VIII
Selective Pulses

Lecture notes by Assaf Tal

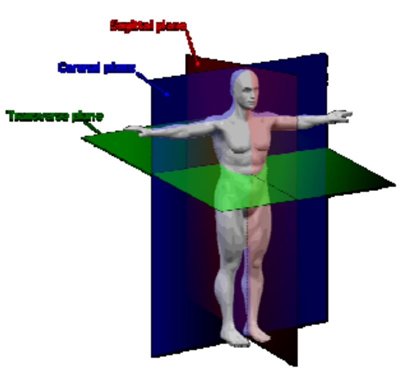
1. Slice Selection

1.1 2D vs. 3D

Imaging sequences can be divided into two categories: those that excite all the spins in the body and obtain a 3D image simultaneously, and those that excite the spins slice-by-slice and obtain sets of 2D images. Both approaches yield in the end a 3D image. There are a couple of reasons for favoring a set of slice-by-slice 2D images over a full 3D acquisition. For example (assuming the slice is selected along the z-axis), to avoid aliasing along the z-axis in a full 3D acquisition, one must set $\Delta k_z < 1/FOV_z$. This means acquiring lots of points in k-space, often more than you need. By exciting just the slices you want you can avoid this problem.

1.2 Terminology

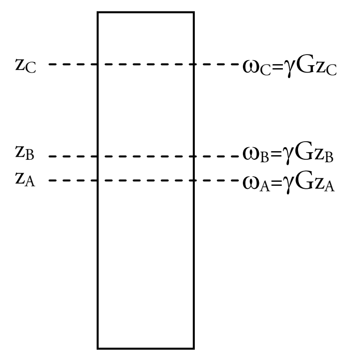
One can excite **axial/transverse** (perpendicular to the field), **sagittal** (parallel to field, from front to back) and **coronal** (parallel to field, from right to left) slices in the human body:



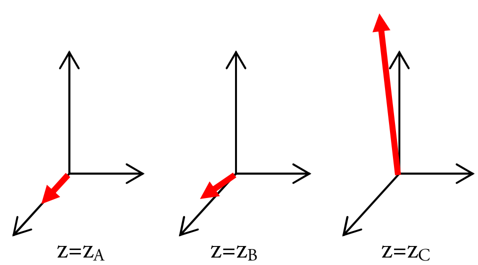
2. Selective Pulses

To excite a slice selectively, all that is needed is a prolonged RF irradiation of the right amplitude. We'll talk about things in 1D (the z-axis); the concepts introduced can then be readily generalized to 2D and 3D.

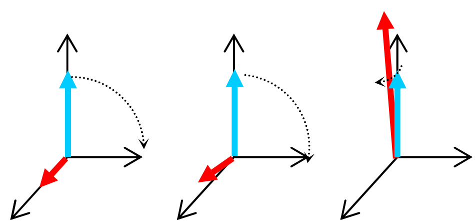
Assume a 1D sample as shown below, and assume there's some gradient G acting in the background. The offset will be $\omega(z)=\gamma Gz$. It will be 0 in the middle (point A), slightly larger above (point B), and much larger at point C:



Assume the spins all start out from thermal equilibrium along the z-axis. How would the effective field look like at z_A, z_B and z_C?



At z_A there is no offset, so the effective field is comprised only out of the RF, which (for the sake of concreteness) is taken to be along the x-axis. At z_B, near z_A, the offset is small compared to the RF (that is, we assume $\gamma Gz_B \ll \gamma B_{RF}$), so the field is approximately along the x-axis. Far away from the center, where $\gamma Gz_C \gg \gamma B_{RF}$, the offset is much larger than the RF and the effective field is, to a good approximation, parallel to the z-axis. Therefore, to a good approximation, the spins around the center (around z_A=0) will get tilted onto the y-axis (provided we calibrate our **pulse's duration**, T, such that $\gamma B_{RF}T=\pi/2$), and those "far away" from the center will remain along the z-axis:



