Optical Neural Interface :Fast Optical Measurement of Neural Activity in Brain Tissue

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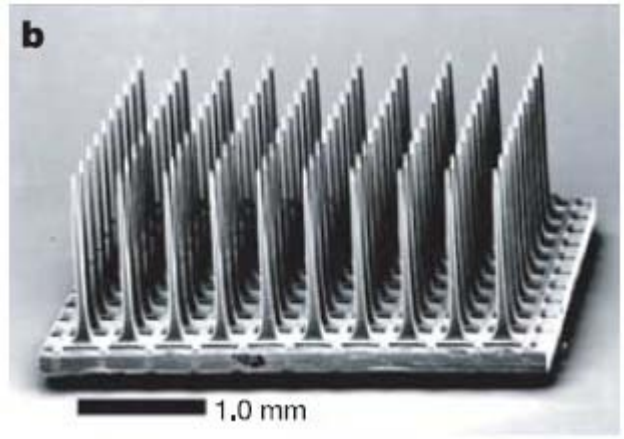
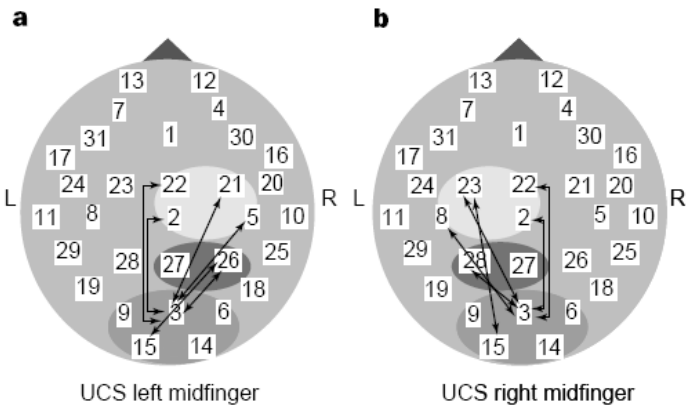
Seoul National University

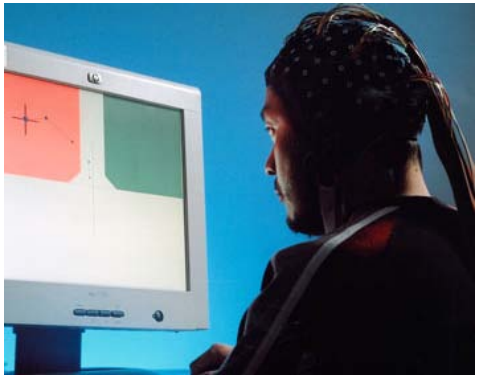
Electrode and EEG

- **Electrode-based brain-machine interface (BMI)** – **Invasive**



- **EEG-based BMI** – **Spatial resolution**

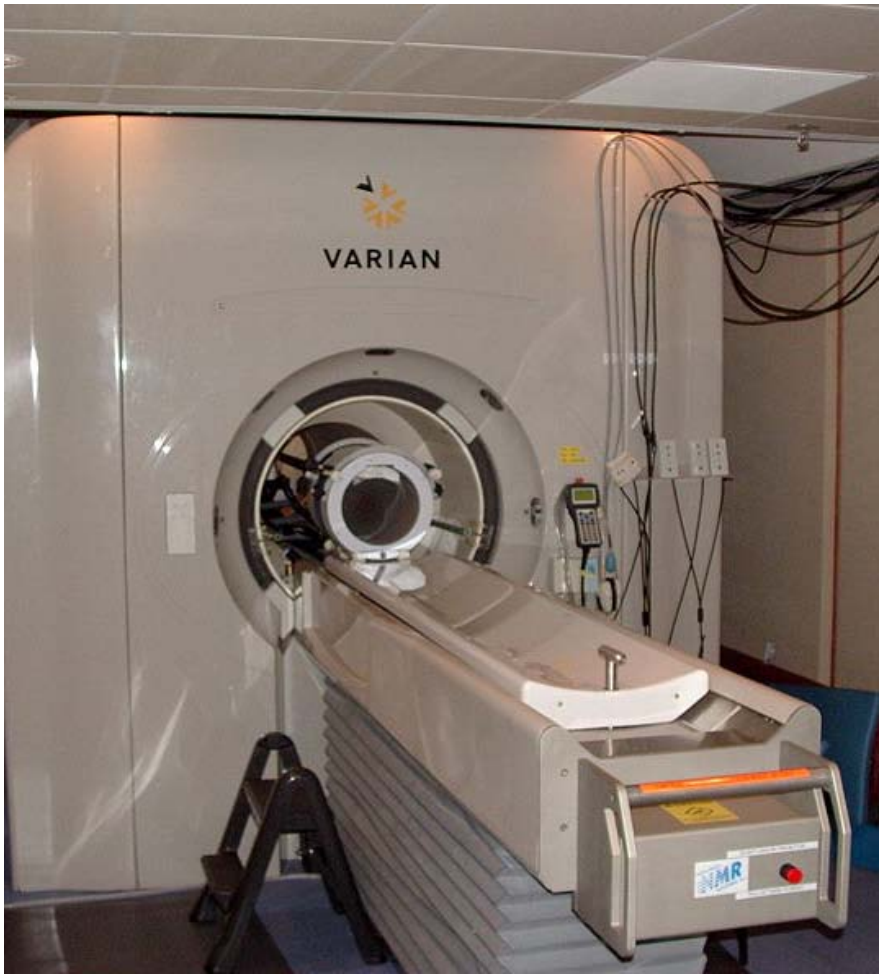


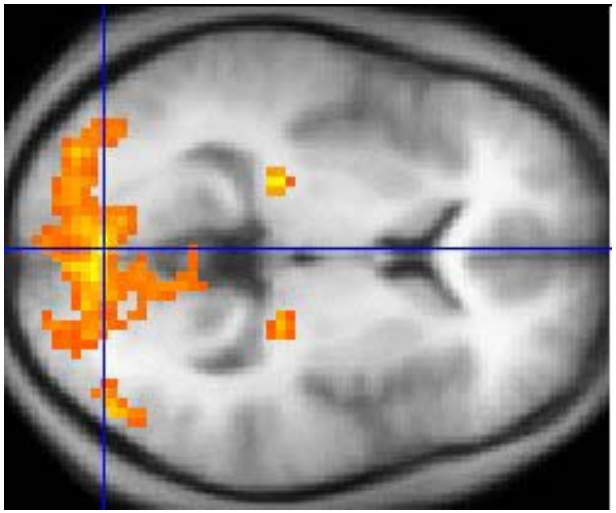


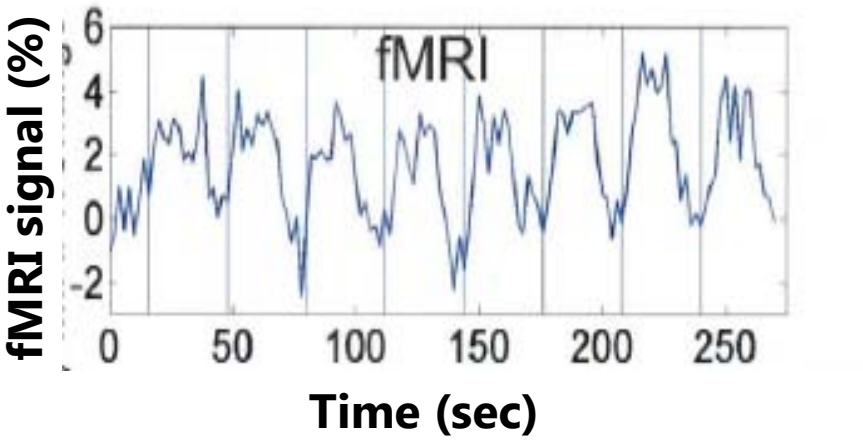
L. R. Hochberg et. al., *Nature* (2006)
H. R. Miltner et. al., *Nature* (1999)

Functional Magnetic Resonance Imaging (fMRI)

- **Neurovascular coupling** **– Time delay & huge device**





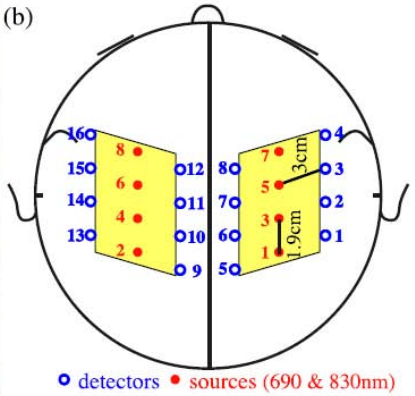


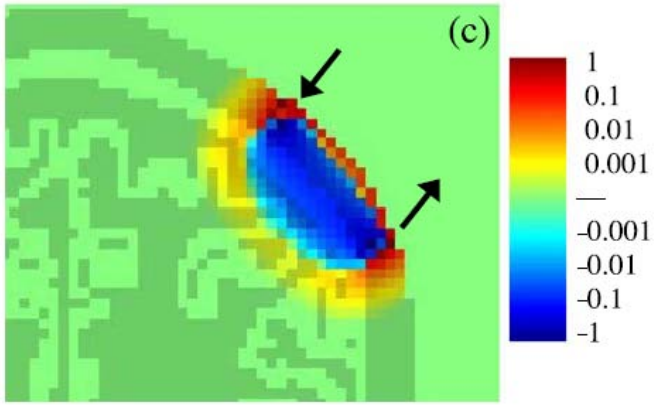
Varian 4T fMRI

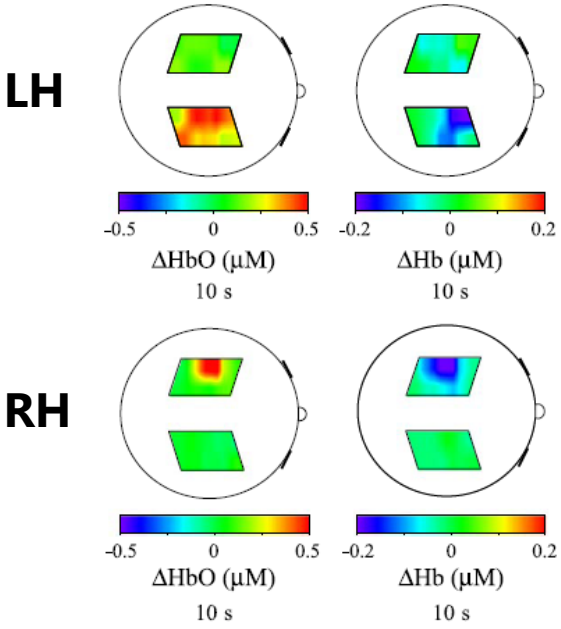
G. Strangman et. al., *Biol. Psychiat.* (2002)

