

Noise and Artifacts in fMRI

Additive Noise in MRI

Sources of noise in MRI

- Thermal noise from body – thermal vibration of ions, electrons, etc. [Dominant source of noise in most MRI systems]
 - Quantization noise in the A/D devices
 - Preamp/electronic noise
 - Thermal noise in RF coil
- (these last 3 sources of noise may more of a limiting factor when imaging very small objects – for example, MRI microscopy)

Some comments on thermal noise:

- Not related to the NMR
 - o Present with or without B_0 , RF, Gradients
- Uniform spectral density (near ω_0) – white
- Comes from the whole body – amount of noise depends on the amount of the body to which the receive coil is sensitive

The signal to noise ratio (SNR) can be determined from the following relationships

- The noise/pixel in a 2D image is:

$$\sigma_n^2 = \frac{1}{N_x N_y} \frac{\sigma}{\Delta t} \propto \frac{1}{N_x N_y \Delta t} = \frac{1}{T_{A/D}}$$

where

N_x and N_y are the number of samples in the x - and y -directions (the number of points that get averaged into an image)

σ is the inherent noise in the system

Δt is the sampling time (faster sampling allows more noise into the system), and

$T_{A/D}$ is the total time the A/D is sampling.

- The signal is proportional to m_0V where
 - $V = \Delta x \Delta y \Delta z$ is the “voxel” volume
 - Δz is the slice thickness
 - m_0 is proportional to ρ - the concentration the nucleus of interest, B_0 , and γ
- The signal to noise ratio is then:

$$SNR \propto \frac{\text{signal}}{\sigma_n} = m_0 V \sqrt{T_{A/D}}$$

Examples

Case 1: Suppose we find that we have an image that is too noisy, so we average together neighboring pixels to achieve $\Delta y' = \Delta y * 2$ (all other dimensions remain the same and Δt hasn't changed either). Since by averaging in image domain, we effectively are discarding samples in k-space, $T_{A/D}' = T_{A/D}/2$ and:

$$SNR' = 2\Delta x \Delta y \sqrt{\frac{T_{A/D}}{2}} = \sqrt{2} SNR_{orig}$$

That is, we've improved the SNR by sqrt(2).

Case 2: Suppose we knew in advance that the SNR of an image was too noisy, and we compensated by acquiring a lower resolution $\Delta y' = \Delta y * 2$ (all other dimensions remain the same) but we've compensated so as to preserve the original acquisition time $T_{A/D}' = T_{A/D}$. Thus:

$$SNR' = 2\Delta x \Delta y \sqrt{T_{A/D}} = 2 SNR_{orig}$$

From these two examples, we see that it is preferable to anticipate the SNR that is necessary for a given image and set the acquisition accordingly. We don't achieve as good of an SNR by smoothing the image after it is acquired than if we had acquired at the appropriate resolution originally.

Case 3: SNR and fMRI. Suppose we have an fMRI study that works well with a 2% signal change with 3mmx3mmx5mm (45 mm³) spatial resolution and 150 time points (using TR=2s, this results in a 5 minute data acquisition). Now, we wish to see finer details by using a 1.5mmx1.5mmx3mm (6.75 mm³) spatial resolution. The duration of the readout (to accomodate

the higher resolution matrix increased from 30 ms to 80 ms). How many time points (and how long) should this study be in order to have the same power to detect a 2% signal change (ignoring the fact that number of voxels in the test and the ROI has changed)? Matching SNR we get:

$$SNR = V_{orig} \sqrt{T_{A/D,orig}} = V_{new} \sqrt{T_{A/D,new}}$$

$$N_{new} = N_{orig} \frac{T_{read,orig}}{T_{read,new}} T_{A/D,orig} \left(\frac{V_{orig}}{V_{new}} \right)^2 = 150 \frac{30}{80} \left(\frac{45}{6.75} \right)^2 = 2500 \rightarrow 83.33 \text{ min}$$

Noise and RF Coils

As previously mentioned, noise in MRI comes from thermal vibrations of ions and electrons and is not dependent upon what you are doing with the MRI device. It doesn't matter:

- which slice is excited or how thick the slice is.
- how big the flip angle is.
- on the presence or absence of gradients, etc.

One consequence of this is that that noise level in MRI is dependent how many ions, electrons, etc. are present to induce noise in the receive coil. Thus, it is important to size the RF coil to the object that you are imaging. There is no point in receiving noise from the whole torso if we are only interested in imaging the head. Thus, in MRI there are coils for everything: head, knee, spine, wrist, shoulder, neck, pelvic, angle, cardiac, breast, ocular, TMJ, and even coils that can be inserted into body cavities. By sizing the coil to the application:

- We minimize noise while still preserving image strength over region of interest.
- Allow us the use a smaller field of view without aliasing (wrap around artifact).

Disadvantages:

- Some small coils have very non-uniform image intensity over the region of interest.

Example:

Suppose we are interested in the visual cortex. Suppose that by using a surface coil positioned over the occipital pole, we can reduce the volume of tissue seen by the coil by $\frac{1}{4}$. Thus, the noise variance σ_n^2 will be reduced by $\frac{1}{4}$, the standard deviation will be reduce by σ_n will be reduced by $\frac{1}{2}$, and the SNR will be increased by a factor of 2. This improved SNR can be traded for higher spatial resolution (decrease V by 2) or shorter data acquisition time (decrease $T_{A/D}$ by 4).

Field Strength and SNR

As with the use of coils to improve SNR (or improve resolution or decrease imaging time), the use of higher magnetic fields can improved the SNR as well. This works in two ways:

- m_0 scales with field strength, thus the underlying SNR is linearly dependent on field strength
- the size of the BOLD effect (e.g. %-signal change) is also proportional to B_0 (for a fixed TE). (Since $T2^*$ is a bit shorted at higher fields, the optimal TE is a bit shorter, but there is still a field dependent gain here).

Thus, the SNR of and fMRI study increases between linearly and quadratically with field strength. Going from 1.5 to 3 T, should improve the SNR by a factor of between 2 and 4.

Other Sources of Noise (non-additive)

All of the preceding discussion about SNR, duration of imaging session, field strength, etc. all apply when the dominant source of noise is the additive noise from thermal processes. We know, however, that there are other sources of signal variation in fMRI, and in some cases, these are more important than the additive noise. We can debate as to whether to call these sources “noise,” “variation,” “fluctuation,” or “artifact,” but they all represent increased variance in the fMRI signals. Major sources of non-thermal variation in fMRI are:

- Cardiac and pulmonary variations
- Head movement
- Low-frequency (1/f) noise
- Spontaneous neural and vascular fluctuations (BOLD noise)
- Behavior variations

Important! These sources of variation are more likely to become significant as we go to higher and higher magnetic field strengths. Also lower spatial resolution makes thermal noise relatively less important.

The above sources of temporal variation will be covered more extensively in a later lecture.