Diffuse optical imaging of biological tissue

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Tufts University | School of Engineering

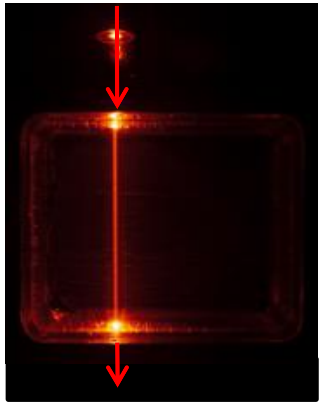
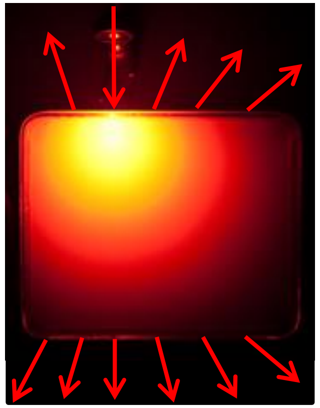
doit Lab
Diffuse Optical Imaging of Tissue

Conference on **Modern Challenges in Imaging**
In the Footsteps of Allan MacLeod Cormack
On the Fortieth Anniversary of his Nobel Prize

August 5-9, 2019, Tufts University, Medford, MA

Outline

- **Diffuse optical imaging:**
  - Breast cancer imaging
  - Functional brain imaging
- **New approach to enhance depth sensitivity in diffuse optical imaging**

No/weak scattering		Strong scattering
	← http://www.urmc.rochester.edu/labs/Choe-Lab/ →	
X-ray image of a hand		Diffuse optical image of a hand
		

Optical Mammography

Year: 2020 – 2010 – 2000 – 1990 – 1980 – 1970 – 1960 – 1950 – 1940 – 1930

- Response to neoadjuvant therapy;
- Photo-acoustics

- Time-resolved methods;
- Broadband spectroscopy;
- Optical tomography;
- Co-registrations;
- Photo-acoustics;
- Optical contrast agents;
- New commercial systems

ART

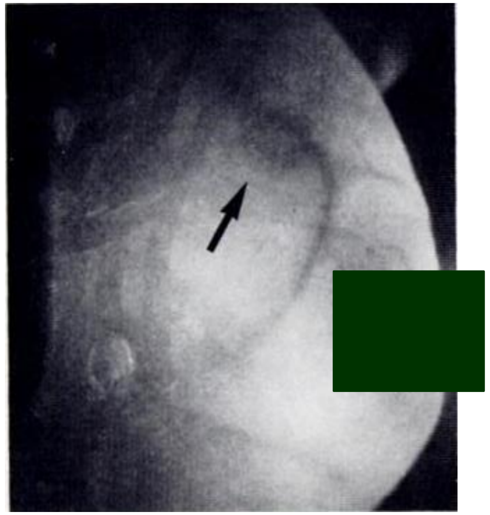
DOBI Medical INTERNATIONAL

DANUM International

Multicenter clinical study
Alveryd *et al.*, Cancer **65**, 1671 (1990).

"The study shows that lightscanning in its current form is inferior to standard mammography."

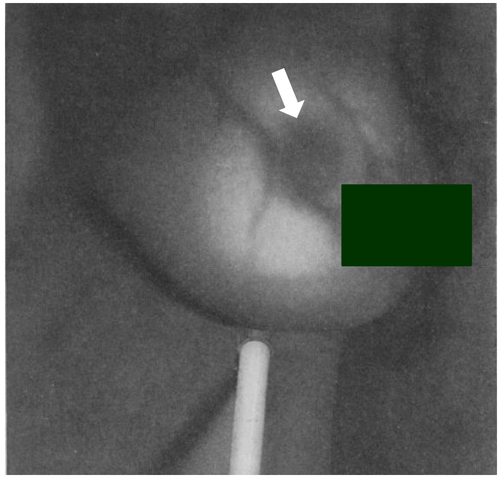
Pilot clinical studies
Bartrum and Crow, AJR **142**, 409(1984).



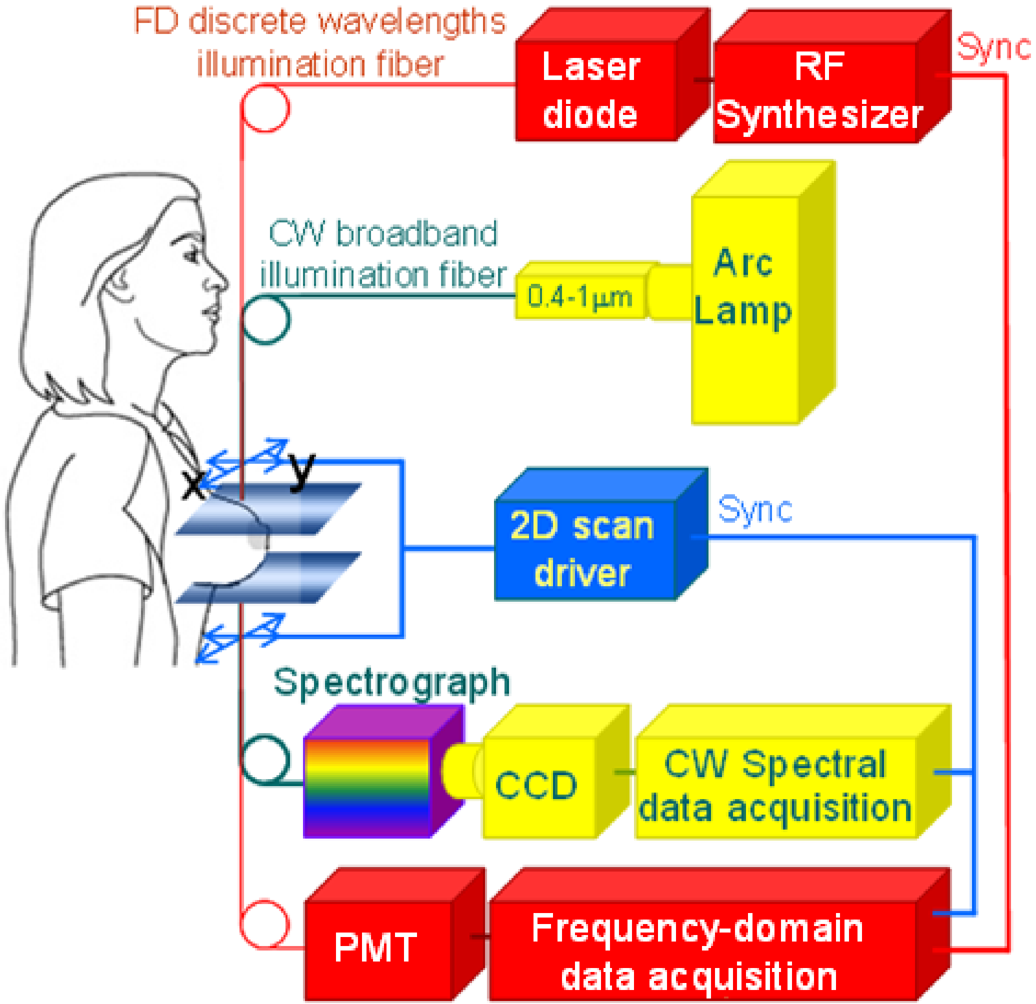
Lightscanning
Carlsen, Diagn. Imaging **4**, 28 (1982).

Diaphanography
Gros, Radiol. Electrol. **53**, 297 (1972).

Breast transillumination
Cutler, Surg. Gynecol. Obstet. **48**, 721 (1929).
(Currently: J. Am. Coll. Surg.)



Optical mammography at Tufts

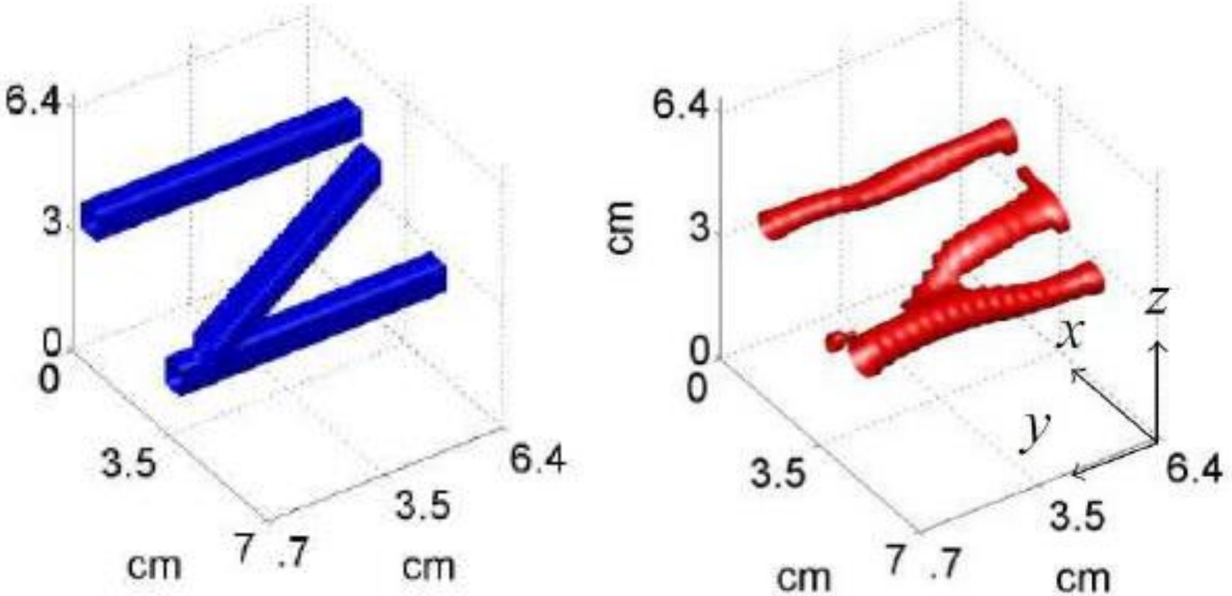


[Yang Yu et al., Appl. Opt. **48**, D225 (2009).]

Parametric estimation of 3D tubular structures for diffuse optical tomography

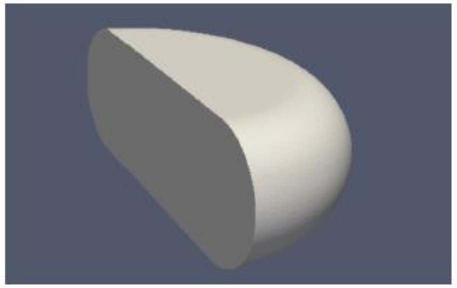
Fridrik Larusson,[1,4,*] Pamela G. Anderson,[2] Elizabeth Rosenberg,[2]
Misha E. Kilmer,[3] Angelo Sassaroli,[2] Sergio Fantini,[2]
and Eric L. Miller[1]

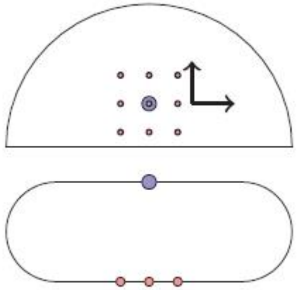
[Biomed. Opt. Express **4**, 271 (2013).]



Ground truth and reconstruction results with a parametric level set method (PaLS) using two detectors for each source location and inter-slice regularization.

SIAM J. Sci. Comput.
Vol. 37, No. 5, pp. B712–B743



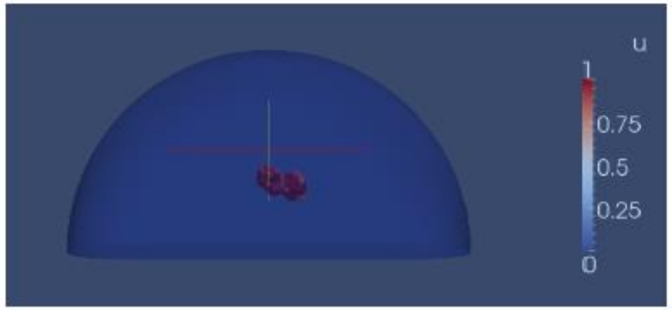


FAST ALGORITHMS FOR HYPERSPECTRAL DIFFUSE OPTICAL TOMOGRAPHY*

ARVIND K. SAIBABA†, MISHA KILMER‡, ERIC L. MILLER†, AND SERGIO FANTINI§

[SIAM J. Sci. Comput. **37**, B712 (2015).]

