Module 3

From the MRI signal to the spatial image – encoding and reconstruction

After reading this module, you will:

- Understand how the NMR signal of the spin is recorded.
- Be familiar with the significance of the MRI gradient fields.
- Understand the composition of the image from the individual voxels.
- Understand how the signals received (frequencies) are translated into a spatial image.

3.1 Signal reception

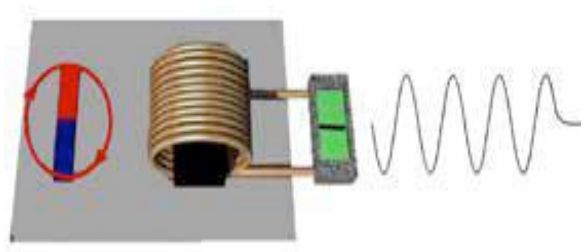
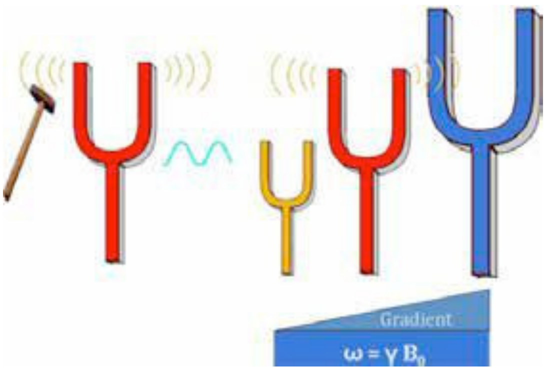


Figure 3.1:
The generation and reception of the NMR signal

A spin is rather like a tiny magnet which turns on its axis. If such a magnet is brought into proximity with a coil, a current is generated in the wires. Over time, the bar magnet in the diagram generates a sinusoidal wave in the coil which can be recorded. The HF coils of an MRI do exactly this. First they emit a stimulus (resonance), then they receive the signal from the spins.

3.2 Spatial encoding



The capacity to receive a signal from the spins is of no use for imaging purposes unless we know the origin of the signal. It is first necessary to position-encode the spin in three dimensions. This was one of the biggest challenges in the development of MRI imaging.

The previous chapter introduced the Larmor frequency of the spin. This depends on the exterior field B_0 impinging on the spin. A frequency is generated only when stimulating the spin with exactly this frequency.

The result: the Larmor frequency of the spin can be subject to local alteration by activating an additional position-independent magnetic field. A gradient G is nothing else than a magnet field with a variable position. It can be activated in addition to the static field where necessary.

3.2.1 The slice selection gradient

The first step in spatial encoding involves selecting an imaging slice. When a spatial gradient is activated along the z axis, not every position along this line has the same static field strength B_0, but a position-dependent value $B_0+Gz•z$.

The spins all have their own Larmor frequency. Stimulation from outside on the "old" Larmor frequency of B0, will result in only a very few spins being charged with energy, which will resonate in a thin slice along the z axis.
This energy is re-emitted as a signal. Choosing different gradient strengths (i.e. the alteration of the Larmor frequency along the z axis) enables the stimulation of slices of various thicknesses (selecting). These gradients are also known as the slice selection gradients.

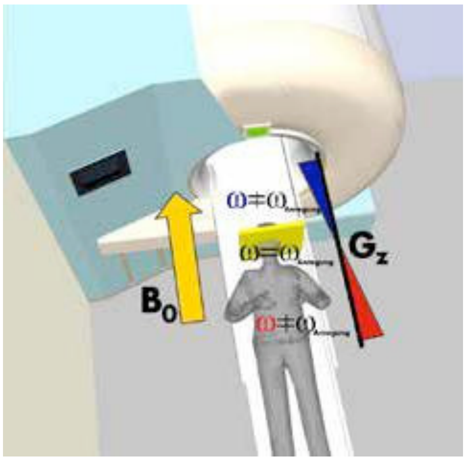


Fig. 3.2:
Slice selection

3.2.2 The phase encoding gradient

After selecting a slice with a slice selection gradient, the target is clear. Success in first dismembering this slice into individual strips and then subdividing these into a number of individual cubes known as voxels, provides the technical conditions requisite to scanning a selected imaging volume voxel for voxel. Using a suitable technique, it is then possible to assemble these slice images of this volume.

