Handbook of Small Animal MRI

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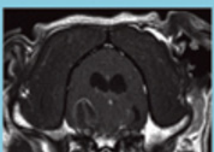

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PART ONE
Physical Principles of MRI

1 Basic Principles

At the time of writing, most veterinary professionals, whether they be surgeons, nurses or students, would probably agree that their knowledge of magnetic resonance imaging (MRI) physics borders on non-existent. Indeed, many may be filled with a deep dread at the very thought of the subject. On the other hand most will have a working knowledge of radiography at least sufficient to know that a radiograph represents a record of the different densities of body tissues through which the x-ray beam has passed. In this chapter the nature of magnetic resonance (MR) will be examined and the measurement parameters involved in constructing a MR image will be discussed.

It is worth beginning by recapping briefly on some radiation physics. In conventional radiography and computed tomography (CT), image contrast, or greyscale, is dependent on density or, more specifically, electron density of tissues in the patient. The more electrons an atom has in its shell the more it will attenuate the x-ray beam. Dense tissues, such as cortical bone, will appear as white in the image whilst air, being least dense, appears black. Since electron density is the only measurement parameter, radiographic and CT appearances are consistent, predictable and, therefore, reproducible. In MRI, however, there are a number of measurement parameters which affect signal intensity and, subsequently, image contrast. This means that the operator can manipulate image contrast to the extent of turning the appearance of water, for example, from black to white. This may appear confusing until the principles are understood. In fact, it is the ability to manipulate contrast in this way that gives MRI its superior soft tissue differentiation.

Later, consideration will be given to how the operator can alter scan parameters in order to produce these changes in image contrast but first of all we should explore the hydrogen proton, how MRI uses radiofrequency (RF) energy to produce resonance and what happens as the proton relaxes when the RF pulse is turned off.

The hydrogen proton

There are several atoms that possess the ability to resonate and can be used to produce images. In fact any atom with an odd mass number such as carbon (13), sodium (23) and phosphorous (31) would be suitable, but in clinical use only hydrogen, with a mass number of one, is used. This is because a single hydrogen atom produces a relatively large magnetic moment and resonates very well; it is said to have a high **gyromagnetic ratio** (γ) and it is abundant within the body.

Hydrogen is the simplest of atoms, having a nucleus composed of a single proton (no neutrons) and has no orbiting electrons; hence it is often referred to simply as a proton.

The proton carries a positive electrical charge and spins on its own axis. This moving electrical charge, according to the laws of electromagnetic induction, creates a corresponding magnetic field around the proton so that it behaves like a tiny bar magnet having north and south poles (Figure 1.1). Such magnetic fields are described in physics as magnetic moments. Each magnetic

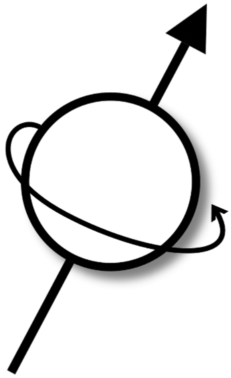

Figure 1.1 The hydrogen proton.

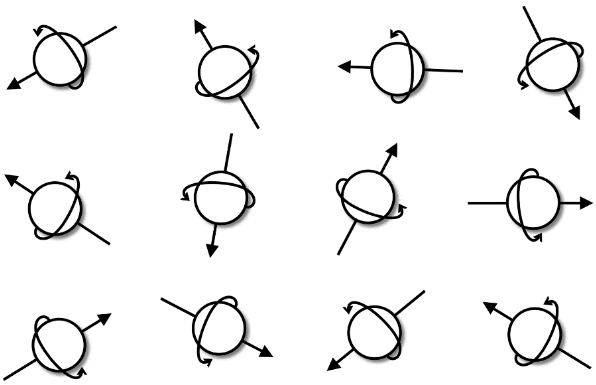

Figure 1.2 In the normal state of affairs magnetic moments are randomly orientated and cancel each other out.

moment possesses the properties of size and direction. Where two or more magnetic moments exist together, their size and direction (or vectors) can be combined to give their net magnetisation. Thus if two magnetic moments exist both having the same size and direction their net magnetisation will be double that of each individual. Conversely if they have the same size but opposite direction the two will cancel each other out and their net magnetisation will be zero. In the normal course of events the body's many billions of microscopic magnetic moments are completely randomly orientated (Figure 1.2) and cancel each other out such that their macroscopic or net magnetic field is zero.

The effects of an external magnetic field B_0

When an animal is placed into the MRI scanner, the external magnetic field (referred to as B_0) causes the protons to abandon their random orientation and 'line up' with the main magnetic field. Current knowledge of magnets and magnetic fields would suggest that the tiny magnetic fields of each proton would adopt an orientation parallel to the main field B_0 with their north and south poles matching those of the main magnet. However the laws of quantum mechanics dictate that certain protons have sufficient thermal energy at room temperature to adopt an opposing, anti-parallel state. Indeed the two populations are almost identical. Moreover the protons are continually oscillating between the two states but at any given point in time, the ratio of anti-parallel to parallel states is one million to one million and six at a B_0 field strength of 1 Tesla (1 T). This excess population of six in one million means that our patient's total hydrogen content has a **net magnetisation vector** (NMV) in the parallel direction (Figure 1.3). With only six in two million protons contributing to the image it seems doubtful that the process will work at all. However, at 1.5 T 0.01 ml of water contains around 3 million billion such excess protons, so things begin to seem feasible.

Since the energy level required to achieve the anti-parallel state increases with the field strength of B_0, and the patient's thermal energy remains fairly constant, it follows that the magnitude of the NMV increases with the field strength of the MRI system we

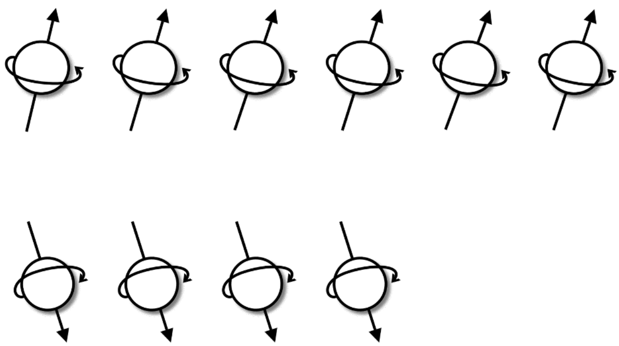

Figure 1.3 The influence of an external magnetic field is to align protons in the parallel and anti-parallel states.

are using. This is an important relationship, since it is the NMV that contributes the useful MRI signal. Hence systems with high field strength magnets generate more signal from the same volume of tissue than lower field systems.

A second influence of B_0 is to cause spinning protons to **precess**. Just as a child's spinning top begins to wobble under the influence of gravity, so protons are made to wobble or precess by B_0. The exact frequency of this precession is given by the Larmor equation:

$$\omega_0 = B_0\gamma$$

where ω_0 can be referred to as the Larmor, precessional or resonant frequency and γ is the gyromagnetic ratio referred to earlier in this chapter and is a constant unique to each atom. Since γ is constant for hydrogen, it can be seen from this equation that precessional frequency is directly linked to field strength B_0 thus:

- The precessional frequency of hydrogen at 1.0 T is 42.57 MHz.
- Therefore its precessional frequency at 0.5 T will be 21.285 MHz.

The exact equation does not have to be remembered, but this is an important relationship to grasp as it will help the understanding of a number of other concepts which follow.

The major effect of this precessional motion is to introduce a transverse component to the magnetic field of each proton since each is now spinning at a slight tilt to B_0 (Figure 1.4). Because the north/south poles of each proton are pointing in random directions at any one time (Figure 1.5), they still cancel each other out in the transverse plane so that the NMV is still in the parallel or longitudinal direction.

The effects of an RF pulse at the Larmor frequency: resonance

If a pulse of radiofrequency (RF) energy is now applied to protons in the system it can cause the hydrogen spins to react to it provided two important conditions are fulfilled. These are that the RF pulse must be applied at right angles to B_0 and that it must be

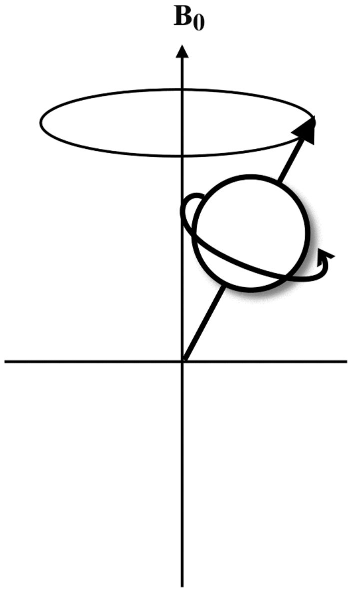

Figure 1.4 Precession.

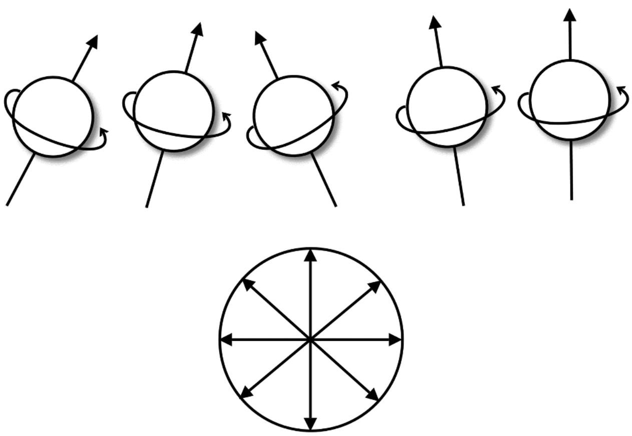

Figure 1.5 Out of phase in the transverse plane.

at the Larmor frequency; any other frequency at this field strength will have no effect on hydrogen.

This reaction to the RF pulse is **resonance** and, essentially, two things happen. One is that the RF pulse imparts sufficient energy to allow more protons to adopt the anti-parallel state The six

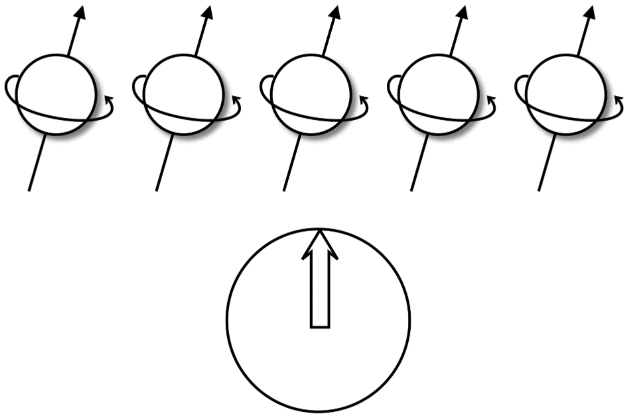

Figure 1.6 In phase in the transverse plane.

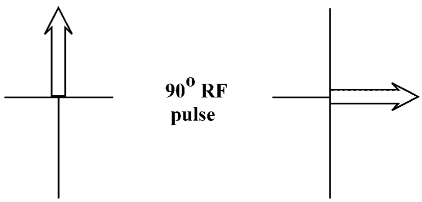

Figure 1.7 Net magnetisation passes through 90° from longitudinal to transverse planes.

excess protons discussed earlier provide an illustration of what happens if enough RF energy is transmitted to allow three of these to flip into the anti- parallel position. They will then cancel out the other three in the parallel state and the NMV in the longitudinal plane will now be zero. The other effect, which takes place in the transverse plane, is to bring all our hydrogen spins into phase with each other. Now, instead of all the spins cancelling each other out, each microscopic magnetic field is in unison with its neighbours; they are said to be 'in phase' (Figure 1.6).

Consequently their individual magnetic fields all add together so that the NMV is now at a maximum in the transverse plane. The NMV has shifted through 90° from longitudinal to transverse. If the RF transmission is terminated at this point it is said to be a **90° RF pulse** (Figure 1.7). Note that the angle through which