IMPACT 18 …ON MEDICINE: Magnetic resonance imaging

One of the most striking applications of nuclear magnetic resonance is in medicine. *Magnetic resonance imaging* (MRI) is a portrayal of the distribution of protons in a solid object. The technique relies on the application of specific pulse sequences to an object in an inhomogeneous magnetic field.

If an object containing ^{1}H nuclei (protons) is placed in an NMR spectrometer and exposed to a *homogeneous* magnetic field, then a single resonance signal will be detected. Now consider a conical flask of water in a magnetic field that varies linearly in the x-direction according to $\mathcal{B}_0 + \mathcal{G}_x x$, where $\mathcal{G}_x$ is the field gradient along the x-direction (Fig. 1). With this field, the protons will be resonant at the frequencies

$$\nu_L(x) = \frac{\gamma_N}{2\pi}(\mathcal{B}_0 + \mathcal{G}_x x) \quad (1)$$

When the spectrum is recorded while this field gradient is applied, the intensity at frequency ν can be interpreted as the total number of protons present at a particular displacement x (the sum of contributions in the other two dimensions). The spectrum is therefore an image of the sample, as shown in Fig. 1.

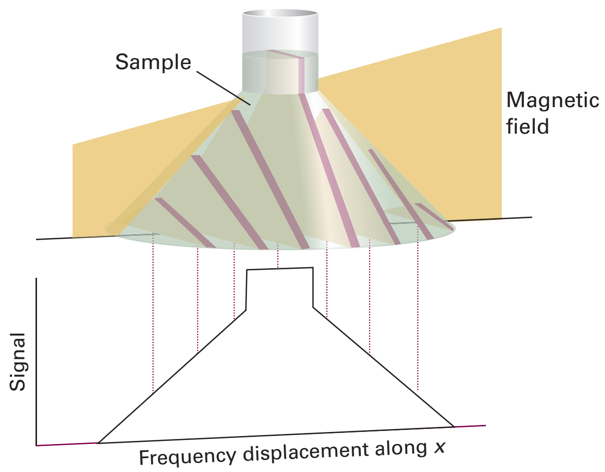

Figure 1 In a magnetic field that varies linearly along the x-direction, the protons in different parts of an object (here a conical flask) resonate at different frequencies. The intensity at a particular frequency in the spectrum depends on the number of protons present at a particular value of x, and therefore the spectrum is an image of the proton distribution in the object.

In principle a three-dimensional image, which gives the density at any point (x, y, z), can be built up by recording spectra while gradients are applied successively along each direction. Current techniques employ pulsed excitation and Fourier transformation and make making extensive use of the special properties of spin echoes (Topic 12C).

To be useful, especially in a medical context, an image needs to show not only the distribution of protons (typically dominated by the protons in water) but also to differentiate between protons in different environments. Achieving this distinction is referred to as creating *contrast* in an image. One strategy takes advantage of the fact that the relaxation times of the protons in water are shorter when the water is bound to various tissues than when it is in bulk form. Furthermore, it is sometimes found that the relaxation times from water associated with healthy and diseased tissues are different. By adapting the experimental protocol used to record the data, it is possible to create images in which the intensity of the signal reflects not only the distribution of the protons but also their relaxation times. Both *T_1-weighted* and *T_2-weighted images* can be obtained, in which the contrast is given by variations in the values of the longitudinal and transverse relaxation times, respectively. It is also possible to differentiate the signals between flowing and static water.

Another strategy involves the use of *contrast agents*, paramagnetic compounds that shorten the relaxation times of nearby protons. Ideally the molecular structure of the contrast agent is developed so that it is distributed differently between healthy and diseased tissues, so highlighting the latter.

The MRI technique is used widely to detect physiological abnormalities and to observe metabolic processes. A development is *functional MRI*, in which blood flow in different regions of the brain is studied and related to the mental activities of the subject. The technique is based on differences in the magnetic properties of deoxygenated and oxygenated haemoglobin, the iron-containing protein that transports O_2 in red blood cells. The more paramagnetic deoxygenated haemoglobin affects the proton resonances of tissue differently from the oxygenated protein. Because there is greater blood flow in active regions of the brain than in inactive regions, changes in the intensities of proton resonances due to changes in levels of oxygenated haemoglobin can be related to brain activity.

The special advantage of MRI is that it can image soft tissues (Fig. 2), whereas X-rays are largely used for imaging hard, bony structures and abnormally dense regions, such as tumours. In fact, the invisibility of hard structures in MRI is an advantage, as it allows the imaging of structures encased by bone, such as the brain and the spinal cord. X-rays cause harmful ionization, so the exposure has to be controlled carefully so as not to be an unacceptable risk to the subject. In contrast, the high magnetic fields used in MRI are not thought to have any deleterious effects. There is some risk associated with the local heating effects of radiofrequency pulses and the switching of the field gradients, but generally speaking the risk from MRI is thought to be low.

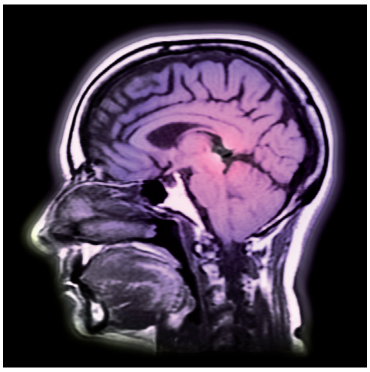

Figure 2 The great advantage of MRI is that it can display soft tissue, such as in this cross-section through a patient's head. (Image copyright: Dr James Holt.)