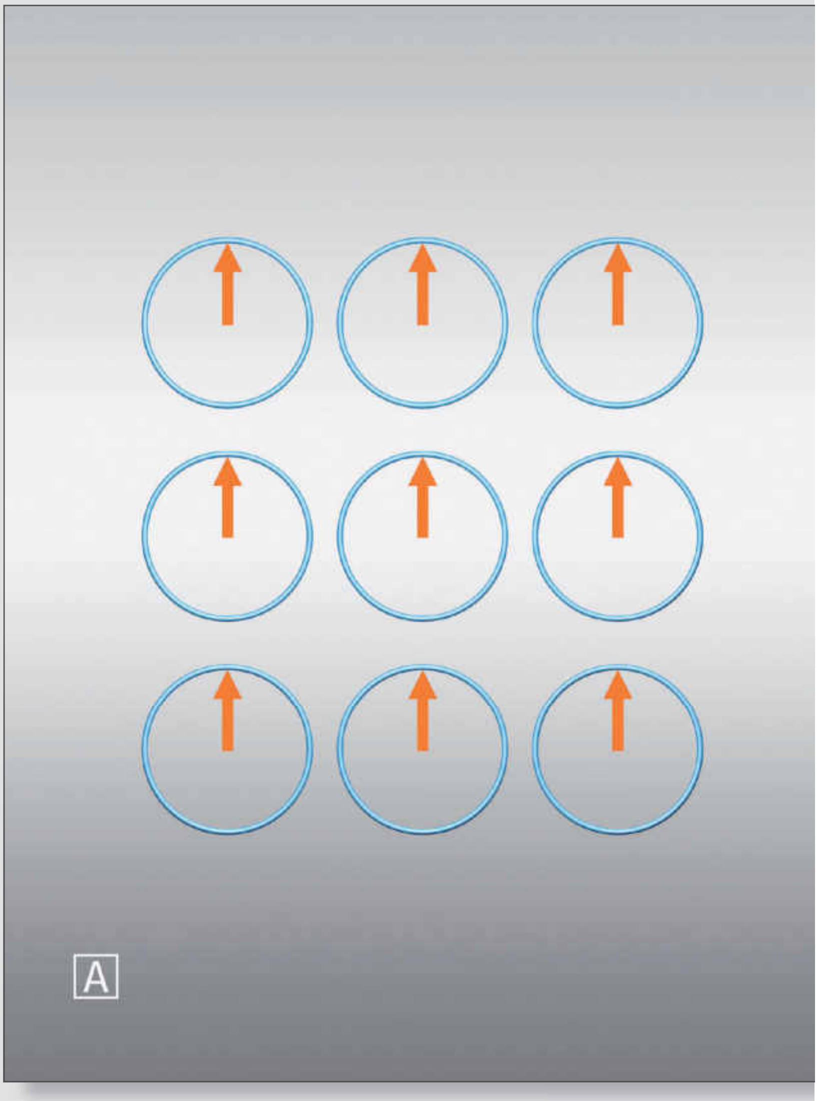
Where does the signal come from?

Now we have selected position and thickness of our slice. But how can we find out, from what point of our slice a certain signal is coming from – information that we must have to construct an image? The trick is similar to the slice selecting gradient, which is turned on only during application of the RF pulse.

After the RF pulse is sent in, all protons in the slice precess with the same frequency.

