Let us start with a general overview of MRI . . .

The single steps of an MRI examination can be described quite simply:

1. the patient is placed in a magnet,
2. a radio wave is sent in,
3. the radio wave is turned off,
4. the patient emits a signal, which is received and used for
5. reconstruction of the picture.

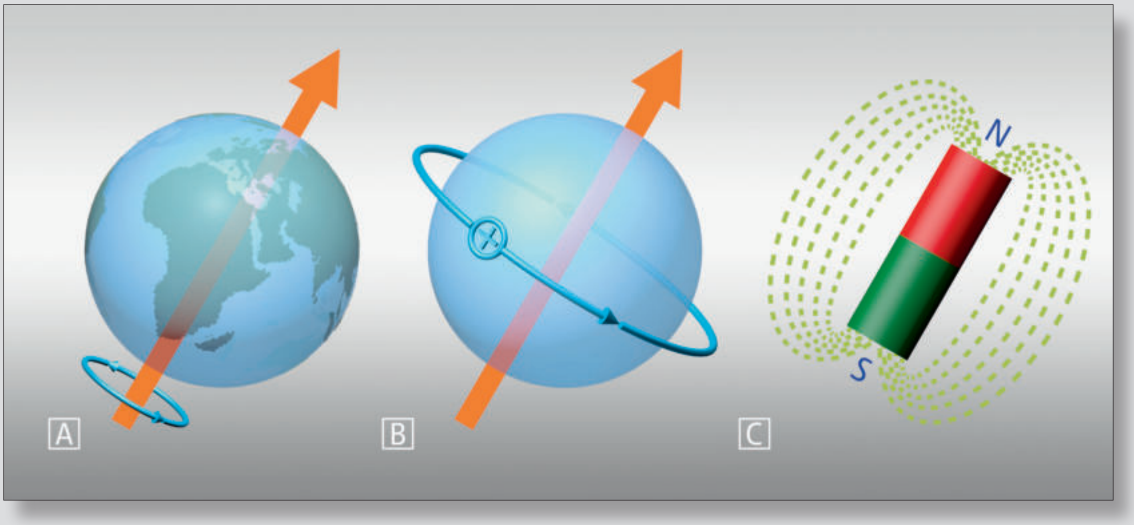


Fig. 1: Protons possess a positive charge. Like the earth, they are constantly turning around an axis and have their own magnetic field.

Let's take a look at these steps in detail

What happens, when we put a patient into the magnet of an MR machine?

To understand this, it is necessary to at least know some very basic physics – even though this may seem to be boring.

As we all know, **atoms** consist of a **nucleus** and a **shell**, which is made up of electrons. In the nucleus – besides other things – there are **protons**, little particles, that have a positive electrical charge (whatever that may actually be). These protons are analogous to little planets. Like the earth, they are constantly turning, or spinning around an axis (figure 1); or – as one says, protons possess a **spin**. The positive electrical charge, being attached to the proton, naturally spins around with it. And what is a moving electrical charge? It is an **electrical current**.

Now, may be you remember from your physics at school that an electrical current induces, causes a **magnetic force**, or **magnetic field**. So, where there is an electrical current, there is also a magnetic field.

This can be demonstrated very easily. Take a rusty nail and approach an electrical outlet – closer, closer. Do you feel it being repelled by the magnetic force, so you do not put the nail into the outlet?

Let's review what we have read

A proton has a spin, and thus the electrical charge of the proton also moves. A moving electrical charge is an electrical current, and this is accompanied by a magnetic field. Thus, the proton has its own magnetic field and can be seen as a little **bar magnet** (figure 1C).

What happens to the protons, when we put them into an external magnetic field?