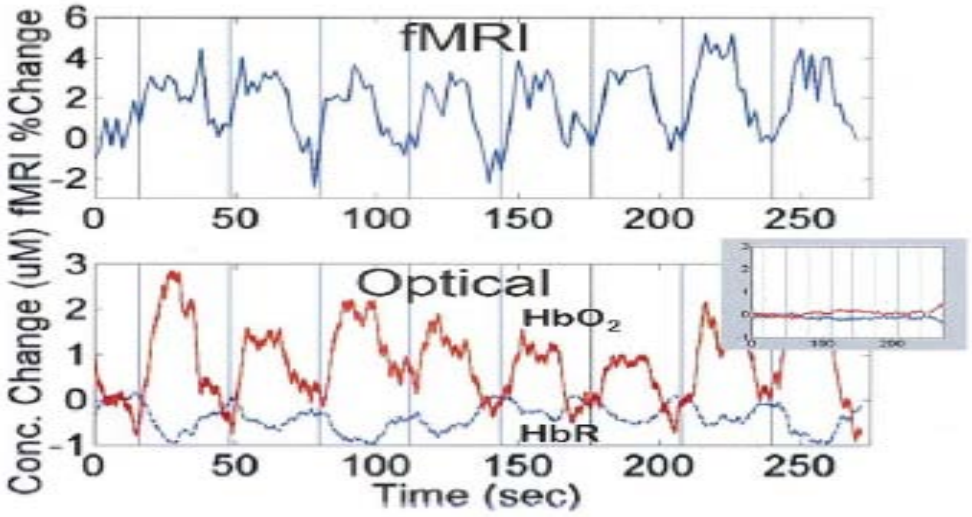
Diffuse Optical Tomography (DOT / fNIRS)

▶ Neurovascular coupling – Time delay



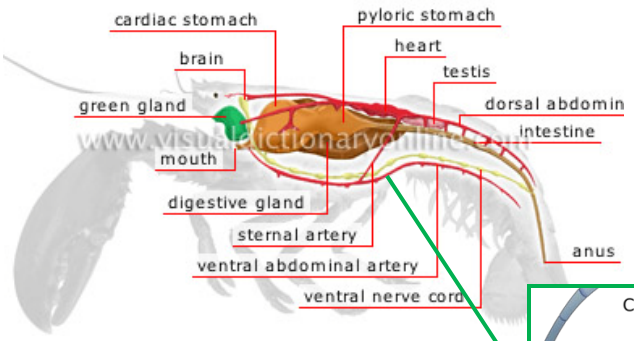


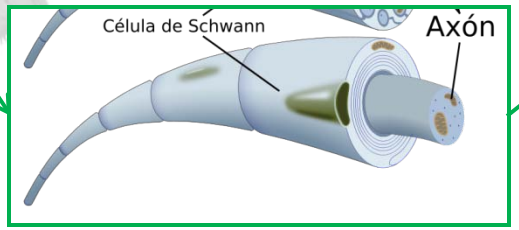


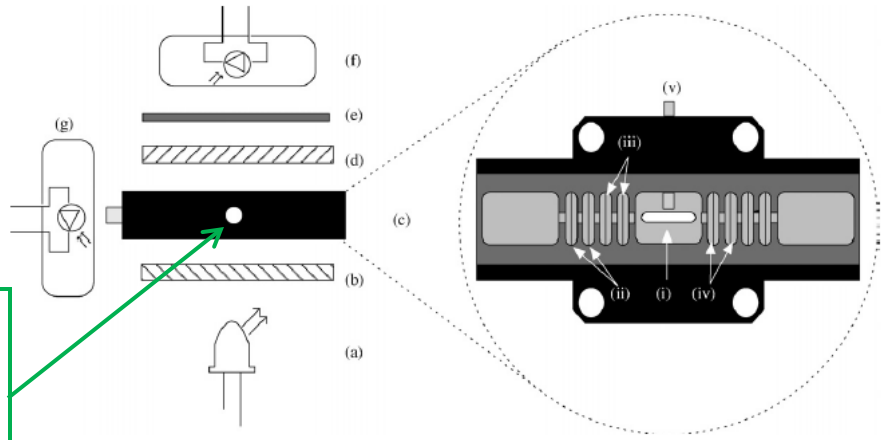


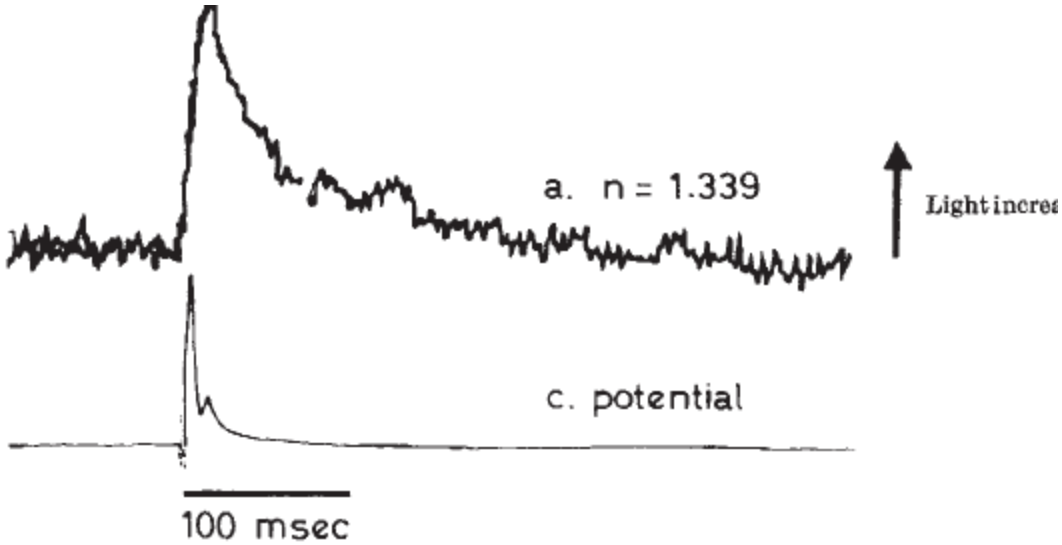
M. A. Franceschini et. al., *Neuroimage* (2004)
G. Strangman et. al., *Biol. Psychiat.* (2002)

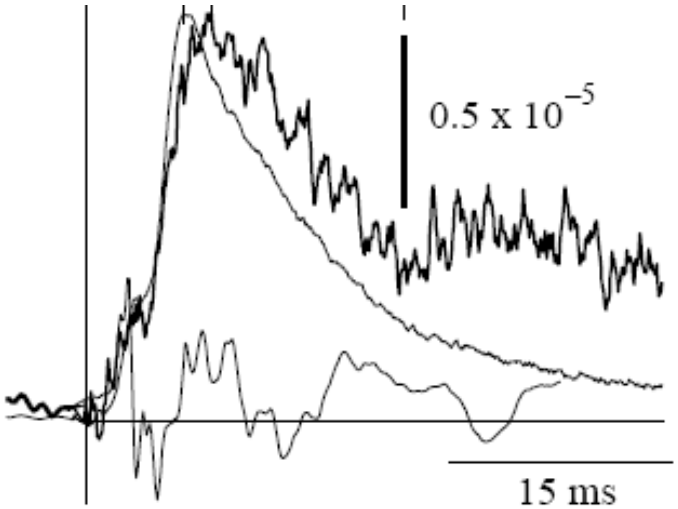
Optical Recording in Isolated Nerves





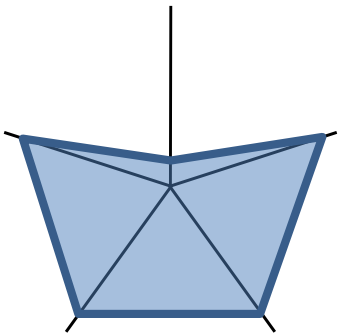




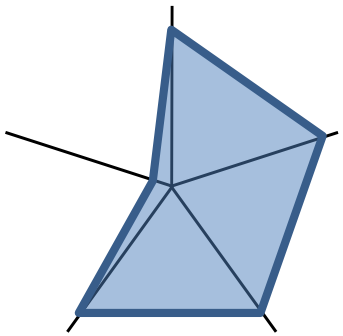


L. B. Cohen et. al., *Nature* (1968)
K. M. Carter et. al., *J. Neurosci. Meth.* (2004)
A. J. Founst et. al., *Neurosci.* (2007)