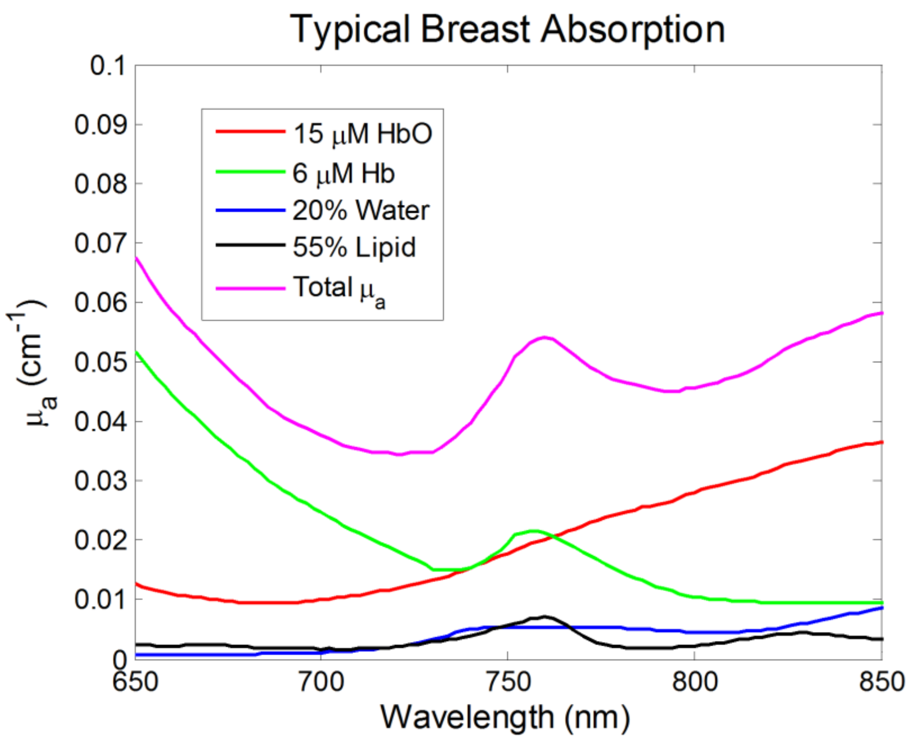
Reconstruction of chromophore concentrations and shape of a localized perturbation in a breast-like phantom using the Born approximation.



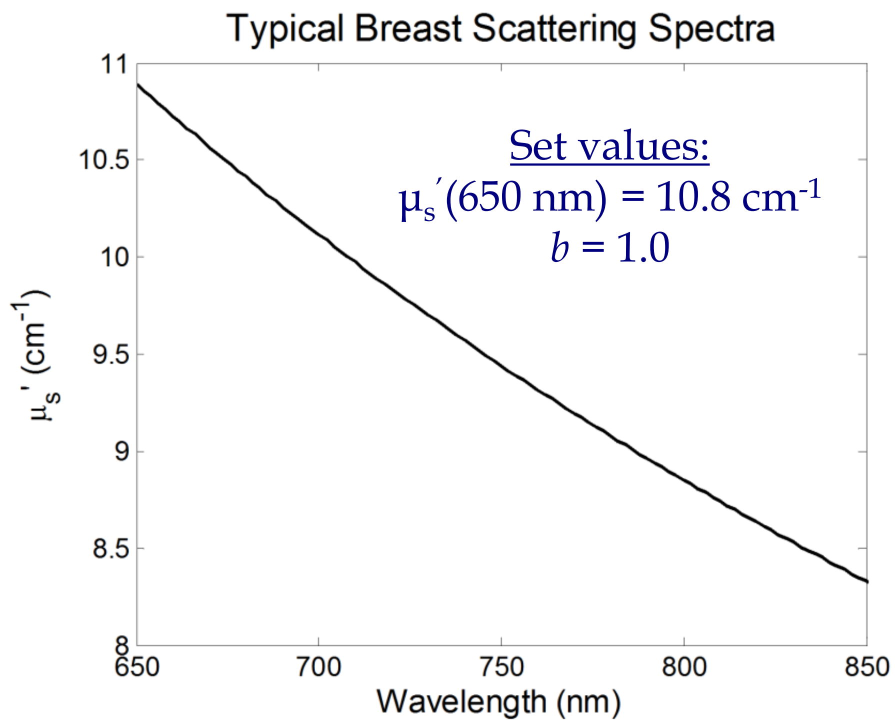
Breast tissue: Absorption and scattering spectra

$$\mu_a(\lambda) = \varepsilon_{HbO}(\lambda)\,[HbO] + \varepsilon_{Hb}(\lambda)\,[Hb] + \varepsilon_{water}(\lambda)\,[water] + \varepsilon_{lipid}(\lambda)\,[lipid]$$

$$\mu_s'(\lambda) = \mu_s'(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-b}$$



[Grosenick et al., Phys. Med. Biol. **50**, 2451 (2005)]



Transmission spectra modeled in each pixel with diffusion theory (slab geometry, extrapolated boundary conditions)

Known — Fixed — Found

$T(\lambda)\ \{\boxed{\varepsilon_i(\lambda), L,}\ \boxed{\mu_s'(\lambda_0), b,}\ \boxed{[Hb], [HbO], [water], [lipid]}\}$

Pilot clinical study on 26 patients with breast cancer

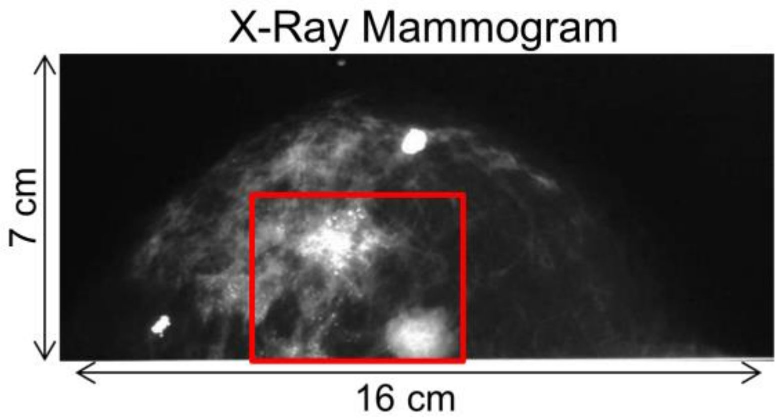
In collaboration with Tufts Medical Center:
Dr. Roger Graham
Dr. Marc Homer
Dr. Shital Makim

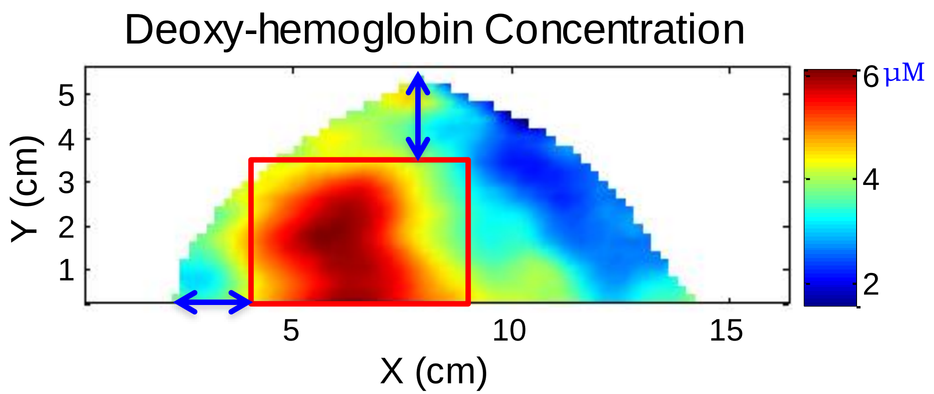
[Pami Anderson et al., PloS ONE **10**, e0117322 (2015)]

Number of Patients	26
Age (years)	
Average	57
Std	11
Range	36-76
Tumor Size (cm)	
Average	2.0
Std	1.4
Range	0.5-5.5
Cancer Type (# patients)	
DCIS	3
IDC	6
IDC/DCIS	12
IDC/DCIS/LCIS	2
ILC	1
ILC/LCIS	2