How far is "far away"? When the offset becomes much larger than the RF:

$$\gamma Gz >> \gamma B_{RF} \quad \text{("far away")}$$

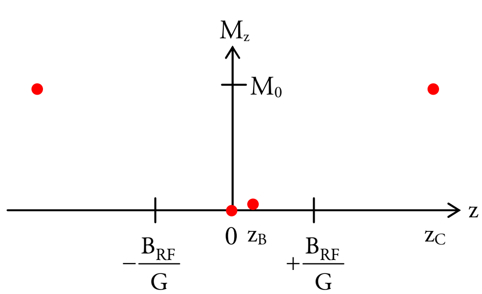
or (equivalently)

$$z \gg \frac{B_{RF}}{G}.$$

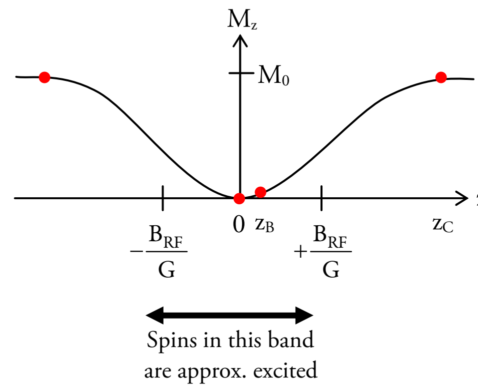
If we were to estimate M_z at the end of the pulse, at points z_A, z_B and z_C, we'd estimate:

$M_z(z_A=0) = 0$	Tilted onto y-axis
$M_z(z_B) \approx 0$	Approximately tilted
$M_z(z_C) \approx M_0$	Approximately not tilted

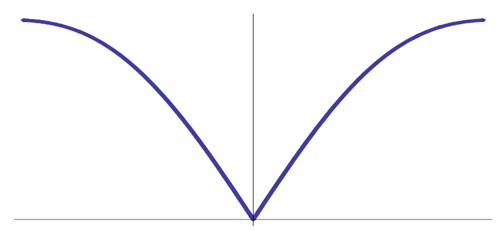
These relationships are symmetric (e.g., $M_z(-z_C)$ is also not tilted, and $M_z(-z_B)$ is approximately tilted). We could plot these points in a graph of M_z versus z and obtain:



Now, if I were to ask you to guess how the entire curve looked like for all z, you'd probably try to interpolate and end up with something like this:



This would be a good guess. I can tell you it's not 100% correct. The actual curve looks more like



but the idea remains the same: approximately speaking, all the spins in the area

$$-\frac{B_{RF}}{G} < z < \frac{B_{RF}}{G}$$

are excited, while spins outside that band are not excited. Furthermore, since we've assumed that on-resonance our RF has been calibrated to yield a 90 pulse, we know that

$$\gamma B_{RF} T = \frac{\pi}{2}$$

so

$$B_{RF} = \frac{\pi}{2\gamma T}$$

meaning that we can write the condition on the excited region also as:

$$-\frac{\pi}{2\gamma GT} < z < \frac{\pi}{2\gamma GT}$$

The slice thickness is therefore about

$$\boxed{\Delta z \approx \frac{\pi}{\gamma GT}}$$

(Note: the γ used here has 2π in it, which are needed to cancel out the π in the nominator)

2.1 Slice Thickness

Using the above conclusions, we can come up with a recipe for exciting a slice of thickness Δz (e.g., Δz=3 mm) selectively:

1. Turn on a gradient in the direction perpendicular to the slice.
2. Apply an RF pulse for a duration T such that (use boxed equation above):

$$\boxed{T = \frac{\pi}{\gamma G \Delta z}}$$

3. Don't forget to calibrate the power of the RF: $B_{RF} = \frac{\pi}{2\gamma T}$.

Notes:

