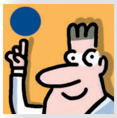
Time to take a break



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.

Sending in a radio wave

What happens after we put the patient into the magnet?

We send in a **radio wave**. The term radio wave is used to describe an electromagnetic wave that is within the frequency range of the waves, which are received by your radio. Well, you can imagine it is not quite like this kind of radio wave. What we actually send into the patient is not a wave of long duration, but a short burst of some **electromagnetic wave**, which is called a **radio frequency- or RF pulse**. The purpose of this RF pulse is to disturb the protons, which are peacefully precessing in alignment with the external magnetic field.

We will hear about the details later. But not every RF pulse disturbs the alignment of the protons: For this, we need a special **RF pulse**, one that can exchange energy with the protons.

This is as if someone were looking at you. You may not notice it, because there is no exchange of energy, so you do not change your position / alignment. However, if someone were to pound you in the stomach, exchange energy with you, your alignment would be disturbed. And this may explain why we need a certain RF pulse that can exchange energy with the protons to change their alignment.

But when can an RF pulse exchange energy with the protons?

For this, it must have the same frequency; the same “speed” as the protons, so to speak. Just imagine that you are driving down a race track on your bike, and someone in the lane next to you wants to hand you a hamburger, i.e. exchange energy with you – as you

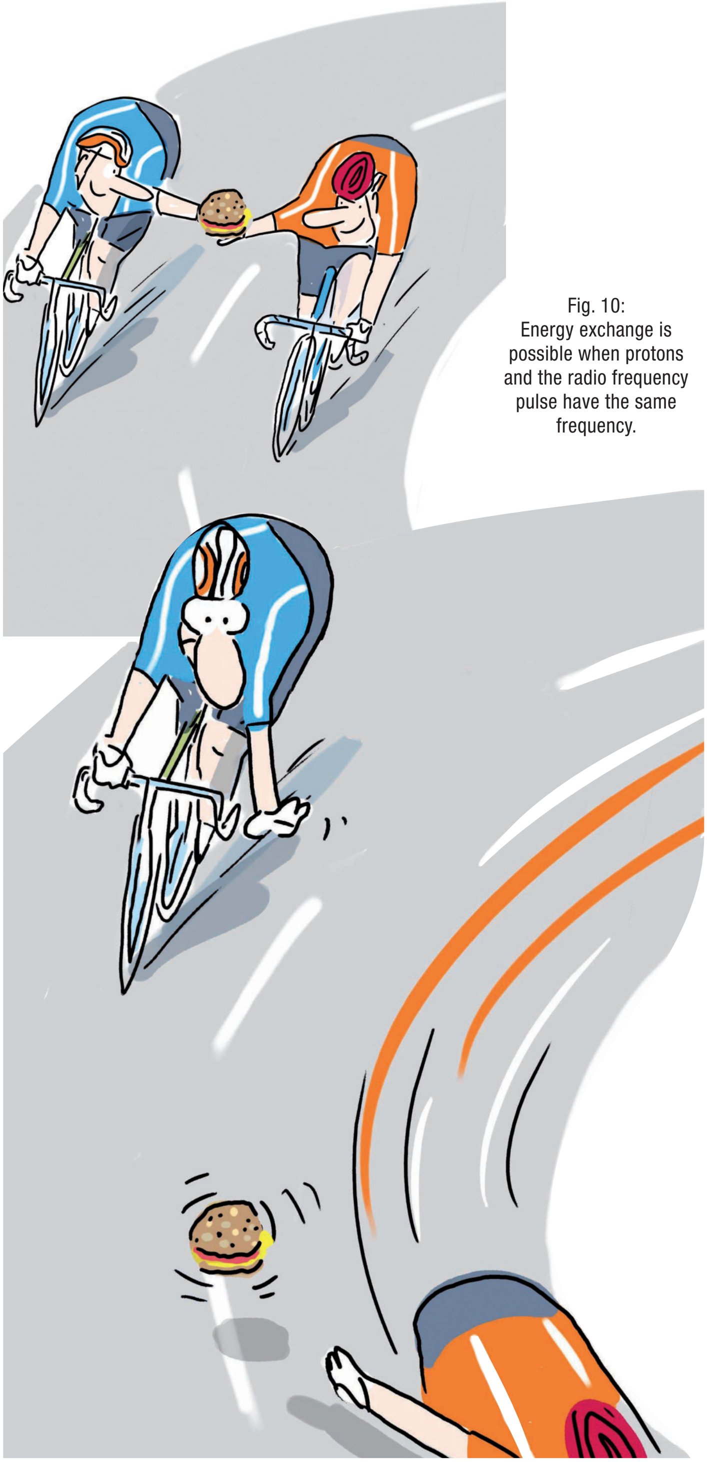


Fig. 10:
Energy exchange is possible when protons and the radio frequency pulse have the same frequency.

are hungry, the hamburger would give you new energy.