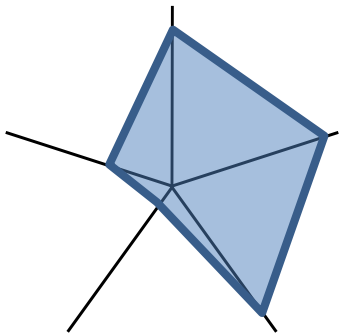
Functional Imaging Techniques



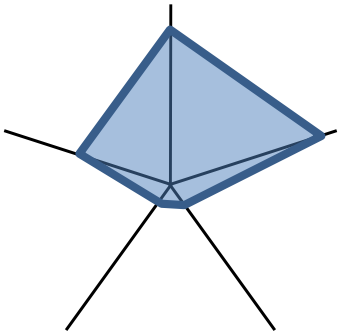
Electrode



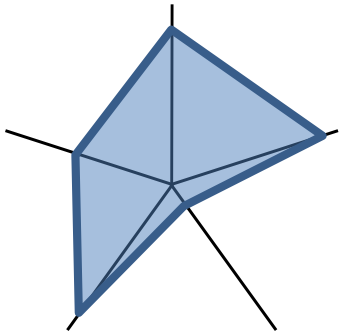
EEG



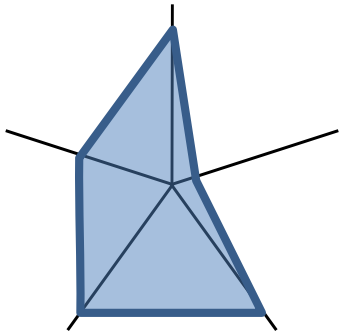
MEG



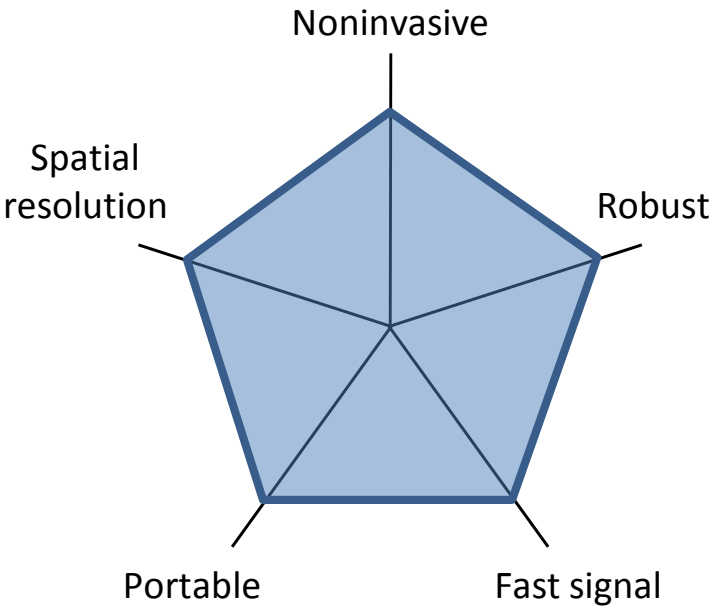
fMRI



fNIRS

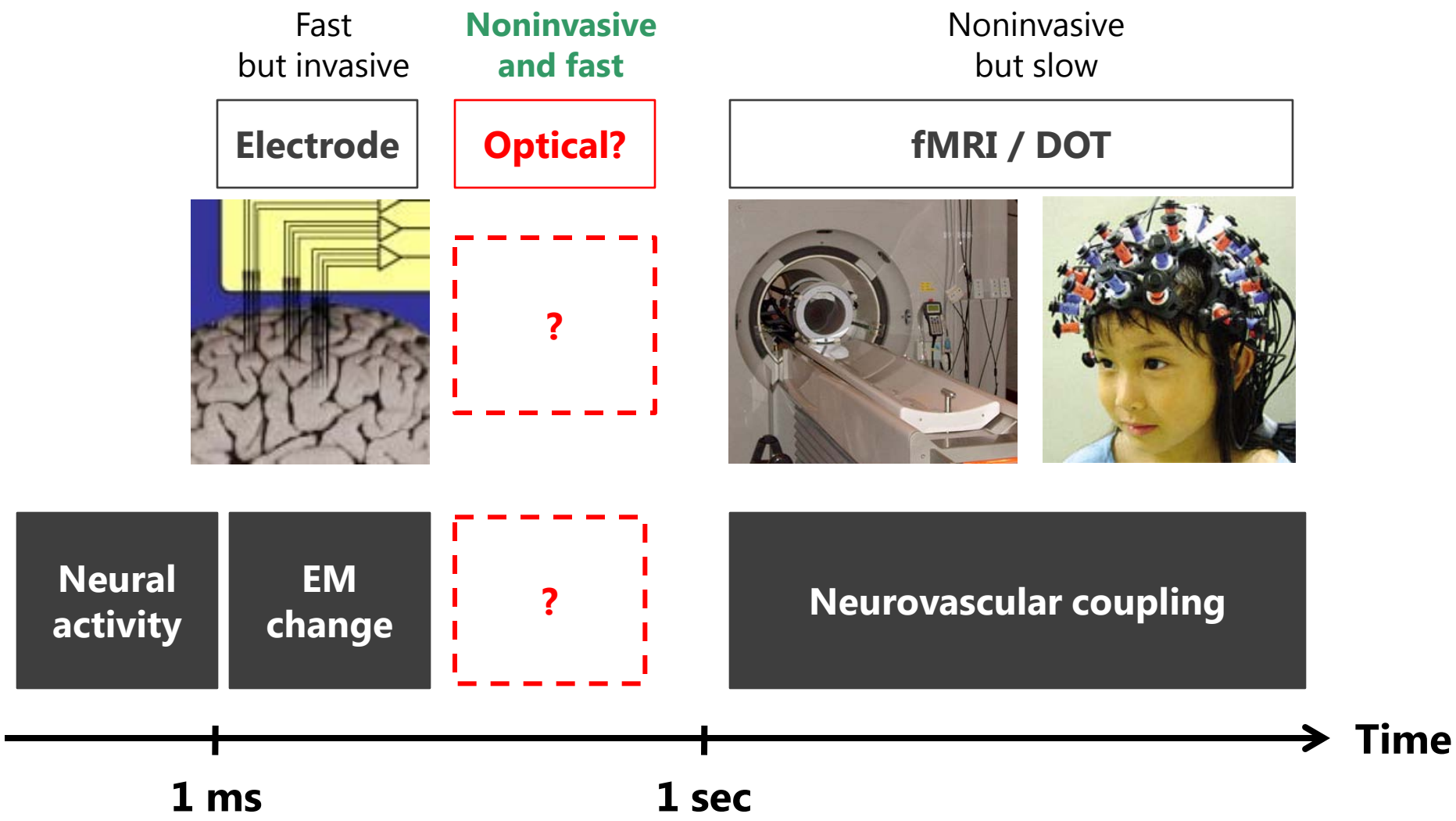


EROS



‘Dream’ technology

Niche

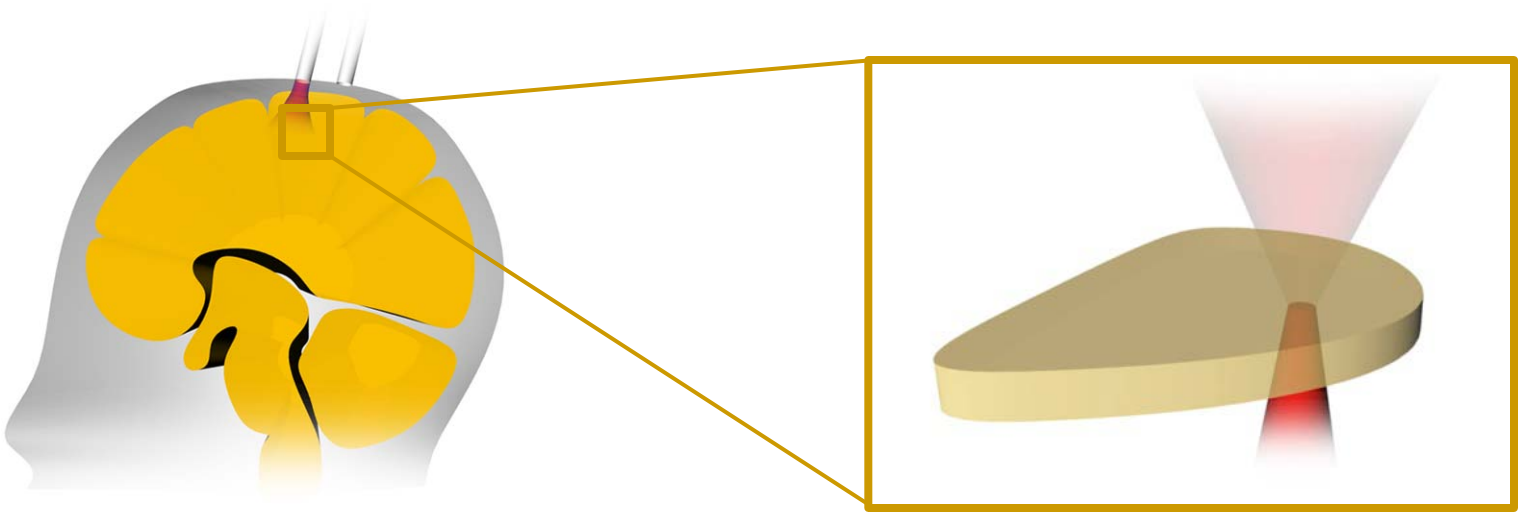

Fast
but invasive
Noninvasive
and fast
Noninvasive
but slow
Electrode
Optical?
fMRI / DOT
?
Neural
activity
EM
change
?
Neurovascular coupling
Time
1 ms
1 sec