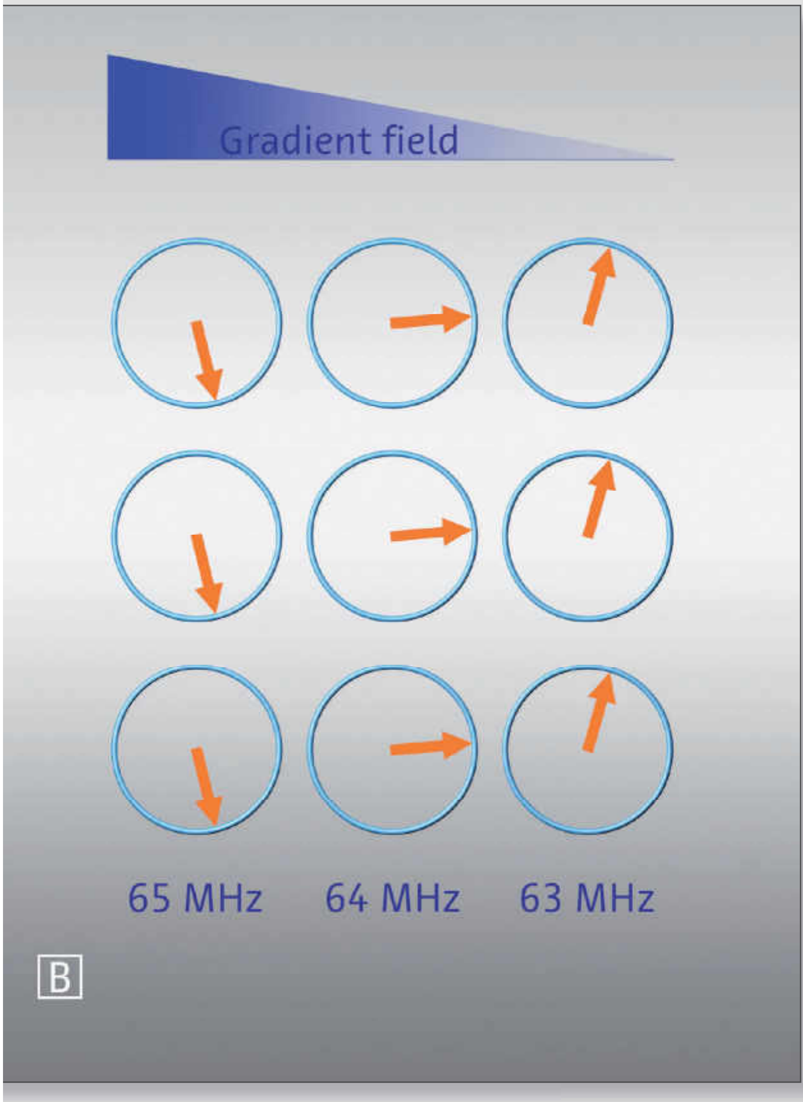
We now apply another gradient field which – in our example – decreases from left to right. So the precession frequency of the protons

Fig. 59: To determine where in a certain slice a signal comes from, we use a magnetic gradient field. In (A), nine protons in the same slice are depicted. They precess in phase with the same frequency, after the RF pulse is sent in. A magnetic gradient field is then superimposed on the external field, which in (B) decreases in strength from left to right. The protons in the three columns now experience different magnetic fields, and thus give off their signals with different frequencies (e.g. 65, 64 and 63 MHz). The corresponding magnetic gradient is called **the frequency encoding gradient.** We now can tell from which column a signal comes from, but still cannot pinpoint the exact place of origin.



will also decrease from left to right (in our example, the precession frequencies are 65, 64 and 63 MHz, respectively).

The result is that the protons in the different columns emit their signals with these different frequencies. The gradient applied is thus called the **frequency encoding gradient**. However, all protons in one column will still have signals with the same frequency. We now can tell by the frequency from which column a signal comes from, but still cannot pinpoint the exact place of origin in a particular column. As this is not enough spatial information, we have to do something else.