Patient #15

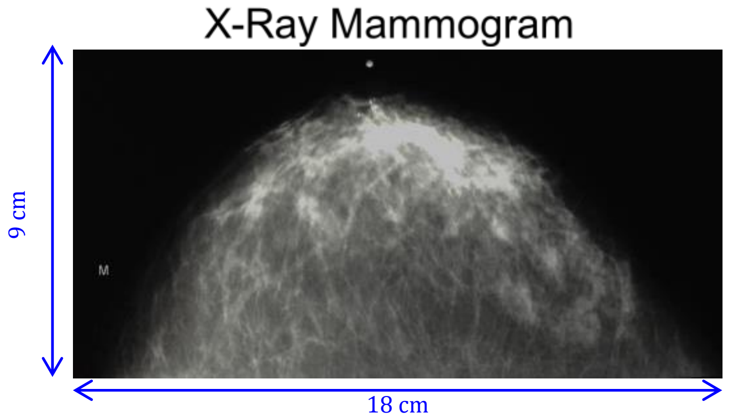
LCC
Cancerous Breast

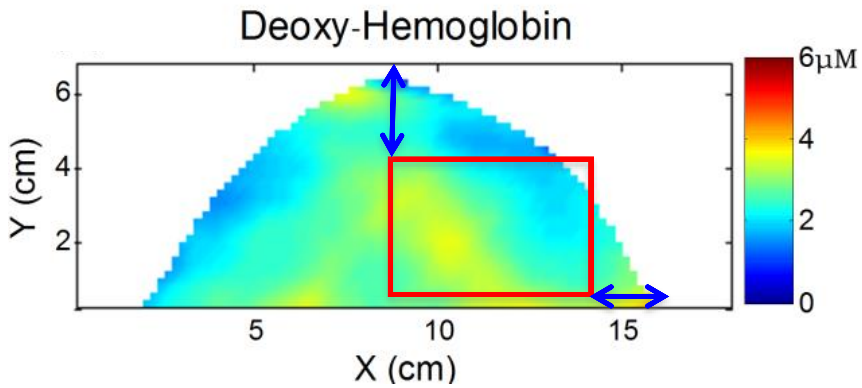




$\Delta Hb = 2.2 \pm 0.8 \mu M$

RCC
Healthy Breast



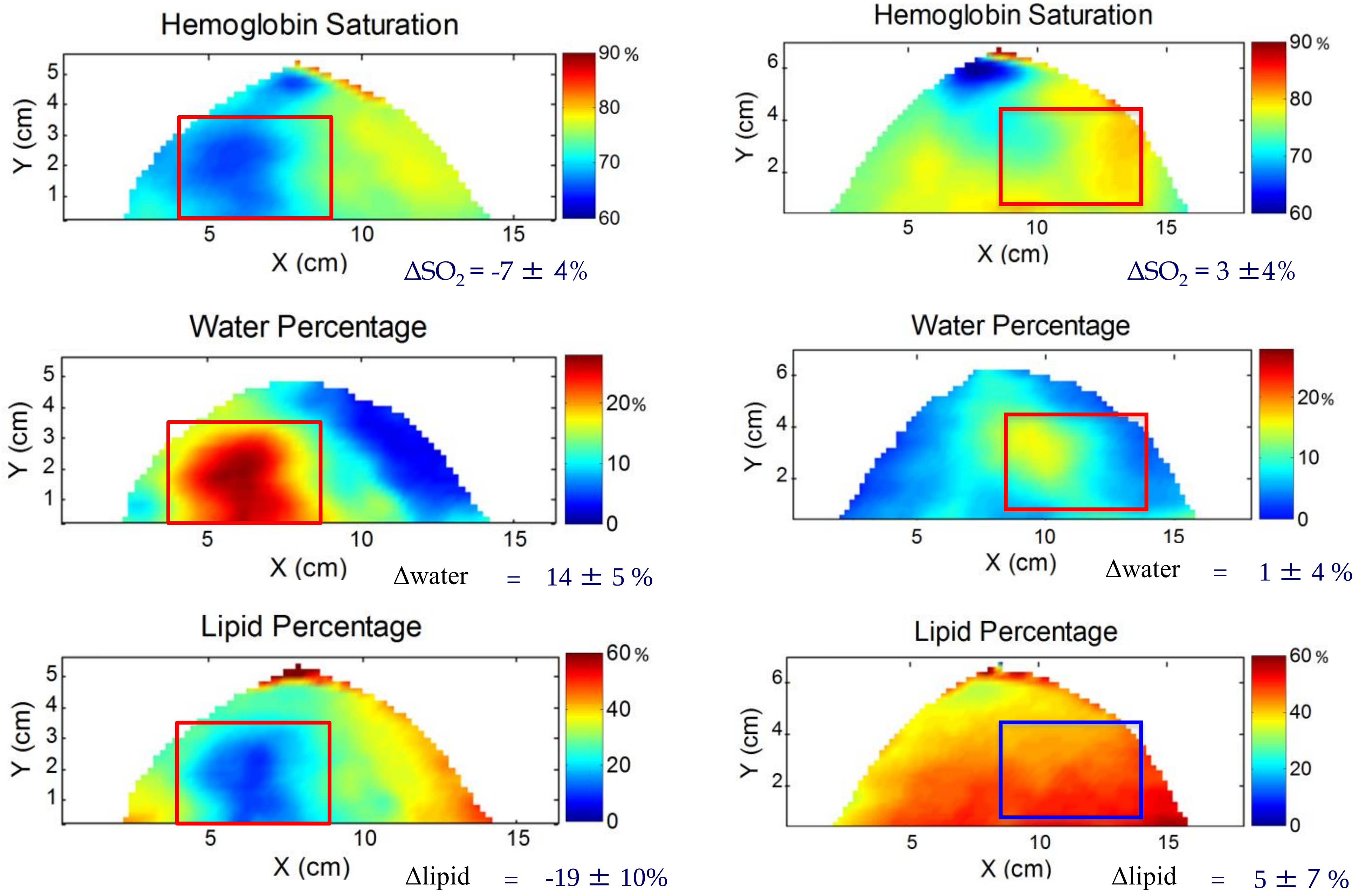


$\Delta Hb = 0.3 \pm 0.7 \mu M$

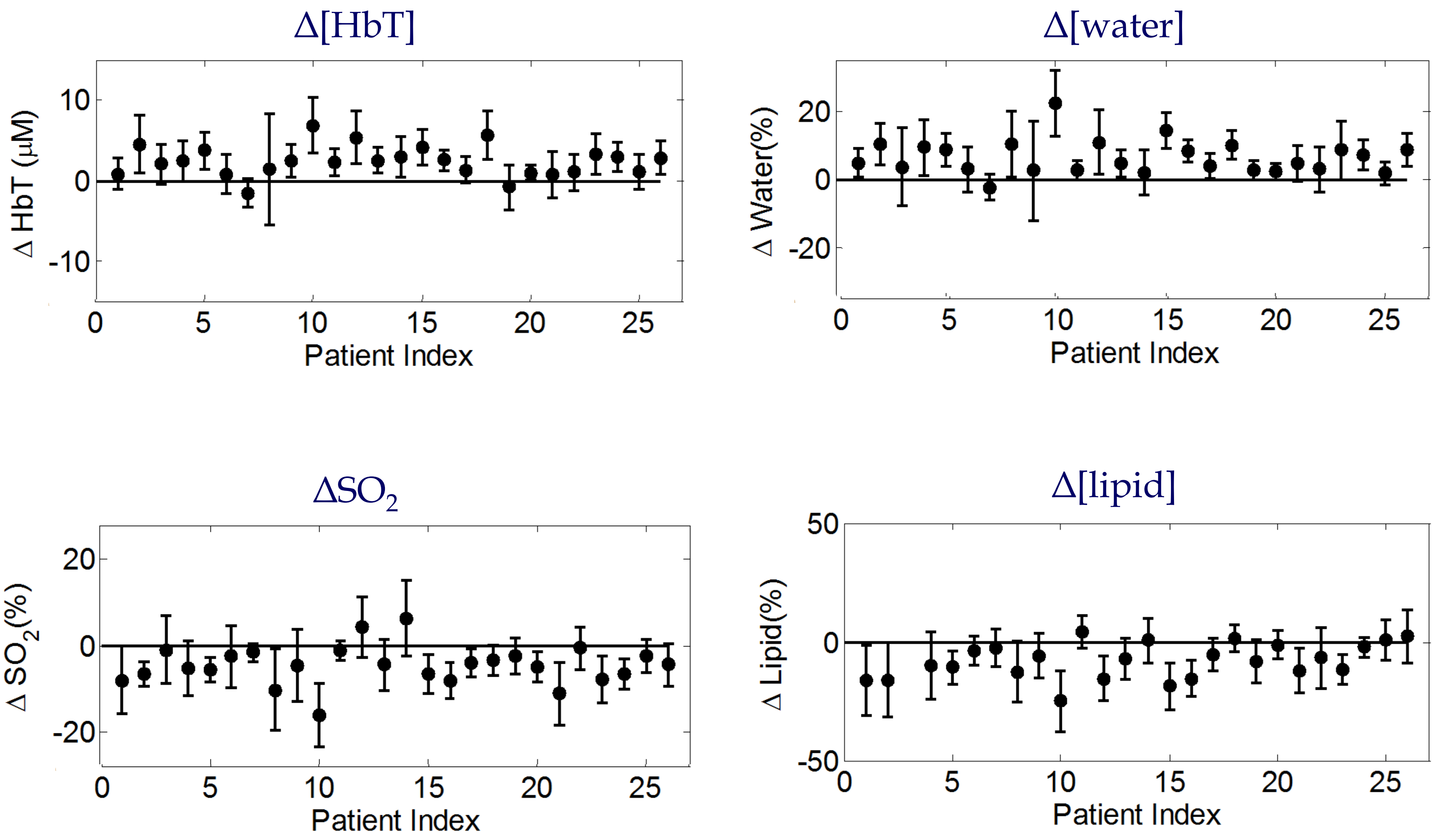
Patient #15

LCC - Cancerous Breast

RCC - Healthy Breast

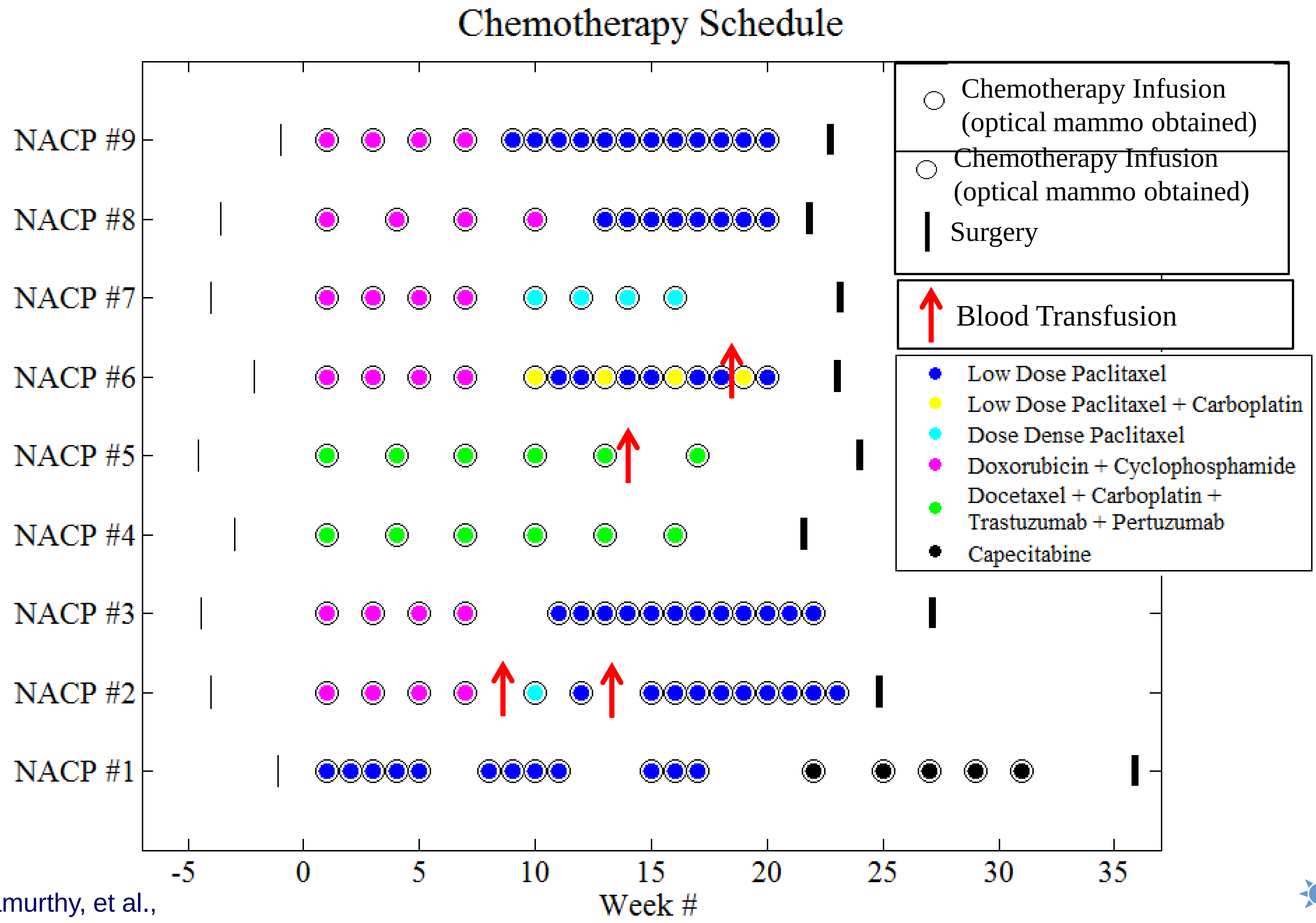


Results on all 26 patients



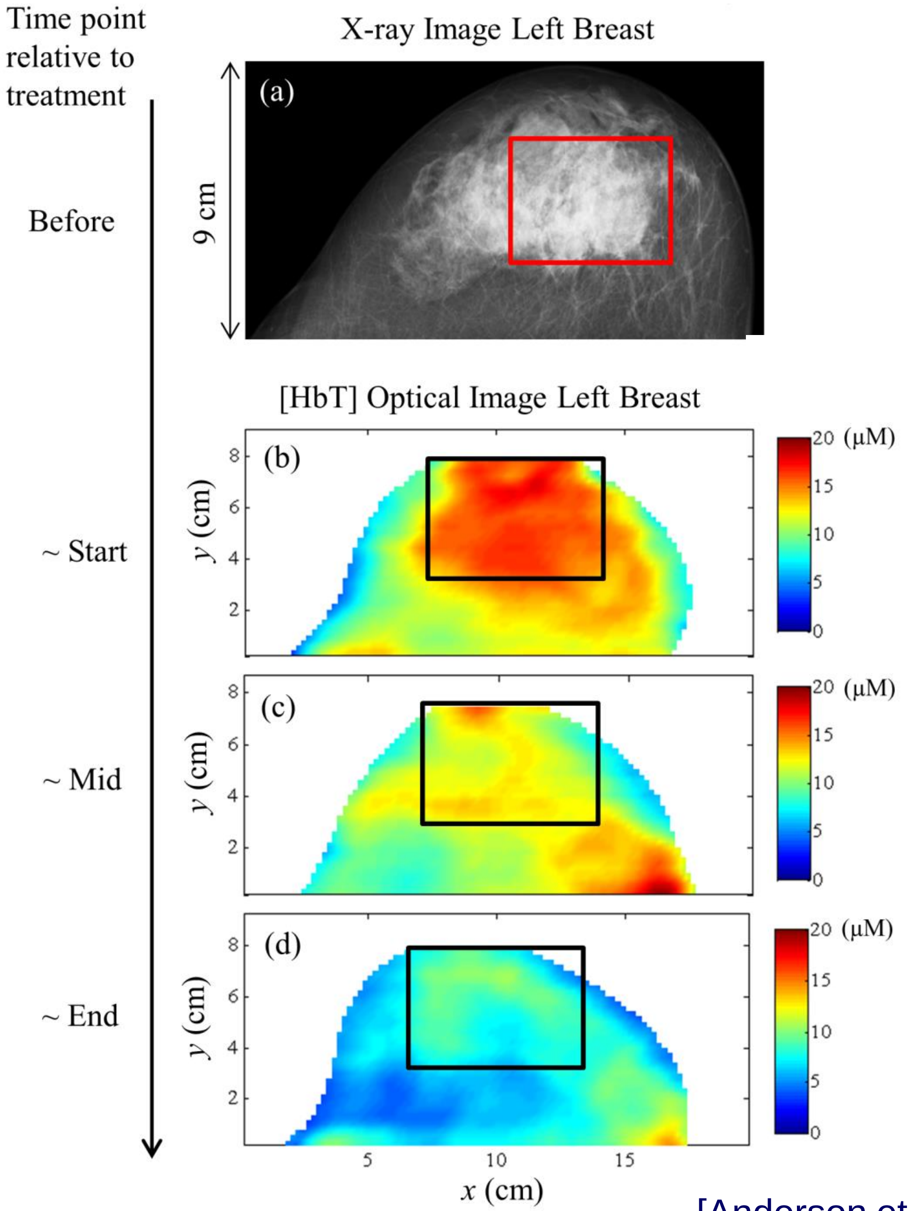
[Anderson et al., PloS ONE **10**, e0117322 (2015)]

