Functional MRI and BOLD effect

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Introduction

- A methodology for detecting **localized dynamic patterns of activity** in the working human brain.
- Introduced by Seiji Ogawa in **1990**.

![Figure 1: a fMRI Image](image1)

![Figure 2: Seiji Ogawa](image2)
Introduction

Figure 3

MRI vs. fMRI

MRI studies brain anatomy.

Functional MRI (fMRI) studies brain function.
Motivation

- We would want to measure functions: fMRI opens prospects for quantitative analysis!
- 3D- Imaging
- Non-Invasive and Requires no external tracers; instead Blood itself gives the contrast.
- Improved localization of the activated region.
- Flexibility
- Numerous Applications

Figure 4: A 3D Image
Foundation

- Localization of the metabolic activity that follows neural activity.
- Neural activity/signaling **requires generation of an action potential and release of Neurotransmitters.**
- Ionic equilibrium → action potential disturbs this equilibrium (downhill task) → free energy reduces → energy required to reset ionic equilibrium → provided by glucose metabolism.
- Relationship between neuronal activity and glucose metabolism.

Figure 5
We track this localized metabolic activity and correlate it with the stimulus. Hence try to infer functional properties of human brain.

The standard experiment for fMRI is the basic Nuclear Magnetic Resonance (NMR).

The effect that fMRI measures to identify the regions of activation results from combined biological processes and is called Blood Oxygen Level Dependent (BOLD) effect.
Terminology

CBF (F) : Cerebral Blood Flow (ml arterial blood per ml tissue per min)

OEF (E) : Oxygen Extraction Factor

CMRO$_2$ (R) : Cerebral Metabolic Rate of Oxygen consumed. (micromoles $O_2$ per ml tissue per min)

CBV : Cerebral Blood Volume
Physiological Basis for fMRI

- *Circulation follows the need of cerebral activity.*

- From past studies and experiments: blood flow and oxygen metabolism increases in activated areas.

- CBF increases much more than CMRO$_2$. The BOLD signal measured with fMRI results from this imbalance.
Physiological Basis for fMRI

- Exploits the basic fact:
  - Oxyhemoglobin - Diamagnetic
  - Deoxyhemoglobin - Paramagnetic

- The MR signal is affected by deoxyhemoglobin (dHb) levels (field distortions) and therefore changes with blood oxygenation BOLD effect.

\[ J(O_2) = E \cdot F \cdot [O_2] \]  \hspace{1cm} (1)

- \( J(O_2) \) - CMRO_2
- E - Oxygen Extraction Factor
- F - Cerebral Blood Flow
- \([O_2]\) - conc. of \(O_2\) in arterial blood
Physiological Basis for fMRI

Figure 2.1 BOLD mechanism of functional MRI

(A) Blood-oxygen level-dependent signal mechanism in magnetic timbre imaging (B) oxyhaemoglobin and deoxyhaemoglobin blood flow during rest and activation

Figure 7
The fMRI Experiment

Basic NMR experiment

- Equilibrium Magnetization - $M_0$; Precess time - $T_1$
- Rf-Pulse $\rightarrow$ Tips $M_0$ away
- Precession of Transverse Magnetisation - $M_T$
- Relaxation $\rightarrow$ FID with a time constant $T_2$
- Field inhomogeneities $\Rightarrow$ FID faster
- $T_2^* < T_2$ $\Rightarrow$ MR signal changes since the strength depends on $M_T$
Biophysical basis of fMRI

- **Susceptibility** of blood varies linearly with blood oxygenation (dHb)
- Field inhomogeneities are produced due to differences in susceptibilities.
- Spins undergo dephasing $\Rightarrow$ faster decay
- $T_2^*$ is shortened $\Rightarrow$ MR signal reduces

*Figure 9: Field Distortions*  
*Figure 10: Free Induction Decay*
Biophysical Basis of fMRI

- Brain activation $\rightarrow$ CBF $\uparrow\uparrow$, $CMRO_2$ $\uparrow$ $\rightarrow$ OEF decreases
  $\Rightarrow$ deoxyhemoglobin (veins and capillaries) decreases $\Rightarrow$
  susceptibility of blood moves closer to susceptibility of tissue
  $\Rightarrow$ less field distortions $\rightarrow$ longer $T_2^*$ $\Rightarrow$ MR signal increases

- Attenuation factor is given by:
  \[
  A(t) = e^{-t\delta(R_2^*)}
  \]
  $\delta(R_2^*)$ is change in $R_2^*$ (Rate of decay) due to susceptibility difference
  between the Blood and surrounding tissue.
Relative measurements → Mapping experiment → Block Design → alternate periods of stimulus and control repeated several times.

Dynamic echo planar images are collected covering full brain.

Each pixel is analyzed to identify areas of activation.

The activated pixels are then color coded and overlayed on a gray scale image of background anatomy.

An important characteristic: BOLD effect lags behind the stimulus. ⇒ the Hemodynamic response model is a delayed trapezoid.
Mapping Brain activation with BOLD Signal Changes

Figure 11
BOLD Hemodynamic Response

- The Response of our system to a stimulus.

![Graph showing BOLD hemodynamic response](image)

Figure 12

Special Features
- **Initial dip** (1-3 s)
- **A ramp** (5-8 s)
- **Post-stimulus undershoot**
Initial Dip: initial increase in deoxyhemoglobin.

→ Suggest that it is the result of rapid increase in $\text{CMRO}_2$ before the flow has begun to increase.

Depends on stimulus and Magnetic field characteristics.

Controversy – not seen always ⇒ could be an artifact.

Ramp: Delay in response of vascular system to the neural activity.

Undershoot: either $\text{CMRO}_2$ or CBV remain elevated post-stimulus.

Experiments ⇒ $\text{CMRO}_2$ closely follows CBF.

⇒ CBV mismatched in recovery.
Future Prospects and Applications

- Quantitative analysis of Brain functions – important to fully understand the physiological effects associated with brain functioning.
- Clinical applications
- Brain decoding ("mind reading")
Are CBF and $CMRO_2$ coupled during activation? How?
Is relation between CBF and CBV uniform?
Transients in the dynamic BOLD response reflect transients of neural activity or temporal mismatch of variables?
References

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Thank You!