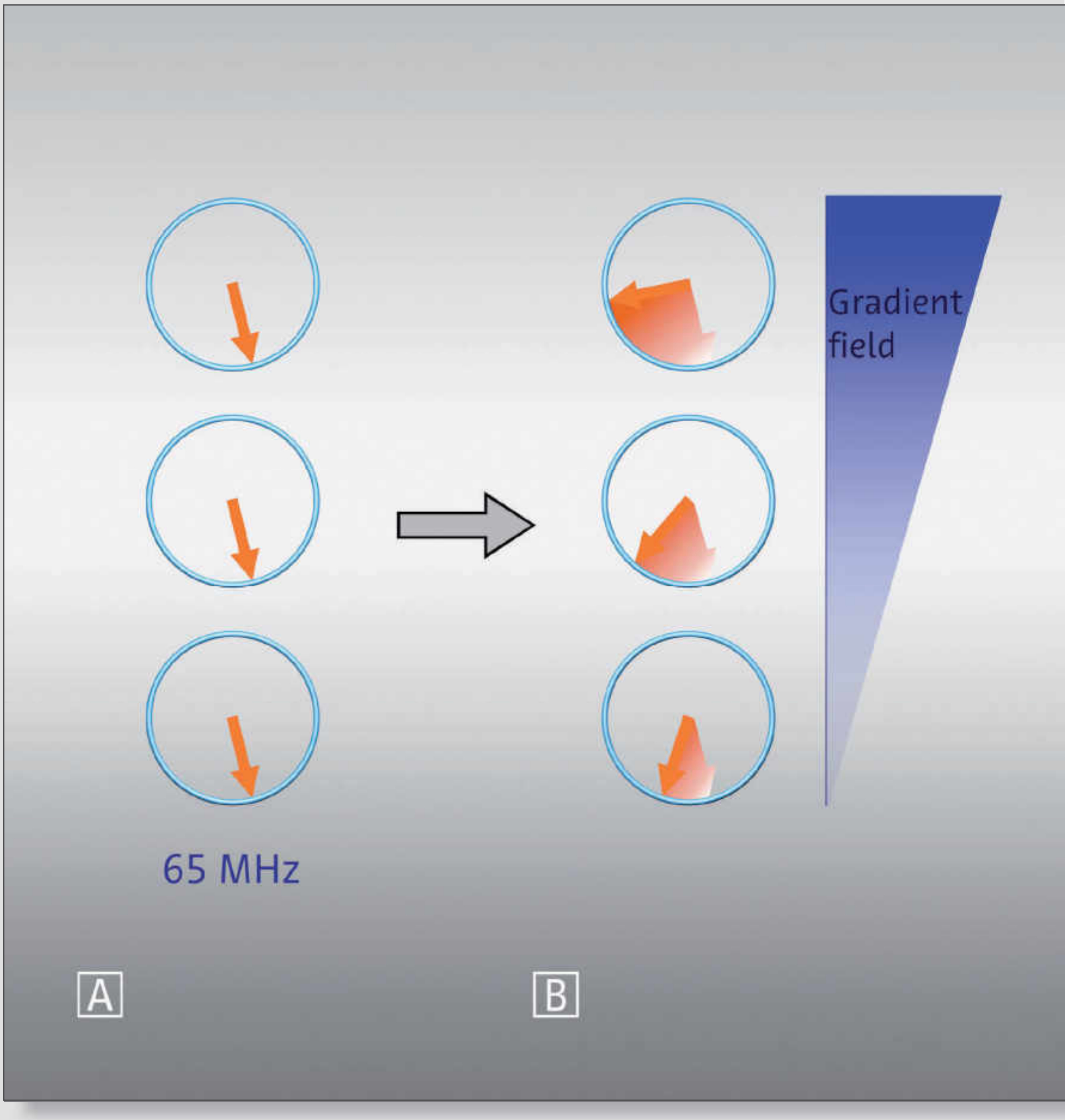
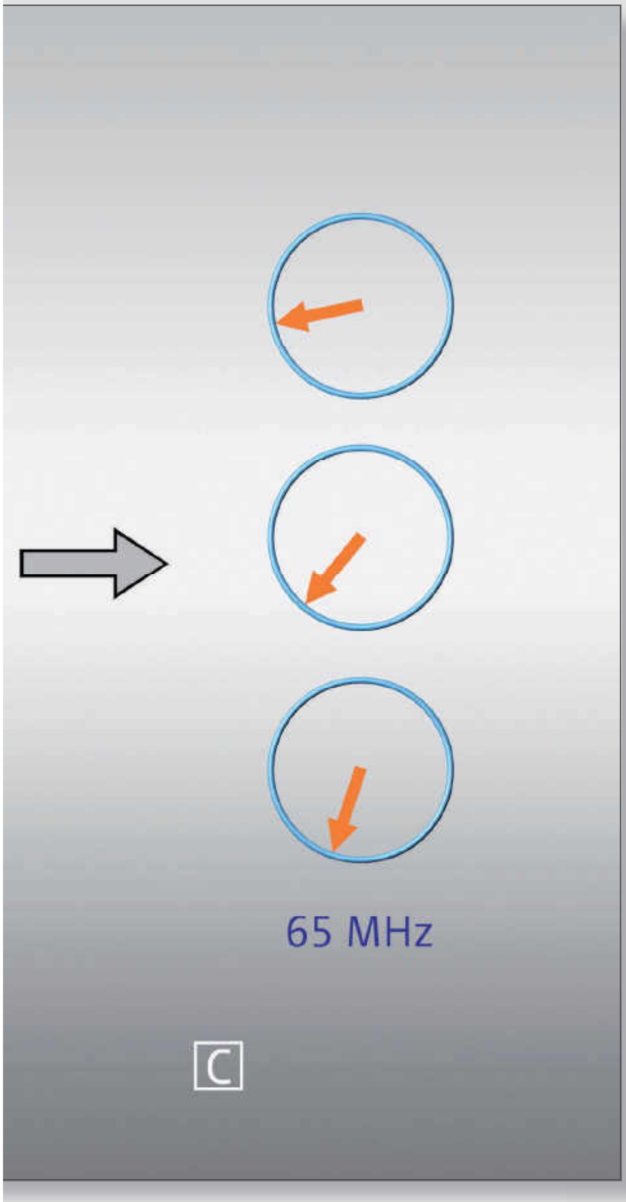