Individual response to neoadjuvant chemotherapy



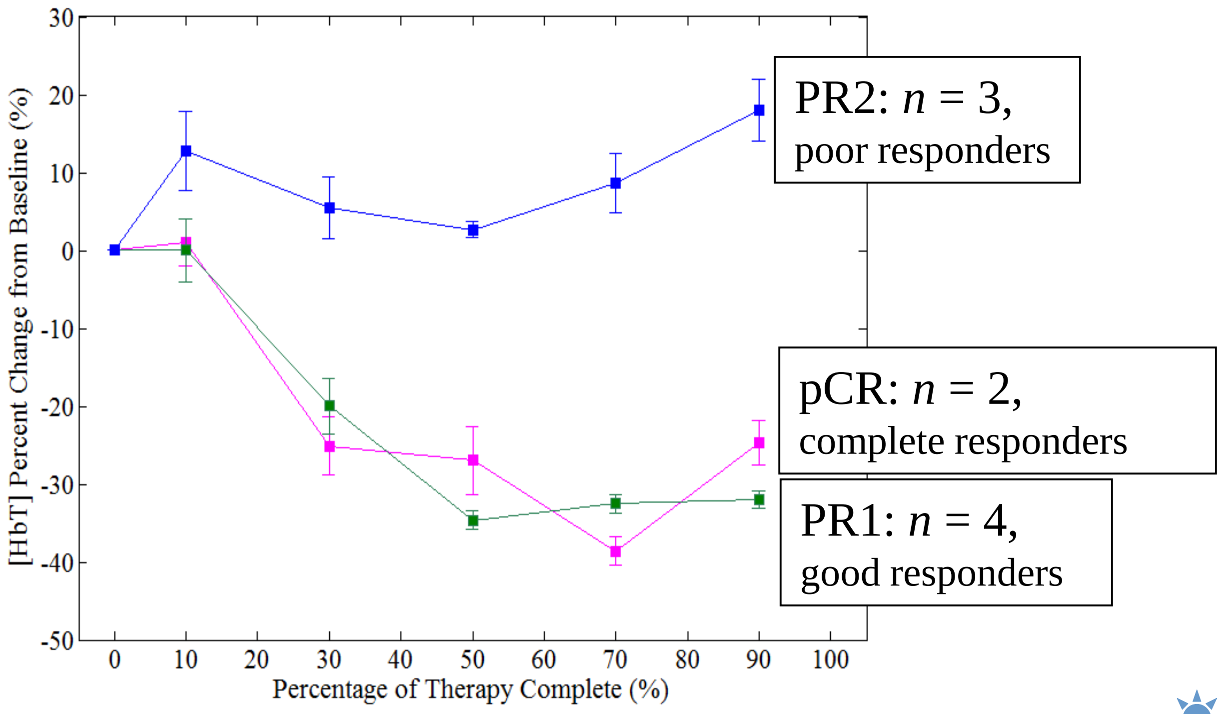
[Pami Anderson, Nishanth Krishnamurthy, et al., Acad. Radiol. **24**, 1240 (2017)]

[HbT] response to therapy: Representative Case (NACP #5) and group results



Age (years)	46
Type	Invasive ductal carcinoma
Max size (cm)	4.4
Response	pCR

Cancerous Breast [HbT] Response to Therapy: Group Results



[Anderson et al., Acad. Radiol. **24**, 1240 (2017)]

Non-invasive optical imaging of the brain

Year

2010

2000

1990

1980

1970

Commercial systems
ISS, Hitachi, Artinis, NIRx, Hamamatsu, TechEn, Shimadzu, etc.

- **Co-registration with fMRI, ERP;**
- **Modeling of NIRS signals;**
- **Studies of functional connectivity;**
- **Oscillatory hemodynamics;**
- **Neurovascular coupling;**
- **Autoregulation assessment.**



SHIMADZU
Excellence in Science

HITACHI
Inspire the Next

Fast optical signal
G. Gratton *et al.*, Psychophysiology **32**, 505 (1995).

Functional brain studies
•Chance *et al.*, PNAS **90**, 3770 (1993);
•Hoshi and M.Tamura, J. Appl. Physiol. **75**, 1842 (1993);
•Kato *et al.*, J. Cereb. Blood Flow Metab. **13**, 516 (1993);
•Villringer *et al.*, Neurosci. Lett. **154**, 101 (1993).

Mamoru Tamura

Arno Villringer

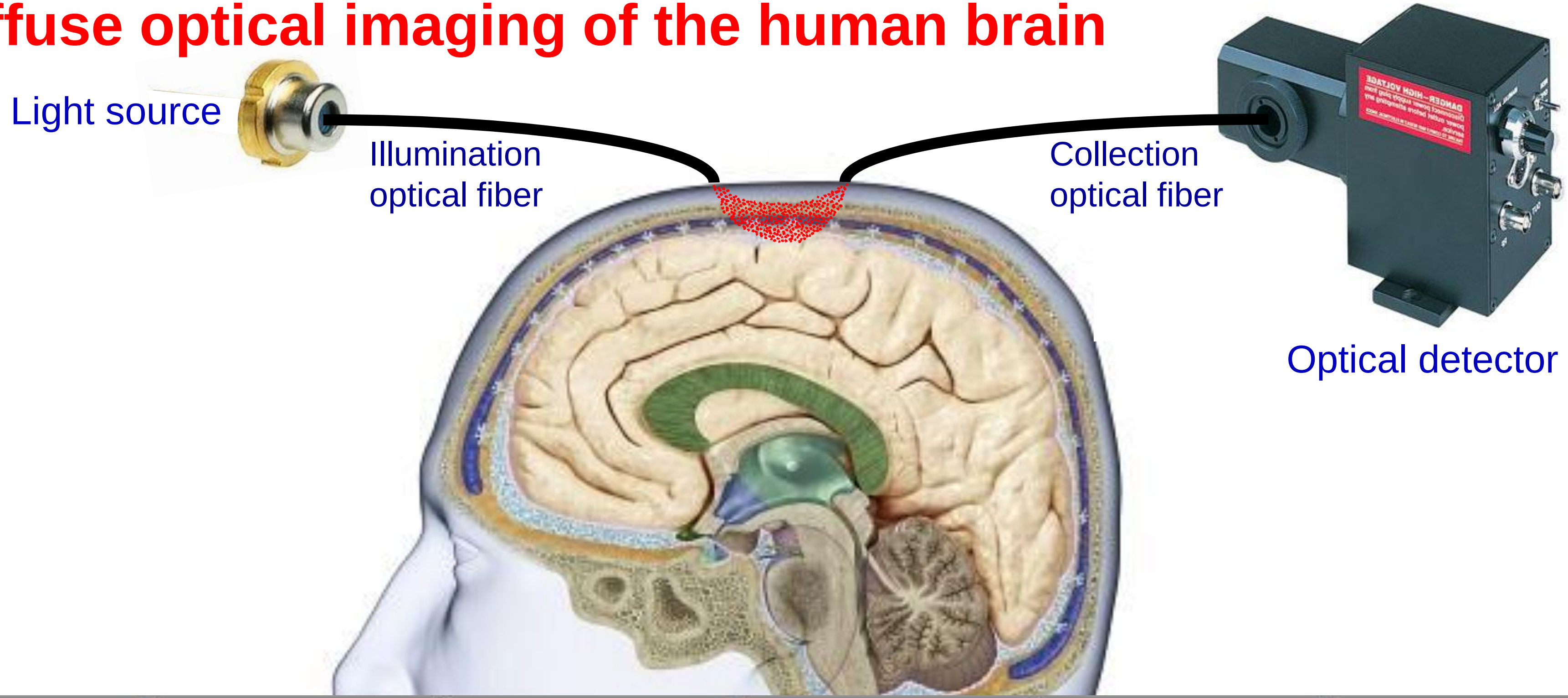
Time-resolved meas. on animal models
D. Delpy*et al.*, Phys. Med. Biol. **33**, 1433 (1988);
B. Chance *et al.*, PNAS **85**, 4971 (1988).

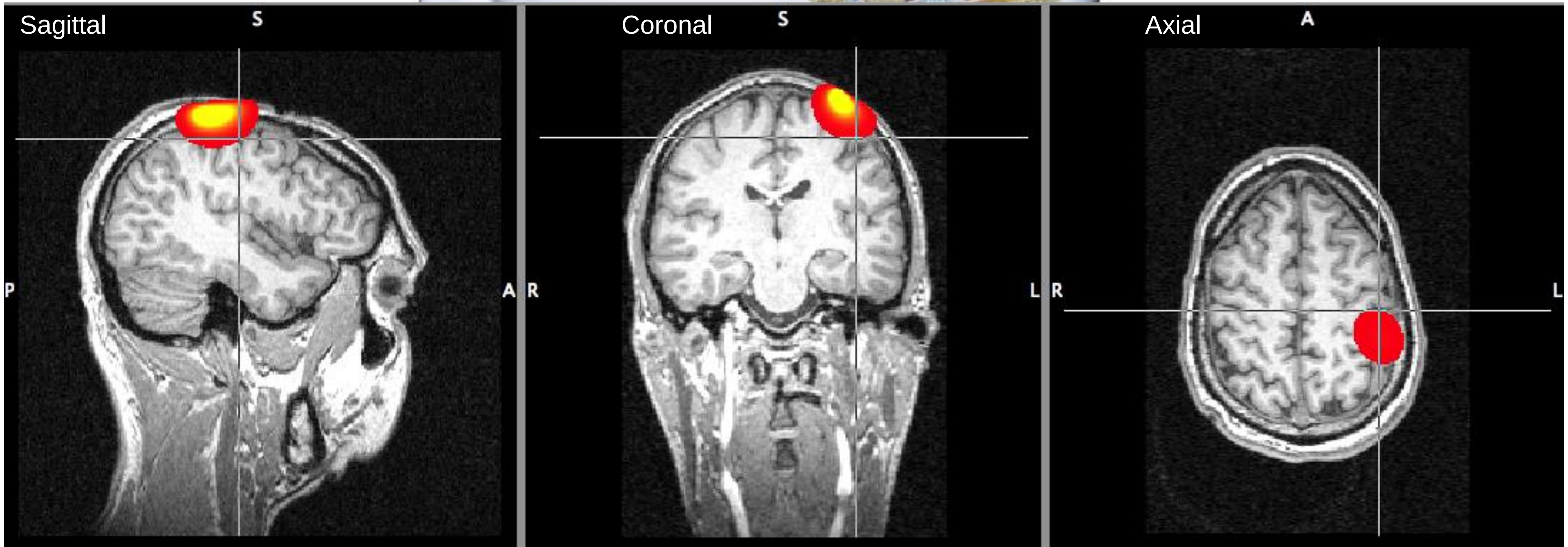
Britton Chance

Non-Invasive optical brain studies
Jöbsis, Science **198**, 1264 (1977).