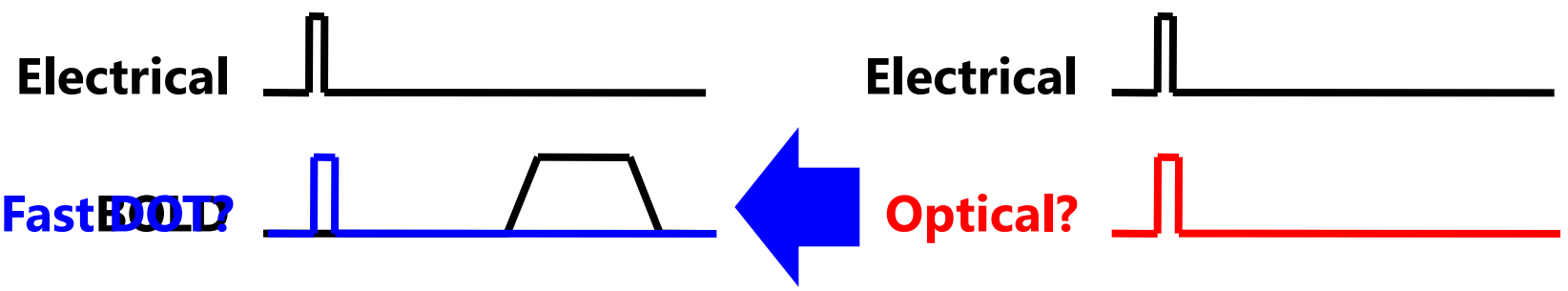
Ex Vivo Study First

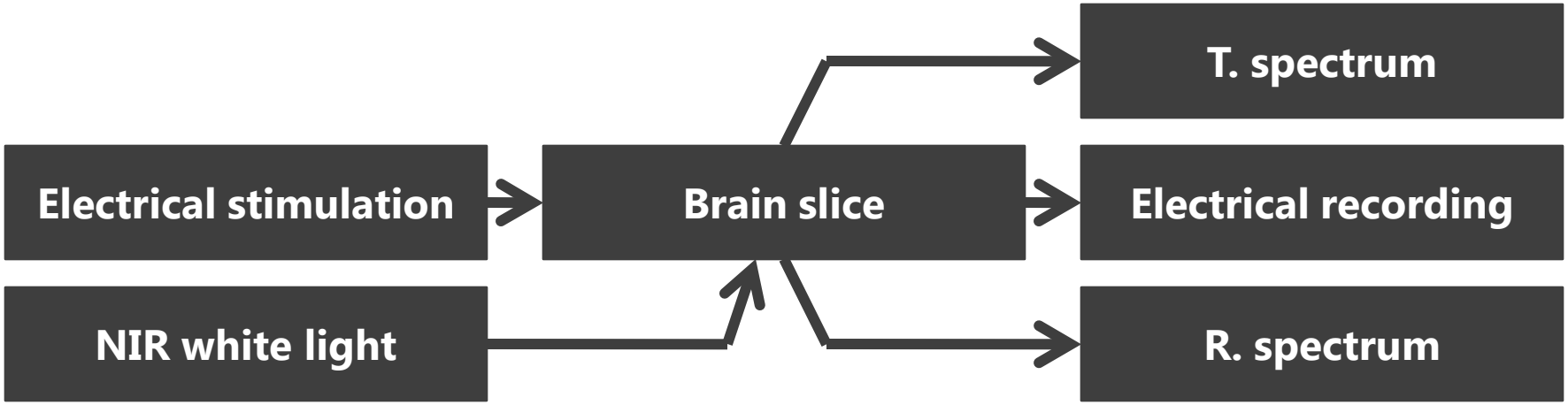
1. **Characterization of optical change of brain bulk tissue**

   Bulk tissue (~100 μm, ~10^2 neurons)

2. Application to noninvasive imaging







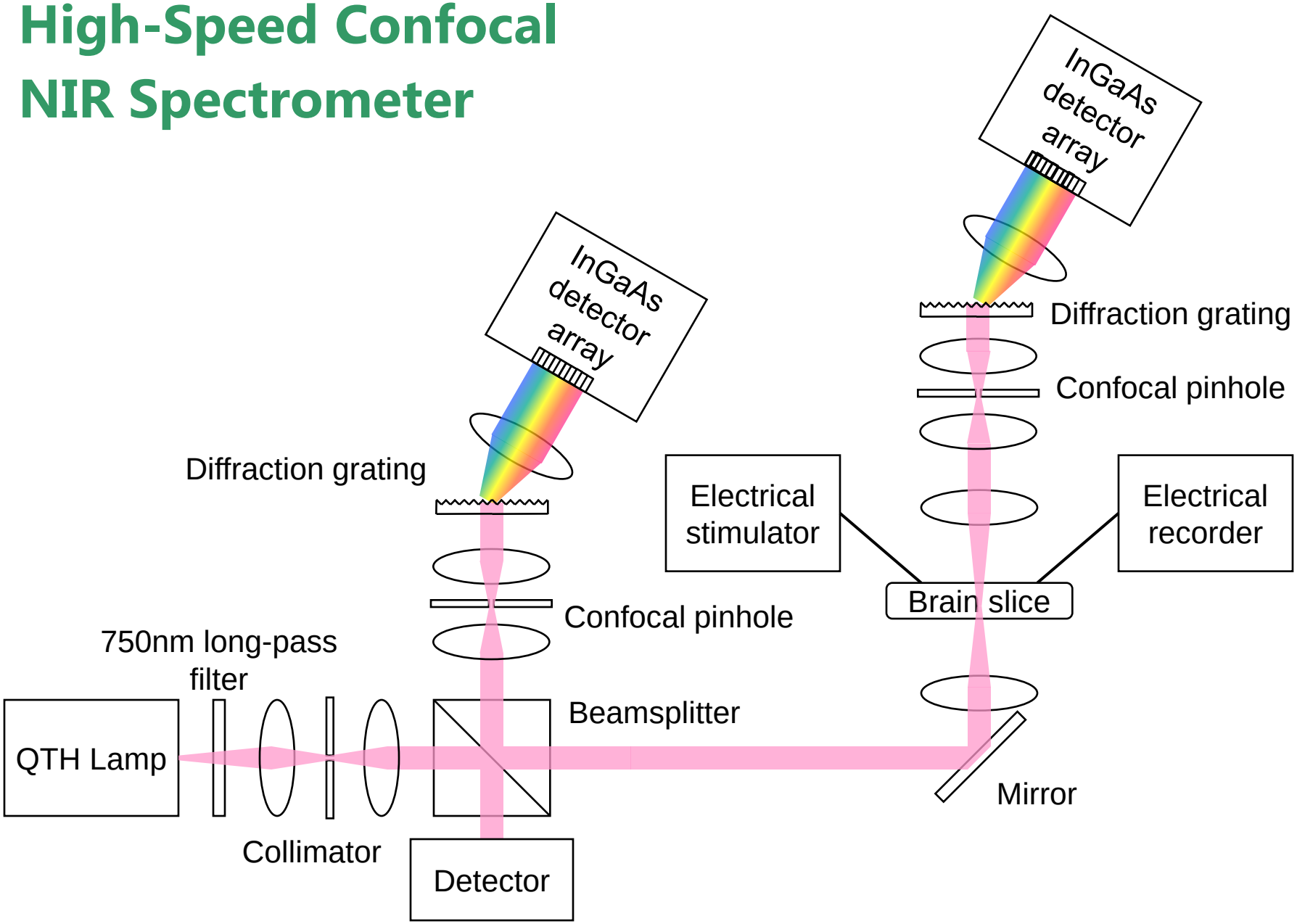
Physical quantity

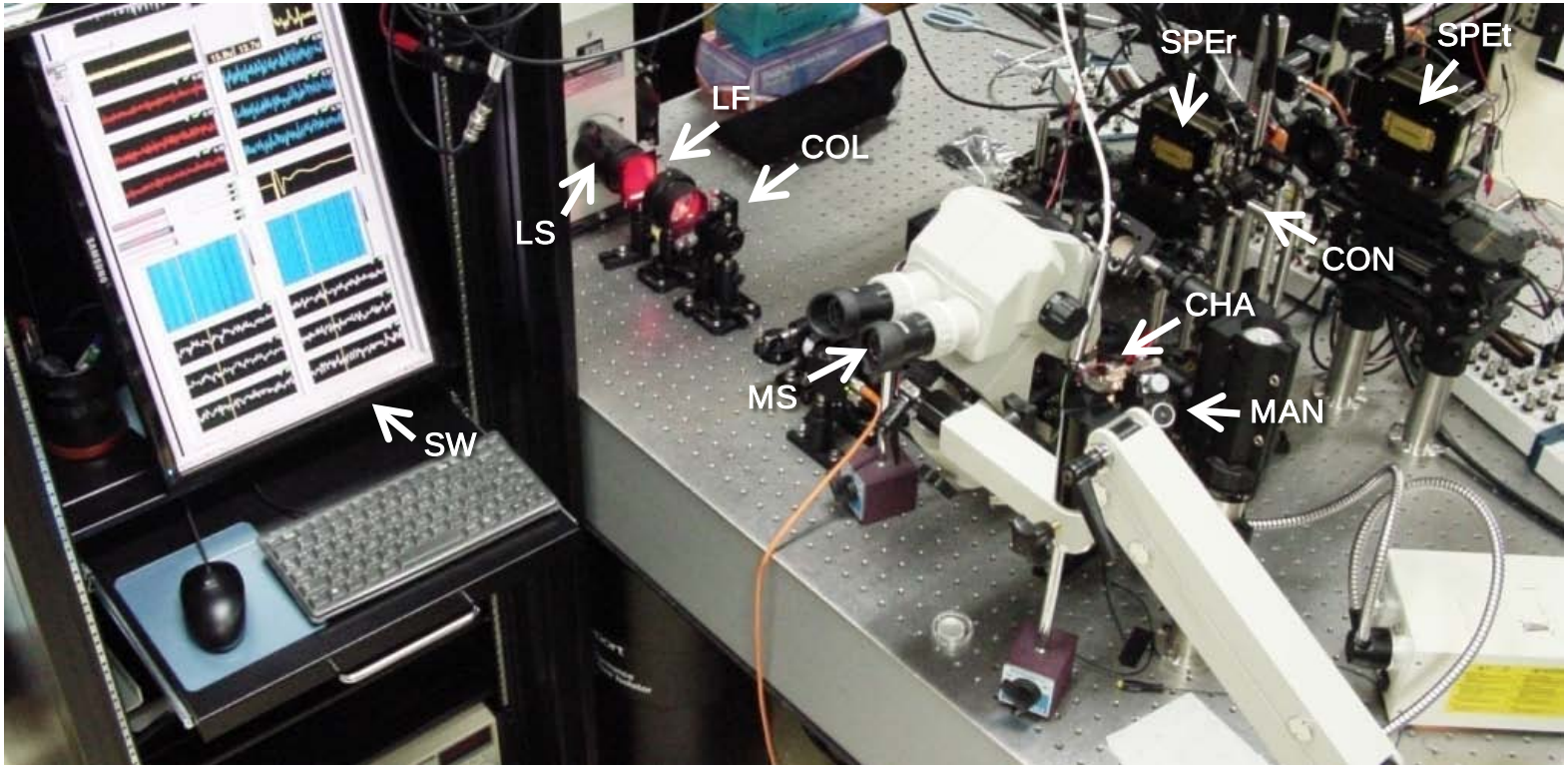
- **NIR (800-1300 nm)**
- **Spectrum**
- **Bulk tissue**