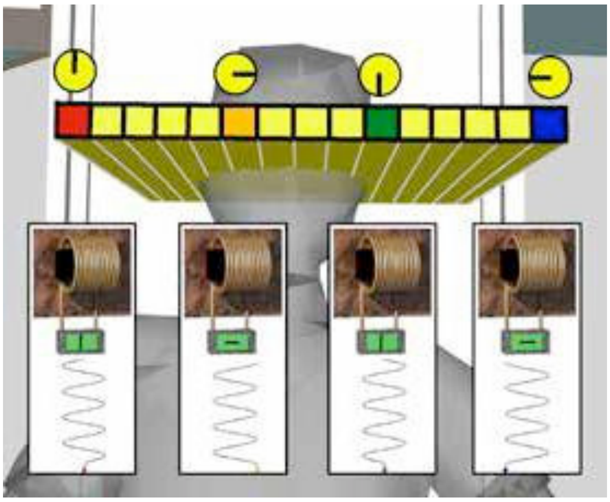


Figure 3.3:
Phase encoding

The second step requisite to spatial encoding is the application of a phase encoding gradient. This is inserted perpendicular to the z gradient in the x axis. This gradient is activated only for a short time before the reception of the NMR signal.

We know that the spins are all in phase shortly after their stimulation. To understand this, picture a number of clock faces which all show the same time. The gradient makes the hands on some of the clocks (spins) move round (i.e. rotate) faster, whilst others move (rotate) more slowly.

After the gradient has been switched off, the hands on the clocks all move around at the same speed, but those on one side are running ahead of time, the others behind time.

The same happens with spins. Now, when we receive the NMR signal, it is "out of phase". This means we are able to identify with high degree of reliability, the strip of the slice in which the spins are located and which signal they are emitting.

3.2.3 The frequency encoding gradient

The third and last gradient required to encode the position information is the frequency encoding gradient. The first gradient was activated at exactly the same time as the stimulus was issued. The second came between the stimulus and signal reception. The third is issued at exactly the same time as the reception.

The gradient runs perpendicular to the other two (i.e. on the y axis) and makes the spins revolve at different speeds during reception of the NMR signal.

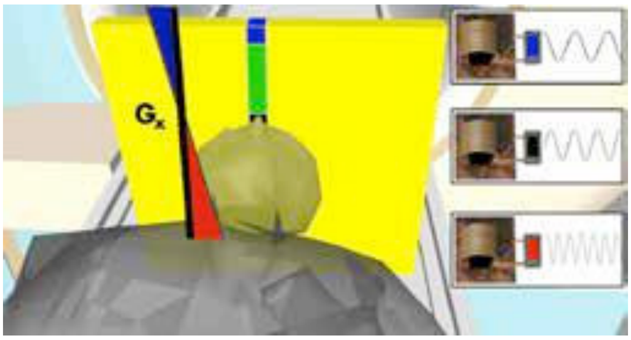


Fig 3.4:
Frequency encoding

The sinusoidal wave recorded as a signal is sometimes compressed and sometimes elongated. The information from the phase and frequency encoding can be used to identify every single voxel in the slice which has been selected using a slice selection gradient.

3.3 Image reconstruction

The resonance provides the "answer" to the "questions" (HF stimulus) addressed to the spins. The NMR signal recorded does not represent an "answer" of an individual spin to a "question", rather it is a composite of an unbelievably large number of such answers. These answers are high-frequency waves of varying amplitudes, frequencies and phases, which are all taken up at the same time.

As these are frequency information, they are saved in a so-called frequency space, known as the "k-space". This space still contains all the position information generated with the gradient encoding and all the intensity information (T_1, T_2 and ρ), albeit in encrypted form. We use a Fourier transform to reconstitute the data from the k- space to the position space.

We need not bother ourselves with the mathematical details of this process. The only consideration of note is that the recorded superimposed high-frequency waves are used to generate a spatially-resolved image of the tissue characteristics (relaxation characteristics). This is analogous to the dispersion of light through a prism. The visible light is separated through a prism (imaging) into its individual colour components. Every colour represents a specific frequency. The Fourier transform works like an inverse prism, creating a "normal" ray of light from this information, i.e. producing a real image.

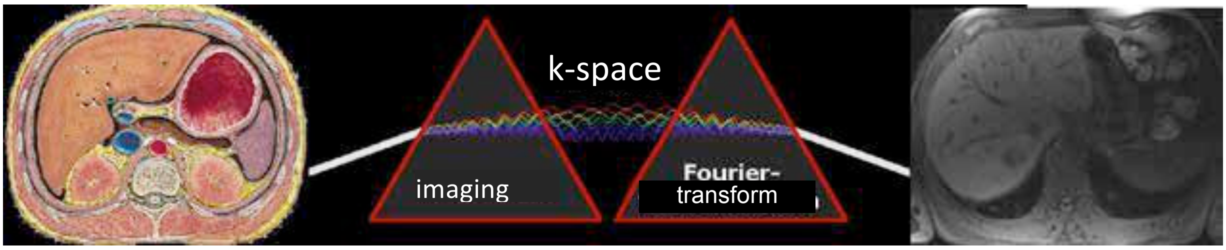


Figure 3.5:
The imaging registers frequency data from the individual spins from the body which is saved in the k-space. Just as the individual colour components from the refracted light include the same information as in white light, the frequency information also contains the complete "real" image information. Working as an "inverse prism", we can use the Fourier transform to "get back" the real pictures from the frequency images.

