Module 1

The structure and safety aspects of a magnetic resonance imaging scanner

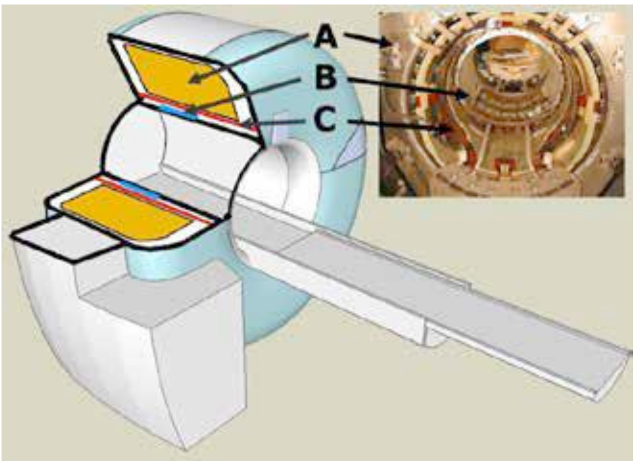
After reading this module, you will:

- Understand of the structures of a scanner, the functions of its components and the associated safety aspects.
- Be familiar with the contraindications of MRI and be able to take them into account before undertaking a patient examination.
- Know about the possible side effects associated with MRI (circulating current in the body, nerve stimulation, knocking sounds, SAR threshold values) and be able to assess and manage them.

1.1 The structure of an MRI scanner

An MRI scanner for clinical use consists of:

- (A) A superconducting magnet for the generation of the static main magnetic field.
- (B) A system of conventional coils for the generation of the gradient fields (the gradient system).
- (C) A transmitter and receiver system for electromagnetic high-frequency waves.
- (D) A computer system for image processing and an operating console for the planning and post-processing of the images.
- (E) A high-frequency shield for the scanner (Faraday cage).



The purpose and necessity of these components in the imaging process will become clear during the course of the next chapters. We need to begin with an examination of the safety aspects associated with MRI technology.

1.1.1 Superconducting magnets

Magnetic resonance imaging is predicated on the presence of a (strong) static magnetic field. This is generated with current-carrying coils. A magnetic field develops in the interior of such a coil: this explains the name "electromagnet." MRI scanners come in a number of forms. The most common are those with closed tubes with a diameter of 60-70 cm. These are known as closed-bore scanners. Open systems, on the other hand, consist of two coils arranged either horizontally or vertically opposite each other. These are sometimes known as the "double doughnut". Providing relatively good access to the patient, such systems are especially suited for interventional procedures. The inhomogeneous static magnetic field which they produce makes them less suitable for diagnostic purposes.

Figure 1.1
Left: The closed Siemens MAGNETOM Trio (3.0 T). The magnetic field runs through the tube, parallel to the position of the patient. Right: The open Philips Panorama (1.0 T). By kind permission of Siemens AG and Philips GmbH.

The MRI scanners most common to clinical practice use a static magnetic field of 1.0 Tesla (T) and greater. A common strength is 1.5 T. The field is generated with superconducting electromagnets. In comparison, at something between 0.00003 T and 0.00006 T, the Earth's magnetic field is considerably weaker. Tesla is thus a large unit of measurement for the magnetic flux density. A great deal of energy would be required to generate a permanent static field of this strength using a conventional coil. The electromagnet would become extremely hot. Instead, the electrical conductor is cooled until the material becomes superconducting. This means that almost no energy is converted into heat: any current fed into this conductor remains (almost) forever. Permanent cooling is required to maintain this superconducting state. Cold (-269 °C) fluid helium is used to this end.

The use of helium is associated with a number of drawbacks and risks. Helium is not only very expensive, but the sudden release of energy following an Emergency-Stop of the magnet causes its evaporation (quenching). Modern systems are fitted with special extraction systems and safety equipment to respond to such incidents. This prevents the risk of thermal burns or asphyxiation for operator and patient alike. Should an accident occur which triggers an Emergency-Stop, it is necessary to check the magnet. It must then be "reloaded" and recalibrated. The costs involved amount to tens of thousands of Euros. The costs of the downtime is not included in this calculation. To quote the Nobel Prize winner sir Peter Mansfield, one of the inventors of the MRI: no member of staff should "quench" a magnet more than once in their lifetime. It is rumoured that a number of his staff have done this many times.