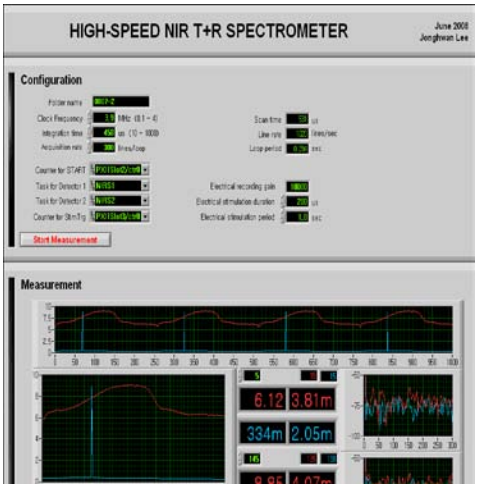
Requirements

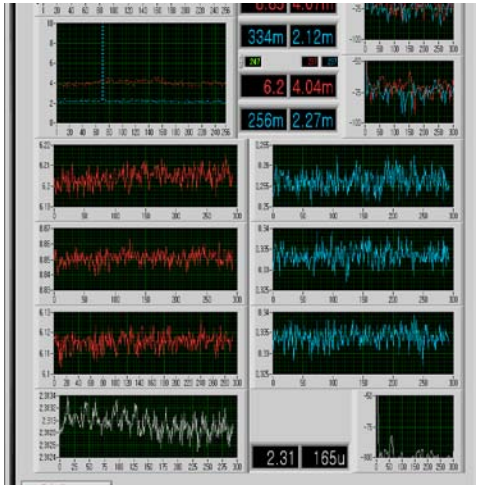
- **Fast** neural activity (~ms)
  - → High speed (>500 spectrum line/sec)
  - → **Array-based spectrometer**
- Detectable even in the **bulk** tissue
  - → Adjustable measurement area (~100 μm)
  - → **Confocal setup**

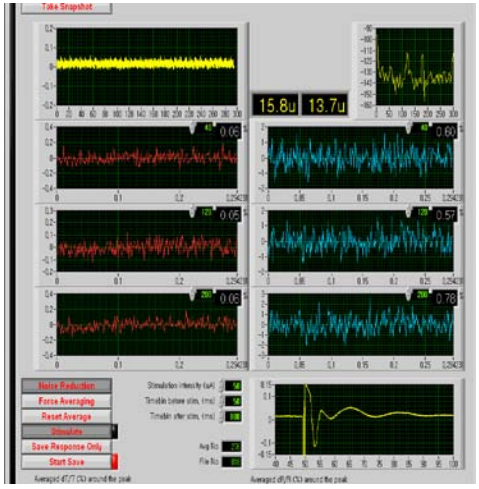
High-Speed Confocal NIR Spectrometer

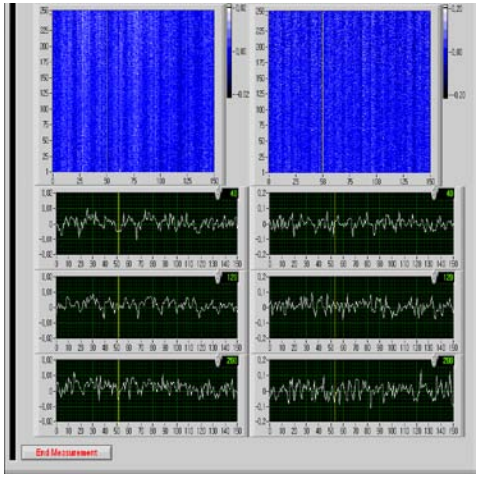



SPEr
SPEt
LF
COL
LS
CON
CHA
MS
MAN
SW

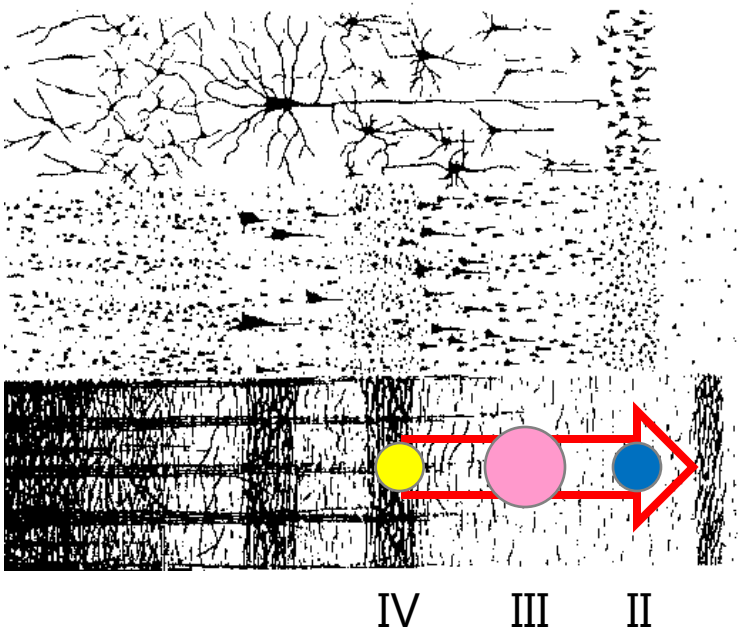

HIGH-SPEED NIR T+R SPECTROMETER
June 2008
Jonghwan Lee
Configuration
Start Measurement
Measurement
6.12
3.81m
334m
2.05m

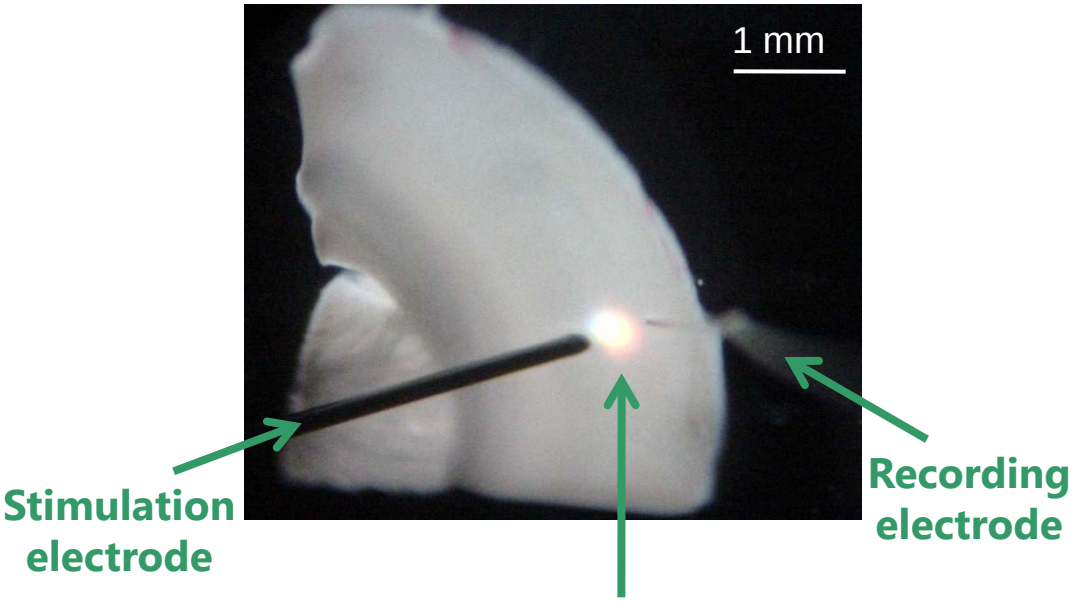

334m
2.12m
6.2
4.04m
256m
2.27m
2.31
165u


Take Snapshot
15.8u
13.7u
Noise Reduction
Force Averaging
Reset Average
Stimulate
Save Response Only
Start Save

