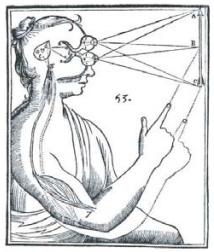
UCLA NITP

July 2011

Relating Neurophysiology and Imaging Signals

Richard B. Buxton
University of California, San Diego

Signals Reflecting Brain Activity



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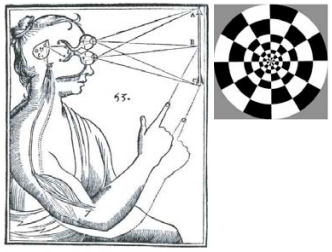

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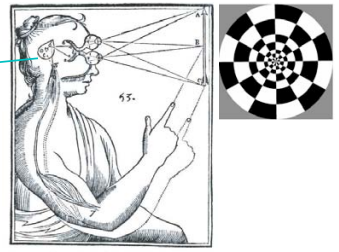
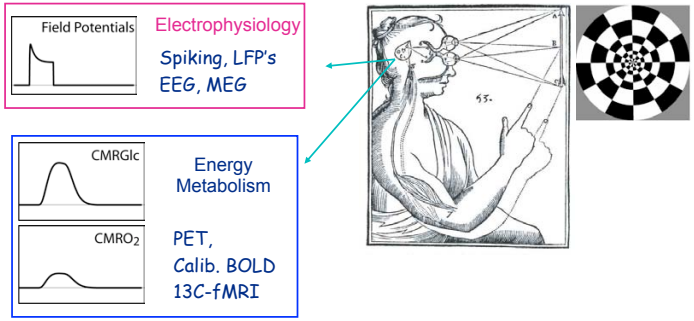


Signals Reflecting Brain Activity



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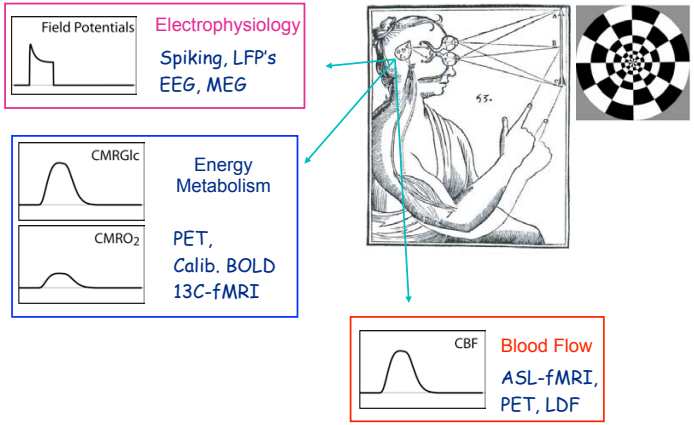