Frans Jöbsis

Diffuse optical imaging of the human brain

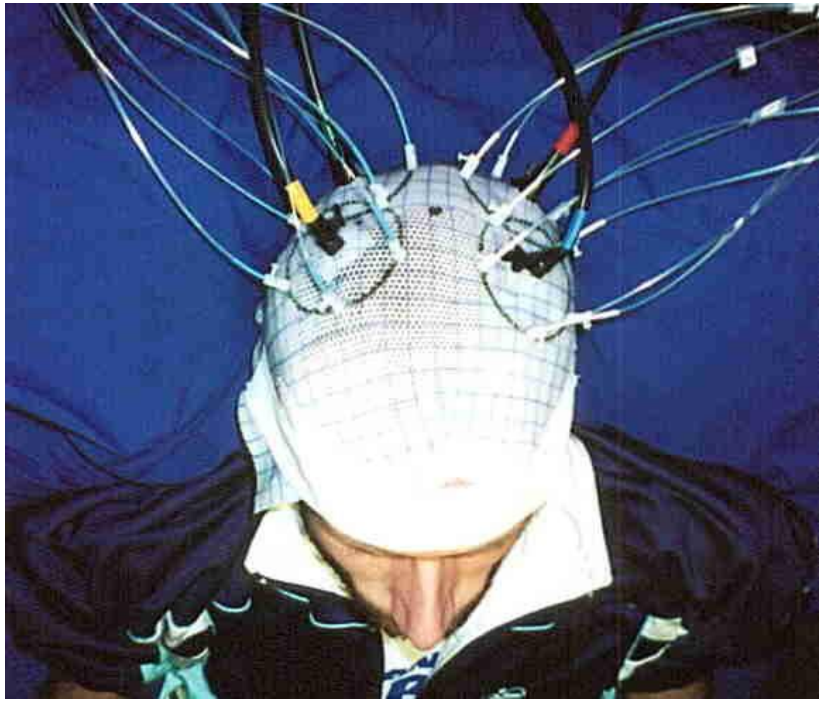


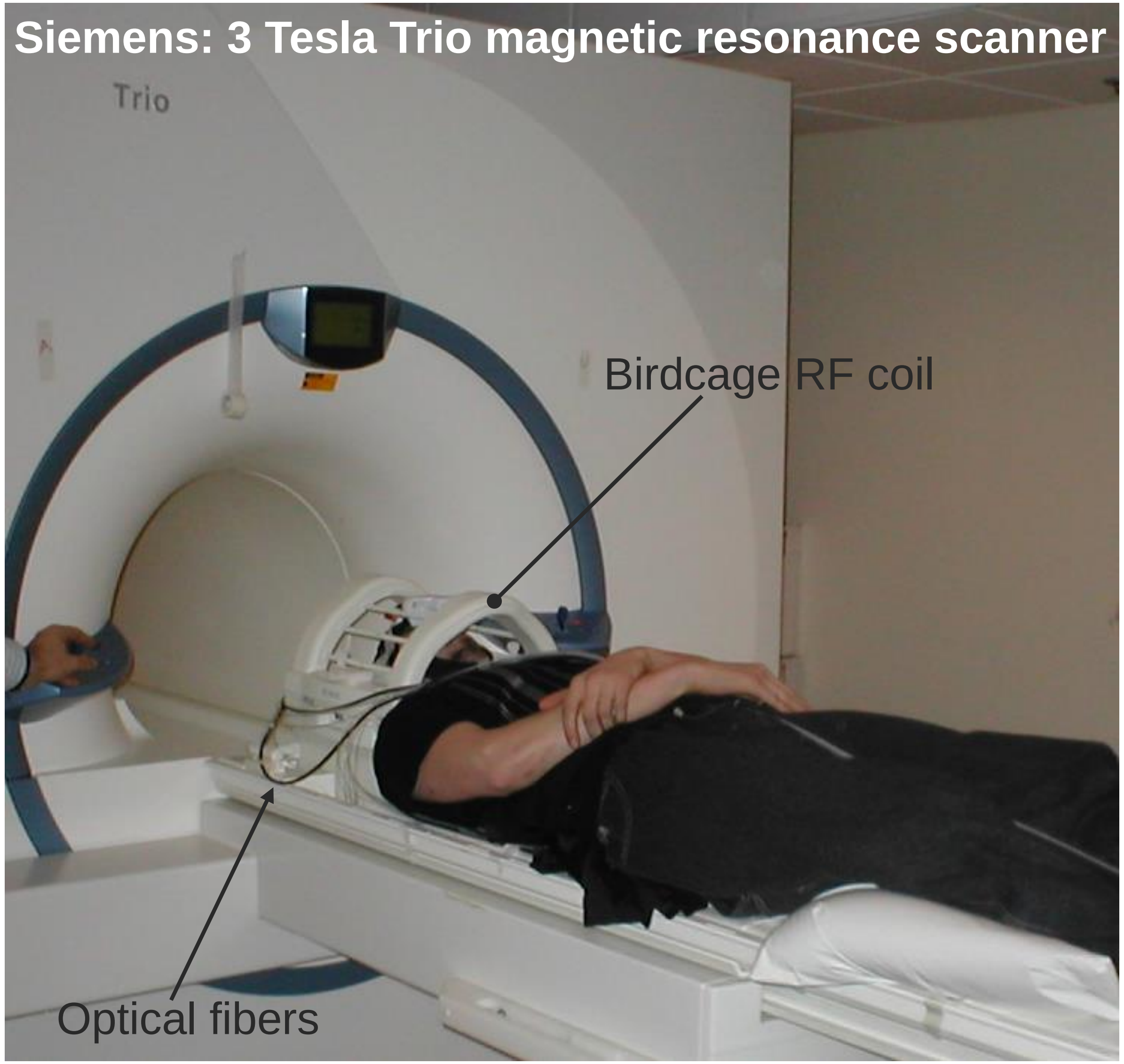


Steven Spielberg *et al.*, 2002.

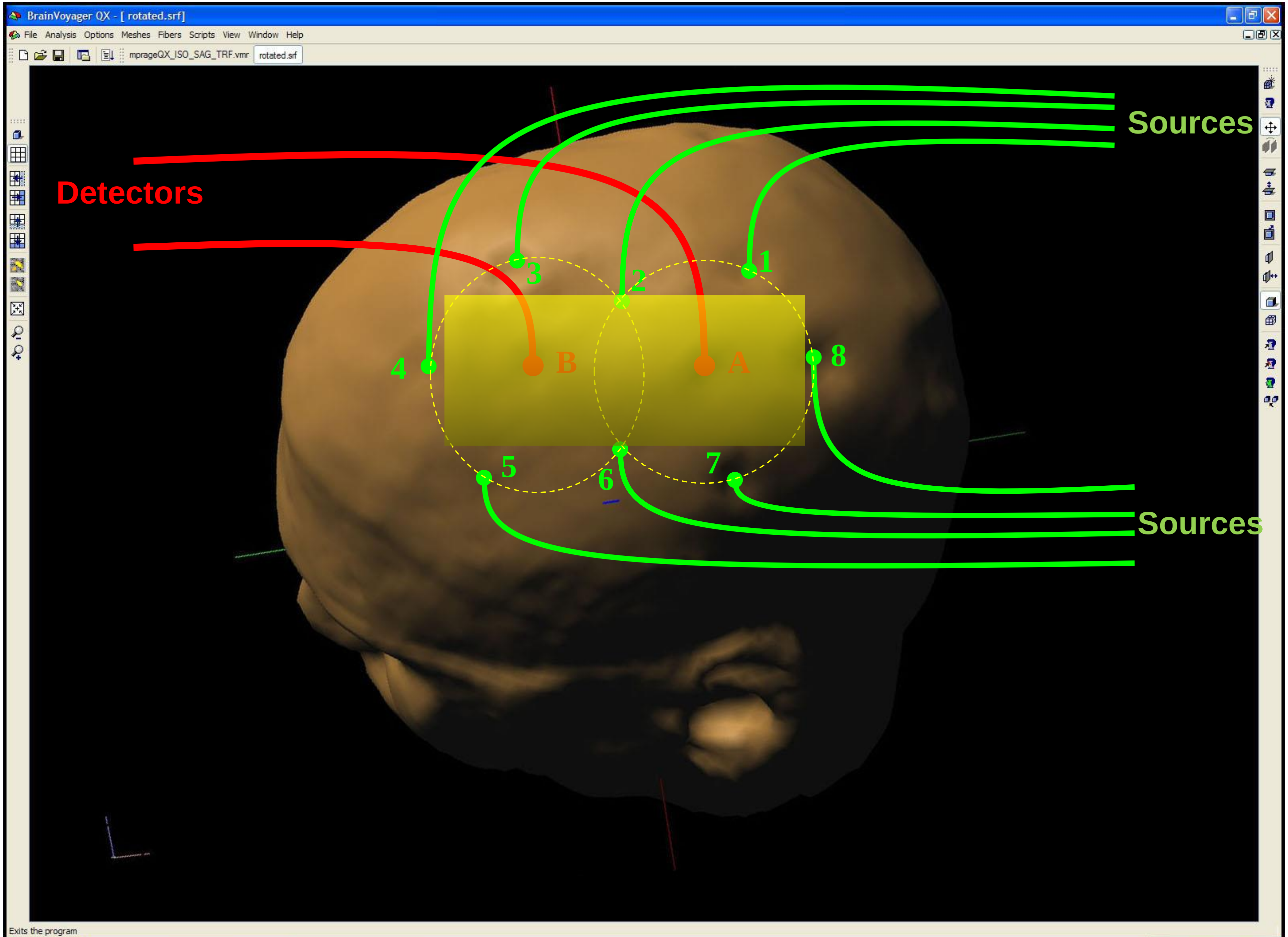
Functional optical imaging of the brain at Tufts:

Concurrent fNIRS and fMRI (with B. Frederick, McLean Hospital, Belmont, MA)



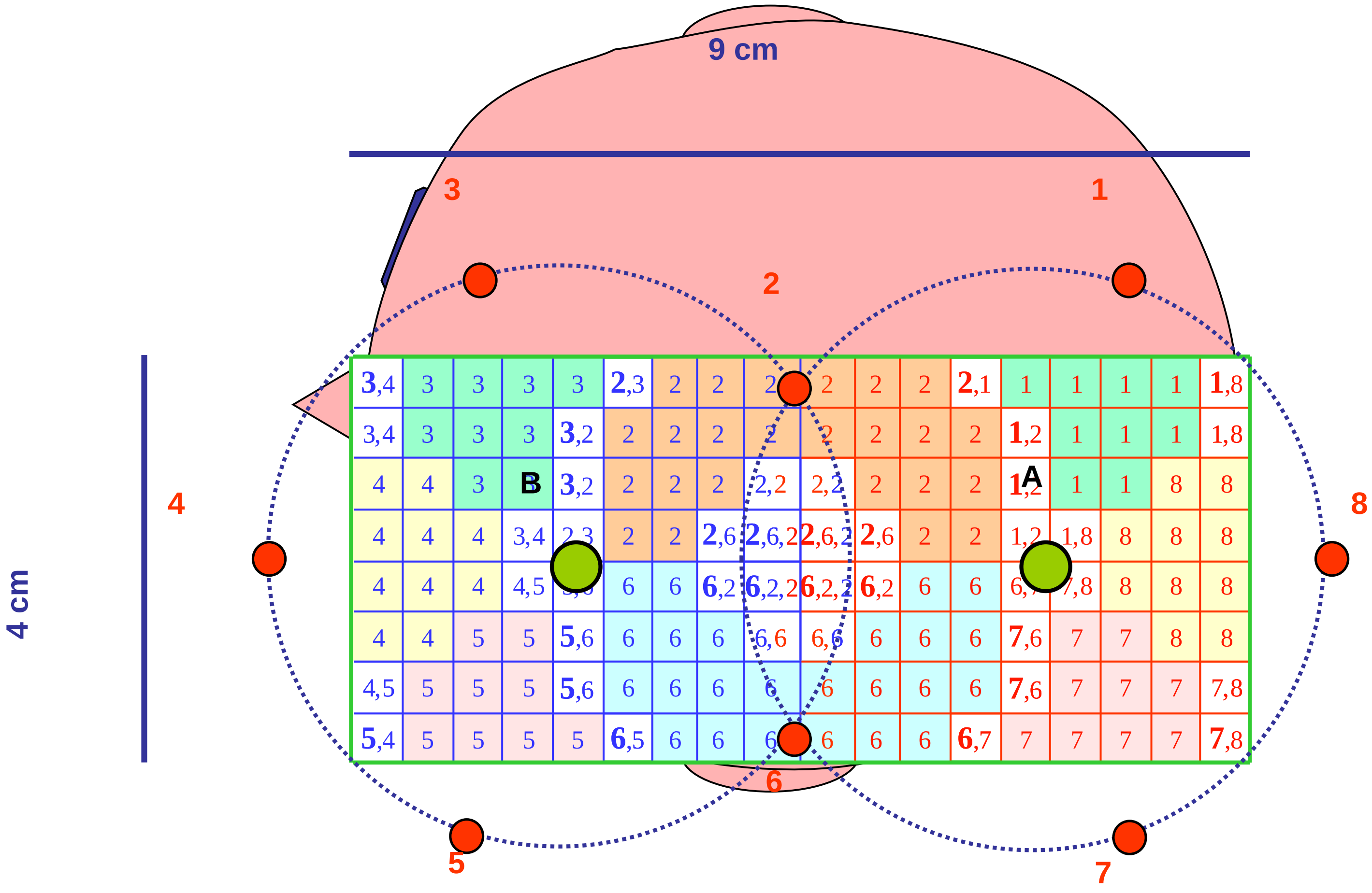


[Angelo Sassaroli, Yunjie Tong *et al.*, NeuroImage **33**, 505 (2006)]

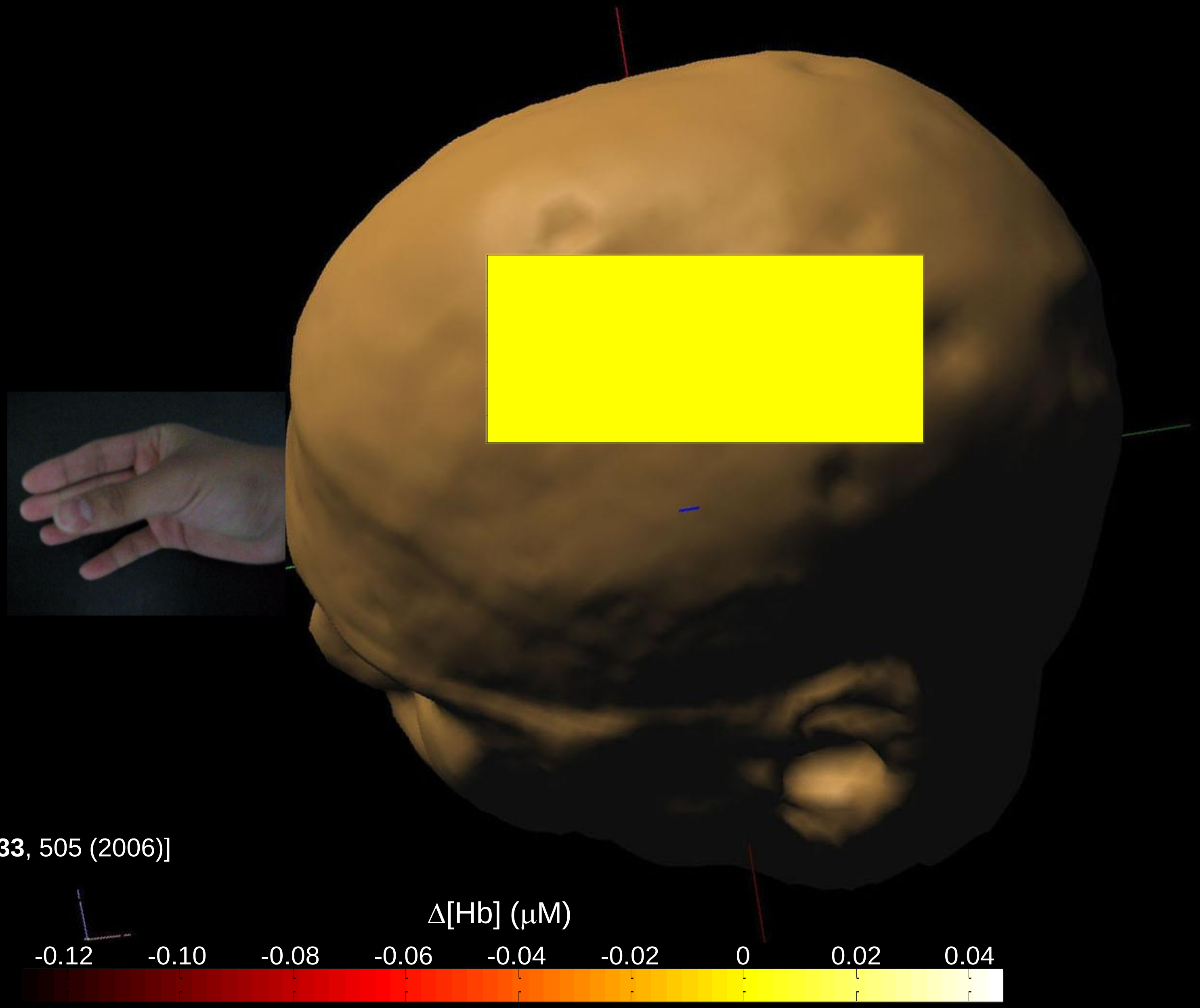


BrainVoyager QX - [rotated.srf]
File Analysis Options Meshes Fibers Scripts View Window Help
mprageQX_ISO_SAG_TRF.vmr
rotated.srf
Detectors
Sources
Sources
1
2
3
4
5
6
7
8
A
B
Exits the program