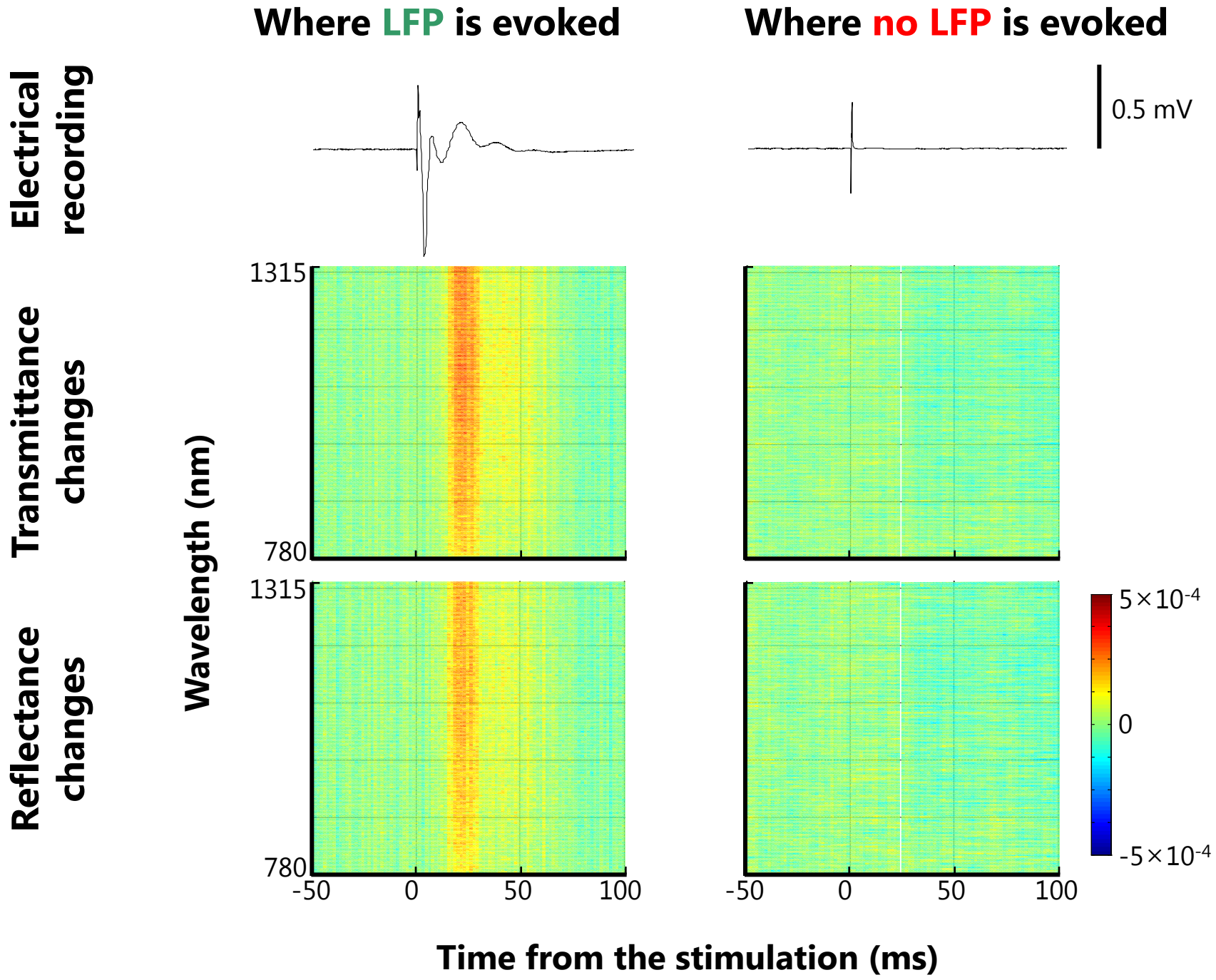

End Measurement

Rat Cortical Slices

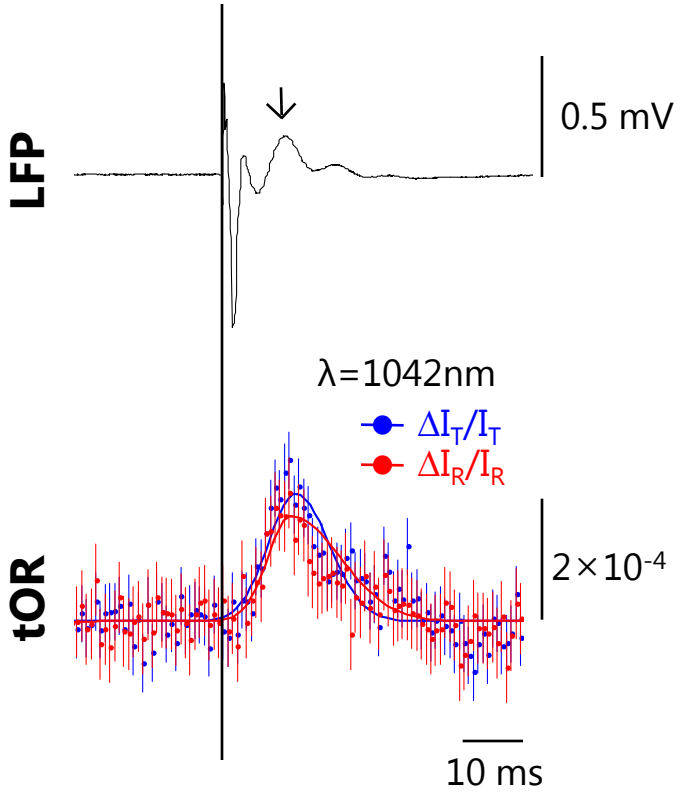


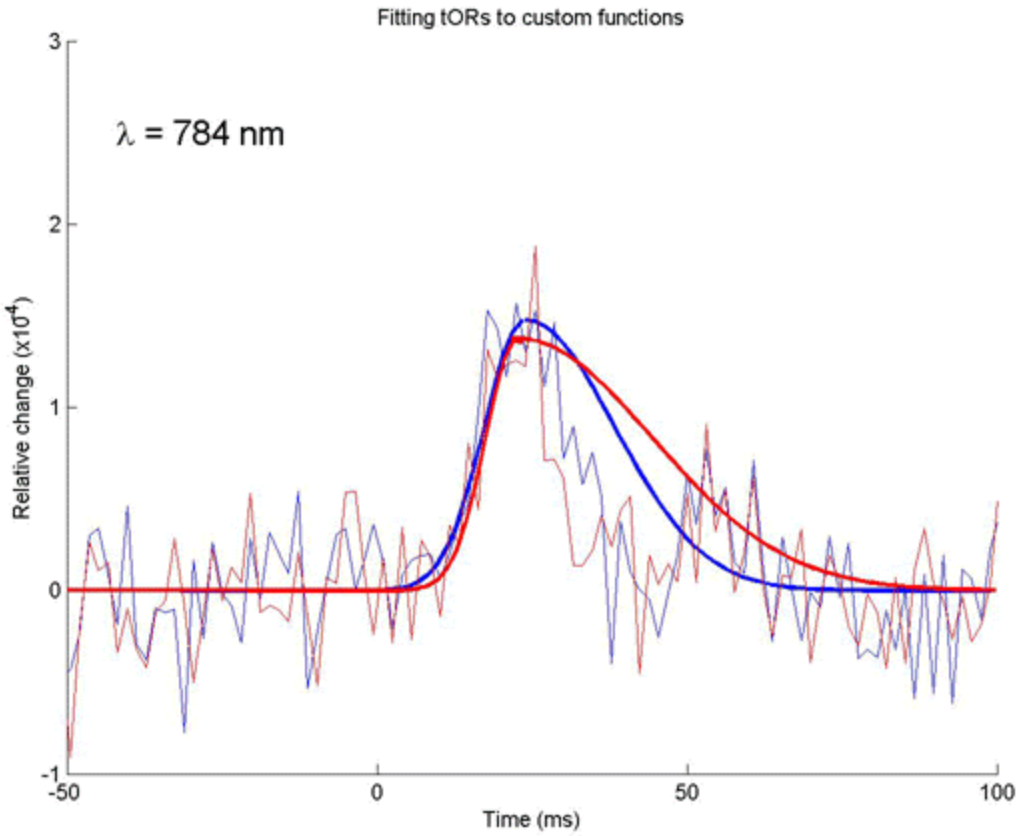


- Electrical stimulation
- Optical recording
- Electrical recording
- Neural activity propagation


Where LFP is evoked
Where no LFP is evoked
Electrical recording
0.5 mV
Transmittance changes
Reflectance changes
Wavelength (nm)
1315
780
1315
780
-50
0
50
100
-50
0
50
100
5×10-4
0
-5×10-4
Time from the stimulation (ms)

Transient Optical Response (tOR)





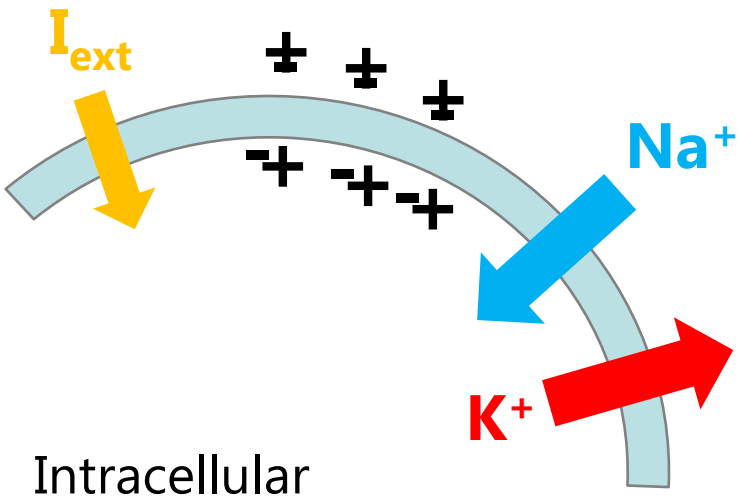
$$f(t)=\begin{cases} A\,e^{-(t-\tau_p)^2/\tau_r^{\,2}}, & t<\tau_p \\ A\,e^{-(t-\tau_p)^2/\tau_f^{\,2}}, & t\geq\tau_p \end{cases}$$

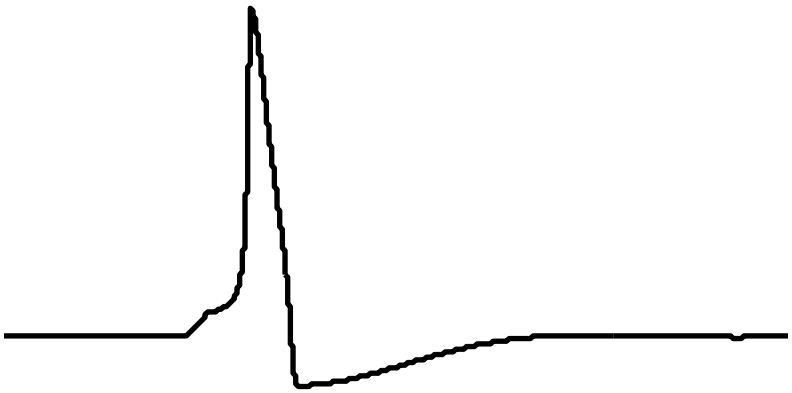
$\boldsymbol{A}$: amplitude $\quad \boldsymbol{\tau_r}$: rising time