1.1.2 The dangers involved with high magnetic fields and the requisite safety measures

A number of fundamental safety conditions must be maintained not only to avoid quenching, but to safeguard the safety and life of patients and staff. The static magnetic field is ALWAYS present and deletes all magnetic data carriers (credit cards etc.), destroys electronic devices (mobile telephones) and attracts metal objects, This does not depend on their weight (e.g. drills), which will fly towards and into the scanner at high speed. Patient beds, wheelchairs, oxygen cylinders (emergency patients) and small objects (keys, biros, scissors etc.) require attention.

Figure 1.2:
"MRI-compatible" contrast agent pump in a Philips Intera (1.5 T)

Patients should not just be checked for metallic objects or electronic devices on their body, but also in their body. Especial attention is to be paid to:

- Intraocular foreign bodies (metal workers).
- Shrapnel or the residue of ballistic traumas, body piercing.
- Intracranial aneurysm clips, metal stents (rare).
- Metal prostheses or implants.
- Pacemakers, neuro-simulators, inner-ear implants and defibrillators (gradients)
- Extensive tattoos, dental prosthetics etc. (HF system).

This chapter now provides a summary of all the important contraindications; as some are not related to the static field they will be classified later.

"Modern" prosthetics (made of non-ferroelectric materials such as titanium, titanium compounds, nitinol and tantalum compounds) are entirely uncritical in this respect. Modern aorta stents are also entirely MRI compatible. The presence of lightly-magnetic materials, such as the stainless steels widely used in orthopaedic prosthetics, the scan must be completed 6-8 weeks after the point of implantation in order to avoid delocalization within the body.

Should you be unsure as to the MRI compatibility of any material, consult www.mrisafety.com. This is of especial significance when working with magnetic fields at the higher end of the spectrum. A number of instruments (e.g. biopsy needles) which do not present a risk at 1.5 T can pose a danger when subject to higher field strengths. This can result in sparks during the imaging procedure.

1.1.3 The gradient system

As later chapters will show, the magnetic field gradients are required for the spatial localization of the images. They produce a linear alteration of the strength of the static magnetic field along a spatial direction. This alteration is significantly smaller than the main magnetic field. It is generated by pairs of non-superconducting coils (i.e. switchable and not on permanently) arranged in each of the three spatial directions. The direction of the main magnetic field is not changed by the gradients.

The capacity of a scanner in terms of image quality, scan time and level of distortion depends to the greatest extent on the quality of the gradient system. This depends on:

- The maximum gradient strength (alteration of the magnetic field in mT/m), which restricts the spatial resolution of the images (slice thickness).
- The time-reversal pulse, i.e. the speed at which the direction of the gradient can be reversed. This is important for fast and ultra-fast imaging and essential for cardiac MRI.
- The gradients' linearity within the scan range. Inhomogeneities result in incorrect localization data and image deformation which hampers diagnostic evaluation.

1.1.4 The safety aspects of gradient systems

A fast gradient reversal induces currents in conductive materials in the surroundings of the gradient coils (cooling system, electrical conductor, shim coils etc.). These induction currents (eddy currents) work against the gradients, disturbing their homogeneity but can also be reduced via active screening.

The gradients generate forces which themselves generate intense vibrations in the coils and the surroundings. These vibrations cause the characteristic noises emitted by the MR device and can easily exceed 100 dB. Patients must wear ear protection.

The eddy currents can also cause electrical malfunctions in devices and destroy pacemakers etc. (see above). The rapid reversal of the gradient magnetic fields can result in a peripheral muscle or nerve stimulation. Potentially dangerous stimulations of the heart have a significantly higher stimulation threshold and can be discounted.

Echo-planar imaging sequences (see chapter 5) are affected most strongly by stimulation effects, as the gradient is reversed from a maximum to a minimum in the shortest of time. Patients should be prepared accordingly. A rule of thumb - the faster the imaging, the greater the stimulation.

1.1.5 The high-frequency system and the control computer

Magnetic resonance imaging contains the word "resonance" because the imaging is based on the resonance (interaction) of electromagnetic high-frequency waves with atomic particles in the body. The high-frequency (HF) system required to implement this consists of multiple components for the transmission and reception of HF waves which are sometimes also referred to as radio frequency waves.

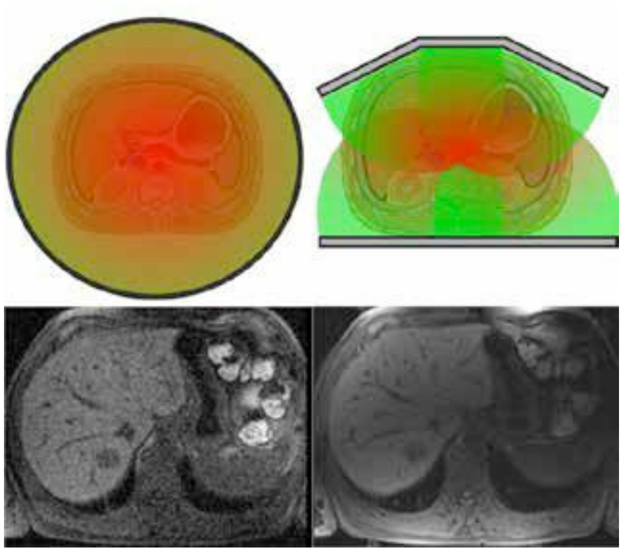


Figure 1.3:
Left: A large coil element (left) has a greater sensitivity volume than multiple coil elements (right). Nevertheless, should these be connected with each other, they absorb significantly less background noise. The SNR increases visibly.

This process serves both to generate the signal and the subsequent (location encoded) signal acquisition. It is subject to detailed explanation in the next chapter. Coils again represent a central element of this system.

The transmission mode seeks to achieve the most homogeneous stimulation possible in the scan volume. In reception mode on the other hand, a high coil sensitivity and a good signal-to-noise ratio (SNR) is required. A MRI scanner is usually equipped with a coil covering the whole extent of the body. Integrated in the cylinder and thus hidden from view (see figure on page 4, element C) and almost the entire scan volume is covered equally. The stimulation is almost always performed by this system, whilst the reception is very often achieved by placing local surface coils placed directly over the examination area.

Although they present a significantly higher sensitivity (SNR), they have a lower range and exhibit highly heterogeneous receiver characteristics. The selection and correct combination of the coils in the practice thus attain considerable significance. The homogeneity and reception depth of the surface coils can be subject to a decisive improvement through interconnection, forming a "phased array." Alternatively, it can be used to accelerate the acquisition in so-called parallel imaging.

All this requires a high-performance and stable computer which is able to convert the raw data into a spatial image and present it for further processing. The co-ordination of the various examination steps, the imaging sequences, and the image reconstruction is performed on an internal computer system and controlled from an external operating console. All the digital processing steps (ADC maps etc.) are also performed on this console.

1.1.6 Disruption of the high-frequency system

By chance, the resonance frequency of the atomic particles in the body subject to examination in the MRI lies in the frequency range of normal radio transmissions in the FM range. Consequently, the scanner is locked in a Faraday cage which isolates the highly-sensitive system of external HF waves.

This complete copper cage (including the doors) must be closed carefully during all examinations. Depending on the imaging sequence, apertures and “antennae” in the interior of the scanner can result in severe distortions of the images produced.

Such an “antenna” could be a connector not plugged into a device properly (e.g. an anaesthetics device) in the MRI room. This matter will be subject to discussion in the section "Image quality and artefacts".

1.1.7 The safety aspects of high frequency systems - SAR

The specific absorption rate (SAR) corresponds to the amount of energy absorbed by a patient through their exposure to high-frequency waves. Although part of this energy is always converted into heat - resulting in a temperature increase - this is always restricted by very strict threshold values.

Expressed in W/kg, the SAR is automatically calculated by a scanner before an examination can be started. In consequence, the operator should always enter the patient weight into the system before starting the scan. The safety standards have been drawn up in such a way as to prevent the warming of patient tissue over 1 °C.

Should the threshold value (IEC 60601-2-33 standard) be exceeded, the operator must adapt the examination parameters in order to be able to start the scan. This can be achieved by, e.g. increasing the TR time (a longer examination time), reducing the number of slices or the flip angle (the strength of the stimulus).

This internal control mechanism does not prevent the risk of skin burns, which under certain conditions, result from exposure to high frequencies and the currents induced in "closed current circuits". In consequence, patients should not fold their hands on their upper body. When connecting ECG devices, you should ensure that the cables do not form loops. Make sure to avoid direct skin contact.

A greater risk is that of the warming of areas of skin covered by extensive tattoos, metallic pigments, subcutaneous implants, body piercings and dental prosthetics. This can result in burns.