Back-projection reconstruction matrix



Deoxy-hemoglobin concentration map during finger tapping

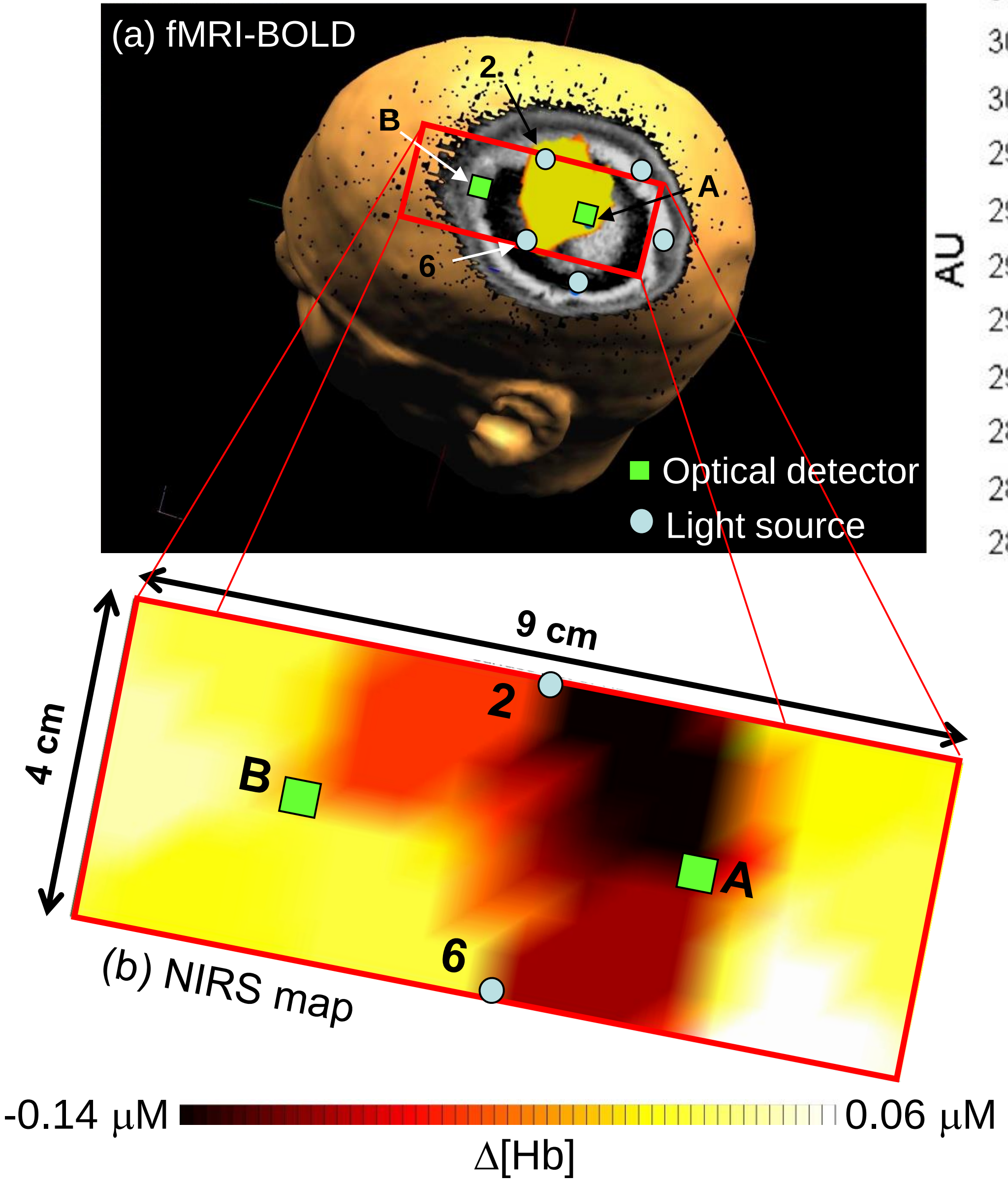


[Sassaroli *et al.*, Neuroimage **33**, 505 (2006)]

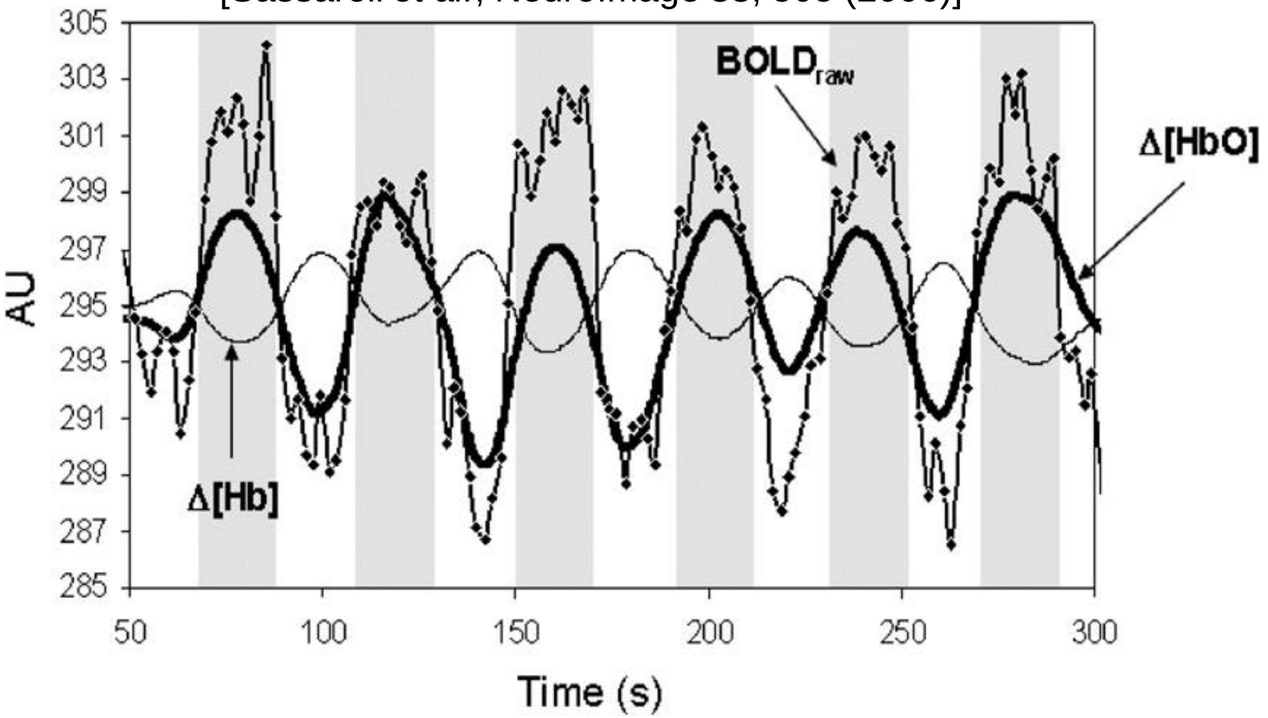
Spatial and temporal comparison of fMRI-BOLD and NIRS mapping

(In collaboration with B. Frederick, McLean Hospital, Belmont, MA)

Right hand tapping



[Sassaroli *et al.*, NeuroImage **33**, 505 (2006)]



$$\Delta[\mathrm{Hb}]^{(\mathrm{tissue})} \propto A\left(\frac{\Delta\sigma_{\mathrm{bv}}}{\sigma_{\mathrm{bv}}}\right) + B\left(\frac{\Delta\alpha_{\dot{\mathrm{O}}_2}}{\alpha_{\dot{\mathrm{O}}_2}} - \frac{\Delta c^{(\mathrm{blood})}}{c^{(\mathrm{blood})}}\right)$$

Blood volume

Metabolic rate of oxygen

Blood flow velocity

[S. Fantini, Phys. Med. Biol. **47**, N249 (2002)]

[S. Fantini, NeuroImage **85**, 202 (2014)]

[S. Fantini, Physiol. Meas. **35**, N1 (2014)]

The region of sensitivity in diffuse optics

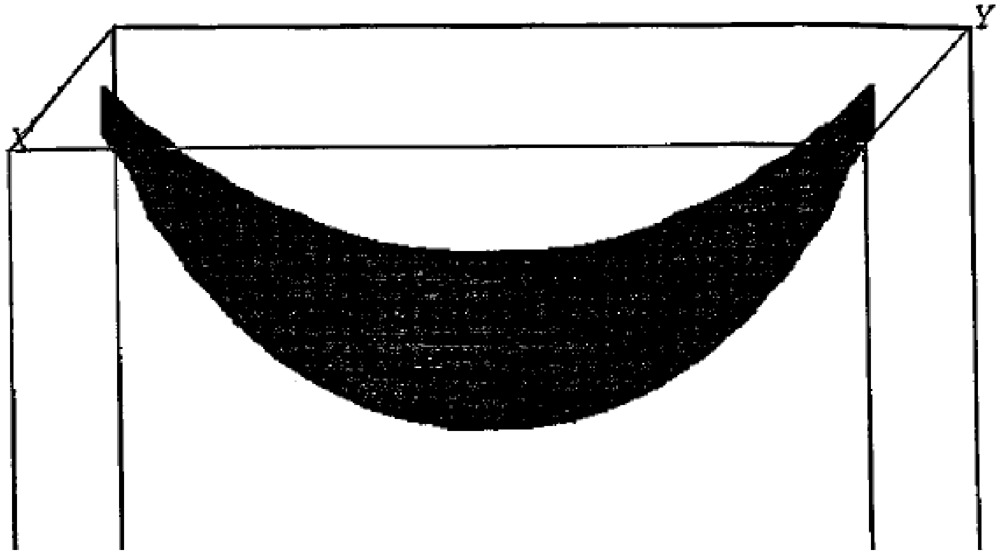
Photon hitting density: J. Schotland et al, Appl. Opt. **32**, 448 (1993)

Photon-measurement density: S. Arridge, Appl. Opt. **34**, 7395 (1995)

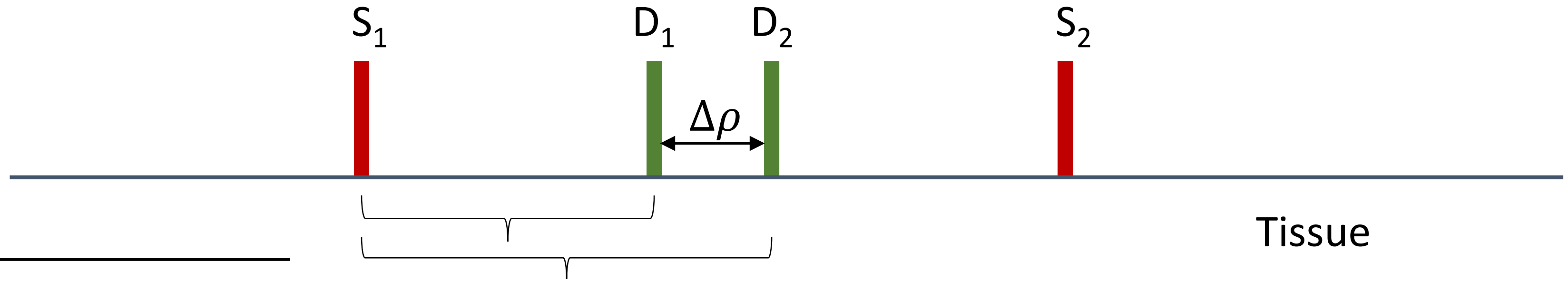
$$J_p^{(M)}(\mathbf{r}_m, \mathbf{q}; \mathbf{r}') \triangleq \lim_{\Delta p \to 0} \frac{F^{(M)}[\mathbf{r}_m, \mathbf{q}; \mathbf{p} + \Delta \mathbf{p}(\mathbf{r}')] - F^{(M)}[\mathbf{r}_m, \mathbf{q}; \mathbf{p}]}{\Delta \mathbf{p}(\mathbf{r}')} .$$