$\boldsymbol{\tau_p}$: peak time $\quad \boldsymbol{\tau_f}$: falling time

J. C. Lagarias et. al., *SIAM J. Optimiz.* (1998)

What happens during neural activation





Resting state

External current stimulation

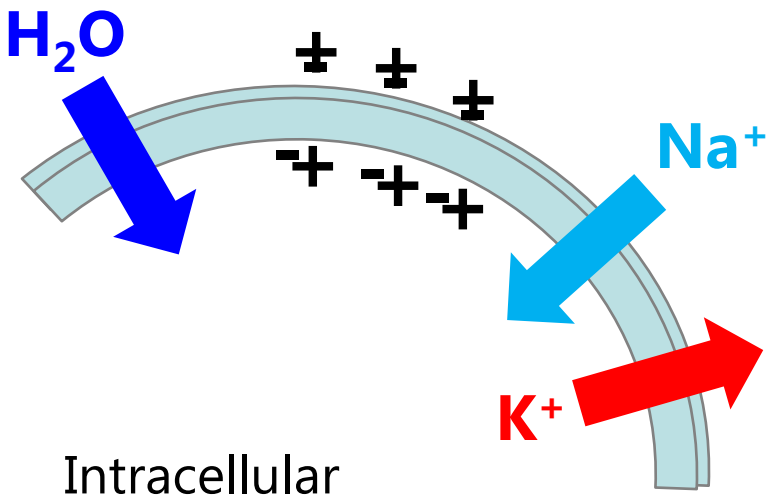
Na^+ channel open & Na^+ influx

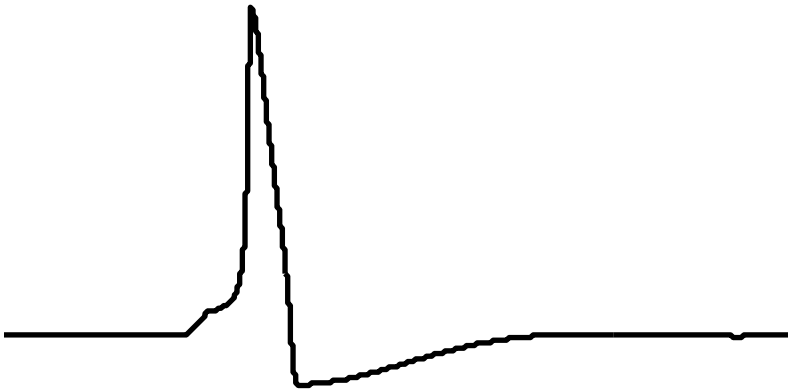
Membrane depolarization

K^+ channel open & K^+ efflux

Membrane hyperpolarization

Transient Cellular Volume Change (tCVC)



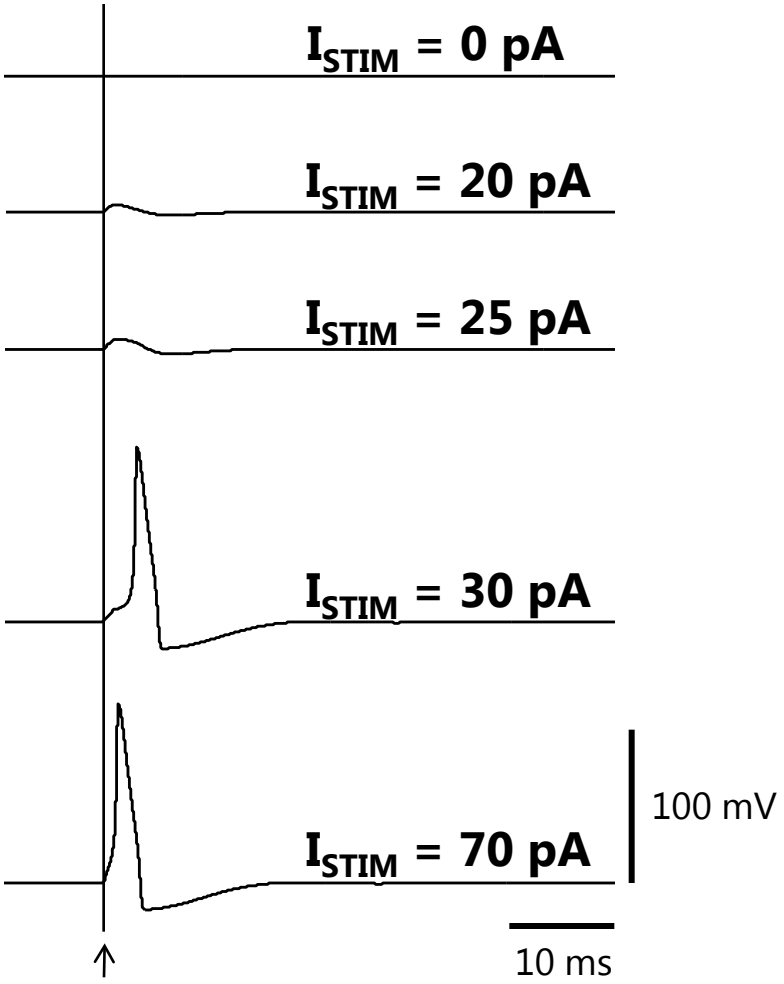


Different time course?

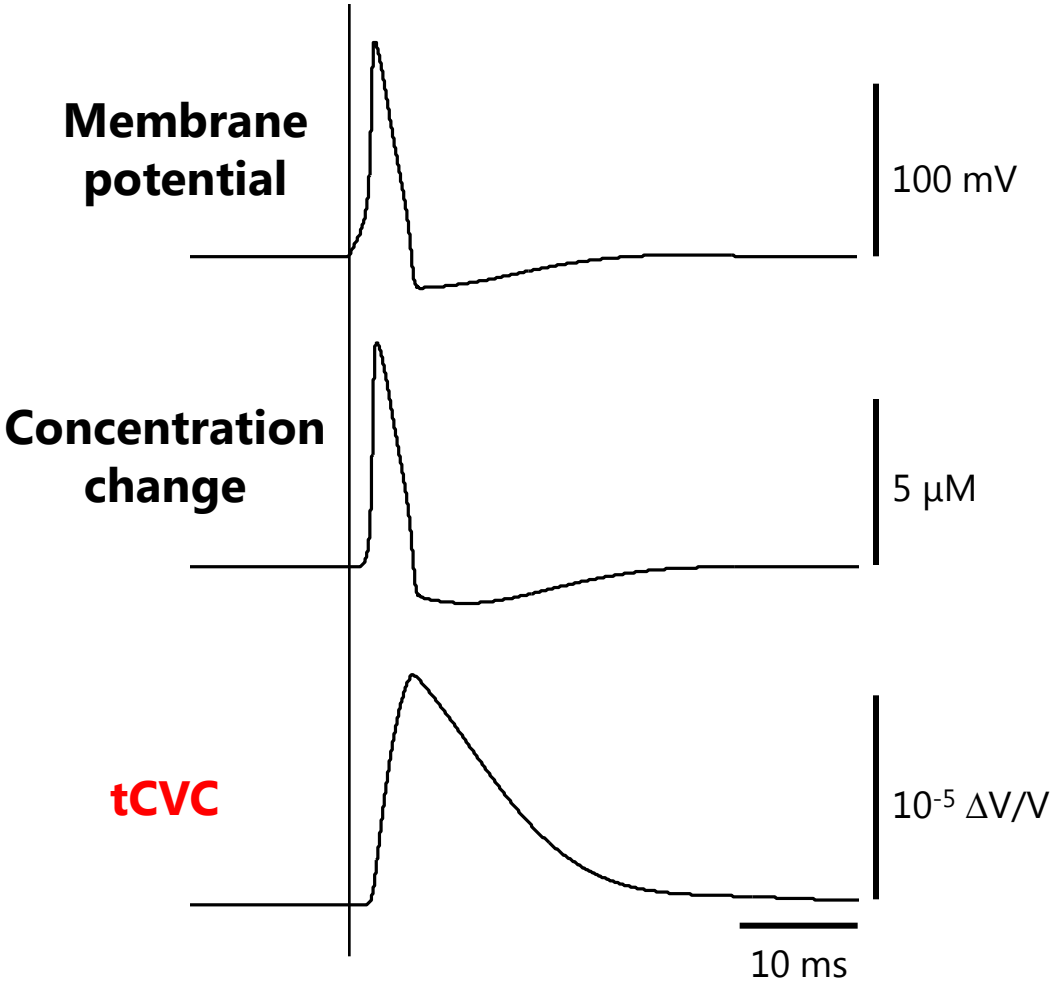
- Resting state
- Action potential
- Na^+ influx & K^+ efflux
- Change in $[Na^+ + K^+]_i$
- H_2O flux by diffusion
- Cellular volume change

