Functional MRI, Supplemental Notes

Functional Brian Imaging using MRI

There are numerous physiological changes related to neuronal activity that can be observed using NMR or MRI:

1. Metabolic changes – these can be observed using magnetic resonance spectroscopy (MRS) or MRS imaging methods. This is done most commonly in the 1H, 31P or 13C spectra (mostly in animal studies, though occasionally in humans). Generally has very poor signal to noise ratio.
2. Blood flow changes – Blood flow can be imaged by "tagging" in spins in the blood stream (mostly water-bound protons) outside of the slice of interest. Tagging is done by saturating or inverting the magnetic moments. These then flow into the slice of interest leading to a signal change as the saturated (inverted) protons diffuse into the tissue and the unsaturated (un-inverted) protons wash out of the slice. Increases in blood flow lead to a decease in image intensity. Usually required a 2 step procedure.
3. Blood volume changes – Blood volume changes can be imaged by tracking an intravascular contrast agent as it passes through the slice of interest. The larger the blood volume the larger the effect of image intensity. Usually, this is done with a T2* contrast agent which reduced image intensity with larger contrast concentration. Usually requires injection of a contrast agent.
4. Blood oxygenation changes – Blood oxygenation changes image intensity through a complex set of mechanisms. This technique, however, is very simple to use, has good SNR, and doesn't require any contrast injections. This is the most commonly used technique for functional brain imaging using MRI. This is often called Blood Oxygen Level Dependent or BOLD contrast.

Magnetic Susceptibility

We now look at the effect of intravascular susceptibility changes on image contrast. Consider a infinitely long cylinder filled with a substance having magnetic susceptibility c, immersed in a medium with neutral magnetic susceptibility $c = 0$. If the cylinder is parallel to the magnetic field, the magnetic field inside/outside the cylinder will be:

$$B_{out} = B_0$$

$$B_{in} = (1 + c)B_0$$

or in terms of shifts in the magnetic field we get:

$$\Delta B_{out} = 0$$

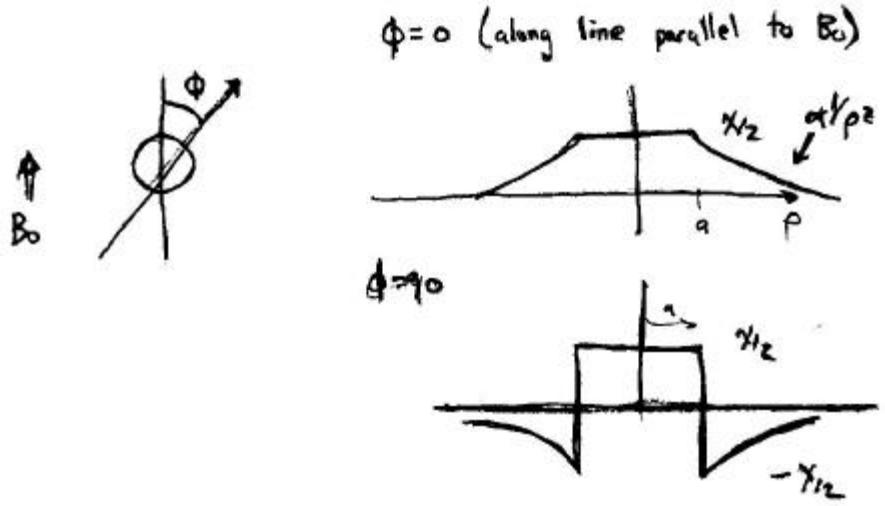
$$\Delta B_{in} = cB_0$$

For a cylinder perpendicular to the magnetic field we get:

$$\Delta B_{out} = \frac{c}{2} B_0 \left(\frac{a}{r} \right)^2 \cos 2f$$

$$\Delta B_{in} = \frac{c}{2} B_0$$

for a = diameter of the cylinder, c is the radial distance from the center of the cylinder, f is the angle between the magnetic field and the point of interest. This expression used an approximation that required $c << 1$. This looks like this:



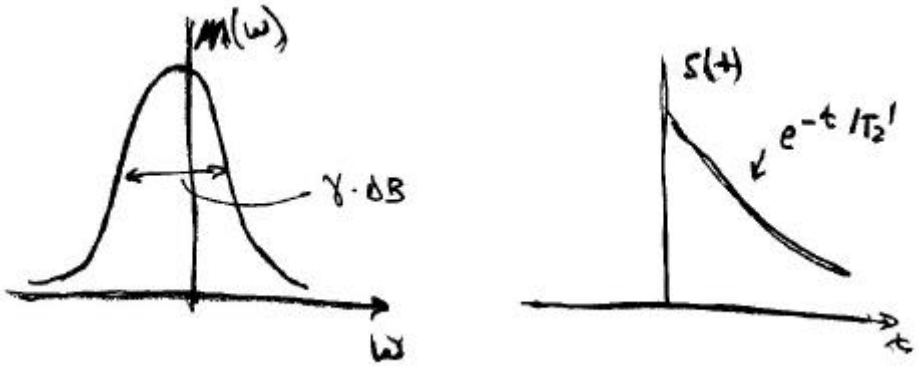
Since the resonant frequency is proportional to the magnetic field strength, the resonant frequency will vary with spatial position relative to the cylinder and also vessel orientation.