[Arridge, Appl. Opt. **34**, 7395 (1995)]

[Feng et al, Appl. Opt. **34**, 3826 (1995)]



Dual slope of phase (or intensity)



Single slope 1:

$$Sl_{\varphi 1} = \sqrt{\frac{3\mu_a\mu_s'}{2}}\sqrt{\sqrt{1+\left(\frac{\omega}{c_n\mu_a}\right)^2}-1}+\frac{\varphi_{D2}-\varphi_{D1}}{\Delta\rho}$$

Single slope 2: $$Sl_{\varphi 2} = \sqrt{\frac{3\mu_a\mu_s'}{2}}\sqrt{\sqrt{1+\left(\frac{\omega}{c_n\mu_a}\right)^2}-1}+\frac{\varphi_{D1}-\varphi_{D2}}{\Delta\rho}$$

Dual slope: $$DSl_{\varphi} = \frac{Sl_{\varphi 1}+Sl_{\varphi 2}}{2} = \sqrt{\frac{3\mu_a\mu_s'}{2}}\sqrt{\sqrt{1+\left(\frac{\omega}{c_n\mu_a}\right)^2}-1}$$

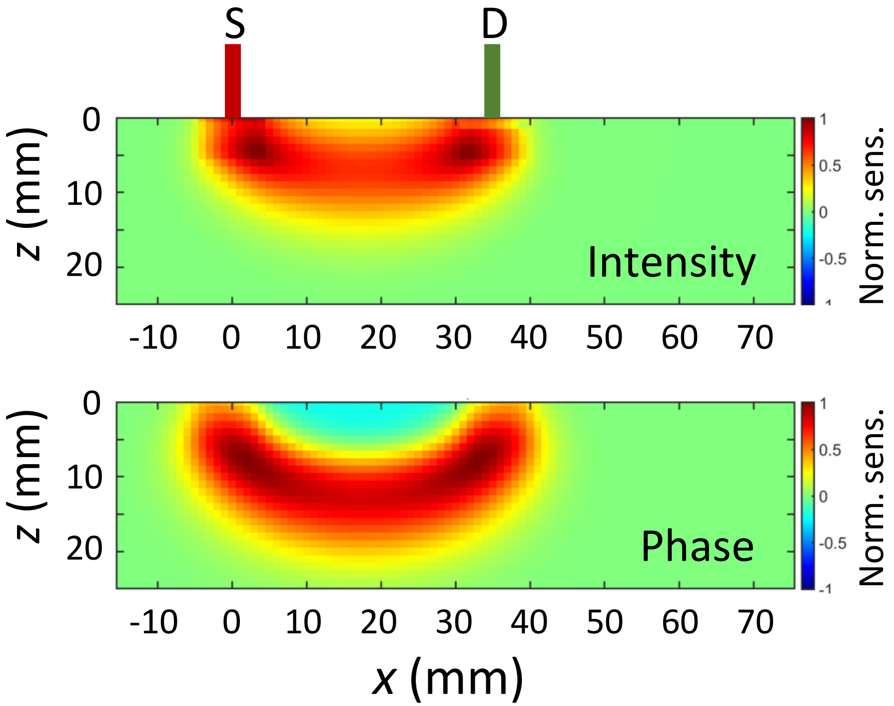
[Hueber et al, Proc. SPIE **3597**, 618-631 (1999)]

Region of sensitivity for intensity and phase measurements

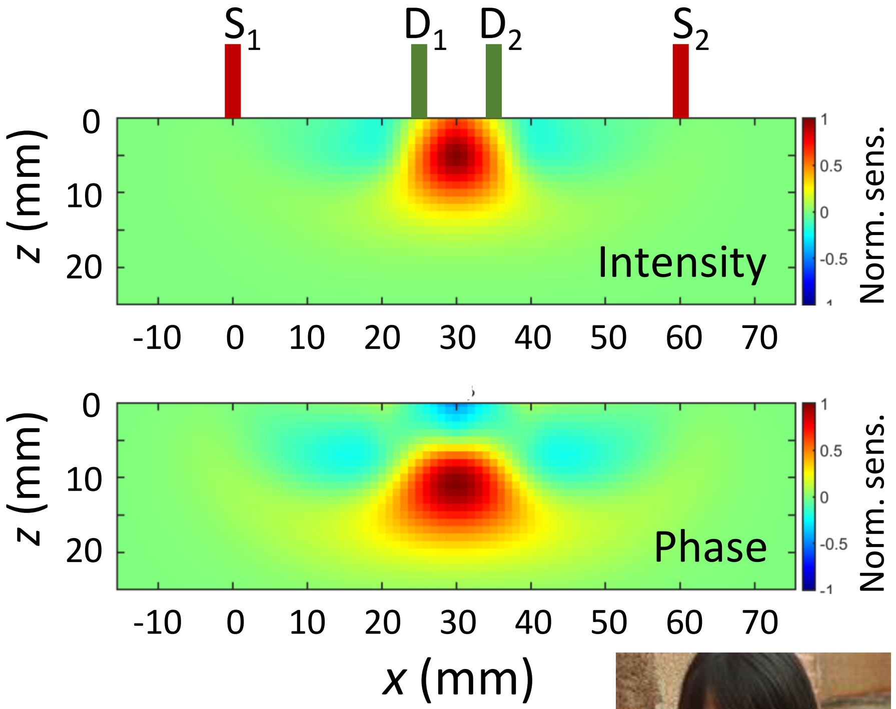
Single-Distance, Dual-Slope

$\mu_{a0} = 0.1\ \mathrm{cm}^{-1}$
$\mu_s' = 12\ \mathrm{cm}^{-1}$
$\Delta\mu_a = 0.03\ \mathrm{cm}^{-1}$
$\Delta V = 0.7\mathrm{cm}^3$

Single-distance (1S-1D)



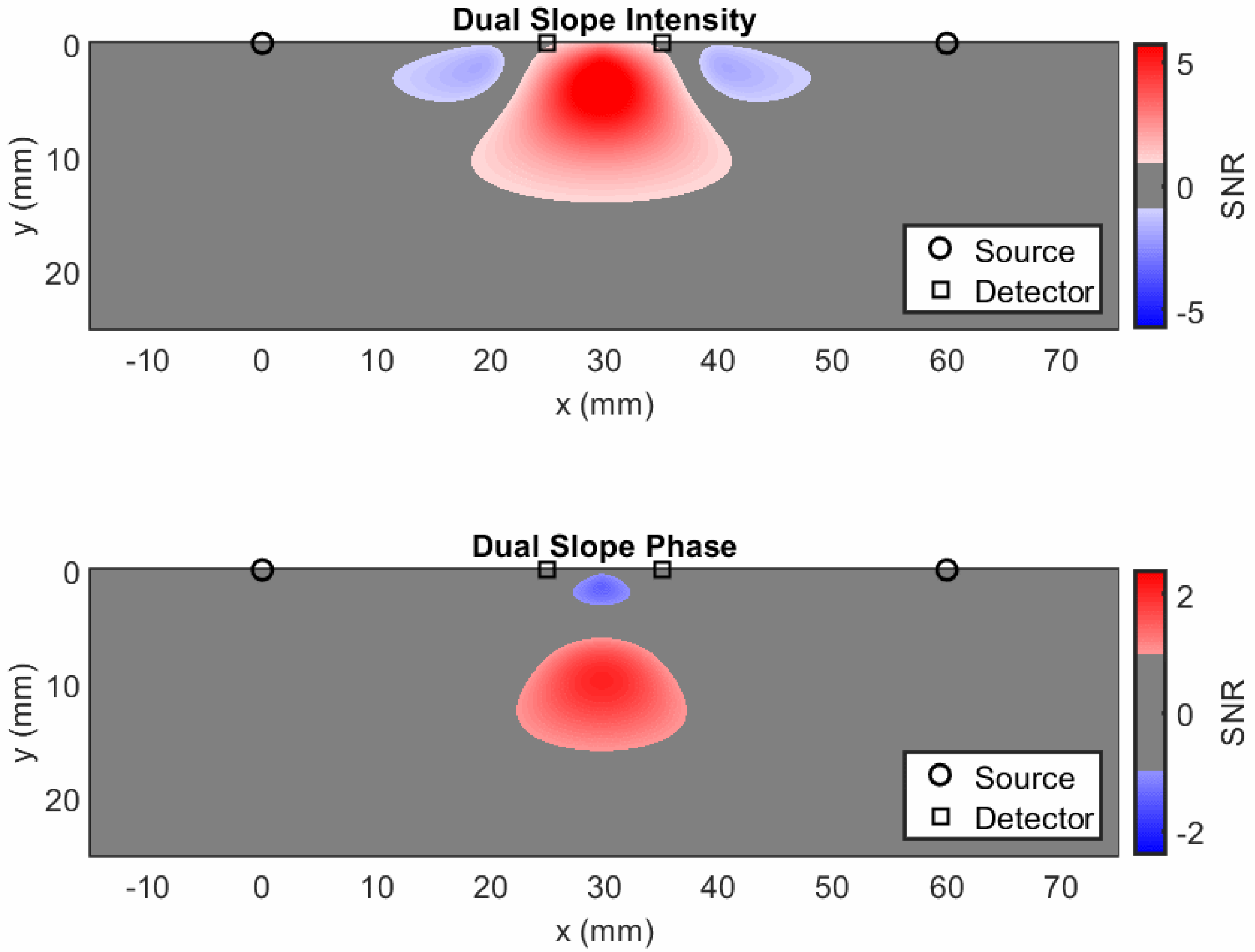
Dual-slope (2S-2D)



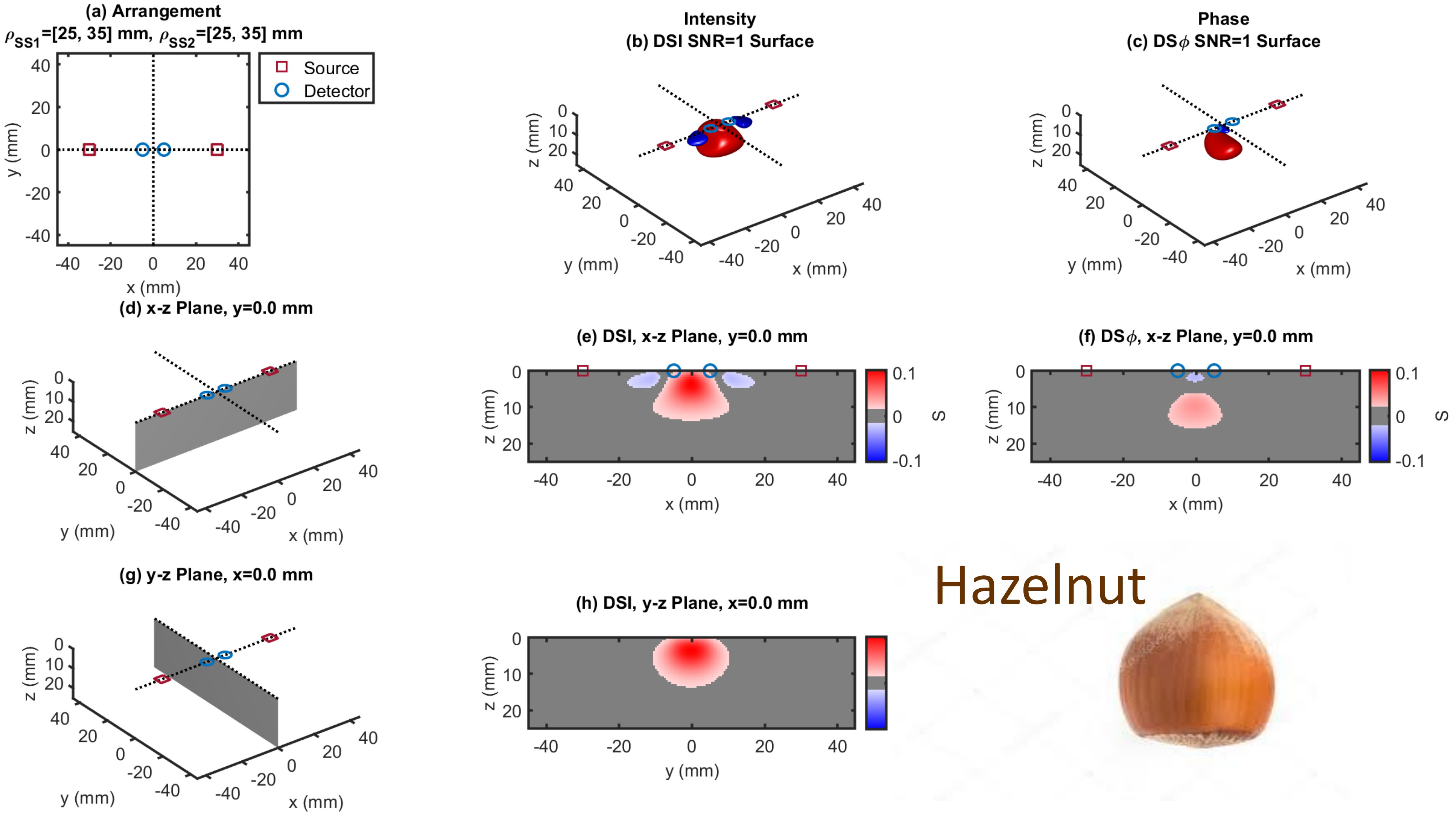
[Giles Blaney et al., J. Biophotonics (*submitted*, 2019)]