The protons – being little magnets – align themselves in the external magnetic field like a compass needle in the magnetic field of the earth. However, there is an important difference. For the compass needle there is only one way to align itself with the magnetic field, for the protons, however, there are two (figure 2):

The protons may align with their South and North Poles in the direction of the external field, parallel to it. Or they may point in the completely opposite direction, anti-parallel. These types of alignment are on different energy levels. To explain this: a man can align himself parallel to the magnetic field of the earth, i.e. walk on his feet, or he can align himself anti-parallel, in the opposite direction. Both states are on different energy levels, i.e. they need different amounts of energy.

Walking on one's feet is undoubtedly less exhausting, takes less energy than walking on one's hands. (In the figures, this will be illustrated as pointing up or down, see figure 2).

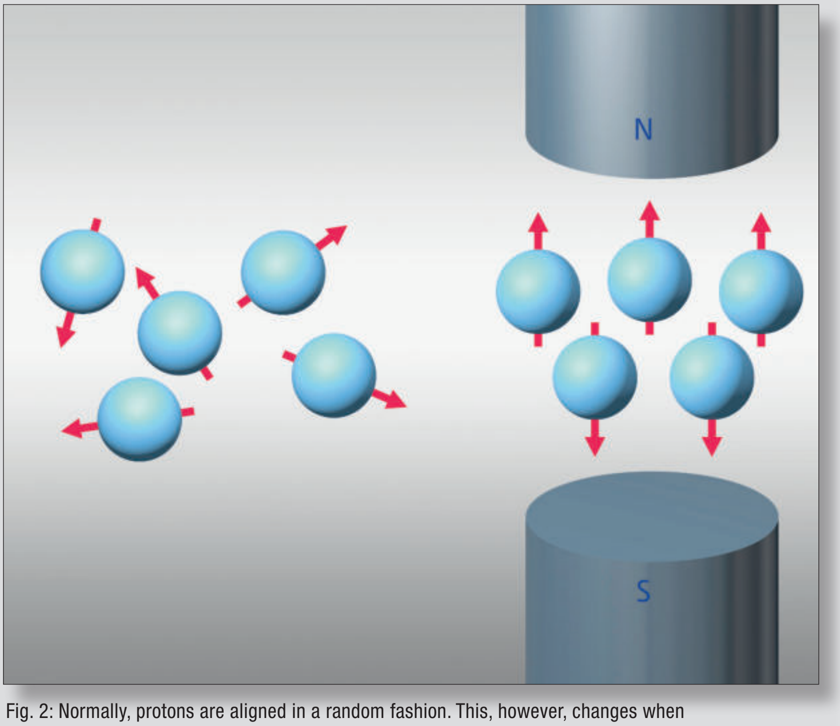


Fig. 2: Normally, protons are aligned in a random fashion. This, however, changes when they are exposed to a strong external magnetic field. Then they are aligned in only two ways, either **parallel** or **anti-parallel** to the external magnetic field.

Fig. 3: When there are two possible states of alignment, the one that takes less energy, is on a lower energy level, is preferred.

Naturally, the preferred state of alignment is the one that needs less energy. So more protons are on the lower energy level, parallel to the external magnetic field, walking on their feet, so to speak. A smaller number is on the higher energy level, anti-parallel, "walking on their hands".

The difference in number is, however, very small and depends on the strength of the applied magnetic field. To get a rough idea: for about 10 million protons "walking on their hands", there are about 10,000,007 "walking on their feet". The difference "007" is probably easy to remember, isn't it?

It may be obvious at this point already that for MRI the **mobile protons** are important (which are a subset of all protons that are in the body).

The movement of protons – precession

Let us take a closer look at these protons

We will see that the protons do not just lie there, aligned **parallel** or **anti-parallel** to the magnetic field lines. Instead, they move around in a certain way. The type of movement is called **precession** (figure 4A).

What type of movement is “precession”?

Just imagine a spinning top. When you hit it, it starts to “wobble” or tumble around. It does not, however, fall over. During the precession, the axis of the spinning top circles forming a cone shape (figure 4B). It is hard to draw such a precessing proton, because this is a very fast movement, as we will see below. For the sake of simplicity, we will just make “freeze frame” pictures, as if we were taking a fast flashlight photograph of the situation at a specific moment in time.

For reasons we will learn later, it is important to know how fast the protons precess. This speed can be measured as precession frequency, that is how many times the protons precess per second. This precession frequency is not constant. It depends upon the strength of the magnetic field (for magnetic field strength, see page 94), in which the protons are placed.

The stronger the magnetic field, the faster the **precession rate** and the higher the **precession frequency**.

This is like a violin string: the stronger the force exerted upon the string, the higher its frequency.

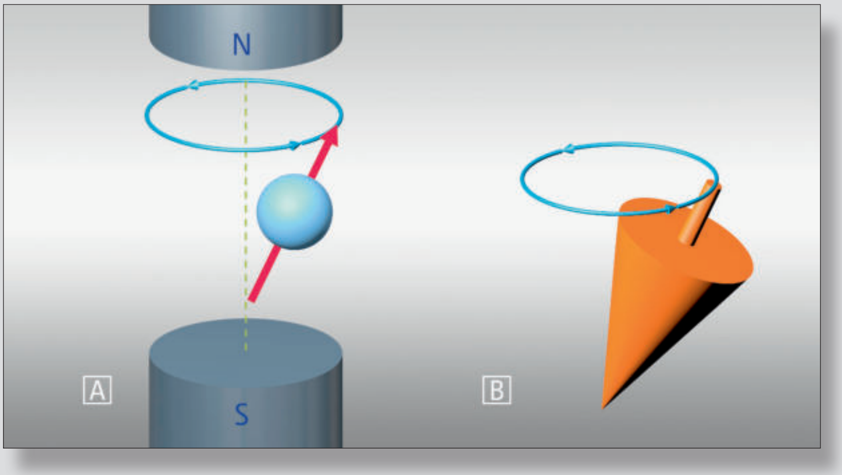


Fig. 4: A spinning top which is hit, performs a wobbling type of motion. Protons in a strong magnetic field also show this type of motion, which is called precession.

It is possible and necessary to precisely calculate this frequency. This is done by using an equation called the **Larmor equation**:

$$\omega_0 = \gamma B_0$$

ω_0 is the **precession frequency** – in Hz or MHz,
B_0 is the strength of the external magnetic field, which is given in **Tesla (T)** (see page 94), and
γ is the so-called **gyro-magnetic ratio**.

The equation states that the precession frequency becomes higher when the magnetic field strength increases. The exact relationship is determined by the gyro-magnetic ratio γ. This gyro-magnetic ratio is different for different materials (e.g. the value for hydrogen protons is 42.5 MHz/T).

It can be compared to an exchange rate, which is different for different currencies.

Time to take a break

However, let us briefly review what we have learned up to now:

- Protons have a positive electrical charge, which is constantly moving, because the protons possess a spin.
- This moving electrical charge is nothing more than an electrical current, and the latter always induces a magnetic field.
- So every proton has its own little magnetic field, and can thus be seen as a little bar magnet.
- When we put a patient in the MR magnet, the protons, being little magnets, align with the external magnetic field. They do this in two ways: parallel and anti-parallel. The state that needs less energy is preferred, and so there are a few more protons “walking on their feet” than “on their hands” (figure 3).
- The protons precess along the field lines of the magnetic field, just like a spinning top that precesses along the field lines of the magnetic field of earth.
- The precession frequency can be calculated by the Larmor equation, and is higher in stronger magnetic fields. Why is this precession frequency important?

It has something to do with the “resonance” in magnetic resonance imaging. But to understand this will take a few more minutes.

After the break you should go over this last summary again, and then continue . . .

Introducing the coordinate system

To make communication (and drawing of illustrations) easier, let us start using a coordinate system like the one used at school (figure 5). As you can see, the z-axis runs in the direction of the magnetic field lines, and thus can represent them. So we can stop drawing the external magnet in all other illustrations.

From here on we will also illustrate the protons as **vectors**, as little arrows.

Maybe you remember: a vector represents a certain force (by its size) that acts in a certain direction (direction of the arrow). The force that is represented by vectors in our illustrations, is the magnetic force.

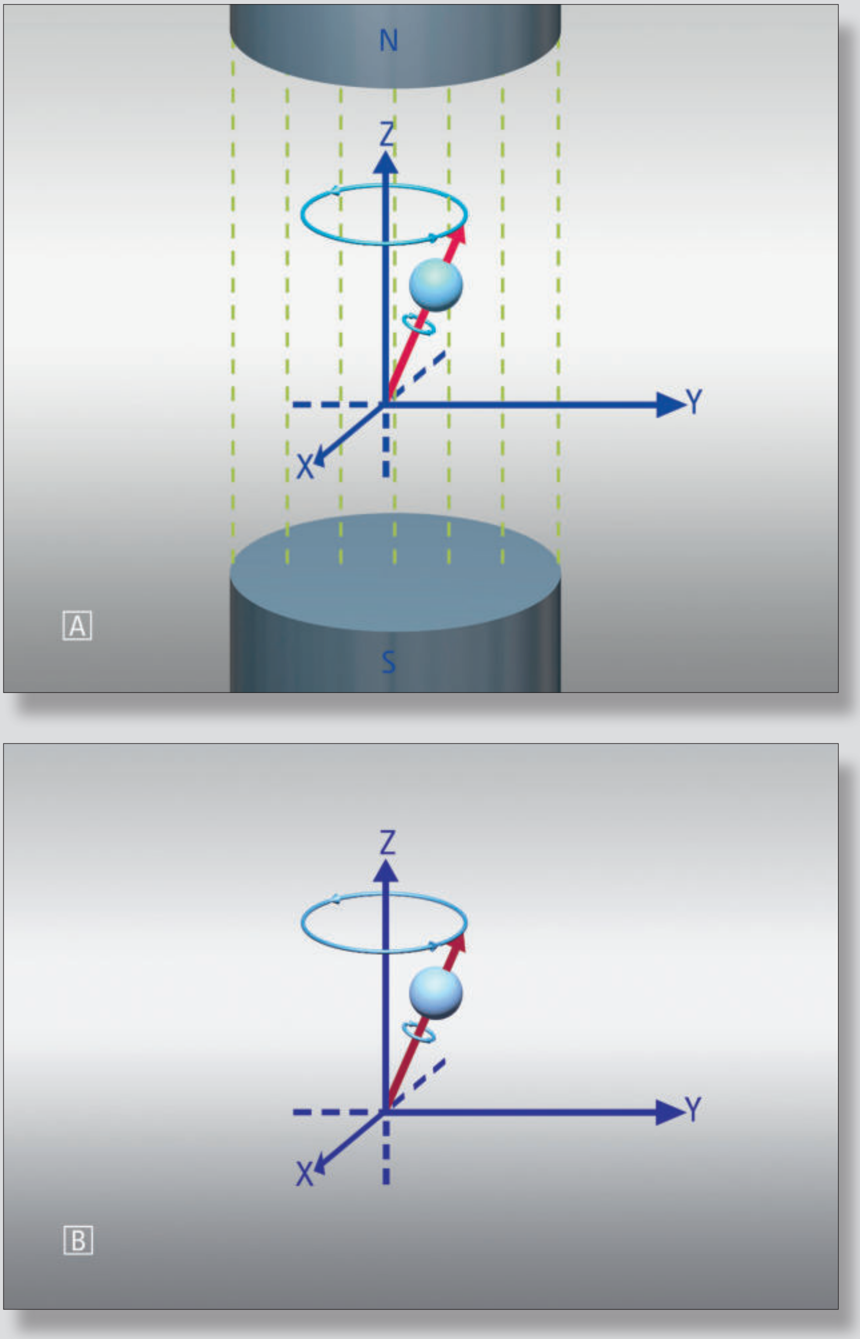


Fig. 5: Using a coordinate system makes the description of proton motion in the magnetic field easier, and we can also stop drawing the external magnet.