Fig. 60: To find out where in a column with the same frequency a certain signal comes from, we use an additional gradient. In (A), the column with the precession frequency of 65 MHz from figure 59 is depicted. We now switch on a gradient field, which is stronger at the top than at the bottom of the column for a very short time (B). The proton at the top thus precesses faster than the one in the middle, which in turn precesses faster than the proton at the bottom. This difference in precessing frequency only lasts for a very short time; when the gradient is switched off, all protons experience the same magnetic field again, thus have the same 65 MHz precession



frequency again (C). However, now we have a little difference among these protons: even though they precess with the same frequency again, they are a little out of phase, and consequently give off signals of the same frequency, which are different in phase and, because of this, can be differentiated. The corresponding gradient is called the **phase encoding gradient**.

Theoretically, we could use the same trick with the magnetic gradient again. This, however, causes some practical difficulties, e.g. this may result in two points at different locations having the same frequency. To solve the problem, something different is done, which is illustrated in figure 60.

In figure 60, we just look at the protons of one column from figure 59, the 65 MHz column. The protons are in phase after the RF pulse "whipping". Now we apply a magnetic gradient along this column for a short time. This causes the protons to speed up their precession, according to the strength of the magnetic field to which they are being exposed. In our example (figure 60B), the proton at the top thus precesses faster than the one in the middle, which in turn precesses faster than the proton at the bottom.

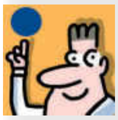
When this short gradient is switched off, all the protons of the column experience the same magnetic field again, and thus have the same precession frequency. However, there is an important difference: Formerly, the protons (and their signals) were in phase. Now the protons and their signals still have the same frequency, but they are out of phase. (This can be viewed as if their magnetic vectors come by the antenna at different times.)