[Angelo Sassaroli et al., J. Opt. Soc. Am A (*submitted*, 2019)]

Comparison of intensity and phase dual slopes

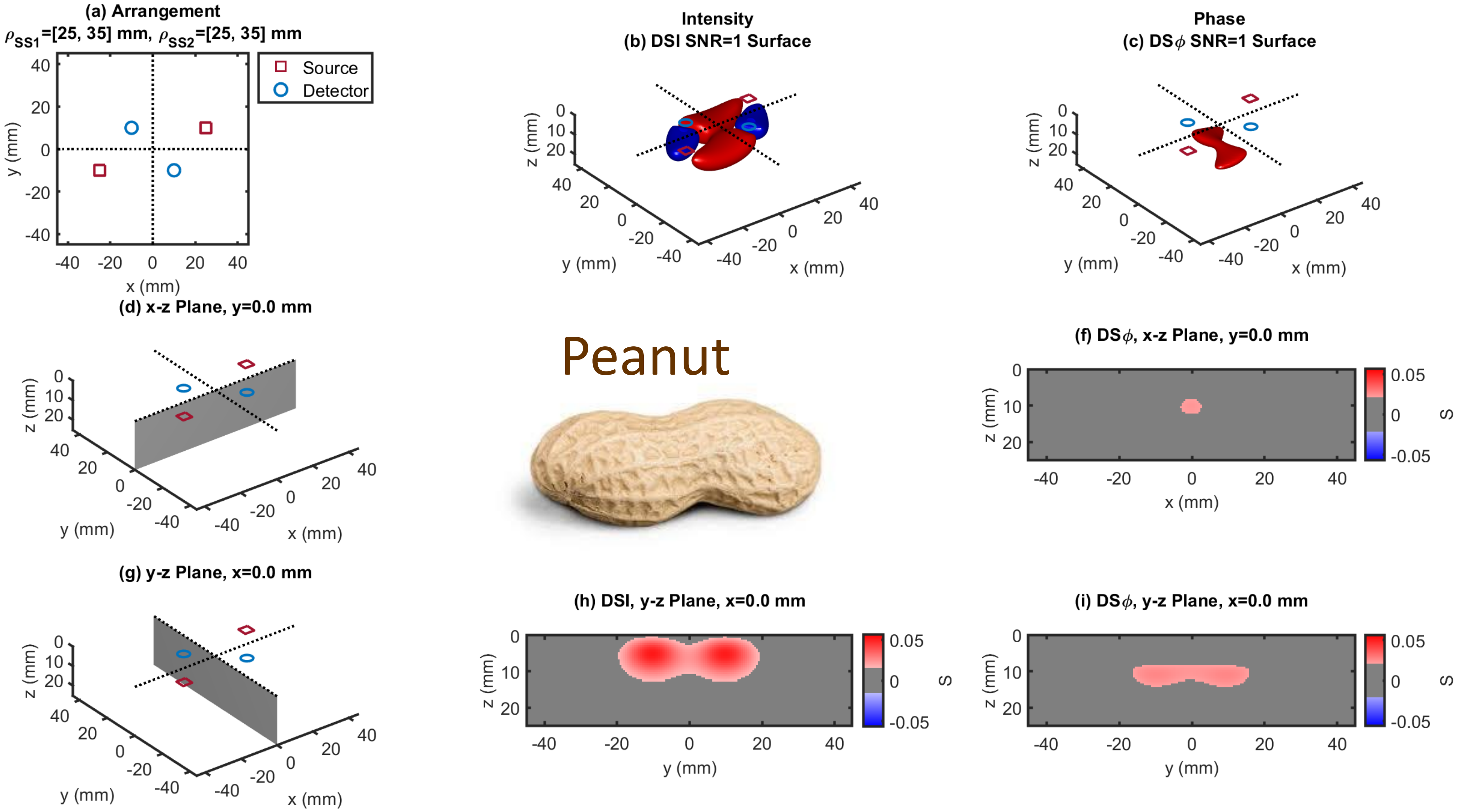


Linear arrangement

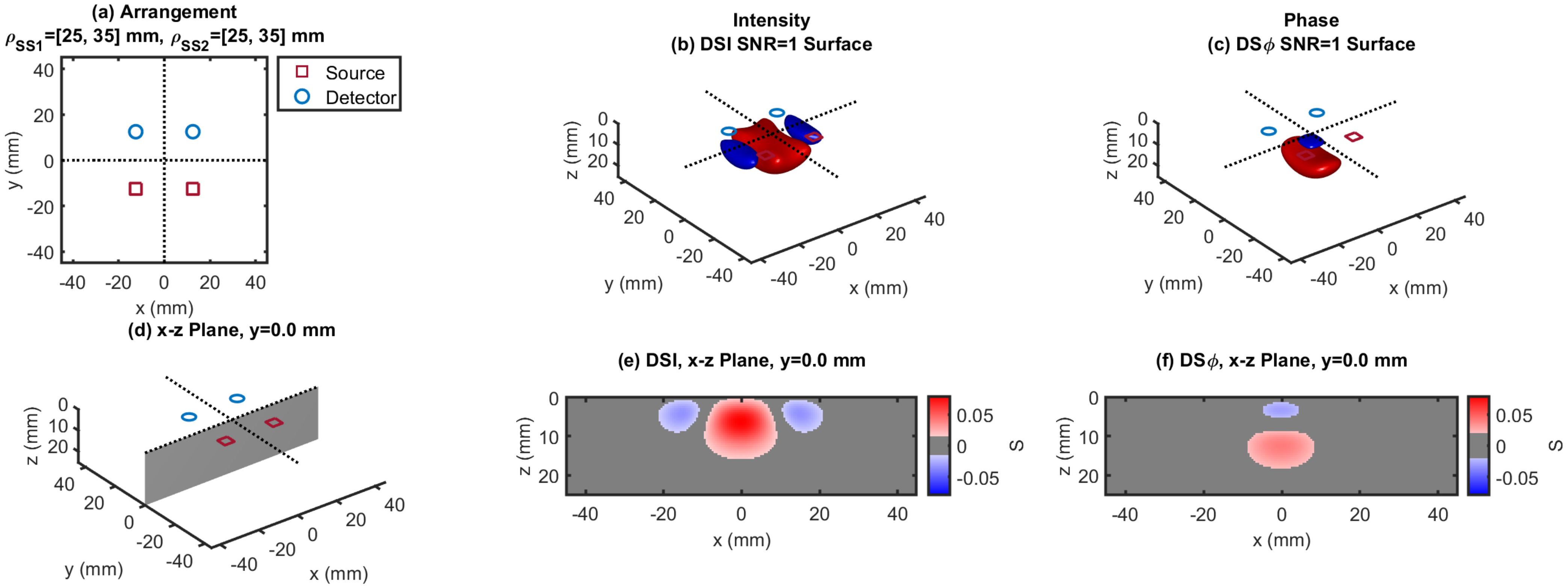


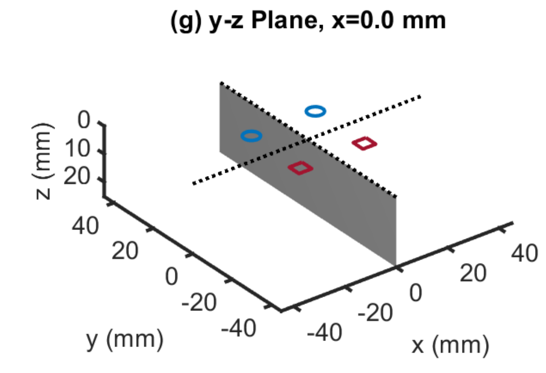
Hazelnut

Rhomboid arrangement

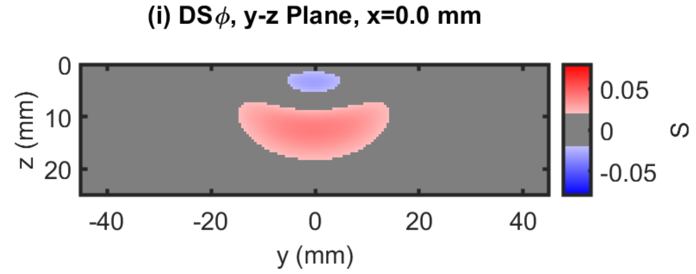


Square arrangement

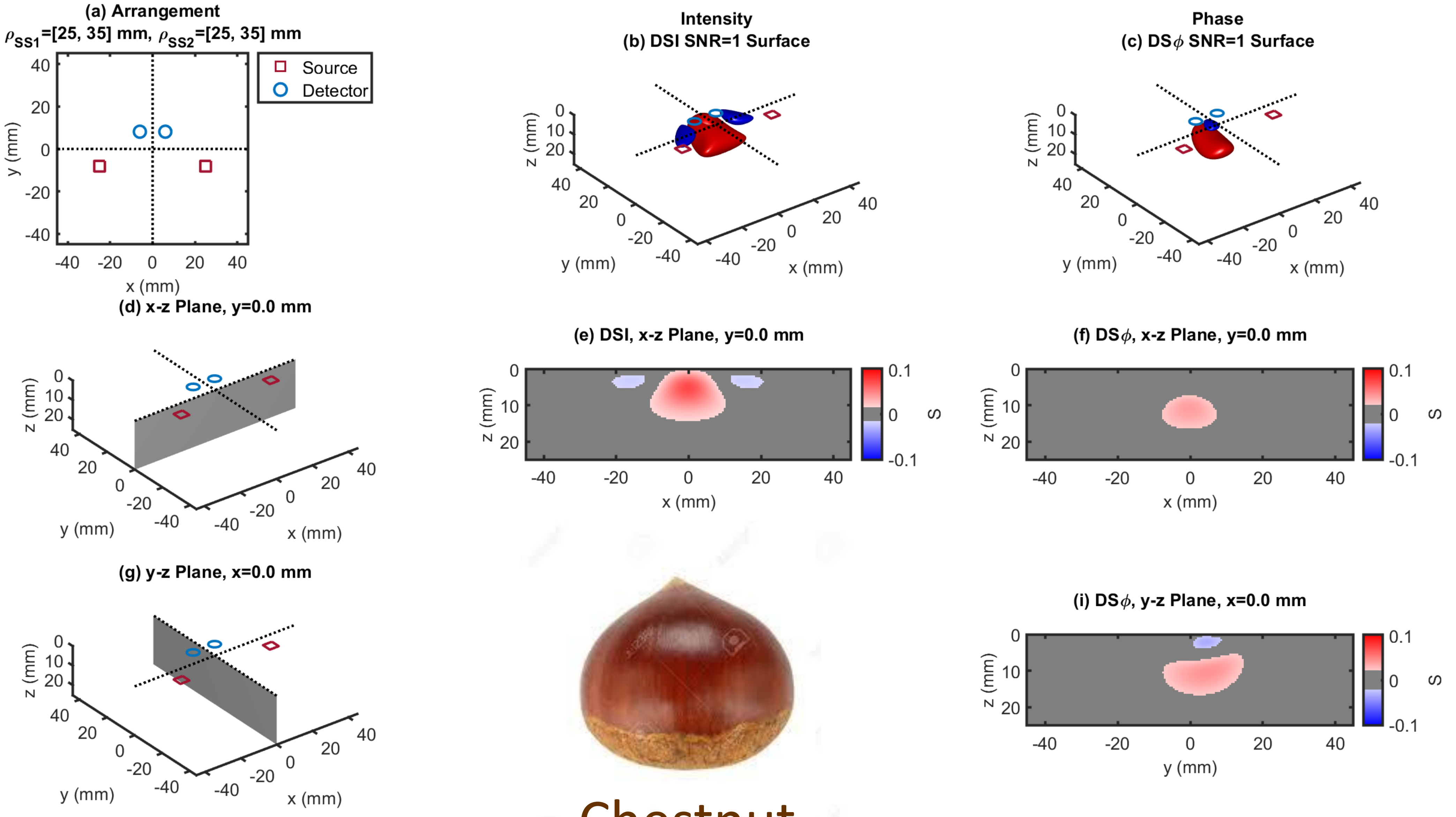




Cashew nut



Trapezoid arrangement



Chestnut

COMING SOON

Sergio Fantini, Giles Blaney, and Angelo Sassaroli

“Transformational change in the field of diffuse optics: From going bananas to going nuts”

J. Innovative Optical Health Sciences, SUBMITTED TODAY

Conclusions

- **Diagnostic applications of diffuse optical imaging:**
  - Breast cancer imaging
  - Functional brain imaging

- **For researchers in the field of diffuse optics it is preferable going nuts than going bananas**

MANY THANKS TO ALL "DOIT Lab" MEMBERS

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Diffuse Optical
Imaging of Tissue

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