Spatial Encoding
Part 3 – Frequency Encoding

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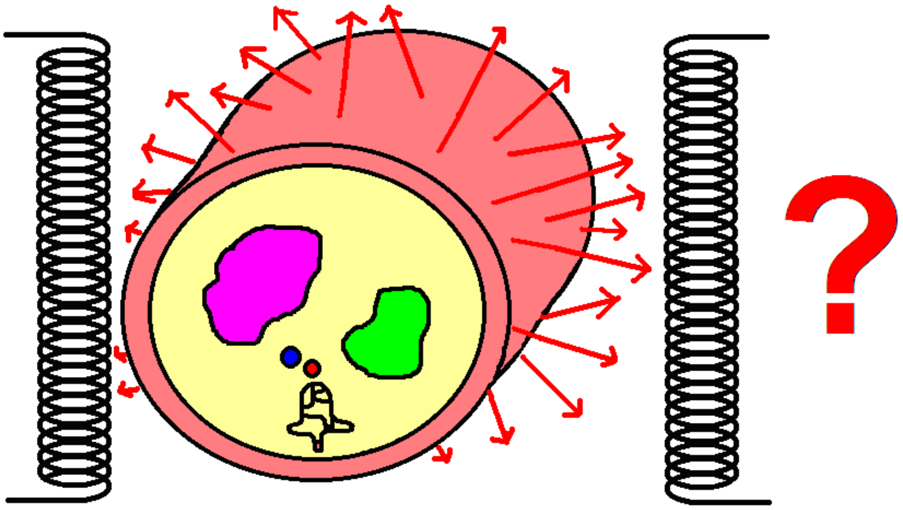
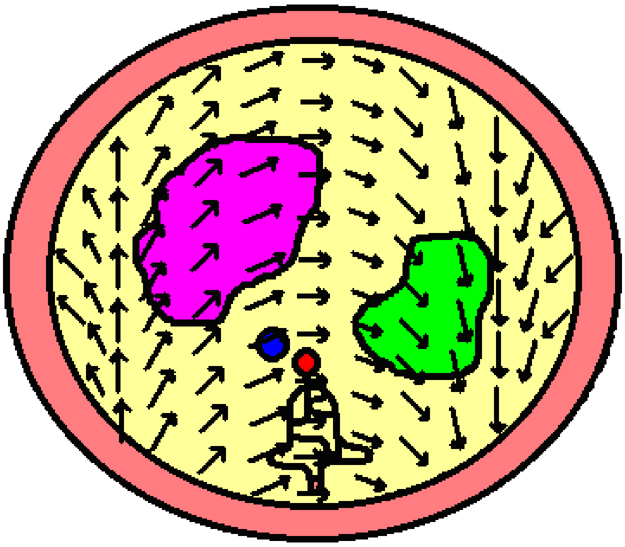
Introduction



Spatial Encoding describes a series of processes employed by an MRI scanner to establish exactly where signals within the patient have originated, such that meaningful images can be produced. The x, y and z gradients all need to be utilised to make this process possible.
In the previous two editions of *BAMRR News* we have looked at the steps of Slice Selection and Phase Encoding. However for standard 2D imaging this is still not enough. One more spatial dimension remains to be encoded in order to finally resolve each point within the patient. This is the process of Frequency Encoding.

With Slice Selection, we established that we are able to excite, and therefore only receive signals from, one slice at a time. Then after Phase Encoding, we could establish from where along either the x or y axis (depending on the directions we choose to perform phase and frequency encoding – we can swap these) the signal originated, i.e. we can establish from which column *or* from which row. Now we will use Frequency Encoding to finally encode the signal to a single point in space.

We will continue describing the process of acquiring axial slices, but remember, merely by changing the use of the x, y and z gradients, the scanner is able to produce slices in any plane we choose.