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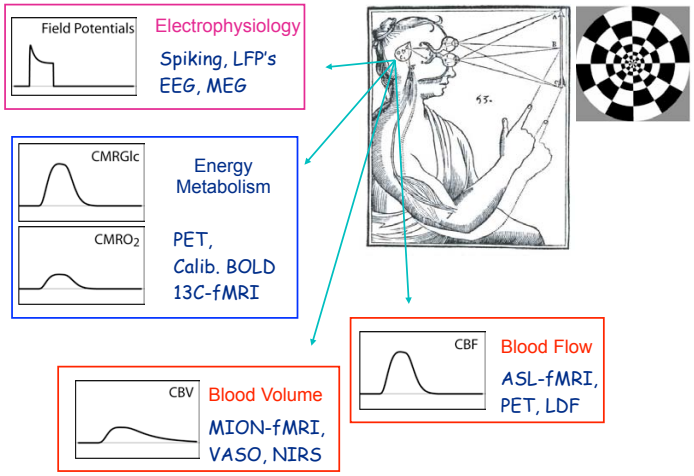
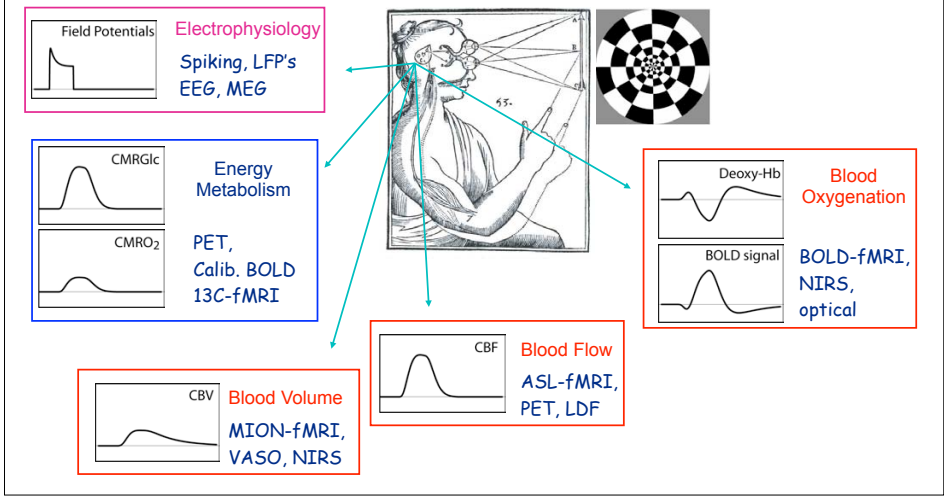
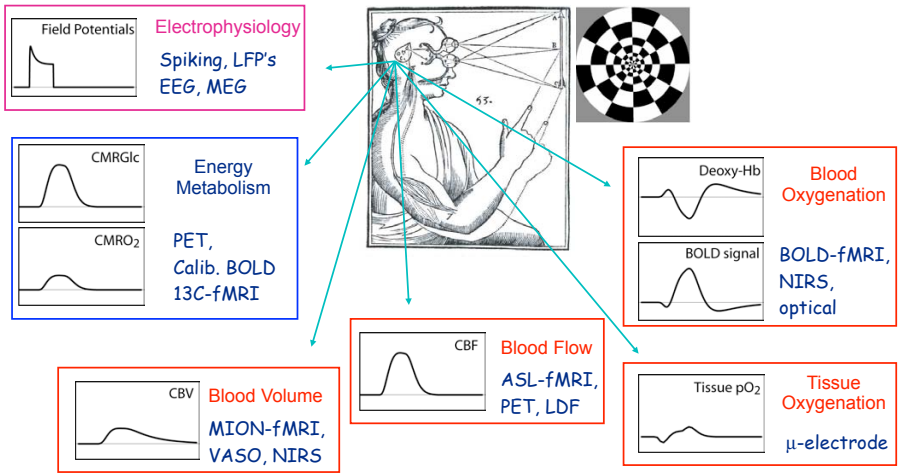


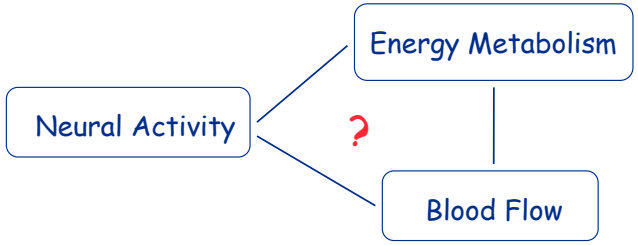
Signals Reflecting Brain Activity



Signals Reflecting Brain Activity



How does it all fit together?



"The view that the hemodynamic response is coupled to signaling processes represents a conceptual shift from the traditional idea that the energy demands of the tissue directly determine the flow increase associated with neural activation."
Attwell and Iadecola (2002)

"Future issues to be resolved: 1) What function(s) does regional brain-blood flow perform when neuronal activity changes?"
Raichle and Mintun (2006)

Outline

Energy metabolism

Neural activity

Cerebral blood flow

Current ideas

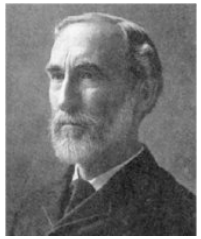
Energy Metabolism

Gibbs Free Energy Change

Gibbs free energy (ΔG) encompasses both energy and entropy changes: in any transformation the net ΔG must be negative.

Any system far from equilibrium will have a negative ΔG if it moves toward equilibrium.

A process that increases ΔG in one system can occur if it is coupled to another system with a larger decrease in ΔG.



J. Willard Gibbs

The brain needs sources of free energy to drive uphill reactions and for signaling.

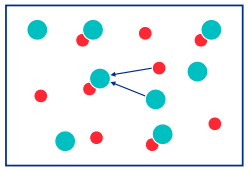
Sources of ΔG

Systems far from equilibrium

Chemical imbalance:

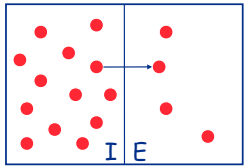
$A + B \rightarrow C$

$$\Delta G \sim -\ln \frac{[A][B]}{[C]}$$



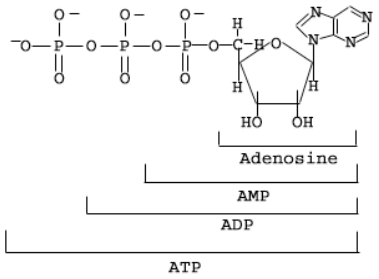
Gradients across a membrane:

$$\Delta G \sim -\ln \frac{[C_I]}{[C_E]}$$



For ions, ΔG depends on potential as well as concentration gradient

Adenosine Triphosphate (ATP)



ATP <<-->> ADP + Pi

At equilibrium,

$$\frac{[ATP]}{[ADP]} << 1$$

But in the brain

$$\frac{[ATP]}{[ADP]} \approx 10$$

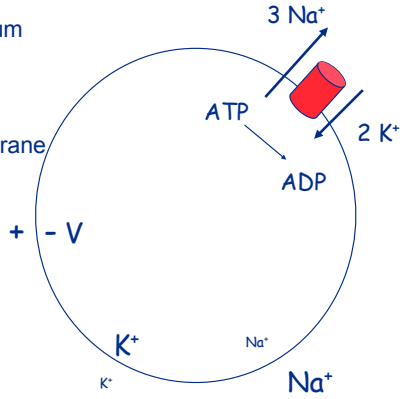
ΔG depends on the phosphorylation potential: $\ln \frac{[ATP]}{[ADP][P_i]}$

Ion Distributions and the Sodium/Potassium Pump

Ion distributions (intra- vs extra-cellular):
Sodium (Na^+) is far from equilibrium
Potassium (K^+) is closer to equilibrium

Sodium pump: The Na/K ATPase couples conversion of ATP → ADP to moving Na^+ and K^+ across the membrane

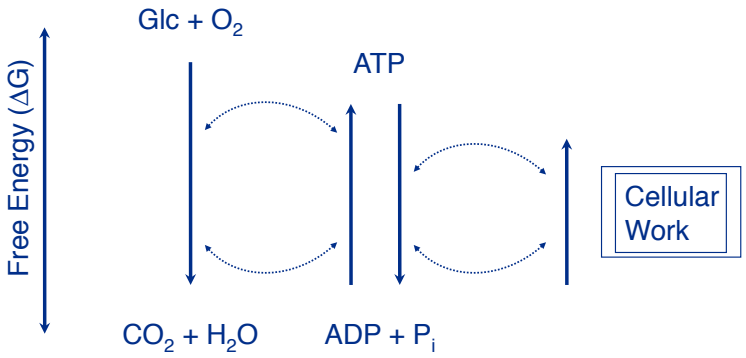
$$\Delta G = \Delta G_{ATP} + \Delta G_{Na} + \Delta G_{K}$$



ΔG:

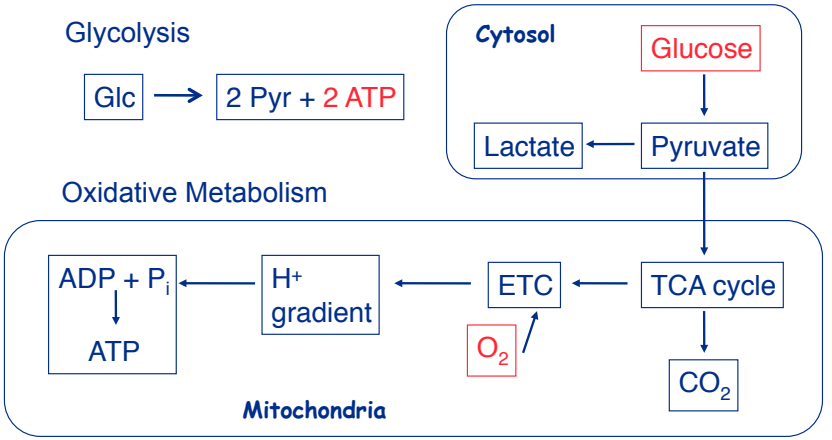
ATP → ADP	strongly negative
$Na^+(I) \rightarrow Na^+(E)$	strongly positive
$K^+(E) \rightarrow K^+(I)$	weakly positive

Bioenergetics



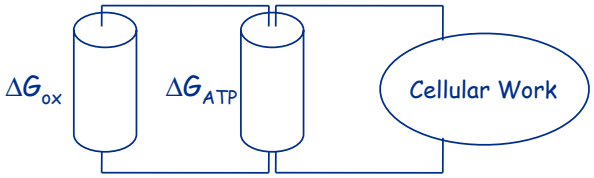
Glc + 6 O_2 → 6 CO_2 + 6 H_2O + 38 ATP

Generation of ATP



2 Pyr + 6 O_2 → 6 CO_2 + 6 H_2O + 36 ATP

Biological Batteries



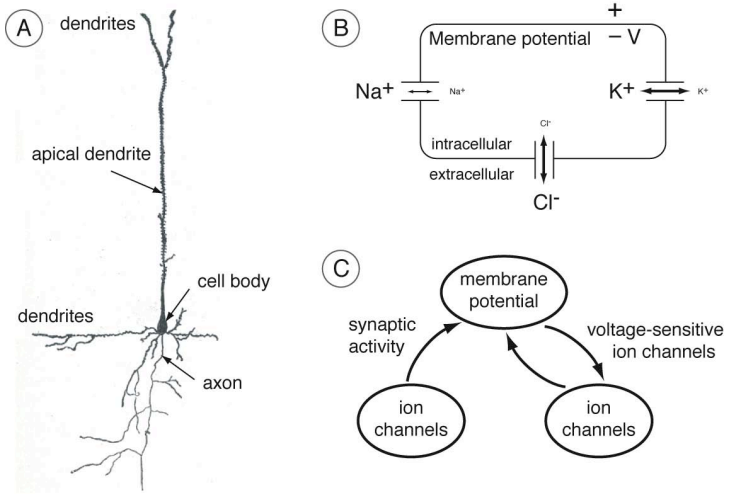
Free energy, either to drive uphill reactions or for signaling, is available from subsystems that are far from equilibrium:

$$\frac{[Pyr][O_2]^3}{[CO_2]^3} \quad \frac{[H^+]_o}{[H^+]_I} \quad \frac{[ATP]}{[ADP][P_i]} \quad \frac{[Na^+]_E}{[Na^+]_I} \quad \frac{[Ca^{++}]_E}{[Ca^{++}]_I}$$

Environment | Mitochondria | Cell | Cell Membrane

Neural Activity

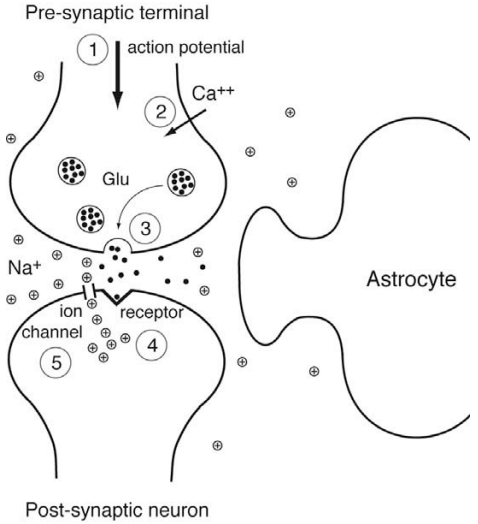
Neuronal Signaling



Synaptic activity initiates ion fluxes

Pre-synaptic Activity:
Arrival of an action potential (1) opens Ca^{++} channels, and Ca^{++} influx (2) causes vesicles to release glutamate into the synaptic cleft (3).

Post-synaptic Activity:
Glutamate binds to post-synaptic receptors (4) opening Na^{+} channels allowing many sodium ions to flow down their gradient into the post-synaptic neuron (5).

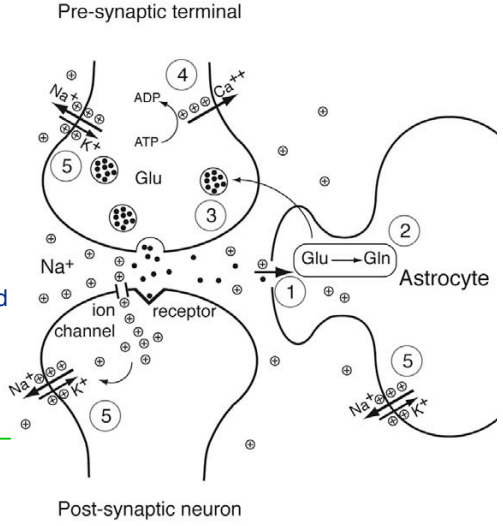


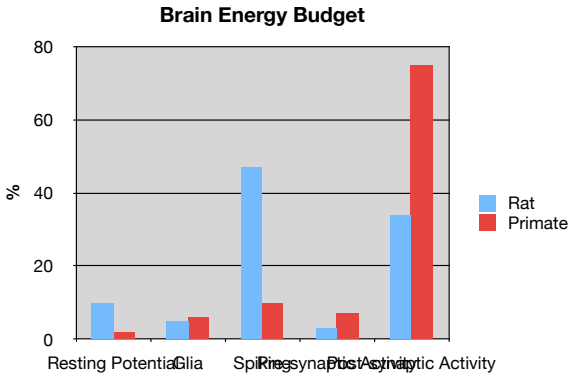
Recovery from signaling requires free energy

Astrocyte Activity:
Glutamate is taken up by the astrocyte (1 – Na^{+} gradient), and converted to glutamine (2 – ATP).