This energy transfer is possible when both bikers have the same speed, move around the race track with the same frequency:
With differences in speed/frequency …
… little or no energy transfer is possible.

The “speed” of protons and resonance

What speed, or better, what frequency did the protons have?

They had their **precession frequency** which can be calculated by the Larmor equation (see page 10). So the **Larmor equation** gives us the necessary frequency of the RF pulse to send in. Only when the RF pulse and the protons have the same frequency, can protons pick up some energy from the radio wave, a phenomenon called **resonance** – this is where the “resonance” in magnetic resonance comes from.

The term resonance can be illustrated by the use of tuning forks. Imagine that you are in a room with different kinds of tuning forks, tuned e.g. to a, e, and d. Somebody enters the room with a tuning fork with “a”-frequency that was struck to emit sound. Of all the tuning forks in the room, all of a sudden the other “a”-forks, and only those, pick up energy, start to vibrate and to emit sound, they show a phenomenon called resonance.

What happens to the protons when exposed to the RF pulse?

Some of them pick up energy, and go from a lower to a higher energy level. Remember, some, which were walking on their feet, start walking on their hands. And this has some effect on the patient's magnetization, as you can see in figure 11. Let us assume that from the net sum of 6 protons pointing up, after the RF pulse is sent in, 2 point down.

The result is that these 2 protons cancel out the magnetic forces of the same number of protons, that point up.

So in effect then, the magnetization in the longitudinal direction – being 6 before the RF pulse – decreases to 2.

What else happens to the protons when exposed to the RF pulse?

As we have just learned, some of the protons pick up energy, and go from a lower to a higher energy level, thus decreasing magnetization in longitudinal direction.

But something else happens. Do you remember what drawings of radio waves look like? Just look at figure 12; they resemble a whip.

And what does a whip make the bears do? It makes them walk in line, in step, in synch – they are in phase.

Believe it or not, the RF pulse also has a whip-like action – not on bears but on protons: When the protons randomly point left/right, back/forth and so on, they also cancel their magnetic forces in these directions (as we read

Fig. 12: The drawing of radio waves normally resembles a whip, and radio waves in MRI also have a whip-like action.

Fig. 11: The radio frequency pulse exchanges energy with the protons (A), and some of them are lifted to a higher level of energy, pointing downward in the illustration (B). In effect, the magnetization along the z-axis decreases, as the protons which point down, "neutralize" the same number of protons pointing up.

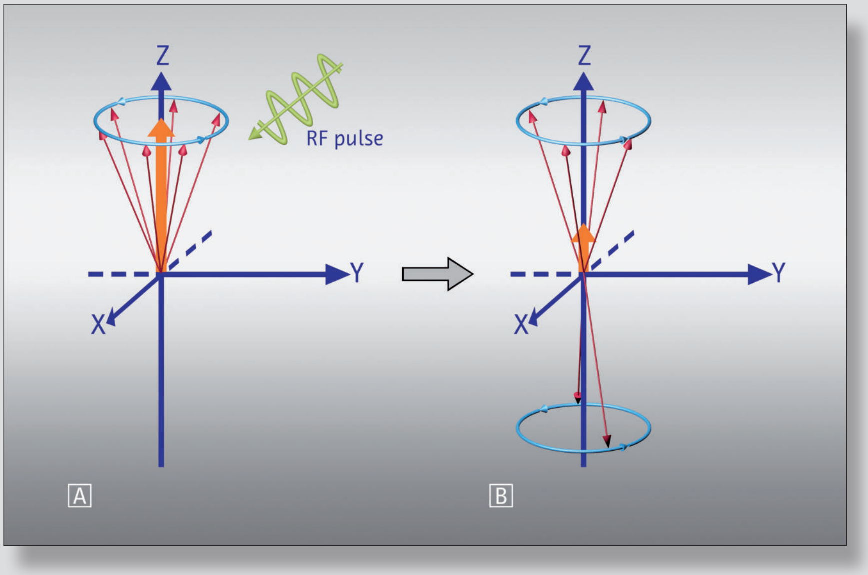
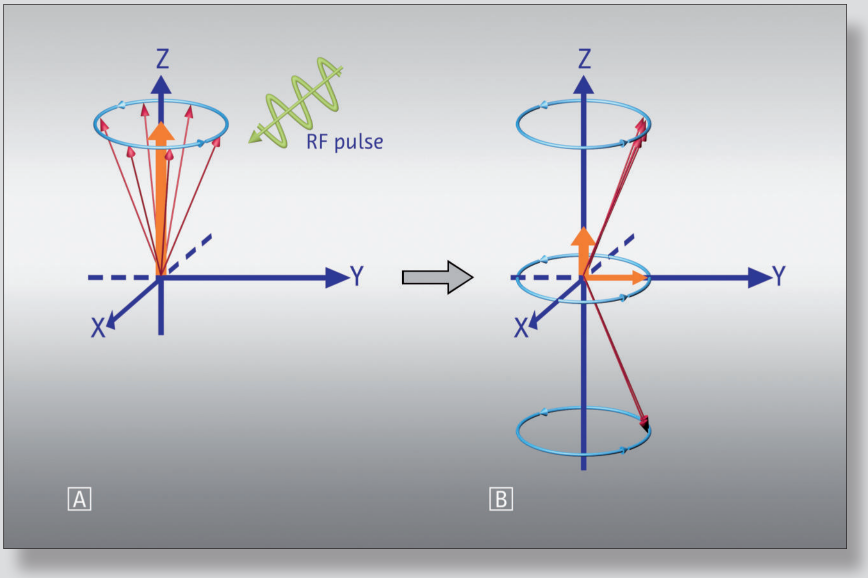