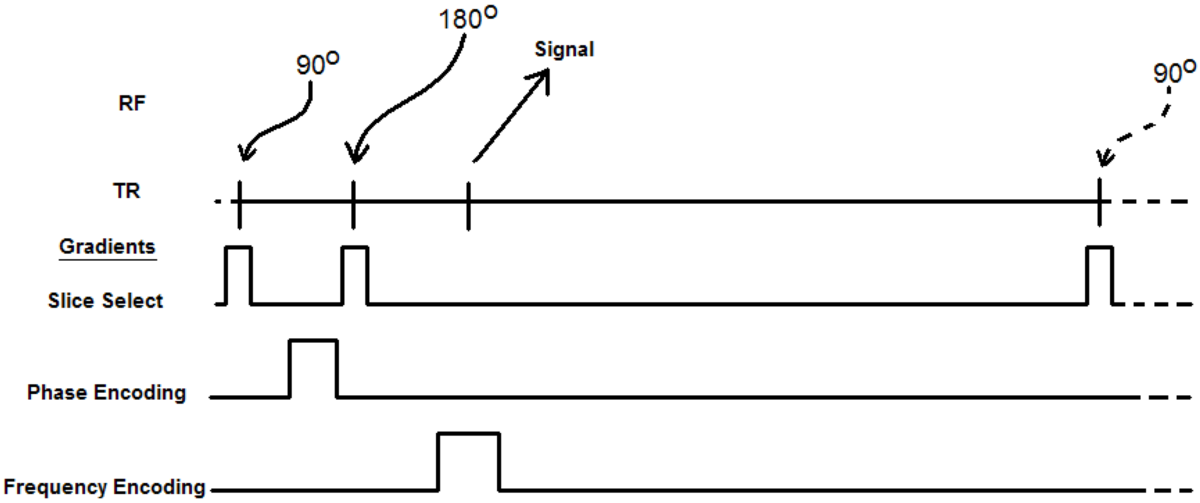


< Phase: Left to Right >

This shows the phase position of the protons as described in the previous article, immediately following left to right phase encoding. The RF aligned protons were either accelerated or decelerated by use of the x gradient, such that it resulted in each column of protons being slightly out of phase with its neighbours by a predictable amount.
The scanner software is therefore now able to establish from which column each signal originates, but as yet, not which row. To establish this, we perform Frequency Encoding. This time, the y gradient is switched on at the same time the signal is being sampled in the receiving coil. This forces the precessing protons to spin at different angular velocities, with a velocity that is dependant on their position along the y axis. Where the gradient strength is reduced, the spins will slow, where it is stronger, the spins will speed up. The net result is that by considering the angular velocity of any signal during read-out, the scanner can establish where along the y axis, i.e. which row, it has originated. Adding this new information to the previous, it can finally resolve each signal to a point in space, and therefore generate an accurate image.

Frequency Encoding and Scan Time

Unlike phase encoding. there is no time penalty for increasing the image resolution in the frequency direction. This is because frequency encoding is performed during each of the already existing TR time periods, whereas for every line of phase resolution chosen, an additional TR needs to be performed. So whilst an increase in either phase *or* frequency resolution will reduce the signal to noise ratio due to voxels becoming smaller, only phase encoding affects overall scan time.



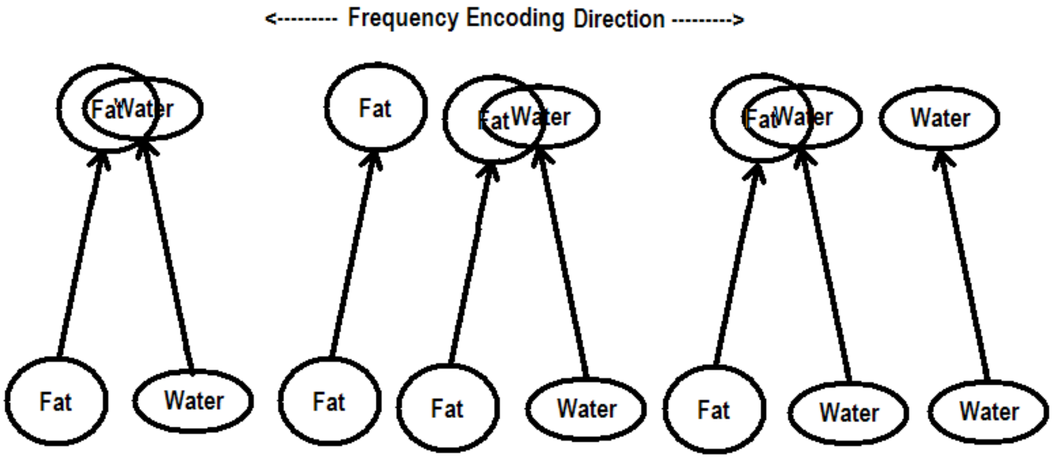
This image shows the use of the x, y and z gradient to show how each is switched on and off so that spatial encoding is achieved. It shows a single TR period, which would fill one line of k space. This needs to repeated with a different strength of phase encoding gradient for each line of k space to be filled, which in turn depends on the phase resolution chosen.

