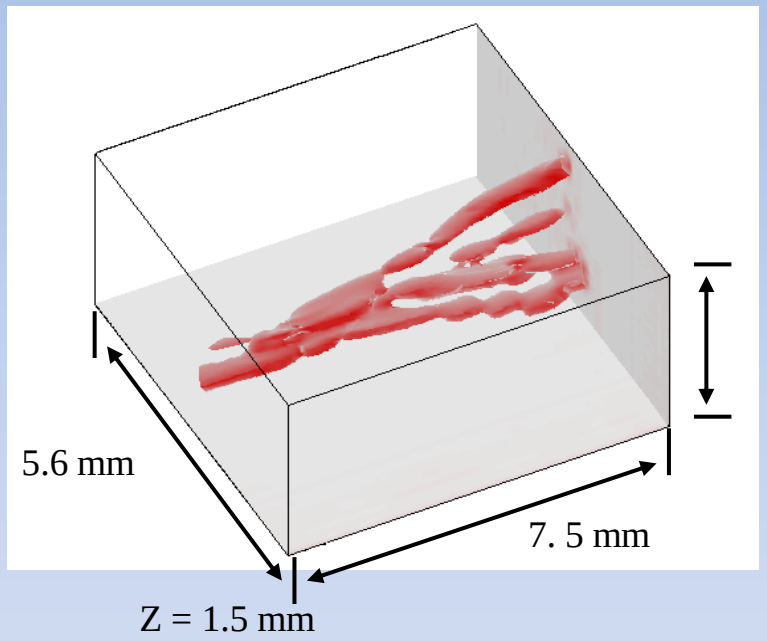

Material: carbon threads (10 μm) on transparent sheets,
in 10 % Intralipid-10%
(resembles human tissue scattering)

# Photoacoustic Imaging

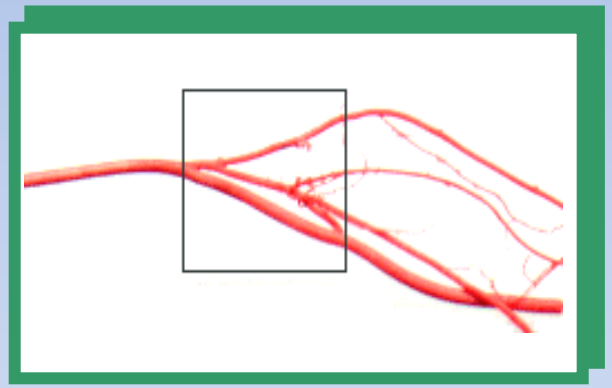
Depth resolution: ≈ 10 μ m



# Photoacoustic Imaging




7.5 mm

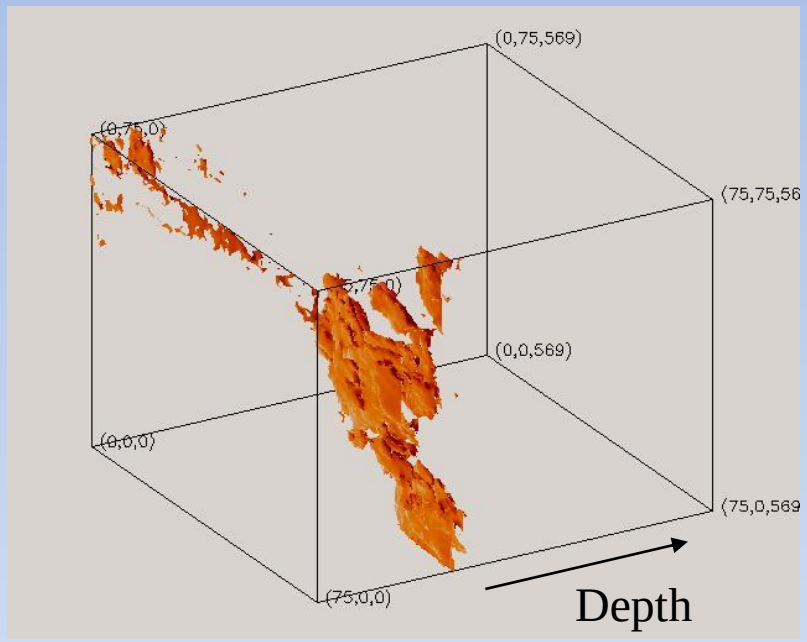


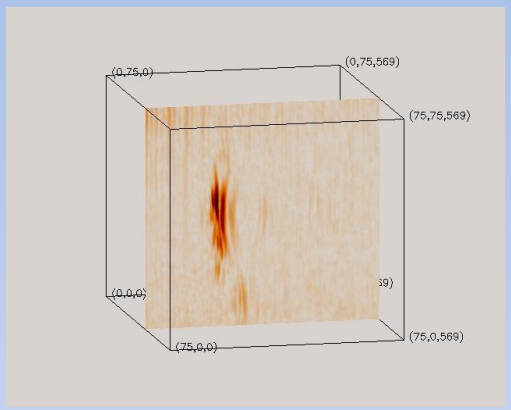
Photograph

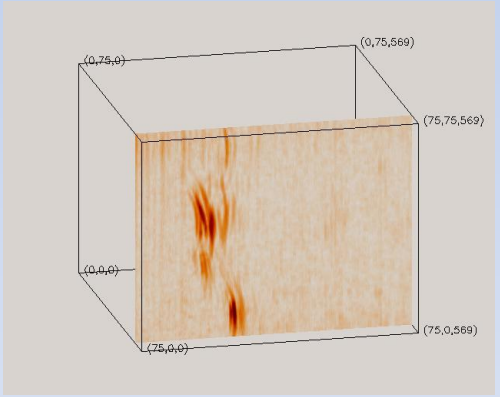
Vascular tree from a branching epigastric artery of a rat.
Ex-vivo; medium: intralipid 1 % (≈ tissue).
Depth (Z-coord.) ≈ 5 mm ; indicated in figure.
Laser power 532 nm, 2mJ/pulse through fiber ∅ 600 μm.
Depth resolution / lateral resolution: 10 / 100 μm respectively.

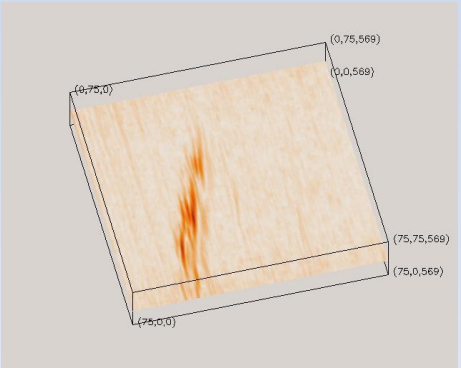
# PA-imaging of blood vessels in tissue

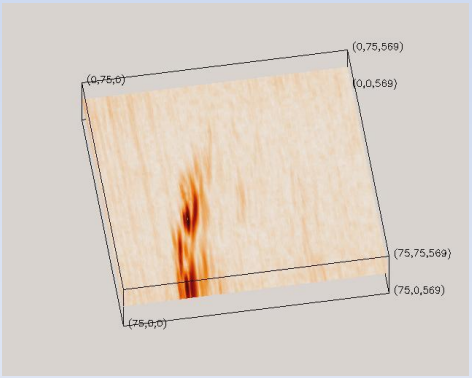
## Live Albino Wistar Rat: Epigastric artery branching



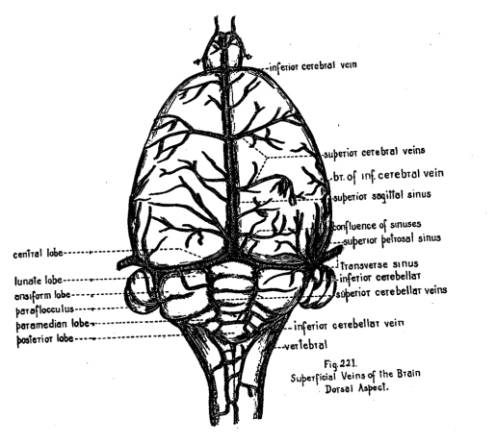




7.5 x 7.5 x 7.5 $mm^3$

# PA-imaging of blood vessels in tissue

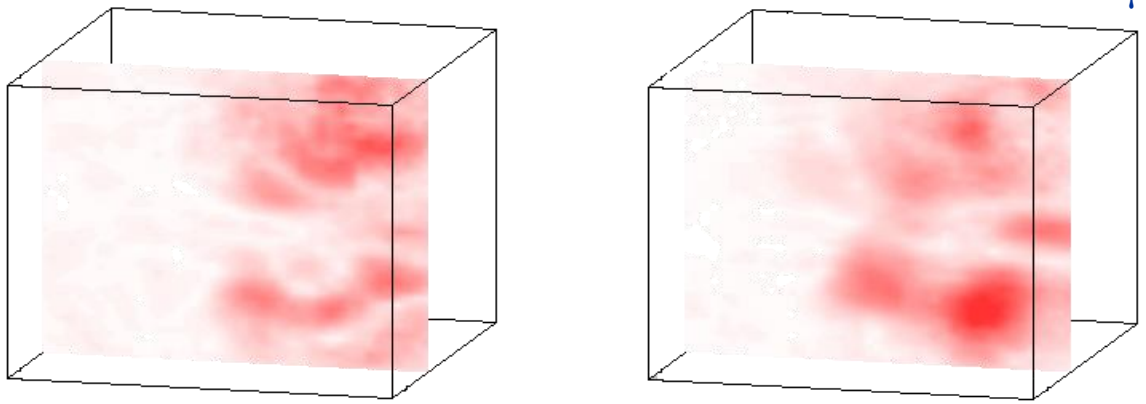
## Albino Wistar Rat: Brain Perfusion

**Alive**
Area: 4 mm x 4 mm
Depth 5mm

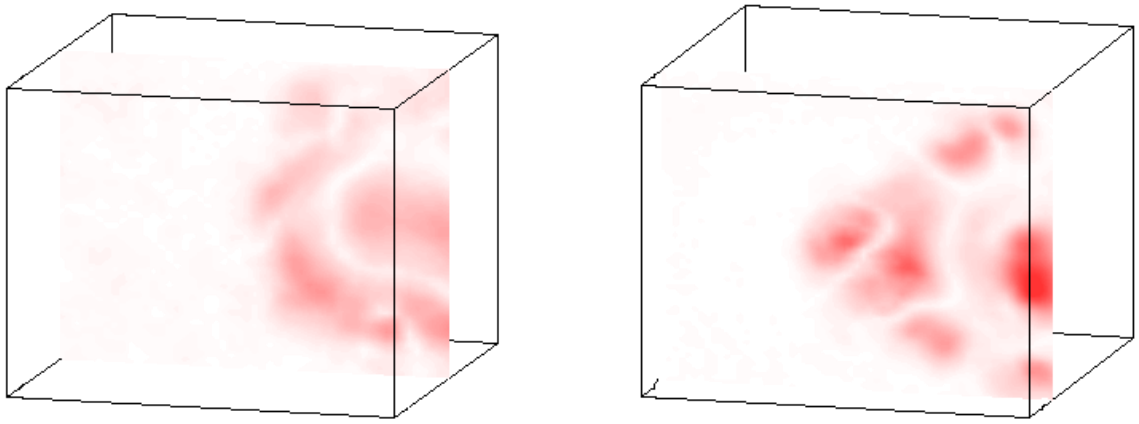



**Dead**
Area: 5 mm x 5 mm
6 mm x 6 mm
Depth 5mm

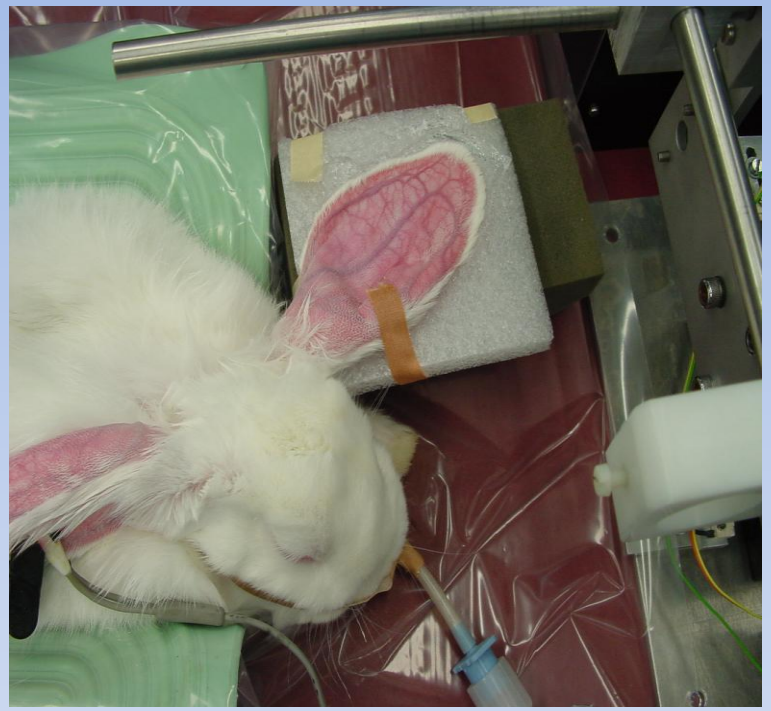
Slices of 100 μm

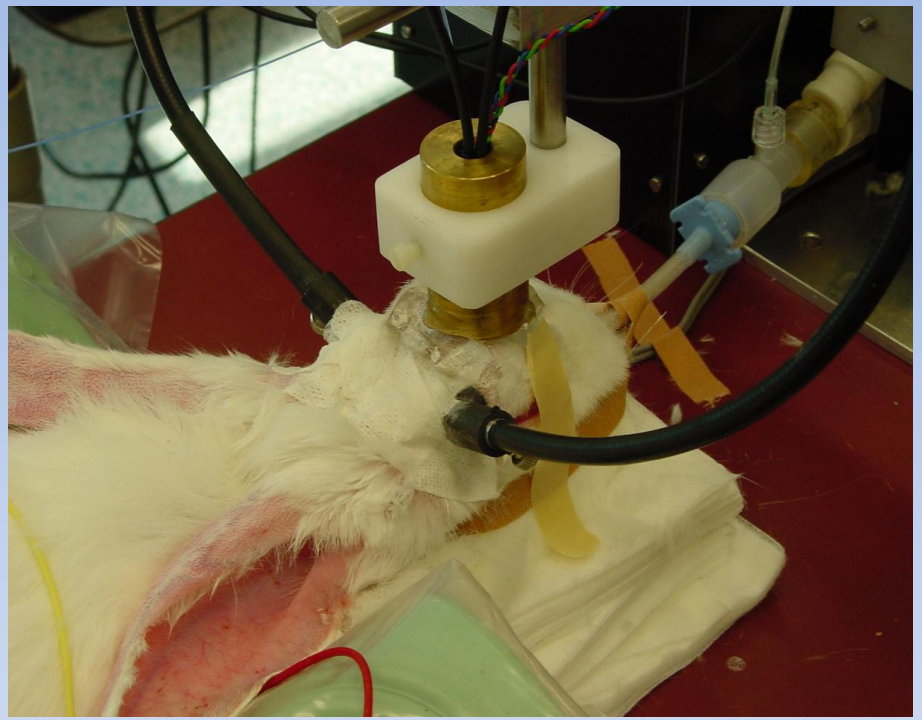


Blood in the cartilage scalp, in the upper part of the occipital bone



# PA-image of Vessels in Rabbit Ear



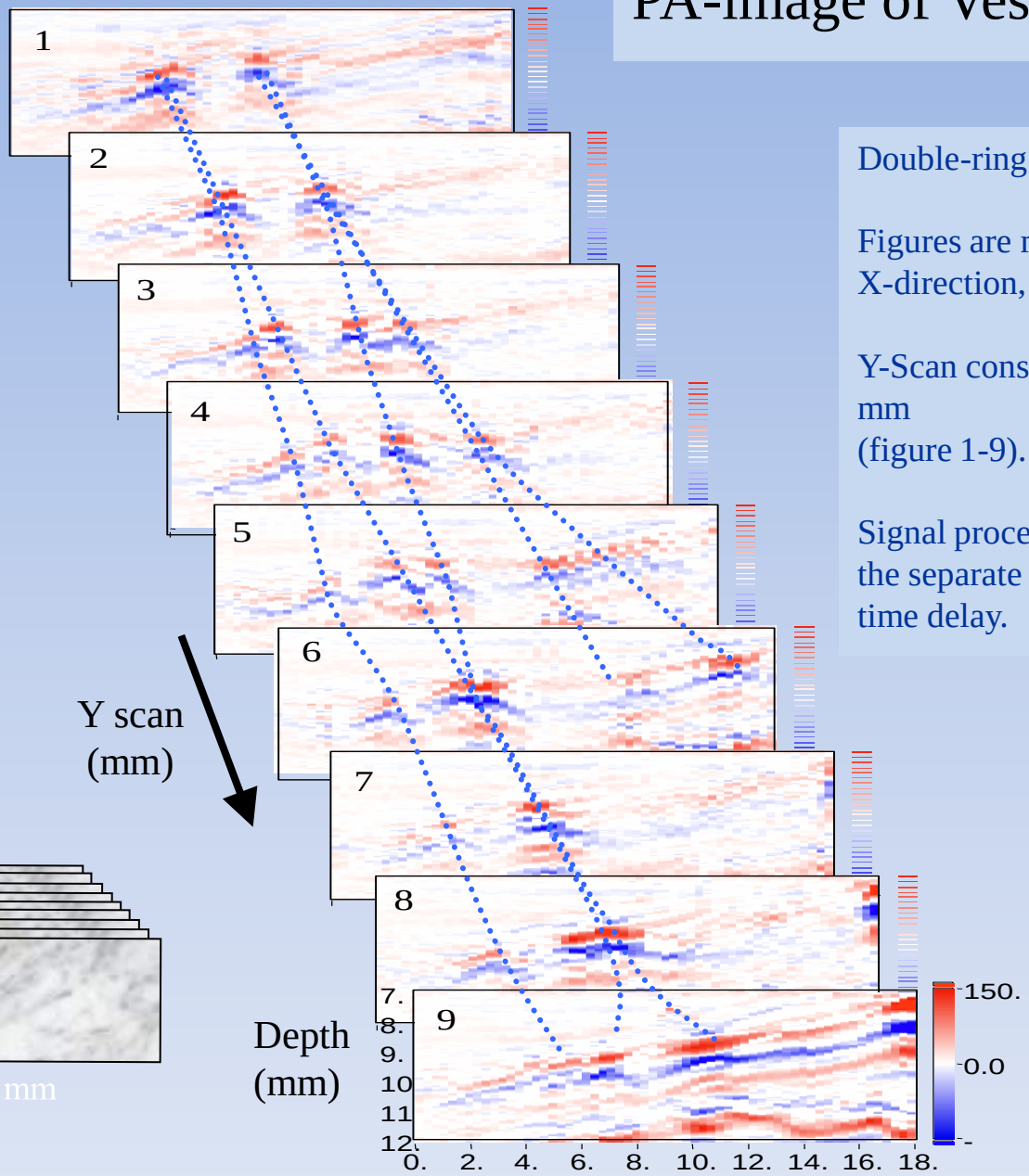


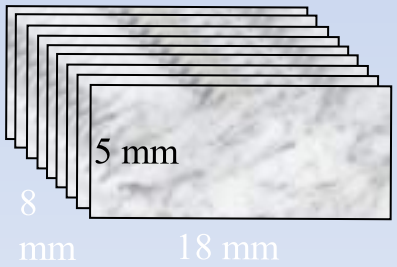
Double-ring detector.