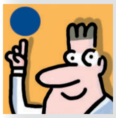
Fig. 13: The radio wave has two effects on the protons: it lifts some protons to a higher level of energy (they point down), and it also causes the protons to precess in step, in phase. The former results in decreasing the magnetization along the z-axis, the so-called longitudinal magnetization. The latter establishes a new magnetization in the x-y-plane (→), a new transversal magnetization, which moves around with the precessing protons.



on page 13). Due to the RF pulse, the protons do not point in random directions any more, but move in step, in synch – they are **"in phase"**. They now point in the same direction at the same time, and thus their magnetic vectors add up in this direction. This results in a magnetic vector pointing to the side to which the precessing protons point, and this is in a transverse direction (figure 13). This is why it is called **transversal magnetization**.

Fig. 14: Protons precessing in phase cause a new transversal magnetization.

So – what were the new things that we have learned?



Repeat them using figure 15.

- When we put the patient in the MR machine, a magnetic field in the patient, longitudinal to the external field, results.
- Sending in an RF pulse that has the same frequency as the precessing frequency of the protons causes two effects:
  - Some protons pick up energy, start to walk on their hands, and thus decrease the amount of longitudinal magnetization.
  - AND: The protons get in synch, start to precess in phase. Their vectors now also add up in a direction transverse to the external magnetic field, and thus a transversal magnetization is established.

In summary: The RF pulse causes **longitudinal magnetization** to decrease, and establishes a new **transversal magnetization** (figures 13 and 15).

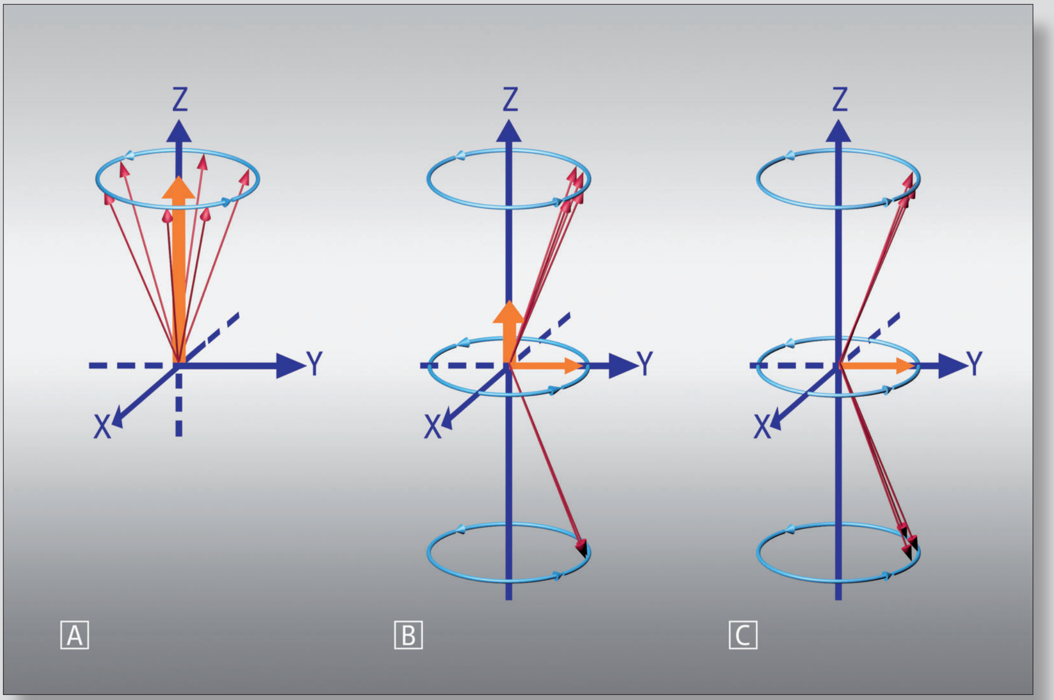


Fig. 15: In a strong external magnetic field, a new magnetic vector along the external field is established in the patient (A). Sending in an RF pulse causes a new transversal magnetization while longitudinal magnetization decreases (B). Depending on the RF pulse, longitudinal magnetization may even totally disappear (C).

The transversal vector – a closer look

Let us have a look at the newly established transversal magnetization vector.