As the gradient which we used causes protons to precess in different phases, it is called the **phase encoding gradient**.

How this phase encoding actually works is too complicated for a basic introduction; if you are interested in more details, grab a copy of "MR Buzzology" for further reading.

For here it is enough to know that all of these different signals now can be assigned to a certain location in the slice, so we now can reconstruct our image.

Let us repeat:



- We can select a slice to be examined by using a gradient field, which is superimposed on the external magnetic field. Protons along this gradient field are exposed to different magnetic field strengths, and thus have different precessing frequencies. As they have different precession frequencies, we can send in an RF pulse that contains only those frequencies, which excite the protons in the slice we want to image.
- Slice thickness can be altered in two ways: by changing the bandwidth of the RF pulse, or by modifying the steepness of the gradient field.
- The slice selecting gradient is only turned on during the RF pulse.
- To determine the point in a slice from which a certain signal is coming, we use two other gradients, the frequency encoding gradient and the phase encoding gradient.
- The frequency encoding gradient is sent in after the slice selection gradient. In our example, it is applied in the direction of the x-axis. This results in different precession frequencies along the x-axis, and thus different frequencies of the corresponding signals.
- The phase encoding gradient is turned on for a short time after the RF pulse, along the y-axis in our example. During this short time, the protons along the y-axis precess with different frequencies. When this gradient is switched off, they go back to their former precession frequency, which was the same for all of them. Due to this phase encoding gradient, however, the protons and their signals are now out of phase, which can be detected.

With all this frequency and phase information we can now assign a certain signal to a specific location which results in our MR image (... finally!).

A few more basics

So far we have discussed just about every important aspect of MR basics. But: why have we always talked only about the proton, the hydrogen nucleus? What about other nuclei?

As you recall, atoms have a nucleus made up by **protons** and **neutrons**. An exception is the **hydrogen** nucleus, which only consists of one proton. And when we talk about the proton, we talk about the hydrogen nucleus, as both are the same (the terms proton and hydrogen nucleus can thus be used interchangeably). The hydrogen nucleus is best for MR imaging, as hydrogen occurs in large abundance throughout the body. Hydrogen also gives the best signal among the nuclei: from an equal number of different nuclei in the same magnetic field, hydrogen gives the most intense signal. All of the routine MR imaging is proton/hydrogen imaging nowadays. However, research is being done on the use of other nuclei, like **sodium**.

Can we use all other nuclei for imaging?

The answer is no. There are two important pre-conditions both of which must be fulfilled.

- Firstly, we can only use nuclei that have a spin.

This can be easily explained: as we saw at the beginning, the protons were spinning around, and thus their electrical charge was also spinning, moving. And the moving electrical charge was the current that caused the magnetic field of the proton, which was the basis for everything. If it weren't for the spin, there would be no magnetic field.

- Secondly, the nucleus must have an odd number of protons (and neutrons, but this will go into too much physics, so we will only talk about the protons). Why an odd number? Just think about the proton as a little bar magnet. If you have a nucleus with two (or any other even number) protons, these little bar magnets would cling together like any other magnets (opposite poles attract).

The result: their magnetic moments would cancel each other out. If we have a nucleus with an odd number of protons, e.g. three, pairs of protons will still cling together and neutralize each other. However, there will always be one proton left that still has a magnetic moment. Nuclei with odd numbers of protons thus have a magnetic moment, and can principally be used for MRI.

Examples are: **carbon-13**, **fluorine-19**, **sodium-23**, **phosphorus-31**.

MR Hardware – an overview

Let us have a look at some hardware. The most important part of the MR machine is the main magnet, which has to be pretty strong to allow MR imaging. The strength of a magnet is given in **Tesla** or Gauss, where 1 Tesla = 10,000 **Gauss**.