Figures are made out of 61 scan steps in X-direction, with a step size of 0.3 mm.
Y-Scan consists of 9 lines, separated 1.0 mm

Signal processing: summing the data of the separate rings,
after correction for the time delay.

# PA-image of Vessels in Rabbit Ear



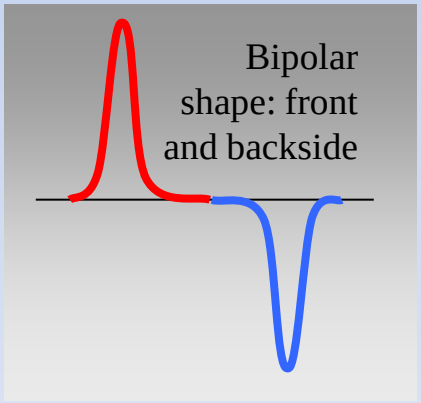




Double-ring detector.

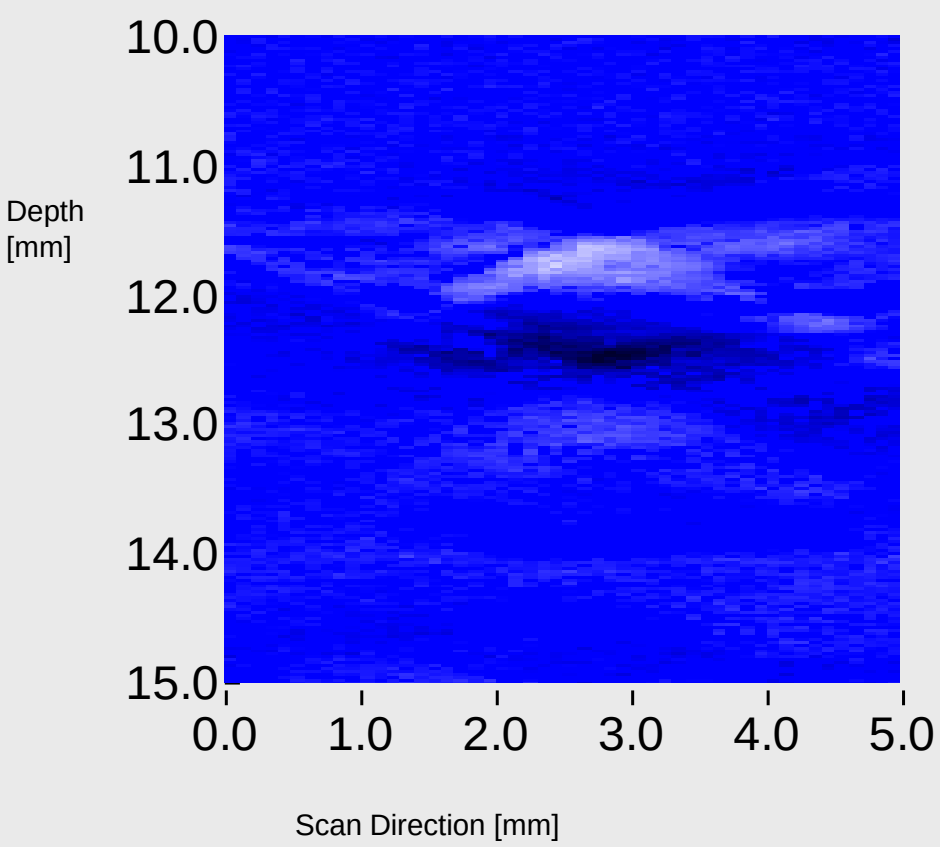
Figures are made out of 61 scan steps in X-direction, with a step size of 0.3 mm.

Y-Scan consists of 9 lines, separated 1.0 mm
(figure 1-9).

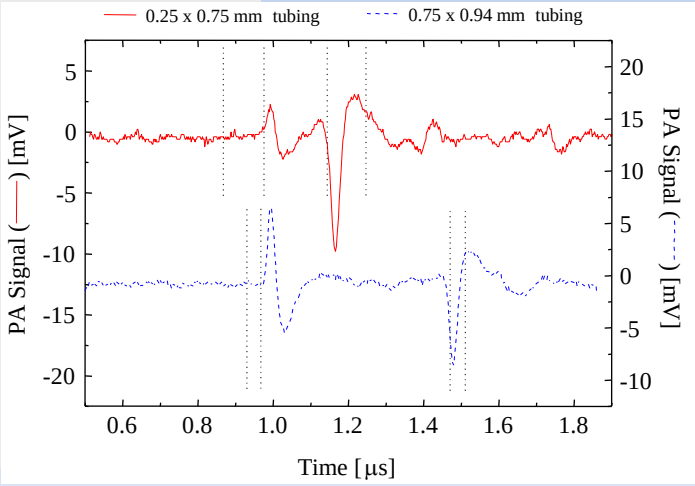
Signal processing: summing the data of the separate rings, after correction for the time delay.