Numerical Results

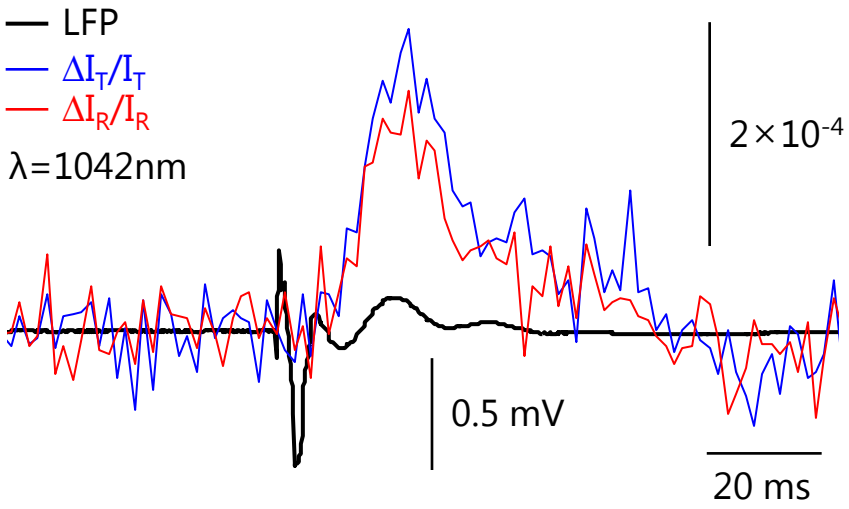
Action potential

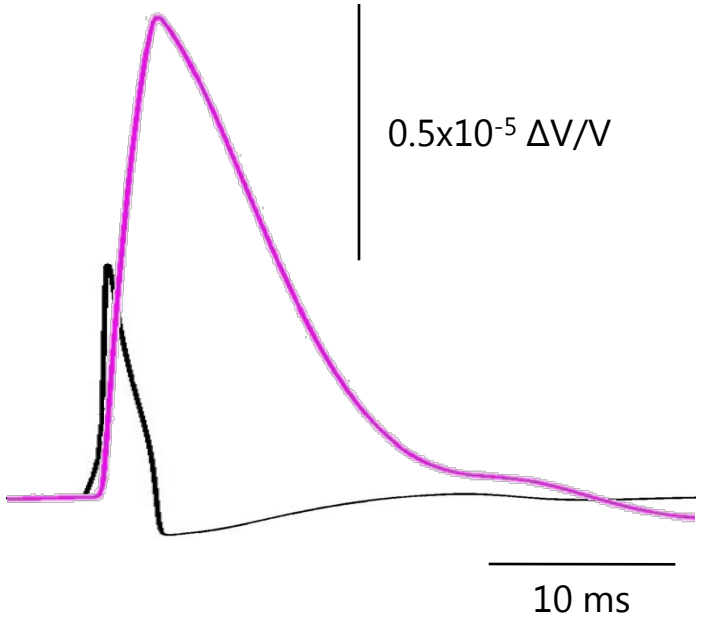


Other dynamics (I_{STIM} = 70 pA)



Comparison to the measured tOR





- Lee, 2009
- **Rat cortical slice**
- NIR transmission & reflection
- **~ 10^{-4}**

- Lee, 2009
- **Single spherical cell**
- Calculated cellular volume change
- **~ 10^{-5}**

Niche Revisited

Fast but invasive

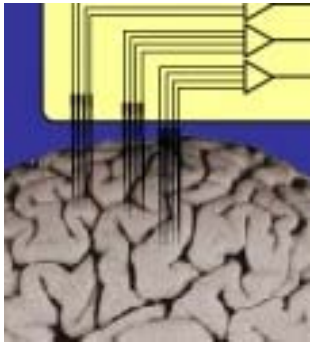
Noninvasive and fast

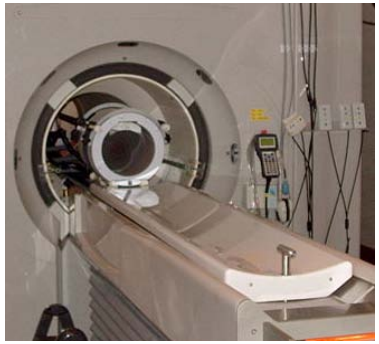
Noninvasive but slow

Electrode

tOR

fMRI / DOT





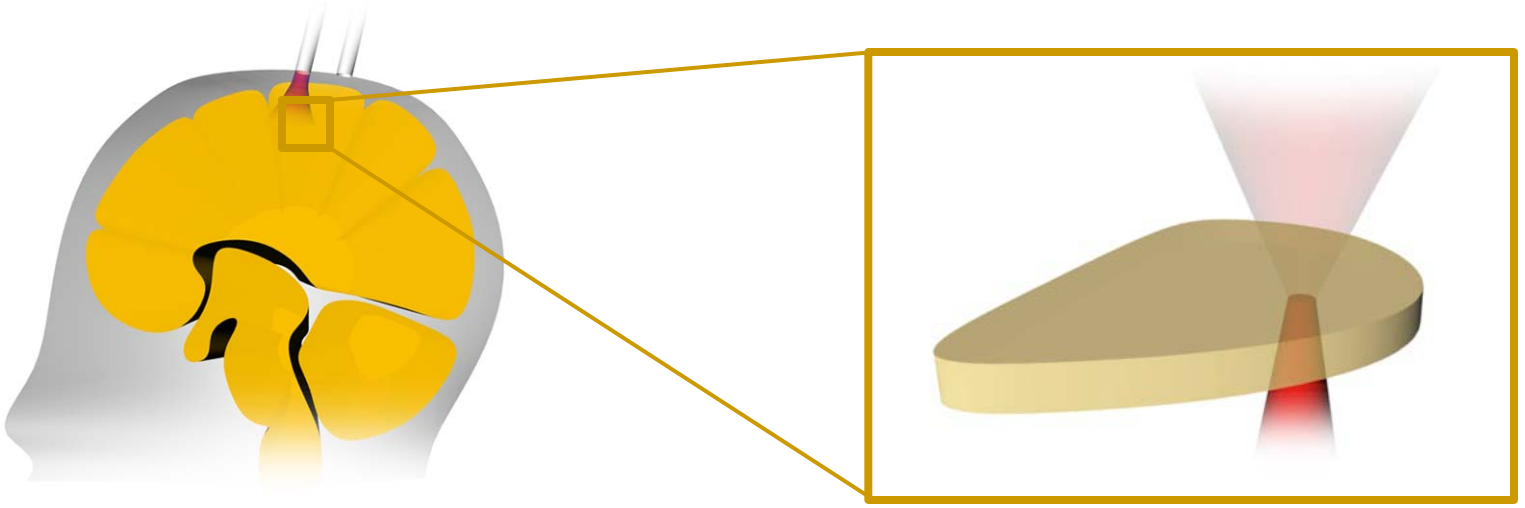
Neural activity | **EM change** | **tCVC** | **Neurovascular coupling**

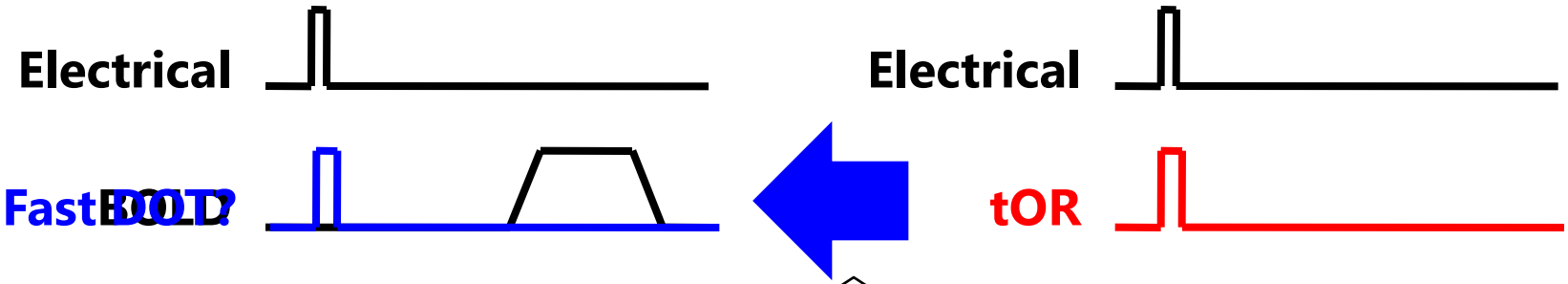
Time

1 ms

1 sec

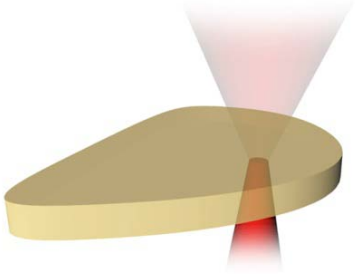
Future Direction



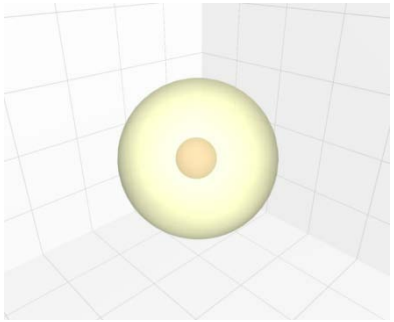


- Confocal probe on the head
- Time-resolved spectroscopy
- Weakly scattered light extraction
- Signal processing such as ICA

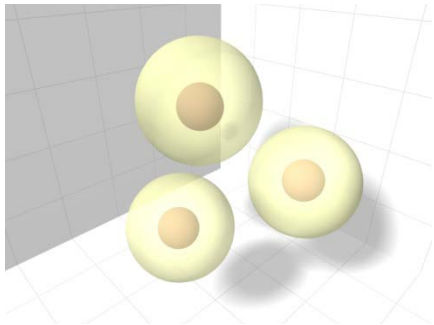
Brain tissue



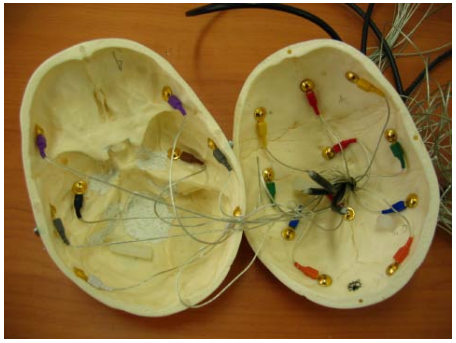
Theoretical study



Expansion

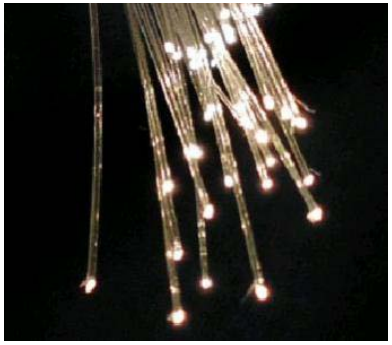


Phantom study

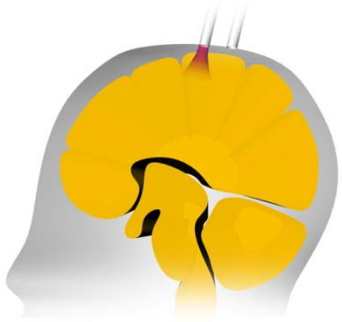


Animal brain

Optical neural probe*



Human brain*



* Patent pending