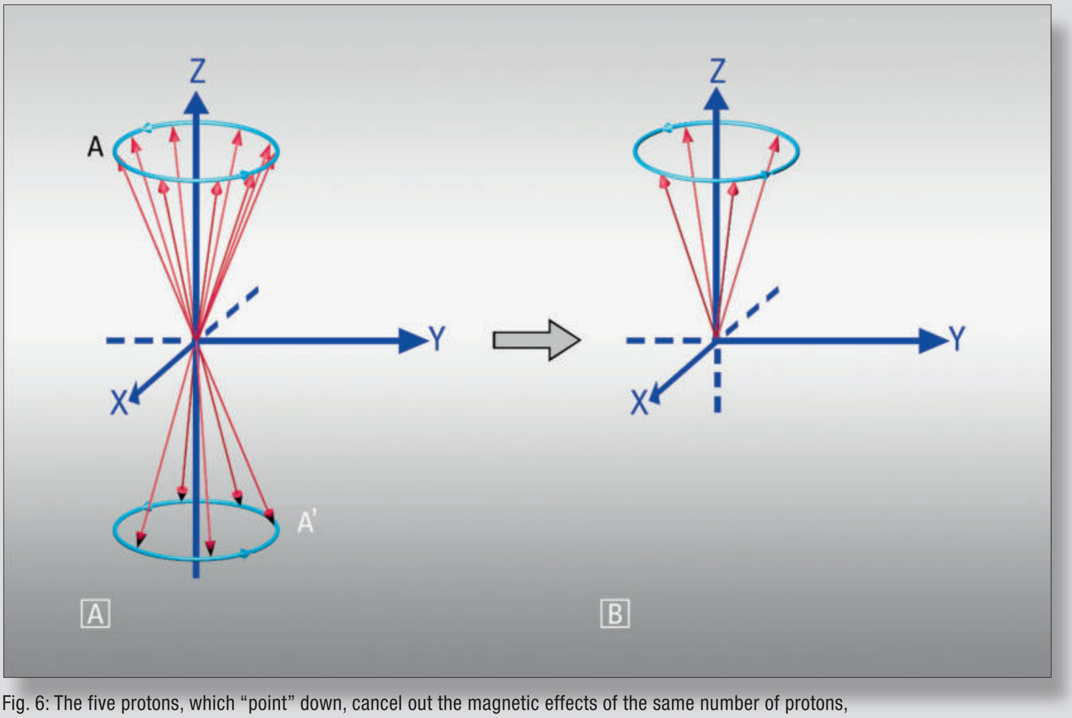
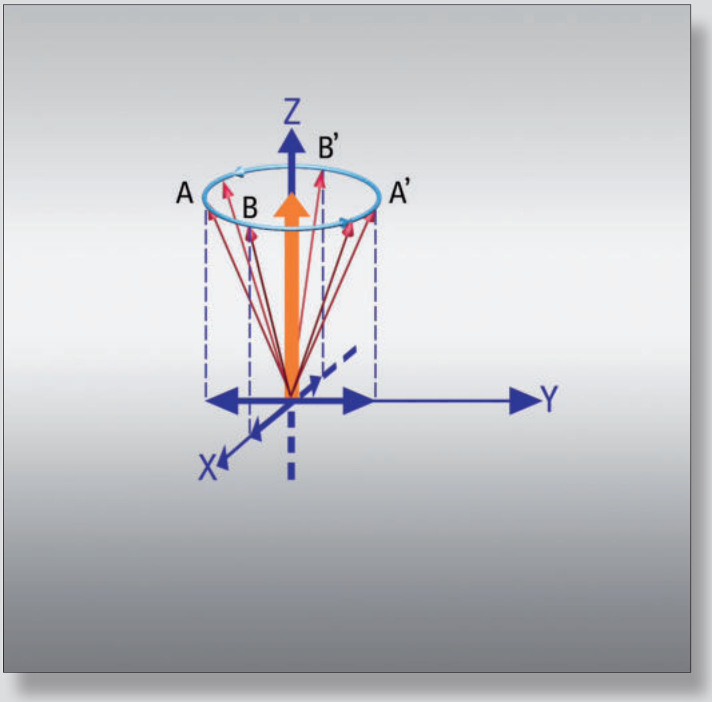