An interesting aspect of the k-space is the division of the later image information which takes place here. High frequencies are saved on the periphery of the k-space, the low frequencies in the centre. The lower amplitudes of the high frequencies mean that they make a lesser contribution to the generation of image contrast. Nevertheless, they have a significant influence on the image resolution, as a high frequency corresponds to a large variation of the image signal within a small spatial area.

This is very important for image generation. Scanning further and wider into the centre of the k-space produces more detailed information from the area of higher frequencies. This increases the resolution of the images but lengthens the examination time. The length of the examination time depends upon the closeness with which the k-space is scanned. The more points scanned within a specific area, the greater the spatial resolution.

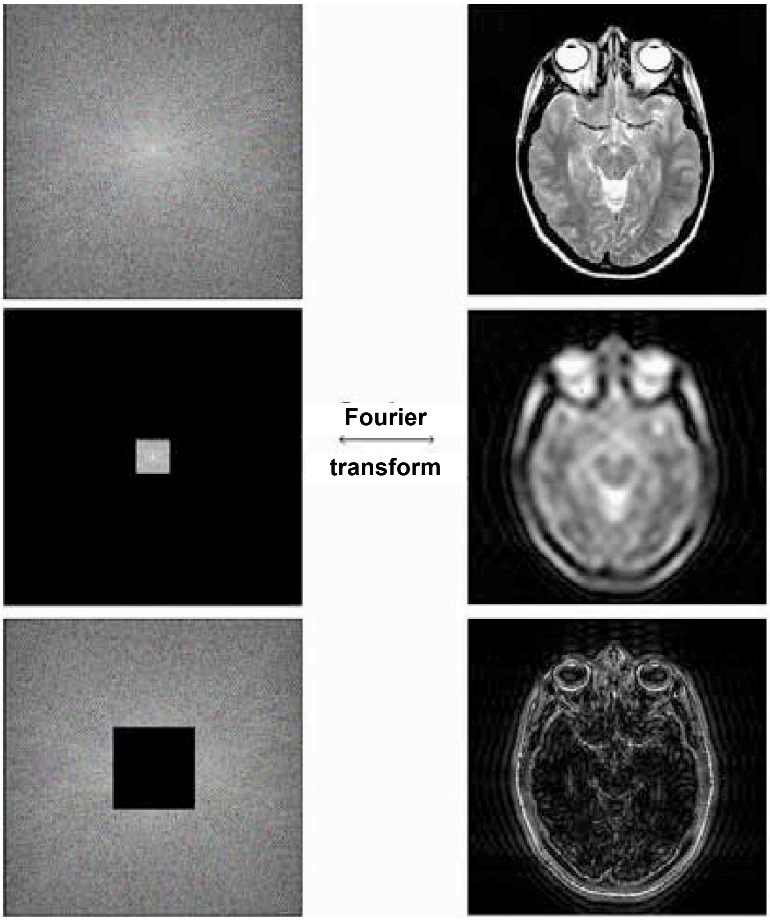


Figure 3.6
Left: k-space images. Right: Fourier transformed (real space). From above to below: complete transformation, transformation of the low frequencies, transformation of the high frequencies

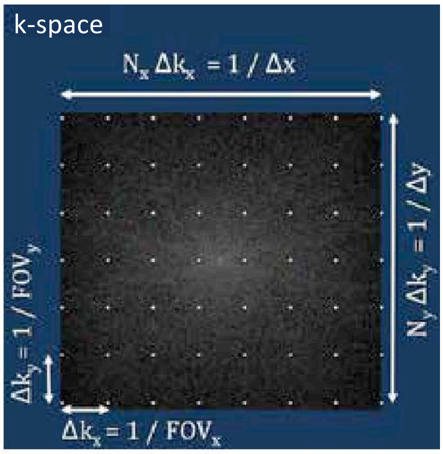


Figure 3.7
Scanning the k-space

The scanning of the k-space plays an important role in the acquisition time. Every repetition of a standard pulse sequence without acceleration techniques fills a single k-space line with information.

The distance between the scan points and the distance between the lines determine the size of the field of view (FOV) in the reconstructed image. The number of these points and rows determines the spatial resolution.