This moves in phase with the precessing protons (figure 16). The new magnetic vector comes towards you, goes away from you, comes again towards you, and so on.

And this is important: the **magnetic vector**, by constantly moving, constantly changing, induces an electric current. We have talked about the opposite already: the moving electrical charge of the proton, the electric current, induces the proton's magnetic field. This also is true the other way around: a moving magnetic field causes an electrical current, e.g. in an antenna. And this electrical current induced by the moving magnetic field is the MRI signal. As the transversal magnetic vector moves around with the precessing protons, it moves with the precession frequency. The resulting MR signal therefore also has the **precession frequency** (figure 16): But … how can we make a picture out of this electrical current, which is actually our MR signal?

For this we have to know, where in the body the signal came from. How can we know that? The trick is really quite simple: we do not put the patient into a **magnetic field** which has the same strength all over the section of the patient, which we want to examine.

Instead we take a magnetic field, which has a different strength at each

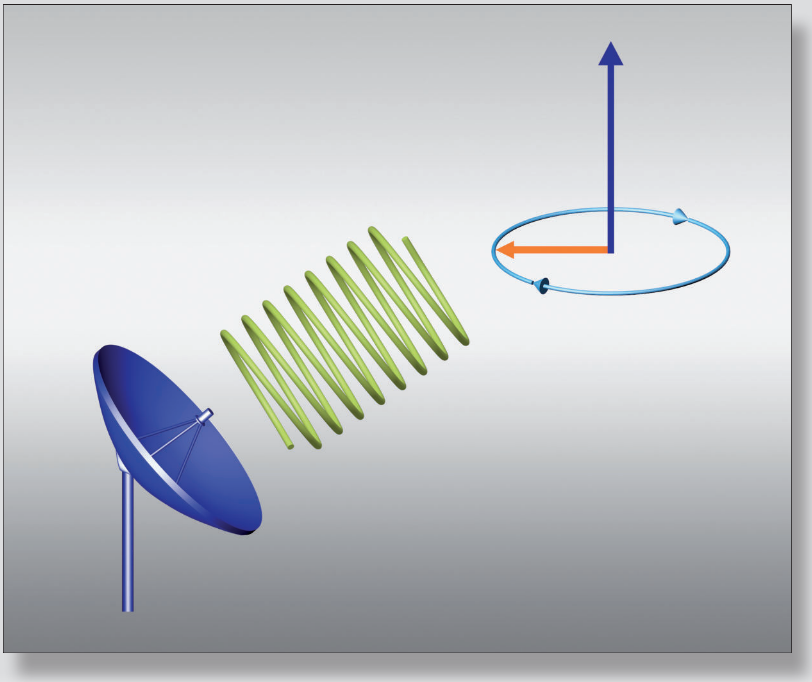


Fig. 16: The new transversal magnetization moves around with the precessing protons (see figure 13). Thus for an external observer, transversal magnetization constantly changes its direction, and can induce a signal in an antenna.

point of the patient's cross-section. What does this do?

We have heard that the precession frequency of a proton depends on the strength of the magnetic field – as the frequency of a violin string depends on the strength with which you pull it.

If this strength differs from point to point in the patient, then protons in different places precess with different frequencies. And as they precess with different frequencies, the resulting MR signal from different locations also has a different frequency. And by the frequency we can assign a signal to a certain location.

It is like with your TV: when you are in the kitchen (where you probably do not have a TV) and hear a sound from your favorite TV show, you know where the sound is coming from. It comes from the spot in your apartment where the TV stands. What you subconsciously do, is to connect a certain sound to a certain location in space.

That is enough about spatial information for now, we will go into more detail about this on page 87.

Further details about the MR signal

If our protons rotated around **in synch**, in phase, and nothing changes, then we would get a signal as illustrated in figure 16.

This, however, is not what happens. As soon as the RF pulse is switched off, the whole system, which was disturbed by the RF pulse, goes back to its original quiet, peaceful state, it relaxes.

The newly established transverse magnetization starts to disappear – a process called **transversal relaxation**, and the longitudinal magnetization grows back to its original size – a process called **longitudinal relaxation**.

Why is that?

The reason why the longitudinal magnetization grows back to its normal size is easier to explain, so let us start with that (see figure 17).

No proton walks on its hands longer than it has to – a sort of human trait. The protons that were lifted onto a higher energy level by the RF pulse go back to their lower energy level, and start to walk on their feet again.

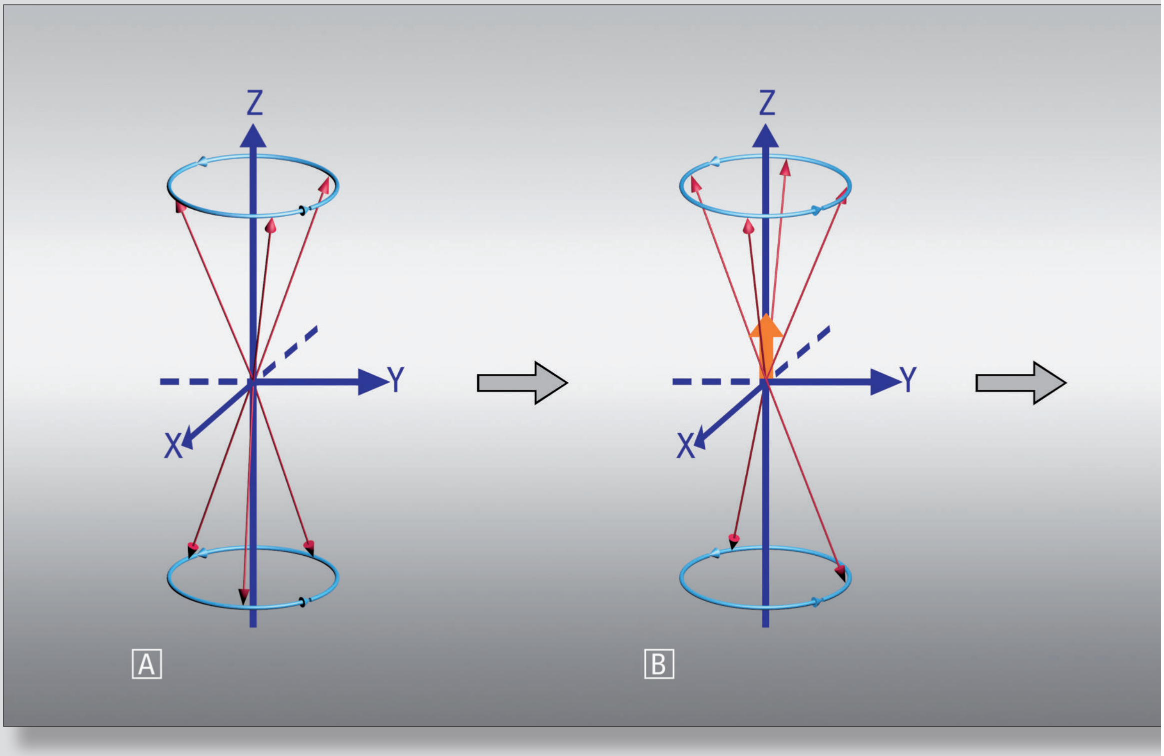


Fig. 17: After the RF pulse is switched off, protons go back from their higher to the lower state of energy, i.e. point up again. This is illustrated “one-by-one”. The effect is that longitudinal magnetization increases and grows back to its original value. Note that for simplicity the protons were not depicted as being in phase: this subject is covered in more detail in figures 20 and 26.

After the RF pulse is switched off, protons go back to the lower state of energy, i.e. point up again, but not all protons do this at exactly the same time. Instead it is a continuous process, as if one proton after the other goes back to its original state. This is illustrated in figure 17 for a group of protons. The effect is that **longitudinal magnetization** increases and grows back to its original value.

What happens to the energy which they had picked up from the RF pulse?

This energy is just handed over to their surroundings, the so-called **lattice**.

And this is why this process is not only called longitudinal relaxation, but also **spin-lattice relaxation**.

By going back on their feet, pointing upwards again, these protons no longer cancel out the magnetic vectors of the same number of protons pointing up, as they did before. So, the magnetization in this direction, the **longitudinal magnetization** increases, and finally goes back to its original value (figure 17).

If you plot the longitudinal magnetization vs. time after the RF pulse is switched off, you get a curve like figure 18. It increases with time. This curve is also called a **T_1-curve**.

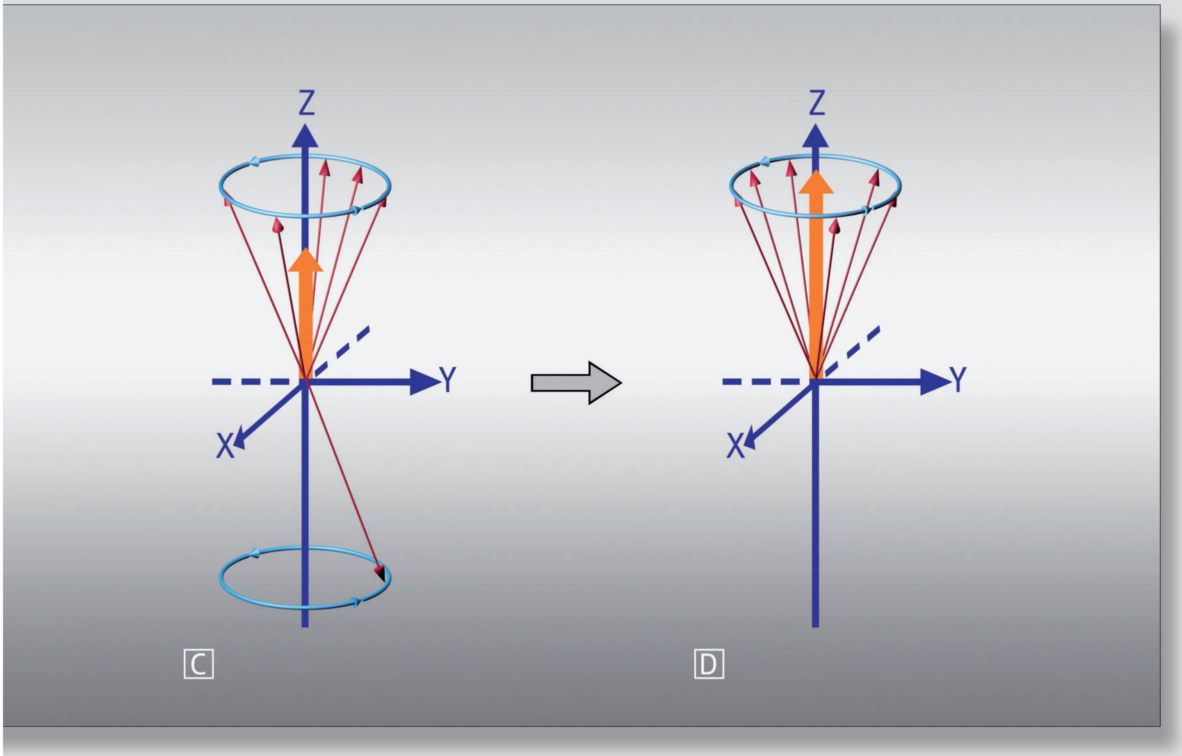
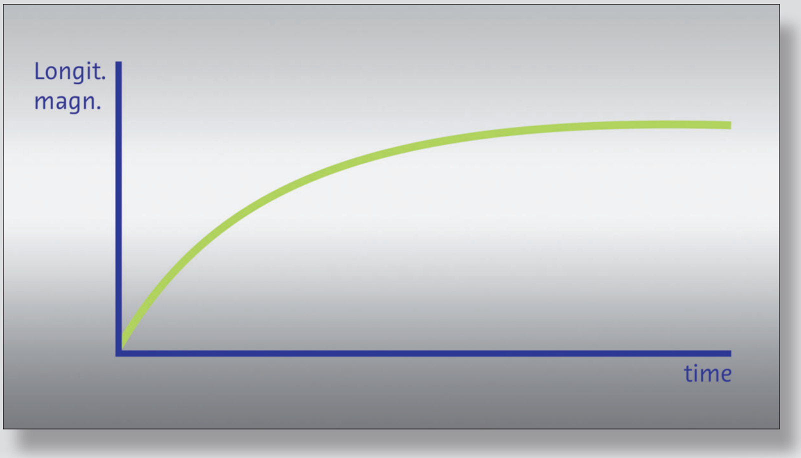


Fig. 18: If one plots the longitudinal magnetization vs. time after the RF pulse was switched off, one gets a so-called T_1-curve.



The time that it takes for the longitudinal magnetization to recover, to go back to its original value, is described by the **longitudinal relaxation time**, also called $\mathbf{T_1}$. This actually is not the exact time it takes, but a time constant, describing how fast this process goes.

This is like taking time for one circuit round at a car race.

The time gives you an idea of how long the race may take, but not the exact time. Or more scientifically, T_1 is a time constant comparable to the time constants that for example describe radioactive decay.

That $\mathbf{T_1}$ is the **l ongitudinal relaxation time**, can easily be remembered:

If you turn the “1” upside down, it looks very much like an “l” as in longitudinal.

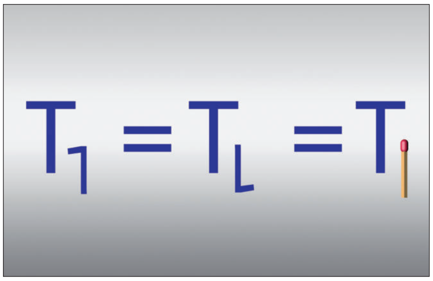
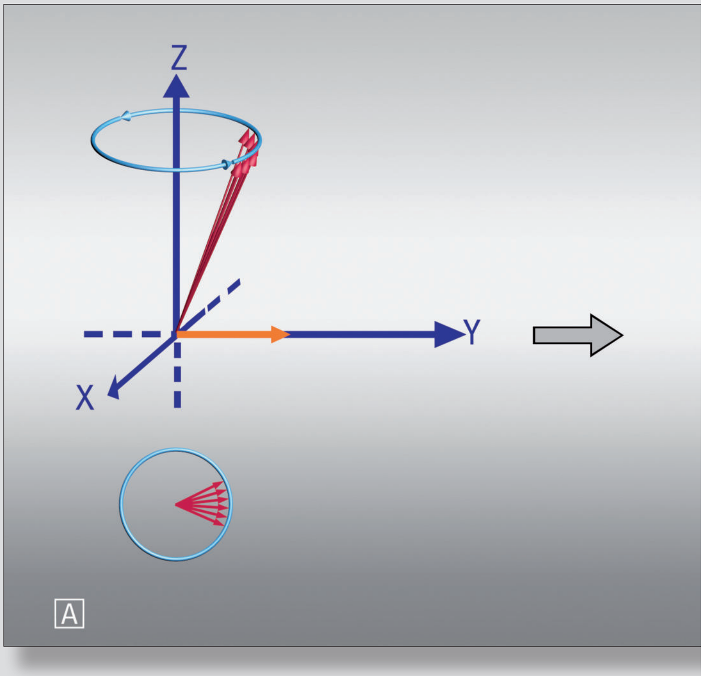


Fig. 19: T_1 is the longitudinal relaxation time that has something to do with the exchange of thermal energy.