# PA-imaging of blood vessels in rabbit ear

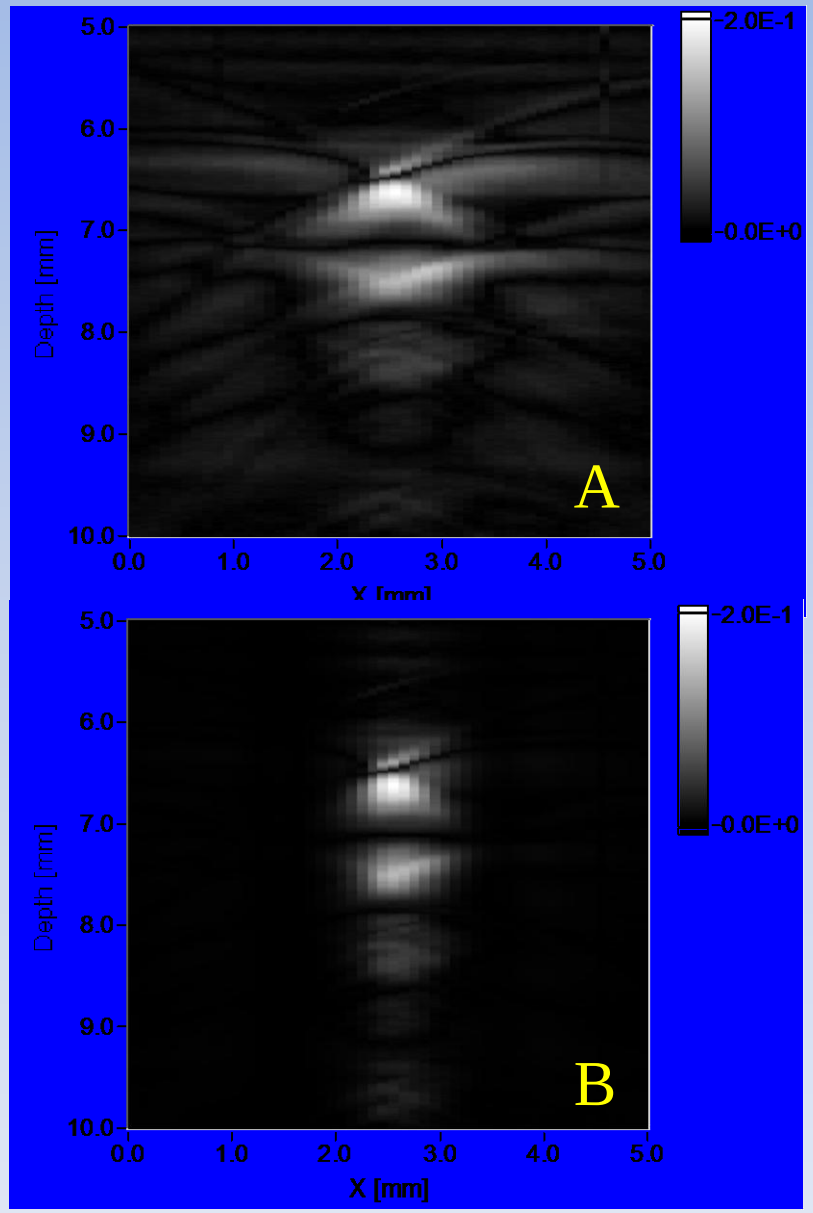



Front and backside of the vessel




PA signals: capillaries in 10% IL-10%

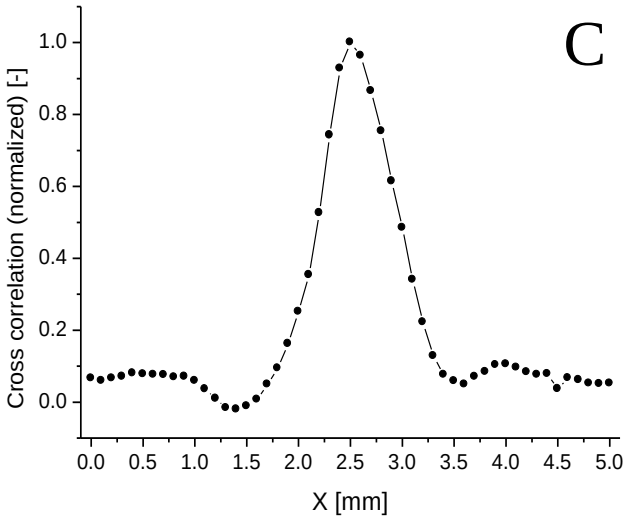
# PA-imaging of blood vessels: image correction



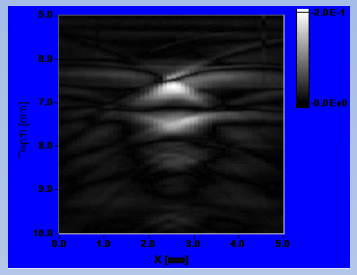

- 1mm diameter rubber tube, filled with human blood, in 7.5% Intralipid-10% dilution.

- Image A : 2D image, from measured time signals (1D-depth images), plotted as lines in the 2D image next to each other.

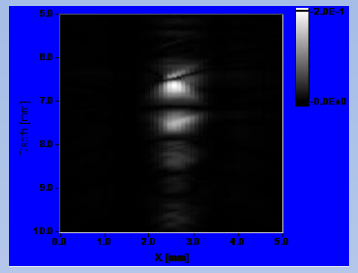
- Image B : 2D image, after correction by multiplication with the zero-time cross-correlation function, (C ) : **STEP 1**



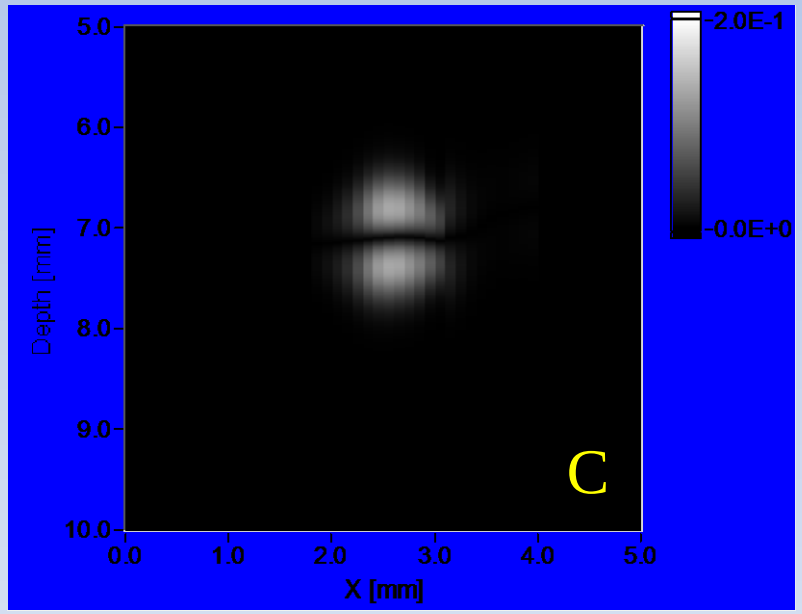
# PA-imaging of blood vessels: image correction



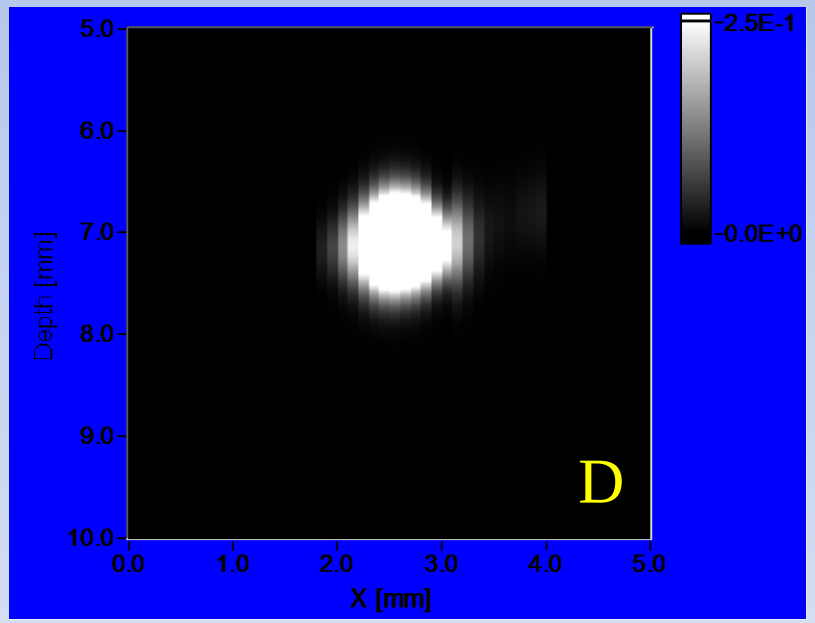
A: originally measured time signals



B: after multiplication with autocorrelation (STEP 1)