Gauss was a German mathematician, who was the first to measure the geomagnetic field of the earth. Tesla is considered to be the "father" of the alternating current. He was a peculiar fellow, having refused to share the Nobel prize with the inventor Thomas Edison in the early 1900s.

Magnets used for imaging mostly have **field strengths** up to 1.5 Tesla, meanwhile also 3 Tesla magnets have become popular (they are referred to as "**high field**", with the term "**ultra-high field**" used for even stronger magnets). Basically, the stronger the magnet, the better the MR signal. Unfortunately, technical problems and image artifacts also increase with **magnetic field strength**. Because of that, only magnets up to 3 Tesla are useful for general clinical work at present.

Just to get an idea about the strength of the MR magnets: the earth's magnetic field is between 0.3 and 0.7 G, the magnet of a refrigerator door has about 100 G = 0.01 T).

The magnetic field of MR magnets has to be very homogeneous, as it directly determines the precession frequency. The **homogeneity** is quoted in terms as **ppm**, part per million, in a defined volume. To calculate this, the difference between maximum and minimum field strength is divided by the average field strength and multiplied by one million. How detrimental even rather small inhomogeneities and thus differences in precession frequency can be, has already been illustrated on page 27. Homogeneity of the magnetic field can be improved by making some electrical or mechanical adjustments, a process called **shimming.**

Types of magnets

In MRI, different types of magnets have been used – here a short description.

Permanent magnets:

Everybody is probably familiar with a permanent magnet. It is that type of magnet that fascinates little kids. This kind of magnet is always magnetic and does not use any energy for work, which are its advantages.

Possible disadvantages are thermal instability, its limited field strength, and its weight (a magnet of 0.3 T may weight about 100 tons!).

This magnet is only used in low field systems today.

Resistive magnets:

In a **resistive magnet**, an electrical current is passed through a loop of wire and generates a magnetic field. Resistive magnets are therefore also called **electromagnets**. They are only magnetic as long as there is an electrical current flowing through them. Thus, they use electrical energy.

As there is a resistance to the flow of the electricity through the wire, these magnets get warm when in operation, and have to be cooled.

Compared with permanent magnets, they achieve a higher field strength. However, resistive magnets are not very practical with high field strengths, because they create lots of heat that must be dissipated. In general, resistive magnets are no longer of central interest.

Superconducting magnets:

Superconducting magnets are the ones most widely used in MR machines. They also make use of electricity, but they have a special current-carrying conductor. This is cooled down to superconducting temperature (about 4 °K or -269 °C). At this temperature, the current conducting material loses its resistance for electricity. So if you send in an electrical current once, it flows in there permanently, creating a constant magnetic field. So-called **cryogens (helium, nitrogen)** are used for cooling of these magnets, and have to be refilled once in a while.

When for some reason the temperature rises above the **superconducting temperature** in these magnets, there will be a loss of superconductivity (so-called **quench**), and sudden resistance to the flow of electricity. This results in rapid heat production, which causes cryogens to boil off rapidly (these leave the system via the so-called **quench lines**). Advantages of superconducting magnets are high magnetic field strength and excellent magnetic field homogeneity. (This is in the order of 10-50 ppm over a region 45 cm in diameter). High field strength and **field homogeneity** facilitate very detailed and fast studies, and allow for spectroscopy.

Disadvantages of the superconducting magnets are their relatively high costs, and use of rather expensive cryogens.

Your insurance card, please. And do you have your protons with you?

Which is the ideal field strength?
This question is as easy to answer as the question about the ideal horsepower for a car. Here are some of the pros and cons:

- higher field strength allows for a better spatial resolution and faster examinations, and may be used for spectroscopy;
- low field systems on the other hand offer better tissue contrast, are cheaper in price and in operating costs.

Most MR units today are 1.5 Tesla systems, with 3.0 Tesla systems becoming increasingly popular.

Another piece of hardware: the coils

In MRI, radio frequency coils are necessary to send in the RF pulse to excite the protons, and to receive the resulting signal. Coil technology is extremely important. The same or different coils can be used for transmission of the RF pulse and receiving the signal. A variety of coils are in use – here just a few comments.

Volume coils

Volume coils are used in all MR units. These completely surround the part of the body that is to be imaged. These volume coils should be close to the size of the subject.

The **body coil** is a permanent part of the scanner, and surrounds the patient. It is important, as it is the transmitter for all types of examinations. It also receives the signal when larger parts of the body are imaged. Head coils, the most frequently used dedicated coil type, may act as receiver coil (with the body coil transmitting the RF pulses), or may transmit the RF pulses as well (so-called transmit-receive coils).

Gradient coils

Gradient coils are used to systematically vary the magnetic field by producing additional linear electromagnetic fields, thus making slice selection and spatial information possible. As we have three dimensions in space, there are three sets of gradient coils. As these coils bang against their anchoring devices, they are the cause of noise that you can hear during an MR examination.

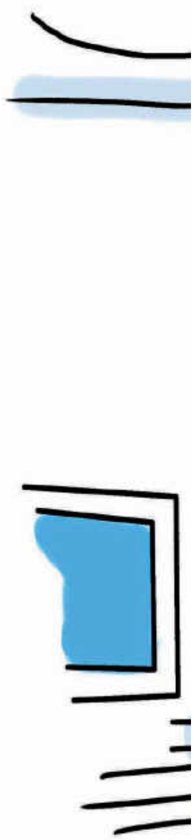
Surface coils

Surface coils are placed directly on the area of interest, and have different shapes corresponding to the part to be examined.

They are usually receiver coils only, most of the received signal coming from tissues nearby; deeper structures cannot be examined with these coils. As with the **head coils**, the RF pulse is transmitted by the body coil in these cases.

Shim coils

As we have already mentioned in connection with the magnets, magnetic fields have inhomogeneities. Better homogeneity can be achieved by electrical and mechanical adjustments. For this process, which is called shimming, the **shim coils** are used.



Why do MR units require special facilities?

As the systems usually weigh a lot, there are certain static requirements to be met. However, there are additional important factors.

The strong magnetic field of the MR system extends beyond the magnet. Naturally, the magnetic field can attract (even very heavy!) metallic objects and transform them into projectiles! So these have to stay outside the

examination room. Also the magnetic field influences mechanical and electrical devices, like computers, monitors, pacemakers and X-ray units – so such devices must be kept at a certain distance away from the MR unit.

On the other hand, there are also external influences. The whole air is full of radio waves – just think about all the stations which you can receive on your radio. To prevent interference between outside radio waves and those sent from the MR unit, the whole system has to be shielded by a **Faraday cage**.

In addition, it has to be taken into account that larger metallic objects, especially when moving (like elevators, cars), can influence the magnetic field of the scanner, and should also be kept away from the MR unit.

MR spectroscopy

MR spectroscopy has been in use for a long time, long before MR was used for imaging. The procedure is used as an analytical tool, as it can identify various chemical states of certain elements without destruction of the sample. Meanwhile, spectroscopy and imaging may be combined (**spectroscopic imaging**). This enables us to obtain in vivo information about the chemistry and metabolism in specific locations, like in the brain, the liver, or even the heart.

As these measurements can be repeated without harm, follow-up studies of cell physiology are possible. This, for example, can be useful in the evaluation of certain diseases and the effects of therapy.

As spectroscopy requires very homogeneous magnets with higher field strengths, it can only be performed with the use of MR units which have superconducting magnets.

The final review

Now that you have made it up to here, it is our sincere hope that you know a little bit (more?) about MRI. A final review?

Yes, but let us try a different approach this time: take a look at the index on the following pages. Check and see if you understand all of the terms mentioned. If not, refer back to the page numbers listed for a short review.

If you understand all or at least most of it, be happy about it!

If you've made it this far, a second book shouldn't be any problem at all.