Reminding you also that it describes the spin-“1”attice relaxation.

But there are more hidden hints to this: the “1” also looks like a match. And this match should remind you of something, which we also have mentioned already: longitudinal relaxation has something to do with exchange of energy, thermal energy, which the protons emit to the surrounding lattice while returning to their lower state of energy.



About T_2

Enough about the longitudinal magnetization – what happens with the transversal magnetization?

Let us assume that this is the situation just before the RF pulse is switched off.

When the RF pulse is switched off, the protons get out of step, out of phase again, as nobody is telling then to stay in step. For the sake of simplicity, this has been illustrated for a group of protons which all “point up” in figure 20. We heard earlier that protons precess with a frequency

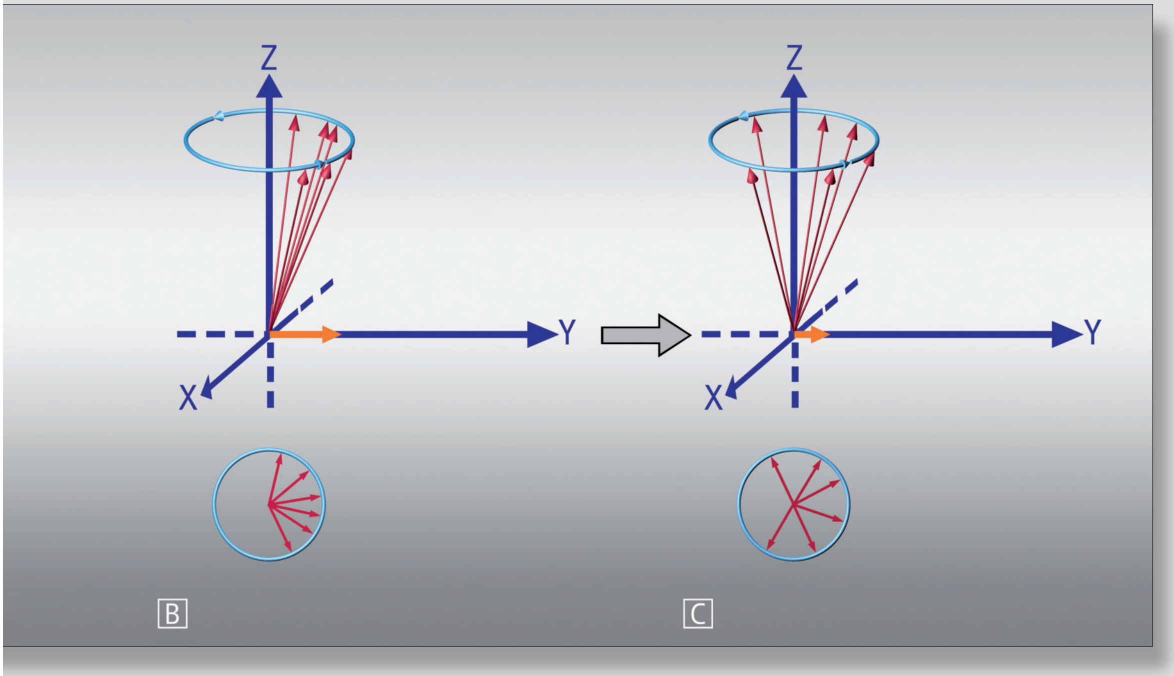


Fig. 20: After the RF pulse is switched off, protons lose phase coherence, they get out of step. When you look at these dephasing proton ensembles from the top (which is illustrated in the lower part of the figure), it becomes obvious, how they fan out. Fanning out, they point less and less in the same direction, and thus transversal magnetization decreases.

which is determined by the magnetic field strength that they are in. And all the protons should experience the same magnetic field. This, however, is not the case:

Firstly, the field of the MR magnet, in which the patient is placed, is not totally uniform, not totally homogeneous, but varies a little, thus causing different precession frequencies.

Secondly, each proton is influenced by the small magnetic fields from neighboring nuclei that are also not distributed evenly, thus causing different precession frequencies, too. These internal magnetic field variations are somehow characteristic of a tissue. So, after the RF pulse is switched off, the protons are no longer forced to stay in step; and as they have different precession frequencies – as we have just learned –, they will be soon out of phase.