1. The slice thickness is inversely proportional to the pulse's length. Longer pulses yield narrower slices.
2. Let's do some math. The maximal gradient on the 3T Siemens scanner we have is about 45 mT/m (= 4.5 Gauss/cm). For a 1 ms pulse, the slice's thickness will be:

$$\Delta z \approx \frac{\pi}{\gamma GT} \approx 0.25 \text{ mm}$$

2.2 Slice Center

The above discussion has shown that a constant RF in the presence of a gradient would excite a slice of a particular thickness, **centered about z=0**. How can we move the slice about? The answer is **make the RF rotate**. The available hardware allows us to do this. Technically speaking, instead of using

$$\mathbf{B}_{RF} = \begin{pmatrix} B_{RF} \\ 0 \\ 0 \end{pmatrix}$$

we should use

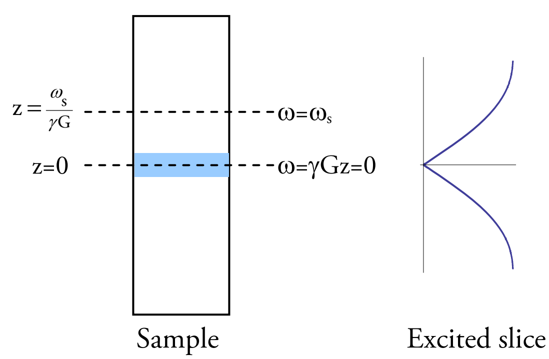
$$\mathbf{B}_{RF} = \begin{pmatrix} B_{RF}\cos(\omega_s t) \\ B_{RF}\sin(\omega_s t) \\ 0 \end{pmatrix},$$

which is just a vector of magnitude B_{RF} going around in a circle at an angular frequency ω_s. This would end up shifting the slice's center from 0 and placing it at:

$$\boxed{z_{center} = \frac{\omega_s}{\gamma G}}$$

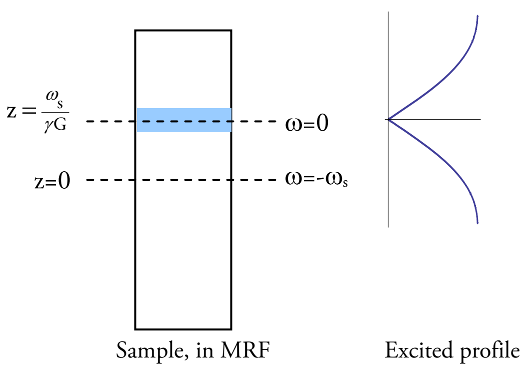
Since ω_s can be negative, so can z_{center}.

Why does that work? Think in terms of rotating frames. Suppose we're in the "regular" rotating frame, where $\omega=\gamma Gz$. Note that at z=0, ω=0, and at $z=\omega_s/\gamma G$, $\omega=\omega_s$:



The constant RF pulse described in the previous section excites a bandwidth centered around ω=0. The insight here is that the bandwidth is centered around ω=0, not z=0 (in our case, they're the same, but in a moment they won't be). This is because the RF has no spatial dependence, so how can it differentiate between different z's? It can't. The position dependence comes from the gradient; but turn the gradient off, and you still get a selective pulse that excites certain offsets but not others (of course, then it wouldn't be *spatially* selective, but *spectrally* selective).

Consider the rotating RF in a frame that rotates with it; let's call that frame a "mini-rotating frame" (MRF). In this MRF, the zero frequency is centered around where ω_s was previously. This position is not z=0, but rather the one for which $\gamma Gz=\omega_s$, or $z=\omega_s/\gamma G$:



Thus, the slice centered at $z=\omega_s/\gamma G$ will be excited.

2.3 Phasing Issues

The plot of M_z versus z shows us which spins got excited onto the xy-plane, but it doesn't disclose anything about where in the xy-plane they got to. That is, what is the phase of the excited spins, as a function of z? It is not 0, because as the spins get tilted they also precess to an extent.

I won't show why, but the spins acquire a phase given by

$$\phi(z)=-\tfrac{1}{2}\gamma GTz$$

To remove that phase, simply apply a gradient –G for a time T/2, which will add to the spins a phase of the form:

$$\Delta\phi_{\text{gradient}}(z)=\tfrac{1}{2}\gamma GTz$$

The total phase (the sum both) will be zero.

2.4 Notation

In pulse sequence diagrams, I will use

to denote selective pulses. Of course, since we're after spatially selective pulses, a gradient will have to be applied concurrently, and a refocusing gradient will almost always follow: