Module 2

Nuclear magnetic resonance - the basis of imaging

After reading this module, you will:

- Be familiar with the magnetic characteristics of the hydrogen nucleus (spin, precession, the Larmor frequency).
- Understand the relationship between the individual spin orientation and overall magnetization direction.
- Be able to describe the phenomenon of magnetic resonance.
- Be able to differentiate between spin lattice and spin-spin relaxation.
- Be able to assign the relaxation times T1 and T2 to the relaxation processes.

2.1 The nuclear spin

An atomic nucleus is made up of two nuclear elements: neutrons and protons. Each one of these nuclear constituents features identical magnetic characteristics. It also exhibits a "spin" or magnetic moment. If a nucleus has an even number of neutrons and protons, the spins cancel each other out. Such a nucleus cannot be used for an MRI examination. This technique queries the total spin, which for such atomic nucleus is equal to zero.

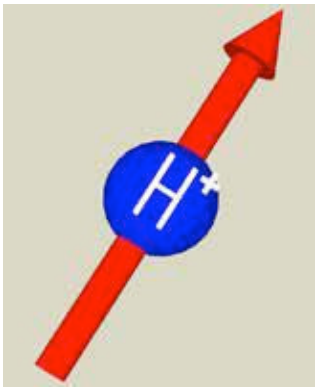


Figure 2.1:
The magnetic moment of a hydrogen nucleus

If a nucleus has more neutrons than protons or vice versa, this produces a total spin other than zero. In principle, all atomic cores with a total spin other than zero (e.g. ^{17}O, ^{19}P, ^{13}C) can be used in a MRI examination.

Hydrogen nuclei have an especial significance in the MRI process. This is due to their special physico-chemical characteristics and the high proportion of hydrogen in organic materials (~99.9%). The atomic core of hydrogen ^{1}H consists of a single proton and thus has a spin of ½.

An individual hydrogen nucleus can be treated as a molecular magnet which is able to revolve and align itself arbitrarily. It is advantageous to assign the spin axis (the direction of the magnetic moment) a vector ("a directional arrow"). The measuring system (including the coils etc.) is aligned to the measurement of hydrogen resonance; conducting examinations with other nuclei types requires considerable effort. Only very few clinical MRIs are not based on the resonance of hydrogen nuclei.

Only highly-specialized applications do not work on this basis. For example, an adapted device can be used to examine ^{17}O, in order to depict local morphological and functional alterations of the lung in patients presenting chronically-obstructive diseases of the lung.

At room temperature and free of any external influences, individual spins present an arbitrary alignment; the small magnetic fields of the nuclei thus balance each other.

This is similar to the principle behind a game of Mikado. With all the sticks lying on the table without any pattern, it is impossible to decide the direction in which they predominantly point. The sum of the combined magnetic moments of all the hydrogen nuclei (some 1^{23} in the body) is referred to as the overall magnetization or the macroscopic magnetization. In this case, it is zero.

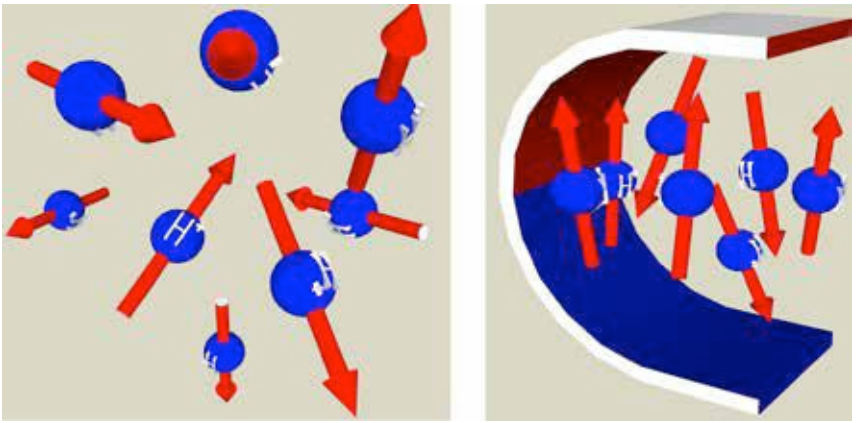


Figure 2.2
Left: nucleus in a random alignment.
Right: A spin system in the exterior magnetic field: the parallel and anti-parallel state.

When a hydrogen nucleus is placed in a magnetic field, it also behaves as a small magnet. As the forces impinging on it are minimal, it straightens itself.

Some of the spins align themselves parallel to the field; others align themselves in an anti-parallel fashion. We would expect that the spins would divide in both directions in identical numbers, bringing the overall magnetization to zero. Nevertheless, the complicated physics of the matter means that the parallel state is favoured slightly. At room temperature and with a magnetic field strength of 1.5 T, only six "excess spins" are matched by a million spins. This minimal difference provides the basis for the MRI process.

Extrapolating this for a water cube of 1 mm edge length makes for 400 billion excess spins. These elementary magnets generate a directed overall magnetization unequal to zero. The state of the overall magnetization with the excess spins in a magnetic field is referred to as the steady state.

2.2 Precession, the Larmor frequency

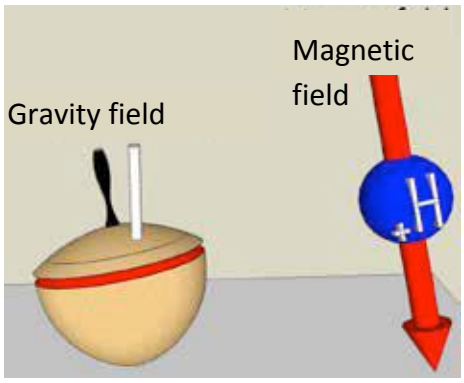


Figure 2.3:
Spinning top vs. spin

The spins rotate on their own axis. At the same time, they also orbit the axis of the adjacent magnetic field just as with a child's spinning top (precession):

Rotating around its own axis of symmetry and usually not standing entirely straight, the influence of the Earth's gravitational field causes it to "stagger" around a perpendicular axis, i.e. along the gravity lines.

This precession movement of the spin is characterized by the Larmor frequency, which is proportional to the strength of the exterior magnetic field B_0.

The proportionality factor is the gyromagnetic factor γ, which is different for every type of nucleus. Placing hydrogen in a magnetic field with a strength of 1.5 T means that it will precess with an almost inconceivable frequency of 63.8 MHz (63 million revolutions per second).

2.3 Nuclear magnetic resonance and stimulation

Were we to hit a spinning top from above (a disruption), it would first stand at an angle, rotate further and then begin to precess. We would also see how it begins to straighten up slowly. Energetically, it is better for the spinning top to align itself parallel to the lines of the Earth's gravitational field. The top must work against the gravitational forces impinging upon it before it begins to straighten up.

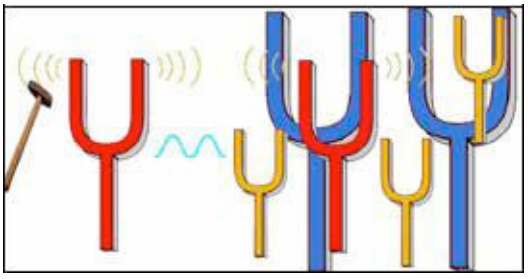


Figure 2.4
Resonance

This process costs energy and the top becomes slower. The behaviour of the spins follows the same principle. In this case, the disruption is generated by a different source: an electromagnetic wave (high-frequency stimulus B1) is issued perpendicular to the static field. If the frequency of the wave is identical to the Larmor frequency of the hydrogen spin, the two can react with each other.

Not in resonance, the other nuclei do not receive a stimulus. This reaction causes the hydrogen nucleus to take on energy and it is deflected from its steady state. Just as with the spinning top, the spin would like to precess along the static field. Whilst the spin system returns to the steady state (relaxed) energy is released in the form of (harmless) electromagnetic radiation. Often referred to as nuclear magnetic resonance (NMR), this signal is measurable.

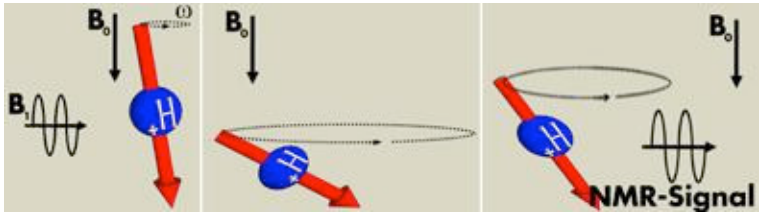
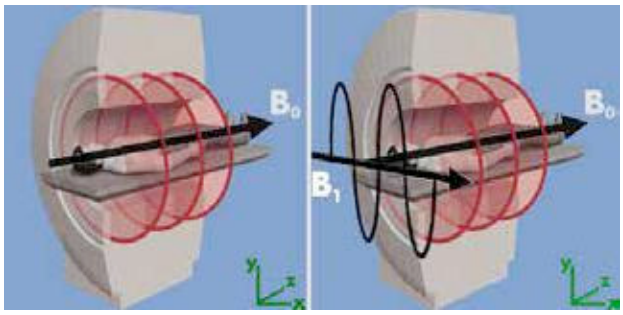


Figure 2.5:
HF stimulus
Relaxation process and NMR signal

2.4 Relaxation processes – T_1 and T_2 time



The return of the overall magnetization to the steady state is referred to here as relaxation. This process can be divided into two parts. First it is necessary to define our terms: "Longitudinal" refers to everything which proceeds along the static field. This is also the craniocaudal direction of the patient in the scanner, usually referred to as z-axis in a co-ordinate system.

Figure 2.6:
The T_1 scanner co-ordinate system

"Transversal" on the other hand, refers to all those processes which take place on the transversal level, i.e. perpendicular to the B0 direction. The stimulus pulses (B1) are projected on the transversal level. Let us return to relaxation. We differentiate between:

- The longitudinal relaxation which corresponds to the restoration of the longitudinal (along the static field) magnetization.
- The transversal relaxation which reflects the loss of magnetization in the direction of the stimulus pulse (perpendicular to the static field).

2.4.1 T_1-relaxation or longitudinal relaxation

Longitudinal relaxation following a stimulus is based on the interaction of the spins and the material surrounding them. In order to return the overall system to a balance (parallel and anti-parallel states) it is necessary to bring the individual deflected spins to emit their additional energy taken from the stimulus to their environment - the lattice.

As a result, longitudinal relaxation is often referred to as spin-lattice relaxation. Regaining macroscopic magnetization along the static field can be depicted with an exponential curve. The speed (rate) of this process is tissue-specific and is described by the time constant T_1.

After the T_1 time, the longitudinal magnetization has returned to 63% of its initial value. Given a field strength of 1.5T, biological materials present typical T_1 values of between c. 200 to 3000 ms. The times extend with larger field strengths (e.g. 3.0 T devices).

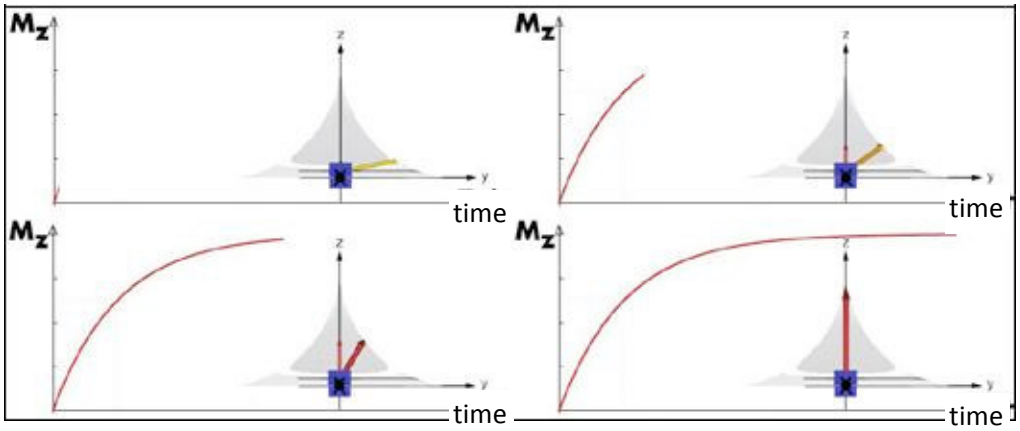


Figure 2.7

T_1-relaxation or longitudinal relaxation

2.4.2 T_2-relaxation or transversal relaxation

Even in their basic state, the spins exhibit continual and short-term random interaction with each other (spin-spin coupling). Over time, this slowly alters their precession movement.

As outlined above, in their basic state, all the spins rotate around their own axis at approximately the same frequency; the spin-spin coupling means however, that they are entirely out of phase.

This changes after the stimulus: the spins are no longer tipped in the x-y area but are now aligned uniformly (in phase).

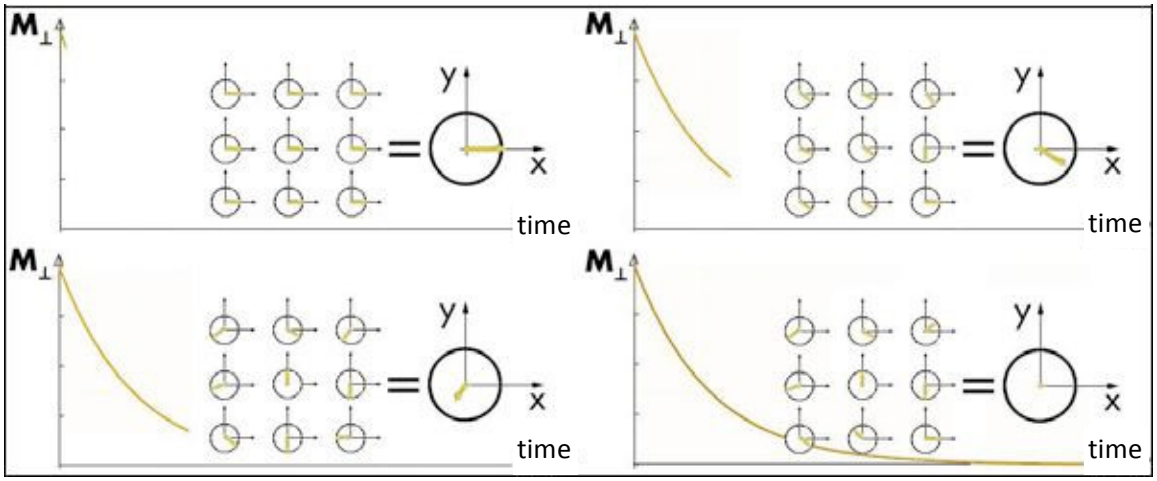


Figure 2.8:
T_2-relaxation or transversal relaxation

All the spins point in the same direction immediately after their stimulation (e.g. 3 o'clock). All the spins should now rotate at the same speed in one direction (e.g. clockwise). This uniformity decreases over time: some spins will interact randomly; one slows down and the other speeds up etc.

After a while (with 63 million revolutions per second per spin this period is short) all the spins are out of phase once again. This is transverse relaxation. Identified with the time constant T_2, and as with T_1, it is tissue-specific. Unlike T_1 however, it is not dependent on the exterior field strength.

The interaction of the spins with each other is significantly more intensive than that with the surrounding "lattice". Transverse relaxation is completed significantly faster than its longitudinal counterpart: the T_2 time (i.e. the time after the transverse magnetization has declined to around 63% of the maximum) is ever-shorter than the T_1 time of the corresponding tissue.

2.4.3 The significance for imaging

Differentiating between different forms of tissue on an image requires a contrast to be generated. Every type of tissue (muscle, grey/white matter etc.) has its own unique specific number of spins per volume unit.

You need only look at the difference between a piece of liver and a piece of meat muscle when cooking and this becomes immediately clear. Just as they present a different consistency, they also contain a different proportion of hydrogen. This means that each material presents its own spin density ρ. Using the various densities as a source for the contrast is nothing new. Indeed, it represents common practice in x-ray imaging.

Nevertheless, two tissues which need to be differentiated in an image often present the same level of radio-density. In the case of prostate cancer, it is not even possible to depict the substructure of this gland with a CT scan. The same applies to the example (see figure 2.9) of a hepatocellular carcinoma (HCC) in the tissue surrounding the liver. The tumour is visible only with the use of a contrast agent. The hypervascularization of this type of tumour leads to the accumulation of the agent in the lesion when added, reducing the regional signal strength and indicating its presence.

It is often impossible to identify soft-tissue tumours even when using a contrast agent.

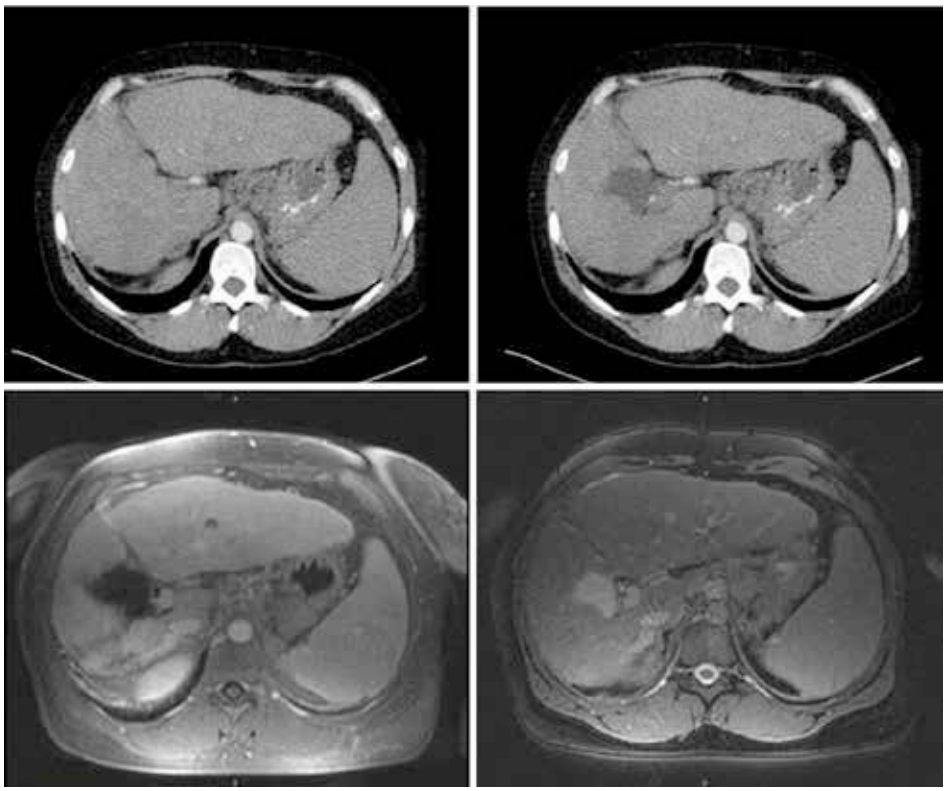


Figure 2.9
Above: With and without a contrast agent. Below: T_1 and T_2-weighted MRI images

An MRI provides a total of three parameters (T_1, T_2, and the spin density ρ). The majority of biological materials present differences in at least one or two of these variables (see table).

These parameters can be used to "weight" the images. This means that MRI can be used not just to measure the density of the spins, but also the strength of their reaction with their nuclear environment (T_1) and other spins (T_2).

The example of the HCC in the liver shows that the lesion can be revealed without contrast material in both the T_1 and T_2-weighting. Chapter 4 explains how we arrive at the individual image-weightings.

Tissue	T_1[ms]	T_1 tumorous [ms]	T_2 [ms]
Grey matter	920 ± 160		101 ± 13
White matter	680 ± 120		92 ± 22
Muscle	870 ± 160	1,200 ± 220	47 ± 13
Liver	500 ± 110	860 ± 120	43±14
Bones	520 ± 100	1,030±160	80 ± 25
Fat	260 ± 70		84 ± 36

Table 2.1:

Typical relaxation times in various tissue types at 1.5T

PP-PF-RAD-ALL-0534-1