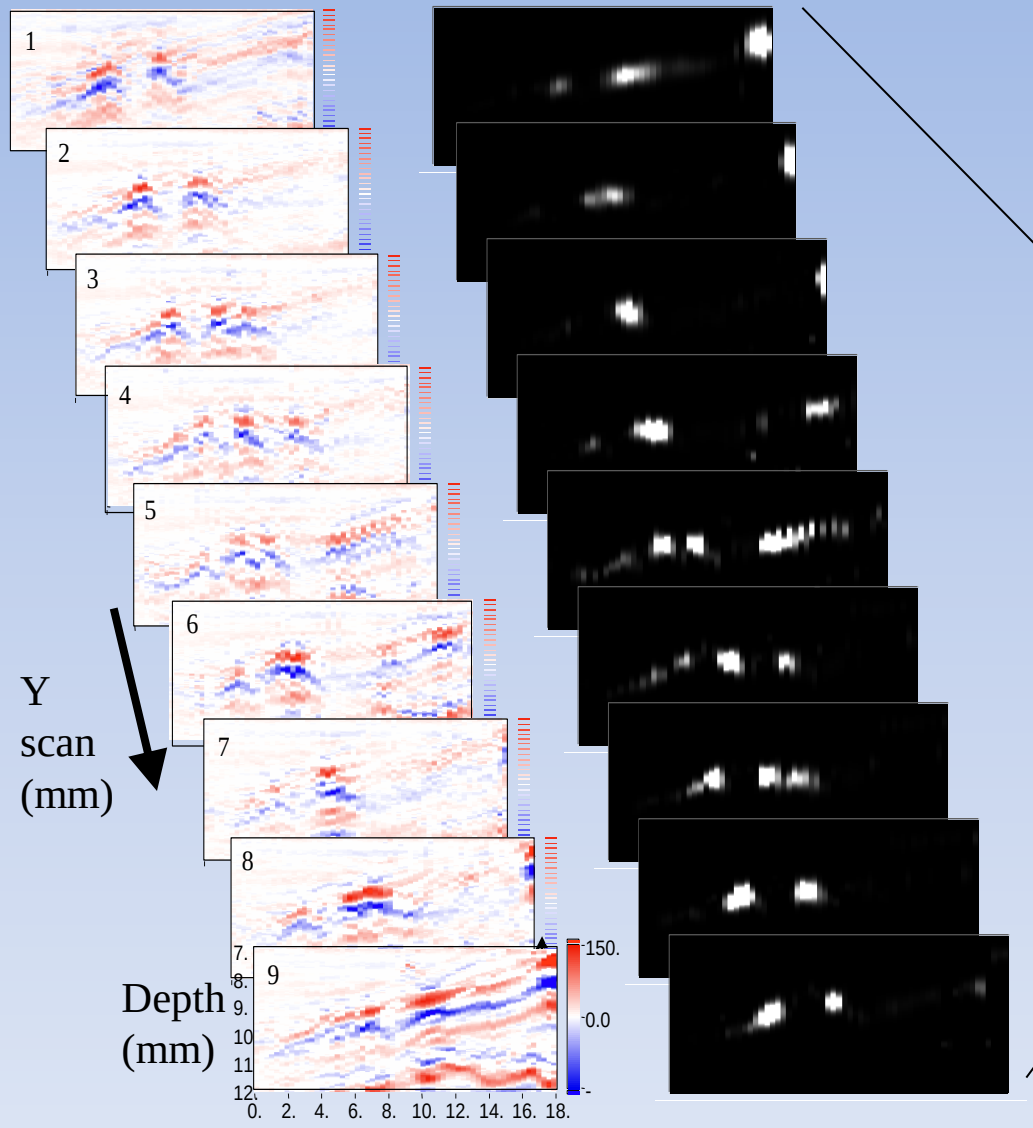


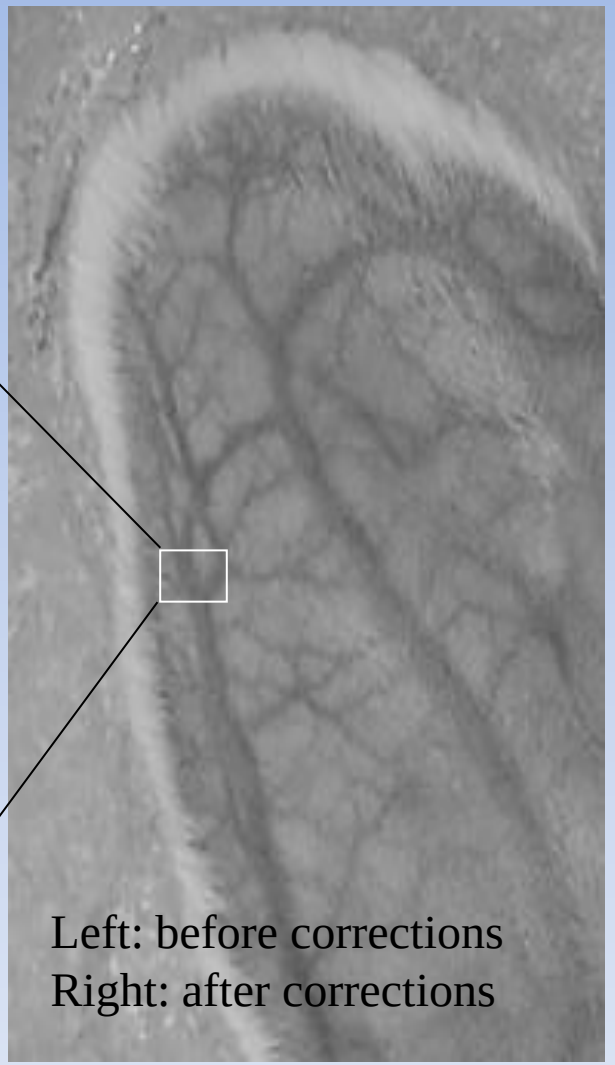

C: after fit to bipolar signal (STEP 2)
Upper/lower image: pos./neg. peak signal (here absolute value plotted)




D: after running integration over depth (STEP 3)

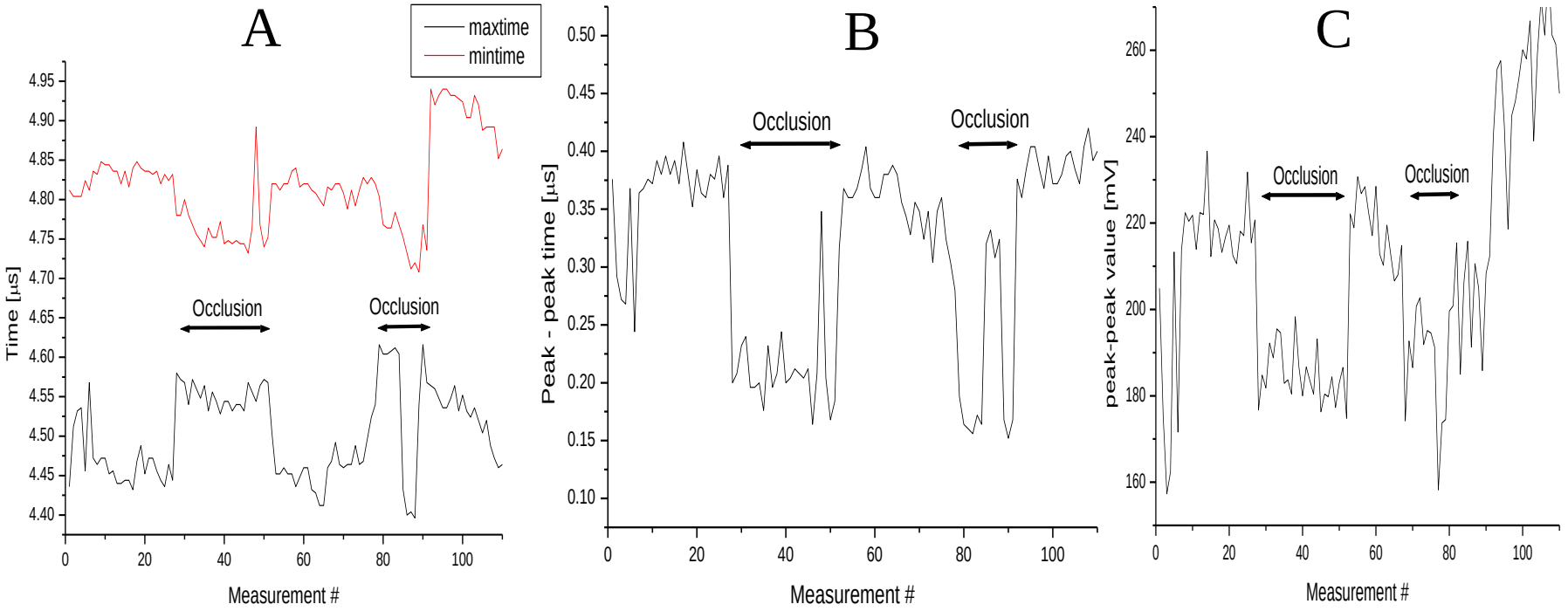
# PA-imaging of blood vessels in rabbit ear