Fig. 6: The five protons, which "point" down, cancel out the magnetic effects of the same number of protons, which "point" up (A). So in effect it is sufficient to look only at the four unopposed protons (B).

Now, let us look at figure 6. Here we have 9 protons pointing up, precessing parallel to the external magnetic field lines, and 5 protons pointing down, precessing anti-parallel to the external magnetic field.

What we see in the figure is just a picture taken at a specific point in time. A picture taken just a little later would show the protons in different positions, because they precess. The precession actually goes very fast, the **precession frequency** for hydrogen protons is somewhere around 42 MHz in a magnetic field strength of 1 Tesla (see page 94); this means that the protons precess around the "ice cream cone" more than 42 million times per second. Now there are millions and millions of protons in your body precessing this fast. It is easy to imagine that at a certain moment, there may be one proton (A in the illustration) pointing in one direction, and another proton (A') pointing exactly in the opposite direction. The result is very important; the magnetic forces in the opposing directions cancel each other out, like two persons pulling at the opposite ends of a rope. Finally, for every proton pointing down, there is one pointing up, cancelling its magnetic effect. But as we have learned: there are more protons pointing up than down, and the magnetic forces of these protons are not cancelled by others. So we are left – in effect – with some protons (4 in our example) pointing up (figure 6).

Fig. 7: The magnetic force of proton A, illustrated as an arrow, a vector, can be seen as resulting from two components: one pointing up along the z-axis, and one in direction of the y-axis. The component along the y-axis is cancelled out by proton A', the magnetic force of which also has a component along the y-axis, but in the opposite direction. The same holds true for other protons, e.g. B and B', which cancel their respective magnetic vectors along the x-axis. In contrast to the magnetic vectors in the x-y-plane, which cancel each other out, the vectors along the z-axis point in the same direction, and thus add up to a new magnetic sum vector pointing up.



However, not only magnetic forces pointing up and down can cancel or neutralize each other. As the protons that are pointing up, precess, there may be one pointing to the right, while another one is pointing to the left; or for one pointing to the front, there is one pointing backwards, and so on (the corresponding protons in figure 7 are marked A and A', B and B' for example). This means that the opposing magnetic forces of the remaining protons cancel each other out in these directions. This is true for all but one direction, the direction of the z-axis, along the external magnetic field (figure 7). In this direction, the single vectors, the single magnetic forces add up, like people pulling on the same end of a rope.

What we end up with in effect is a magnetic vector in the direction of the external magnetic field (the orange arrow on the z-axis in figure 7); and this vector is a **sum vector** made up by adding the magnetic vectors of the protons pointing upwards.

Now – what does this mean? This means that by placing a patient in the magnet of the MR unit (or in any other strong magnetic field), the patient himself becomes a magnet, i.e. has his own magnetic field. Why? Because the vectors of the protons that do not cancel each other out, add up (figure 8).

As this magnetization is longitudinal to the external magnetic field, it is called **longitudinal magnetization**.

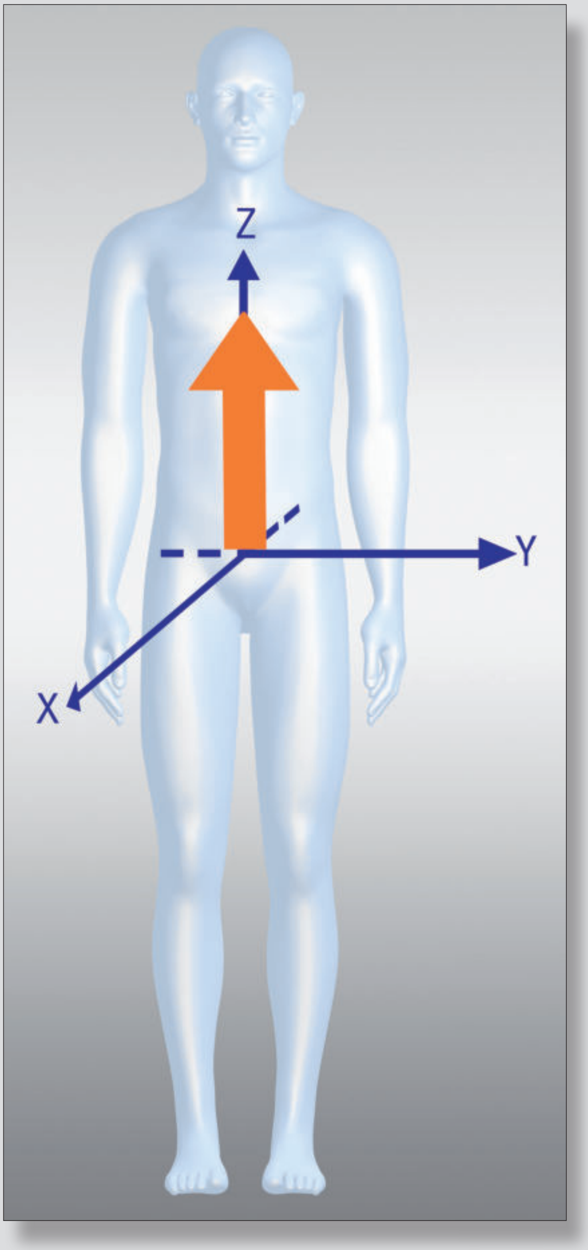


Fig. 8: In a strong external magnetic field, a new magnetic vector is induced in the patient, who becomes a magnet himself. This new magnetic vector is aligned with the external magnetic field.

As we have seen, the resulting new magnetic vector of the patient points in the direction of the external field, along its field lines. This is described as longitudinal direction. And it is actually this new magnetic vector that may be used to get a signal. It would be nice if we could measure this magnetization of the patient, but there is a problem: we cannot measure this magnetic force, as it is in the same direction, parallel to the external magnetic field (figures 7 and 8).

To illustrate this: Imagine that you are sitting on a boat, floating down a river. You have a water hose in your hand and squirt water into the river. For somebody who is watching you from the shore, it is impossible to tell how much water you pour out (i.e. how much new magnetization is added in the old direction).

However, when you point the water hose at the shore, change the direction of the new magnetic field, then the water may perhaps be directly picked up and measured by an impartial observer on the shore (figure 9). What we should learn from this is: magnetization longitudinal to the external magnetic field cannot be measured directly. For this, we need a magnetization which is not longitudinal, but transversal to the external magnetic field.

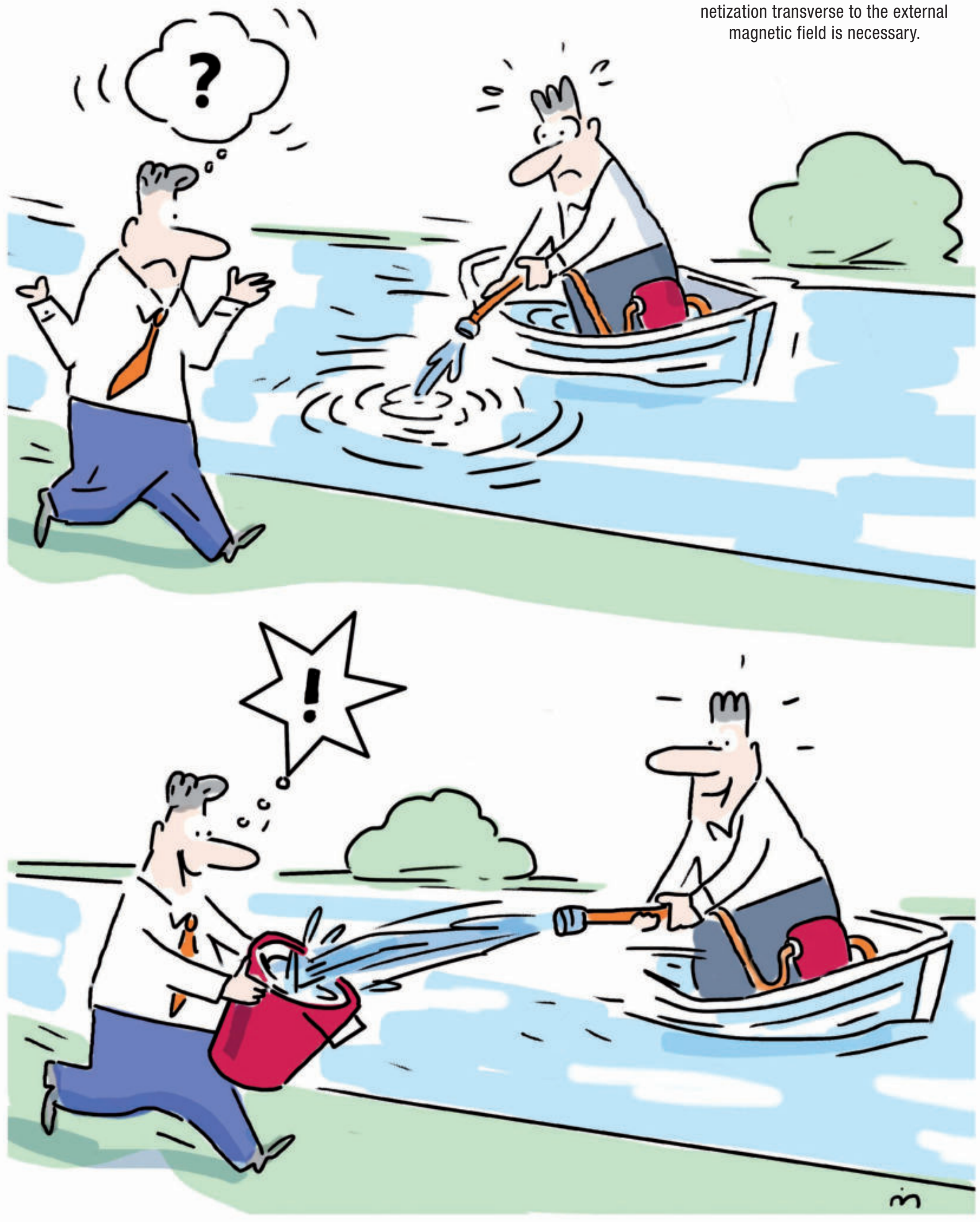


Fig. 9: Magnetization along an external magnetic field cannot be measured. To achieve this, a magnetization transverse to the external magnetic field is necessary.

Time to take a break

Before you walk away, let us just sum up. And when you come back, start out with this summary again.

- Protons have a **positive charge** and possess a spin. Due to this, they have a magnetic field and can be seen as little bar magnets.
- When we put them into a strong external magnetic field, they align with it, some parallel – pointing up –, some anti-parallel – pointing down.
- The protons do not just lie there, but precess around the magnetic field lines. And the stronger the magnetic field, the higher the precession frequency, a relationship that is mathematically described in the Larmor equation.
- Parallel and anti-parallel protons can cancel each others forces out. But as there are more parallel protons on the lower energy level ("pointing up"), we are left with some protons, the magnetic forces of which are not cancelled. All of these protons pointing up, add up their forces in the direction of the external magnetic field. And so when we put the patient in the MR magnet, he has his own magnetic field, which is longitudinal to the external field of the MR machine's magnet (figures 7 and 8). Because it is longitudinal, however, it cannot be measured directly.