The above picture is based on a continuous media, but for blood in a vessel, the actual picture is a bit more complicated due to discrete nature of the magnetic field perturbations (the deoxy

hemoglobin groups). Nevertheless, the above findings should give you some insight into magnetic field effects.

T2* - Decay with magnetic susceptibility effects

We've previously talked about T2 being a random dephasing of spins from the interaction with other spins. Ignoring the diffusive motion of the spins, we also get signal loss due to static disturbances in the field. Take for example the above described cylinders with different magnetic susceptibilities. Spins inside the cylinder will precess at a different frequency than those outside the cylinder. This dephasing is represented as a decay of the signal. Suppose we have a distribution of frequencies within a pixel (voxel), whose histogram is show here and the signal will be the Fourier transform of this distribution:



Roughly speaking, the decay time will be inversely proportional to the bandwidth of the histogram of frequencies. Alternatively, the decay rate will be proportional to the bandwidth:

$$R2' = kg\Delta B$$

where ΔB is the width of the distributions of the magnetic field strengths and were k is some constant that is on the order of 1. The time constant $T2' = 1/R2'$.

The strength of the transverse magnetization decays away at the sum of the decay rates:

$$R2^* = R2 + R2'$$

The combined decay time is $T2^* = 1/R2^*$. We might note that for convenience, we commonly assume that the signal decay is:

$$m_{xy}(\mathrm{TE}) = \exp(-\mathrm{TE}/T2^*)$$

the decay shape for the *T2'* component is usually not exponential.

Magnetic susceptibility effect of blood oxygen level

The iron in hemoglobin is shielded by the oxygen in its fully oxygenated state and is "exposed" in the deoxygenated state. Thus, the magnetic susceptibility of blood is affected by the level of oxygenation (Y = fractional oxygentation):

$$c_{blood} = \text{Hct}(Yc_{oxy} + (1\text{-}Y)\ c_{deoxy}) + (1\text{-Hct})c_{plasma}$$

where Hct is the hematocrit (fraction of blood volume occupied by red blood cells). We commonly assume that $c_{oxy} = c_{plasma} = c_{tissue} = c_{water} = 0$ (it's not really 0, but we'll do everything relative to water). Then we get:

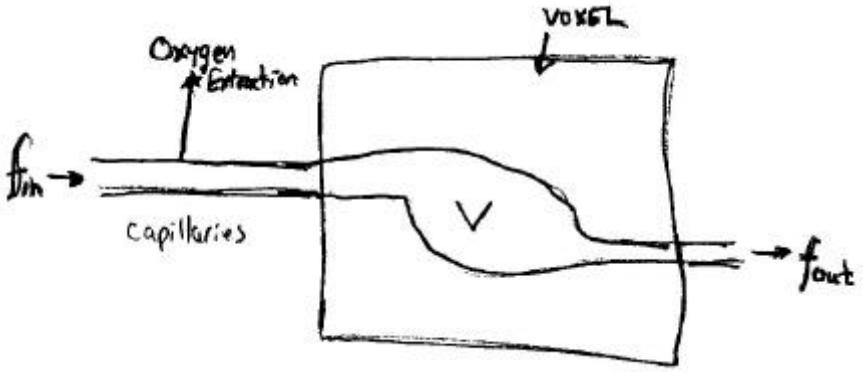
$$c_{blood} = \text{Hct}(1\text{-}Y)\ c_{deoxy} = 4\pi(0.18 \times 10^{-6})\ \text{Hct}(1\text{-}Y)$$

A change in oxygenation will result in a change in the susceptibility of blood:

$$\Delta c_{blood} = -\ \Delta Y\ \text{Hct}\ c_{deoxy}$$

Model for Tissue Compartment

In BOLD imaging, most of the signal comes from the venous side where the blood oxygenation effects can be seen – the arterial blood is nearly fully oxygenated ($Y = 1$). Consider the following model of an imaging pixel (voxel) on the venous side of the capillaries:



Here we have a flow rate (measured as perfusion in ml/min/(100 g of tissue)). Oxygen is extracted from the blood stream with a particular efficiency (OEF – oxygen extraction fraction). The blood entering the voxel will therefore have an oxygenation level of $Y = 1$ - OEF. The compartment has a particular blood volume fraction, V. In steady state, $f_{out} = f_{in}$.

Physiological changes with brain activation and their effect on BOLD contrast

There is a cascade of events following neuronal activity.

Blood Flow	↑↑↑
O_2 Utilization	↑
Blood O_2 Level (Y)	↑↑
Deoxy-Hemoglobin Level ($1-Y$)	↓↓
Susceptibility of blood	↓↓
Distortions to B_0 (ΔB)	↓↓
Phase dispersal of $\mathbf{M}$	↓↓
Effective Decay Rate ($1/T_2^*$)	↓↓
T_2^*-weighted Signal	↑↑

See also Homework #4.