Pre-synaptic Activity:
Glutamine diffuses to pre-synaptic terminal, converted to glutamate and concentrated in vesicles (3 – ATP), and Ca^{++} ions are pumped out (4 – ATP).

Post-synaptic Activity:
Na^{+} ions are pumped out and K^{+} ions are pumped in by the Na^{+}/K^{+} pump (5 – ATP).



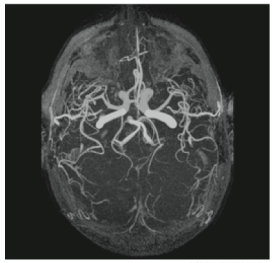


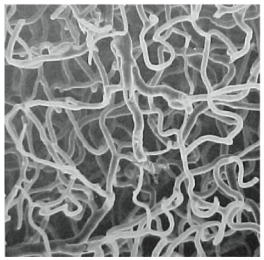
Most of the energy is consumed by the Na/K pump in recovering from post-synaptic excitatory activity

Attwell and Laughlin (2001)

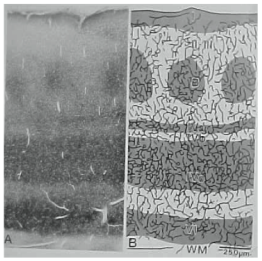
Cerebral Blood Flow

Cerebral Blood Flow

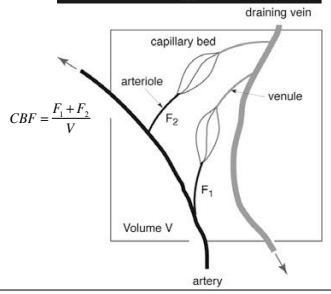




Duvernoy, et al 1981



Zheng, et al 1991



CBF = Rate of delivery of arterial blood to an element of tissue:

Human brain: CBF ~ 60 ml/(100 g)-(min)
~ 0.6 ml/ml-min

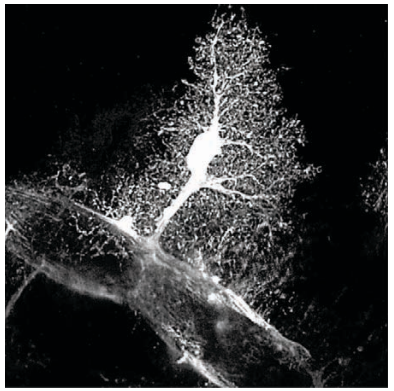
Control of CBF

Systemic: hormonal and neural effects control the distribution of blood flow to different parts of the body while maintaining CBF

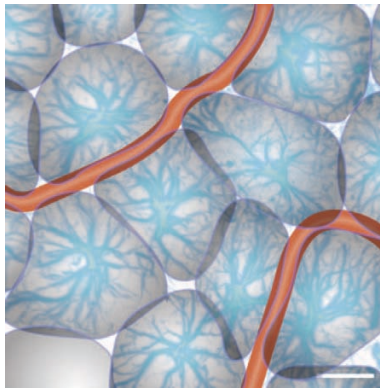
Autoregulation: If blood pressure drops, cerebrovascular resistance decreases to maintain CBF

Functional activity: Local neural activity increases CBF, but function is still unclear

Astrocytes bridge neurons and vessels



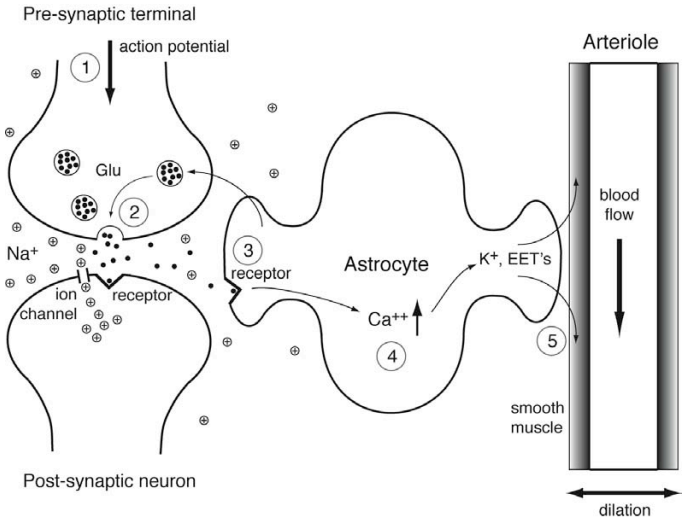
Single astrocyte expressing GFP, 2-photon imaging



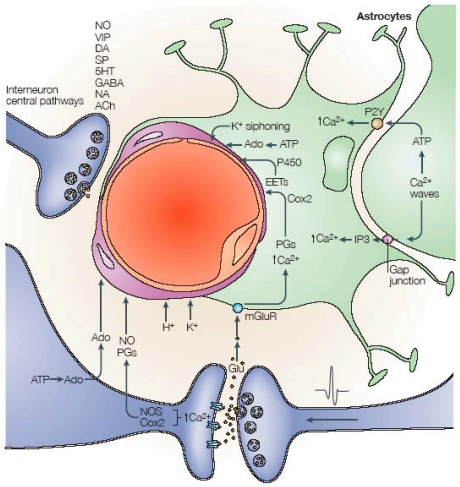
Schematic of astrocytes organized along vessels

Nedergaard et al, 2003

Blood flow changes with neural activation



Mechanisms of CBF Control



Vasoactive ions:
K^+, H^+, Ca^{++}

Diffusible gases:
Nitric oxide (NO),
Carbon monoxide (CO)

Metabolic factors:
lactate, CO_2, hypoxia,
adenosine

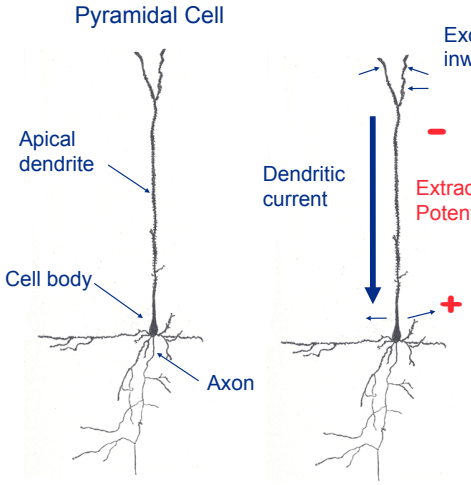
Vasoactive neurotransmitters:
dopamine, GABA,
acetylcholine,
Vasoactive intestinal peptide

Arachadonic acid pathways
COX, P450, EET's, HETE's

Girouard and Iadecola 2006

Current Ideas and Speculations

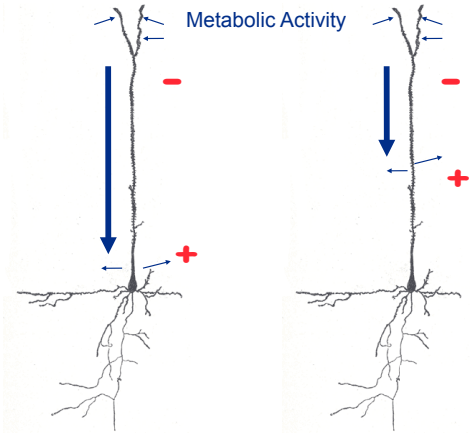
Electrophysiology Signals



Extracellular Potentials
electrodes
EEG

Current Dipole
MEG

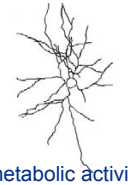
EEG/MEG and fMRI reflections of neural activity



EEG/MEG signals depend on the geometry and spatial coherence of dendritic currents

Metabolic signals primarily reflect ion pumping at the synapses

Spiny stellate cell



Similar metabolic activity but weak net current dipole

BOLD response reflects synaptic activity

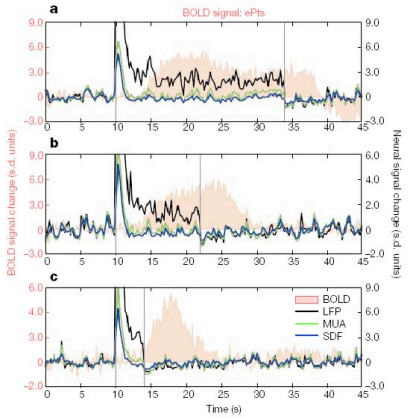


Figure 3 Simultaneous neural and haemodynamic recordings from a cortical site showing transient neural response. **a**–**c**, Responses to a pulse stimulus of 24, 12 and 4 s. Both single- and multi-unit responses adapt a couple of seconds after stimulus onset, with LFP remaining the only signal correlated with the BOLD response. SDF, spike-density function (see text); ePts, electrode ROI—positive time series.