Sampling Time and Bandwidth

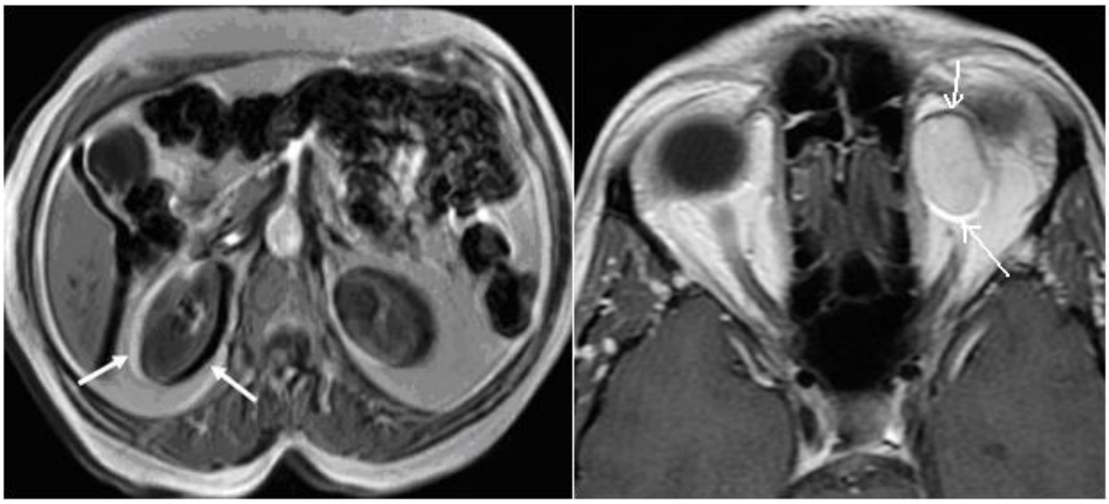
The length of time the frequency encoding gradient is switched on for is called the sampling time. Whilst the gradient is on, protons will be forced to precess at different frequencies across the gradient. This range of frequencies is known as the receive bandwidth. The higher the chosen image resolution in the frequency direction, the more samples are needed and therefore either the bandwidth will need to be increased, or alternatively, the bandwidth can be kept the same if more time is allowed to collect the samples, i.e. the sampling time is increased. If the sampling time is increased too much, this will affect the minimum TE available as it will encroach on the rephasing pulse. Generally scanner operators have no control over sampling time, however the receive bandwidth is available to adjust. This may be useful in certain circumstances, e.g. increasing it to reduce distortion artefacts from metallic prostheses. It should be remembered that increasing bandwidth (just as increasing resolution) has an adverse effect on signal to noise ratio. Some scanner manufacturers measure bandwidth in Hz (or kHz) whilst others use Hz/pixel, so a small calculation may be needed to compare protocols between vendors.

Chemical Shift Artefact

The Larmor equation tells us that in a fixed magnetic field, hydrogen precesses at a predictable and fixed frequency. In reality minor changes in this frequency occur in vivo as hydrogen is bonded to form part of different molecules. The obvious examples are hydrogen in fat and hydrogen in water, where in a 1.5T scanner, fat precesses 224Hz slower than water. This is not a great deal, but remember that the frequency sampled during frequency encoding governs where the signal is placed in the image. The result is that the hydrogen producing signal in fat can be mapped to a slightly shifted position in the frequency encoding direction, to that of fat.



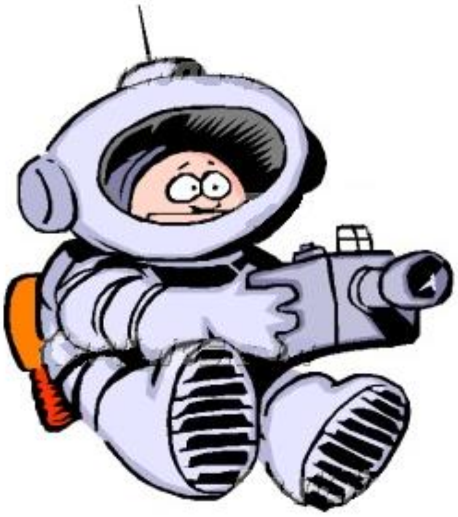
You are more likely to see this mismapping artefact in areas where fat and water coexist, e.g. the edges of the renal cortex or the borders of the orbits. The appearance is of dark or light bands along these borders in the frequency direction of the image.



To help reduce chemical shift artefact the bandwidth can be increased so that the physical difference of the two shifts is smaller. This is a bit like the fact that missing an archery target by 20 cms is better than missing by 20 inches.

Frequency Wrap

So based on the frequency of a spin, we have learned that it is mapped into its correct position in the frequency direction of the final image. It is therefore of course important that the frequency sampled and measured is correct. If not, it could be mismapped into a false position and possibly even wrap. Consider this analogy. If you were floating in space and saw planet earth in the distance you may realise that it is spinning and be curious how fast.



If you took a photo every 30 hours and then reviewed them after a week, would this be enough? The answer is no, because it would lead you to believe that it was turning just 90^{o} between each picture and therefore had a day length of 120 hours. The problem is that you are not taking a sample picture often enough. What about a photo every 15 hours, is that enough? The first picture would correctly suggest just over ½ a turn, the next would suggest (correctly also) a turn and a quarter. By photo 9 the earth will be in the same position as it was for photo 1, and will have appeared to have spun 5 times, i.e. 5 times in 120 hours, suggesting a day length of 24 hours. So what changed? Why was a sampling rate of 15 hours enough to get the correct result, but 30 hours was not? This is explained by a principal called the Nyquist-Shannon Theorem (or Sampling Theorem) which states that each signal must be sampled a minimum of twice per cycle in order to correctly measure it. It is therefore built in to all modern MRI scanners for this to happen so that samples are correctly measured, and frequency wrap does not occur.

So by the use of Slice Selection, Phase Encoding and finally Frequency Encoding MRI signals can be spatially resolved in all 3 dimensions such that diagnostic images can be accurately created.