Left: before corrections
Right: after corrections

# PA-imaging of blood vessels in rabbit ear: occlusion

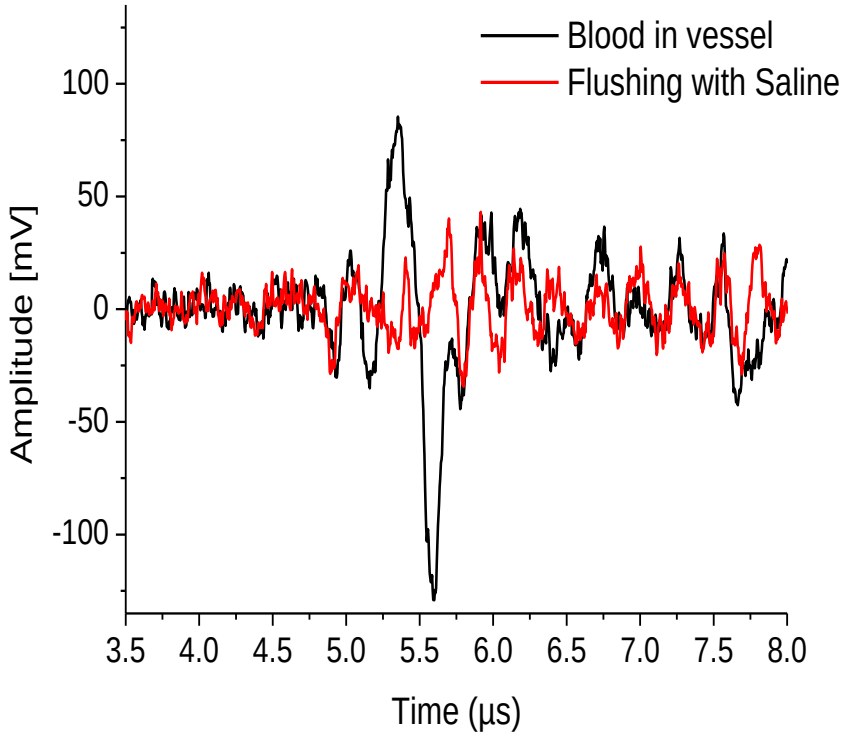


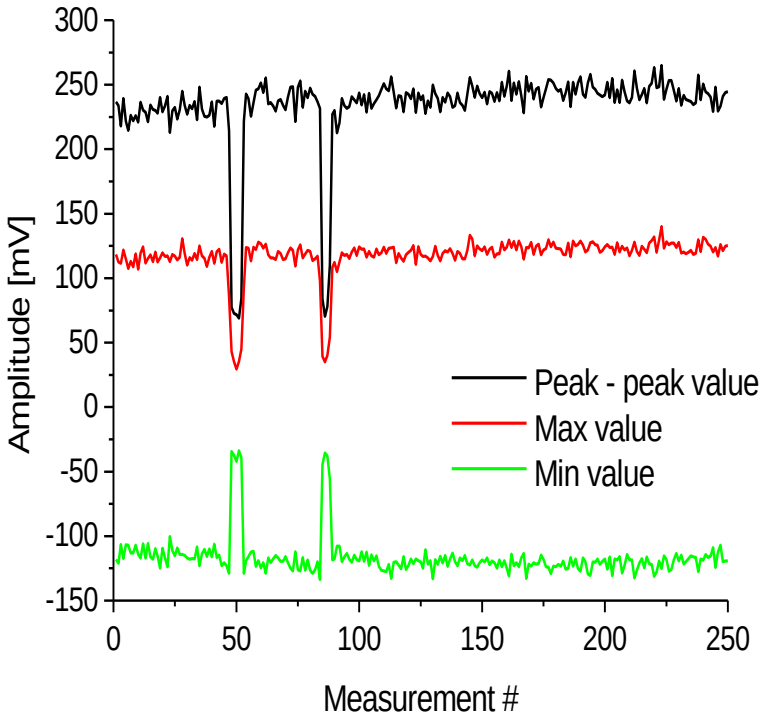

During occlusion: A: Time between max / min peak reduced ( 0.1 µs ≈ 0.2 mm)

B: Peak-peak time delay reduced => vessel thinner

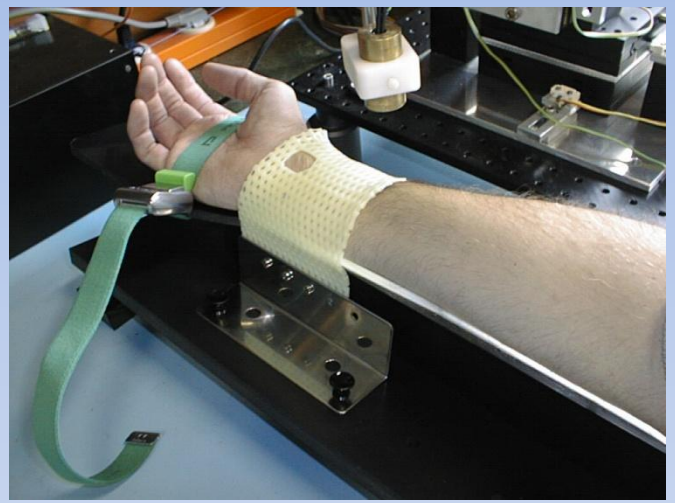
C: Peak-peak amplitude reduced => amount of blood lower

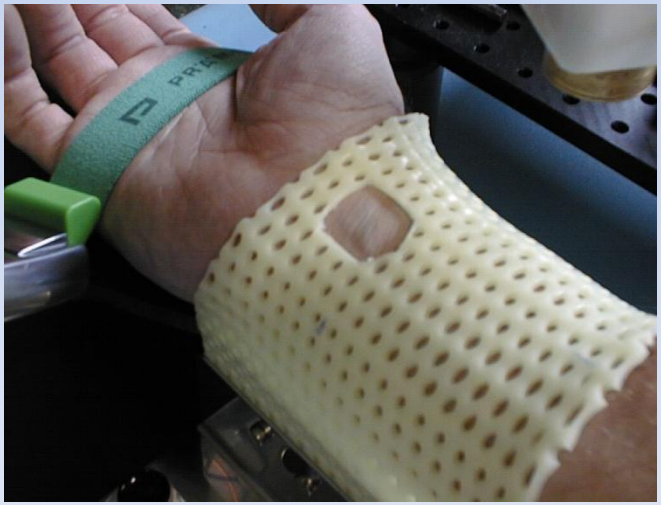
# PA-imaging of blood vessels in rabbit ear: flushing with saline