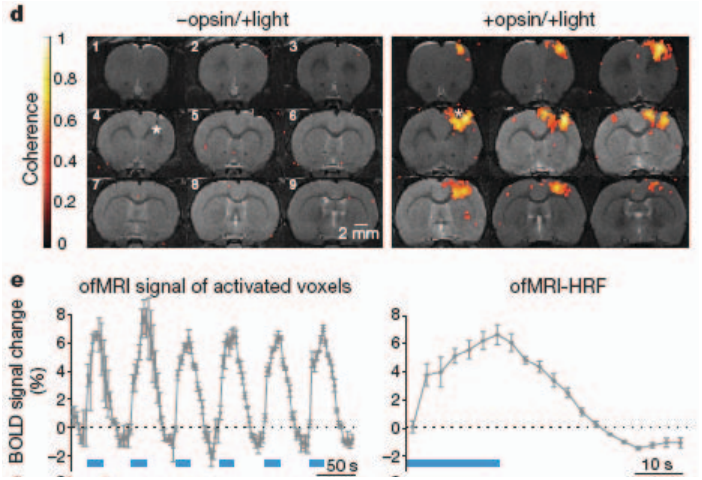
Local field potentials (LFP) reflect synaptic currents

Multi-unit activity (MUA) reflects spiking activity

MUA attenuates quickly, while LFP shows an extended response that correlates better with the BOLD response

Logothetis, 2001

Optogenetic fMRI: BOLD response to light stimulation of principal neurons



Lee et al, 2010

Glucose metabolism increases more than oxygen metabolism during activation

Lactate Shuttle Hypothesis (Magistretti, et al): Glycolysis increase is more prominent in astrocytes, producing lactate that is transported to the neurons as fuel for oxidative metabolism

Key questions:

Do CBF and Glucose metabolism always vary together? (usually, but not always)

Does CBF need to increase to support Glucose metabolism? (no)

Is glycolysis preferred for providing ATP for synaptic activity? (maybe)

Do neurons primarily use lactate for oxidative metabolism? (maybe)

No simple relation between blood flow and inhibitory neural activity

Inhibitory interneurons can drive (Cauli, 2004)

constriction with release of: somatostatin (SOM)
neuropeptide Y (NPY)

dilation with release of: nitric oxide (NO)
vasoactive intestinal peptide (VIP)

Astrocytes can constrict or dilate through multiple released agents, possibly depending on current tone or pO_2. (Gordon, 2008)

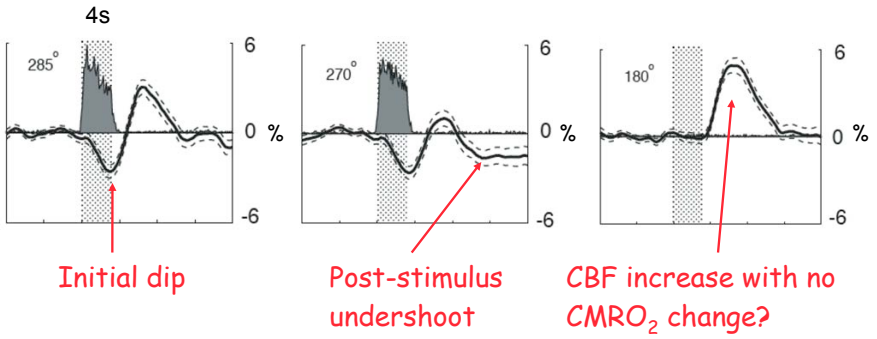
Adenosine inhibits neural activity but dilates vessels. Caffeine blocks adenosine receptors and: (Griffeth, 2011)

lowers baseline CBF
raises baseline $CMRO_2$
alters $CBF/CMRO_2$ activation coupling

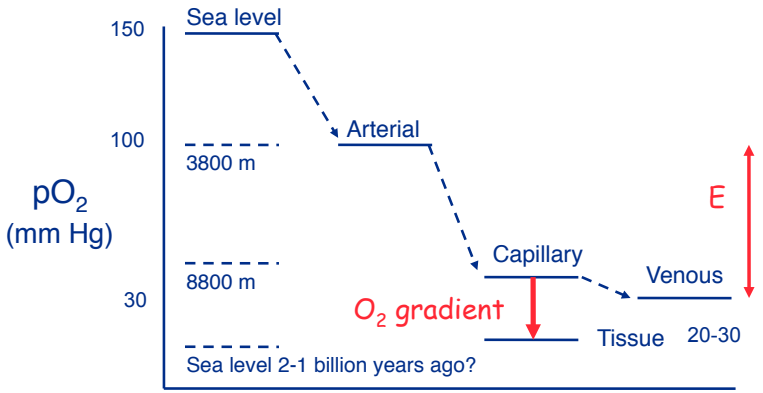
Tissue pO_2: Dynamic Responses

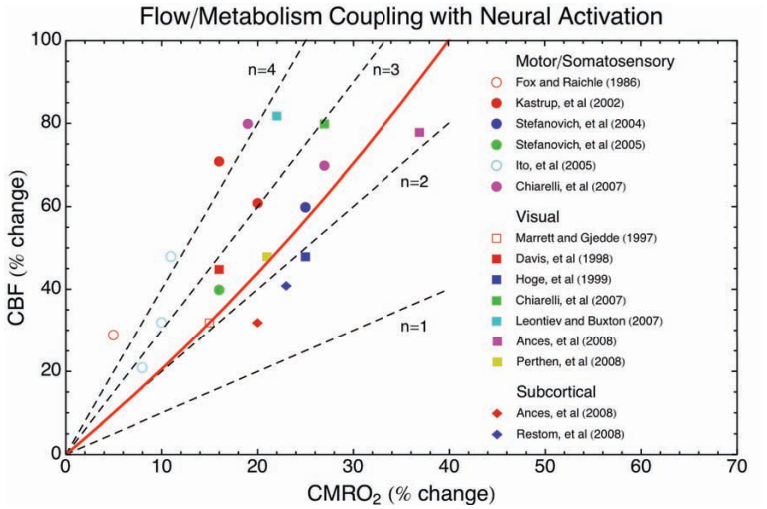
Thompson, et al (Science 299:1070, 2003):

- Cat model with visual stimulation
- pO_2: O_2 microelectrode
- spike rate: single unit electrode



Oxygen Concentration



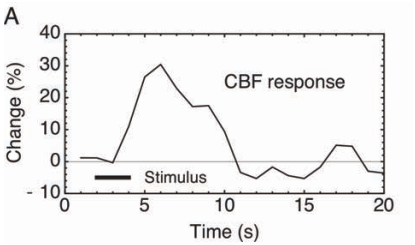


Buxton, *Frontiers in Neuroenergetics*, 2:8, 2010

$$n = \frac{\%\Delta CBF}{\%\Delta CMRO_2}$$

Does the brain try to maintain tissue pO_2 as $CMRO_2$ increases?

Potential answer to basic questions:



Why is the flow change so large?
CBF change needs to be ~2-3 times larger than the $CMRO_2$ change to maintain constant tissue pO_2.

Why is the flow change so quick?
O_2 in brain: concentration ~ 0.3 mM (mostly in blood)
metabolic rate ~ 1.6 mM/min
depletion time ~ 10 sec

Why does blood oxygenation change?
Allows the capillary/tissue O_2 gradient to increase without changing the tissue pO_2.

But the pO_2 itself is probably not the signal for changing CBF

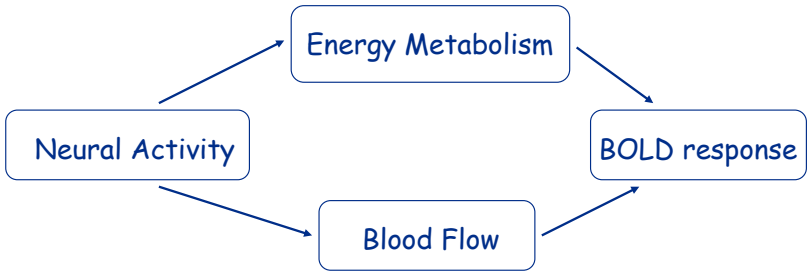
Buxton, *Frontiers in Neuroenergetics*, 2:8, 2010

Current Ideas: CBF and energy metabolism responses

Initial CBF response:
- Feed-forward, driven by neural activity, rather than a feed-back response to the increased energy demand.
- Strongly driven by excitatory synaptic activity.
- Feed-back control related to metabolism operates more slowly (?).

Energy metabolism response:
- Major energy cost is related to pumping sodium after excitatory activity.
- CMRGlc also may be strongly driven by synaptic activity to provide energy for recycling neurotransmitter.
- $CMRO_2$ increases to cover total energy costs.

Working Hypothesis



CBF driven primarily by local synaptic activity.
$CMRO_2$ driven by total energy costs (synaptic plus spiking).
BOLD response depends on both!