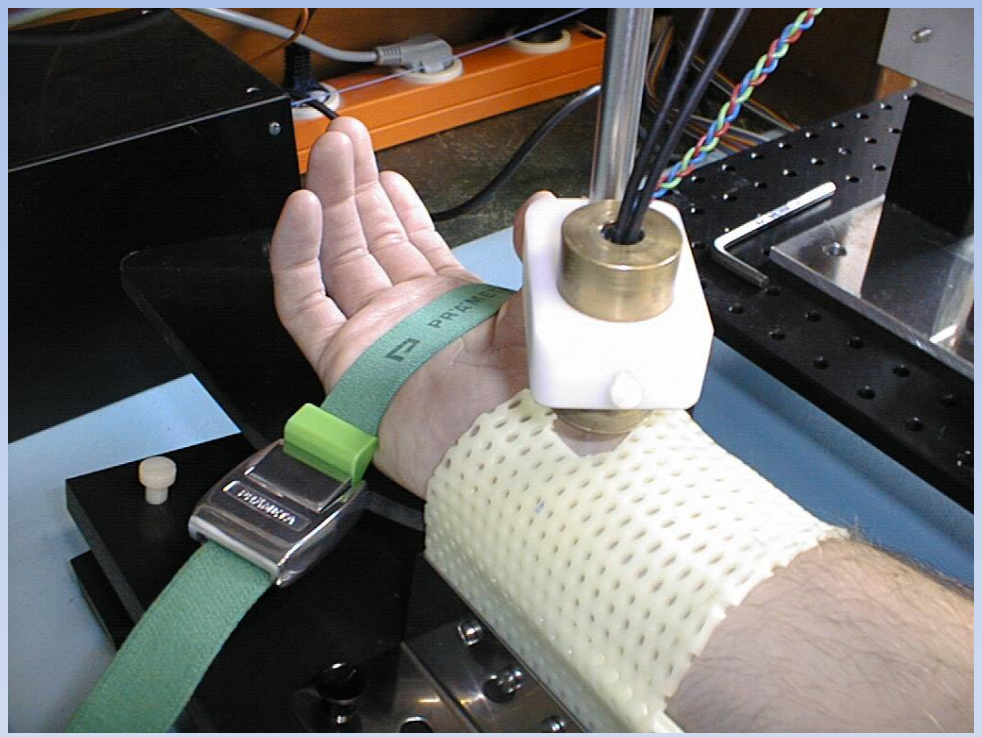


# In vivo Scan:
# Human Blood Vessels

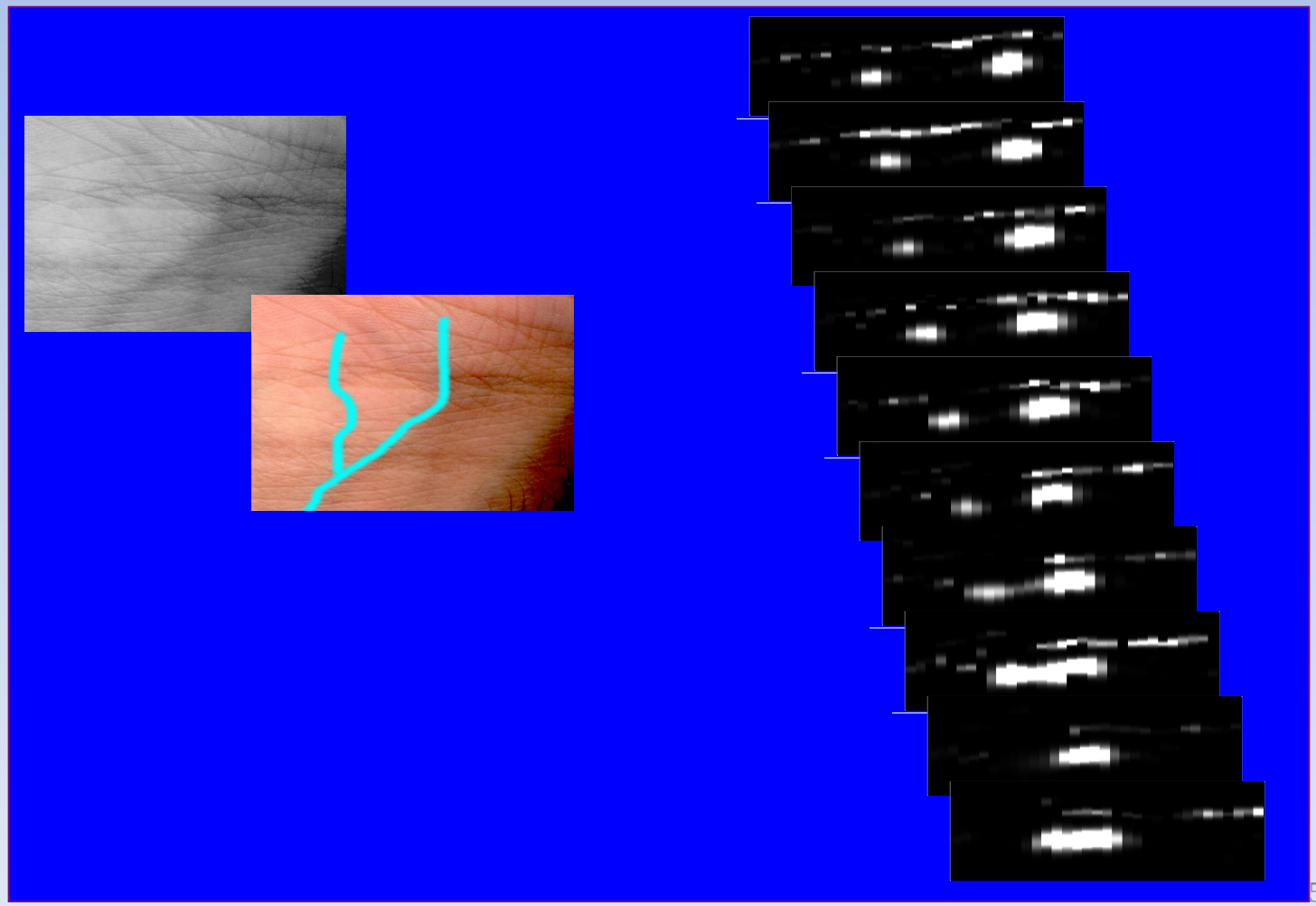




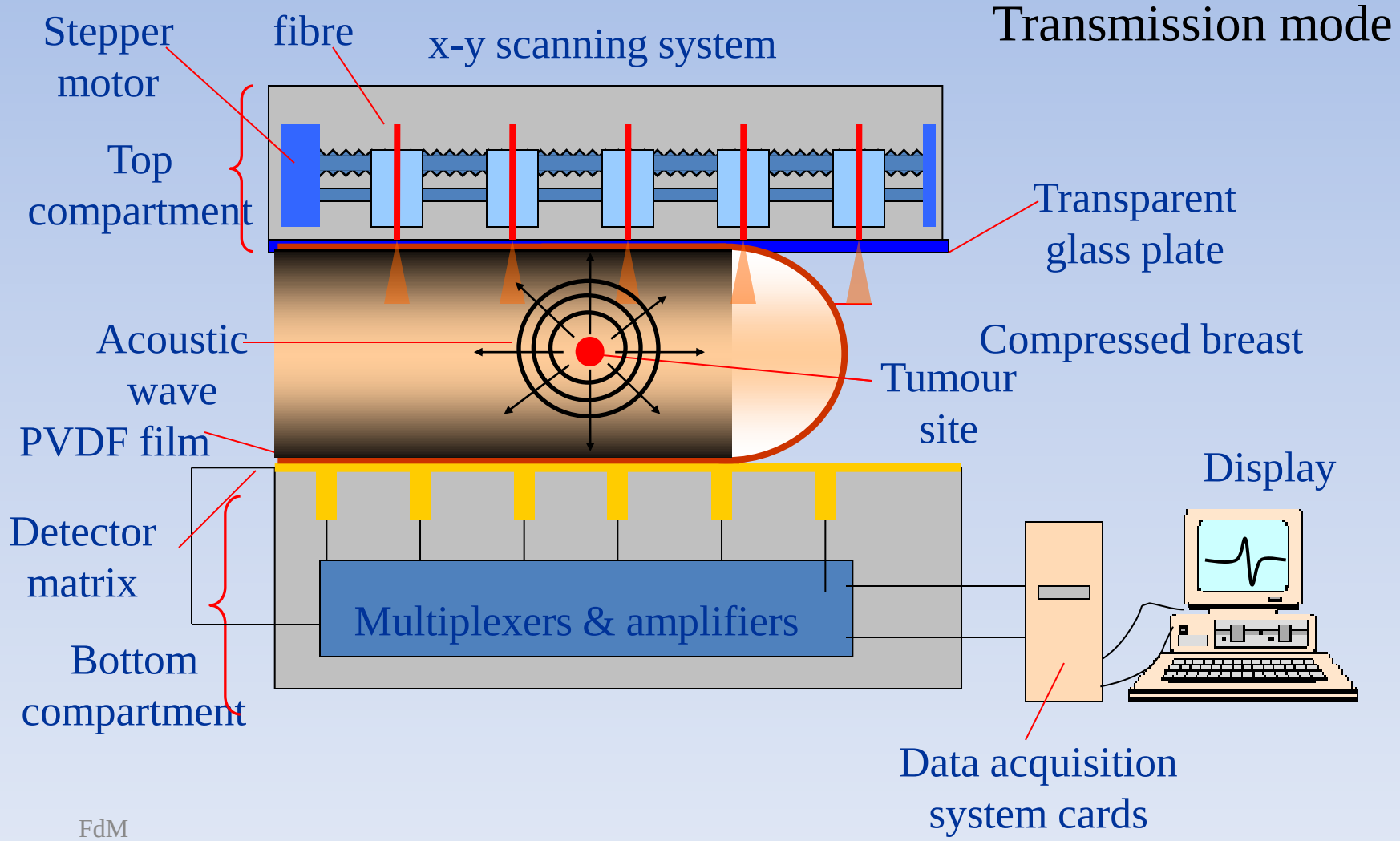


# PA-imaging of blood vessels in human arm

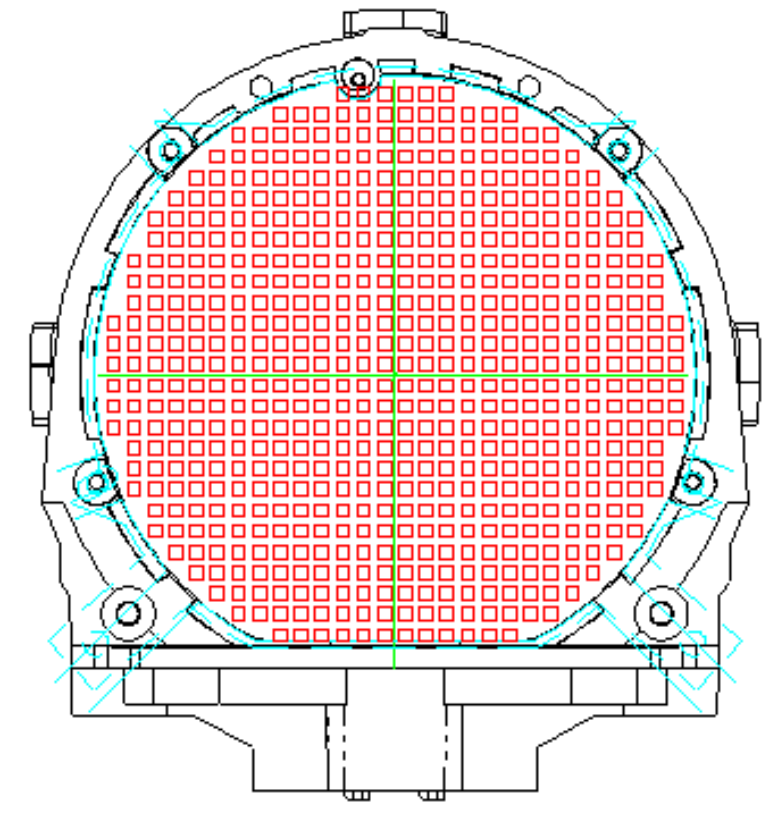
Depth ≈ 1-3 mm

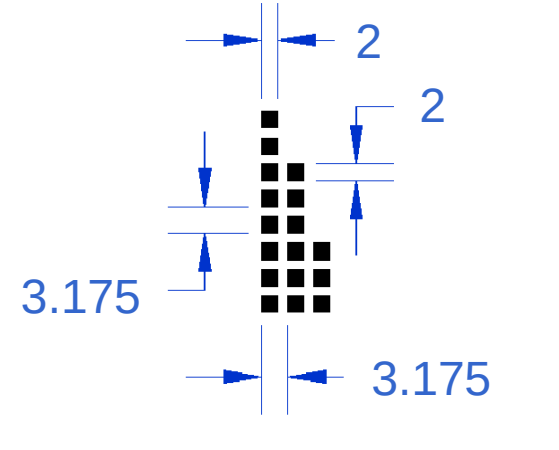


# Photoacoustic Mammography



# The detector matrix

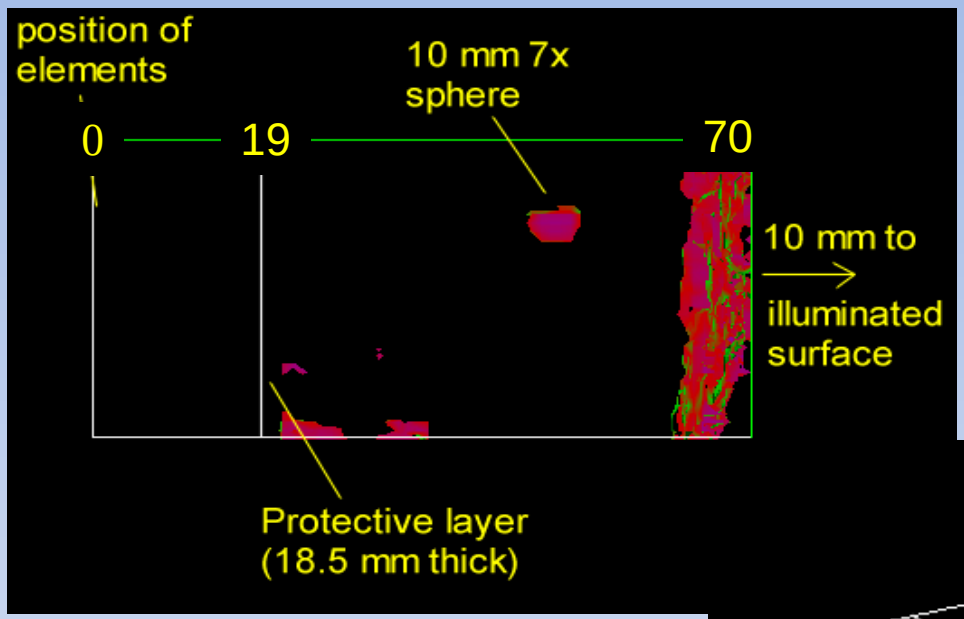





- 590 element microphone matrix
- active area: 90 x 85 mm

- arranged in a cartesian grid
- elements size: 2x2 mm
- separation: 3.175 mm
- 1 element accessed at a time

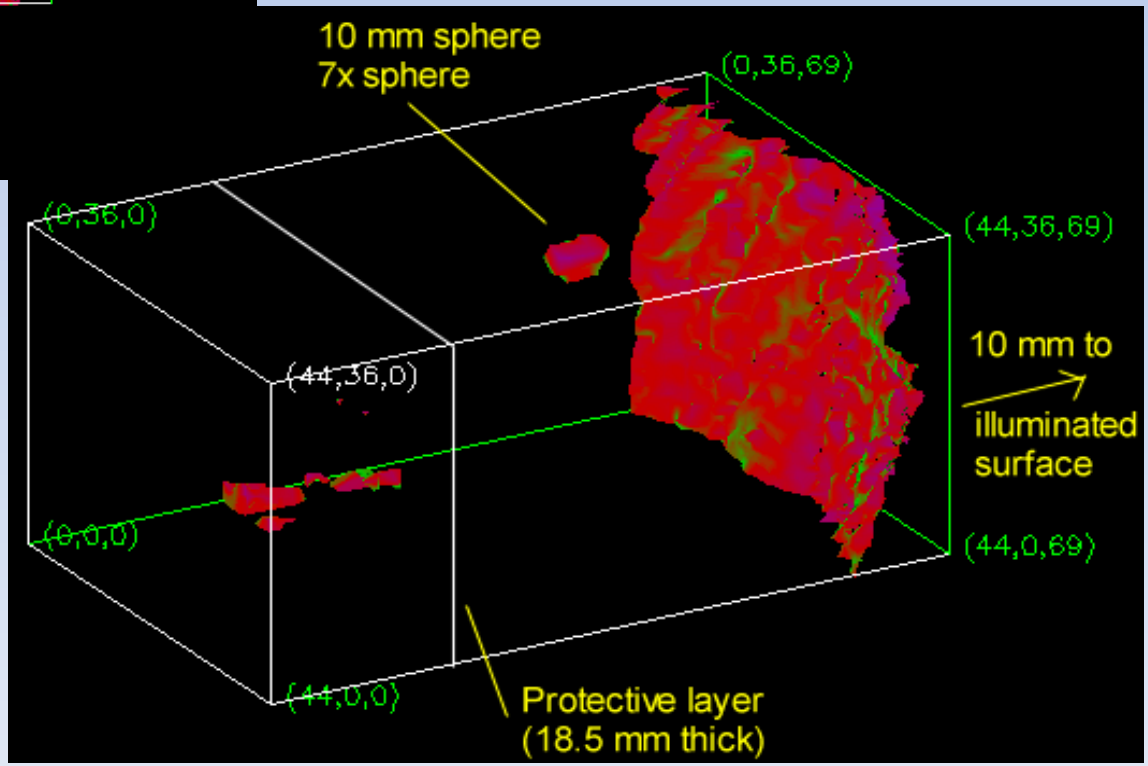
# Phantom: 10 mm, 7x sphere at depth 30 mm




Absorption contrast
Sphere : medium = 7 : 1

side view

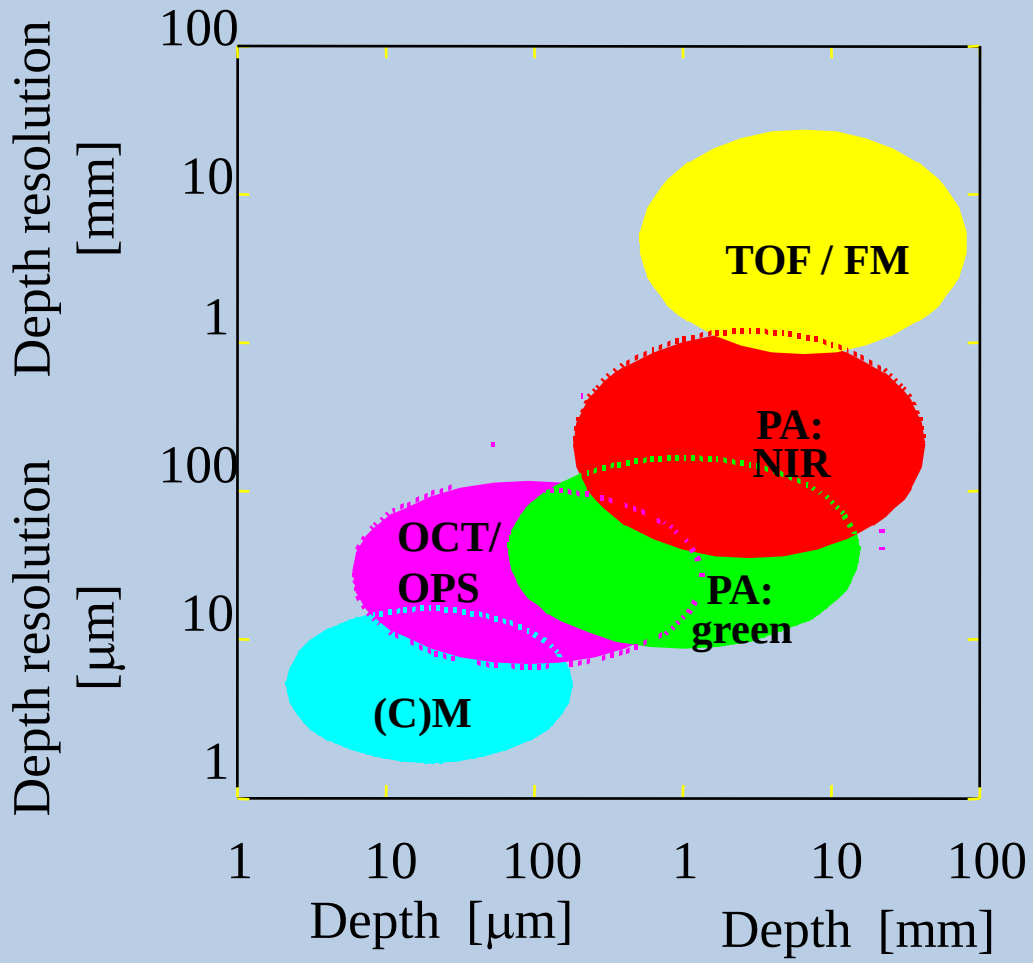
isometric view



# Photoacoustic Imaging

| | Green 550 nm | | NIR 800-1064 nm | |
|---|---|---|---|---|
| | dermis | blood | dermis | blood |
| • Absorption coefficient [1/mm] | 0.03 | 32 | 0.01 | 1.2 |
| • Scattering coefficient (reduced) [1/mm] | 3 | 1 | 1 | 0.5 |
| • Absorption Contrast | 1000 | | 100 | |
| • Penetration into tissue [mm] | ≈ 10 | | ≈ 30 | |
| • Applications | Cutaneous perfusion<br>Wound healing<br>Diabetes<br>Vascular malformations<br>Skin tumours | | Cerebral perfusion<br>Muscular perfusion<br>Mammography<br>Angiogenese | |

# Imaging methods for hidden structures in turbid media (tissue)




C(M) : (confocal) microscopy

OCT: optical coherence tomography

OPS: orthogonal polarization spectral imaging

PA: photoacoustics

TOF: time-of-flight tomography

FM: frequency-modulated tomography

# Photoacoustic Imaging Of Blood Vessels in Tissue

The end