It is interesting to see, how fast the protons get out of phase: just suppose that one proton – p1 – is rotating at 10 million revolutions per second, i.e. with a precessing frequency of 10 megahertz.

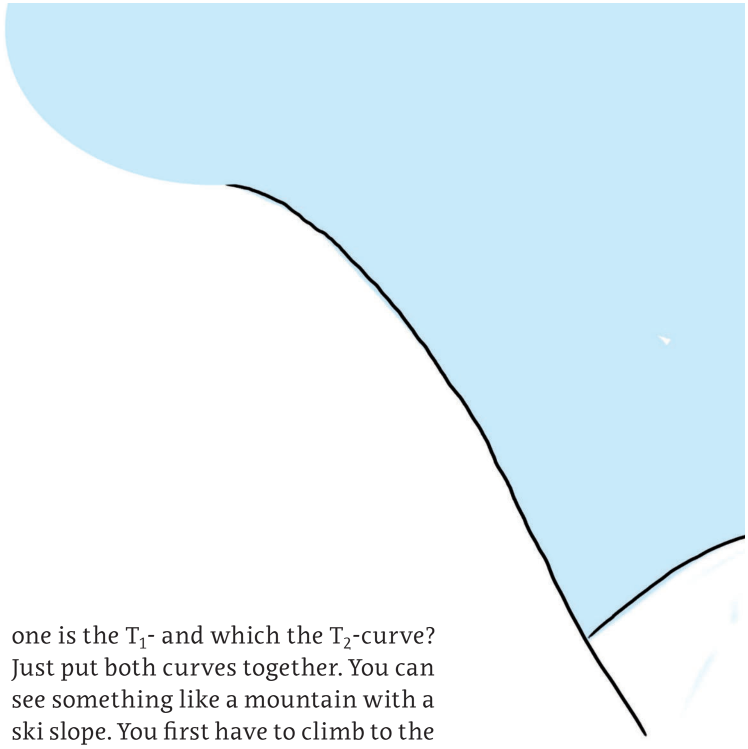
Due to inhomogeneities, a neighboring proton – p2 – is in a magnetic field, which is 1% stronger; this proton has a precession frequency of 10.1 megahertz, 1% more. In 5 microseconds (0.000005 sec or 5×10^{-6}), p2 will have made 50.5 turns or revolutions, while proton p1 will have made only 50. So in this short time span, the protons will be 180° out of phase, cancelling their magnetic moments in the respective plane.

Similar to what we did for the longitudinal magnetization, we can plot transversal magnetization versus time. What we get is a curve like in figure 21. This curve is going downhill, as **transversal magnetization** disappears with time. And as you probably expect: there is also a time constant, describing how fast transversal magnetization vanishes, goes downhill. This time constant is the **transversal relaxation time** T_2.

How to remember, what "$\mathbf{T_2}$" is?
Easy:

T_2 is T x 2 is TT is Tt

and this means, it describes the "T transversal", thus the relaxation of the transversal magnetization. The resulting curve in figure 21 thus is called a **T_2-curve**. Another term for transversal relaxation is **spin-spin-relaxation**, reminding us of the underlying mechanism, a spin-spin interaction. How to remember, which one is the T_1- and which the T_2-curve? Just put both curves together. You can see something like a mountain with a ski slope. You first have to climb to the top – T_1-curve –, before you ski down – T_2-curve (figure 22).



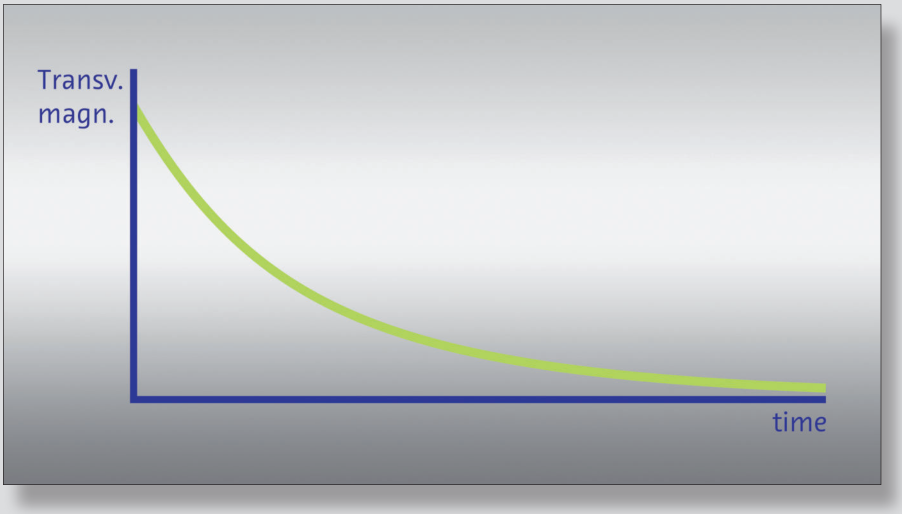
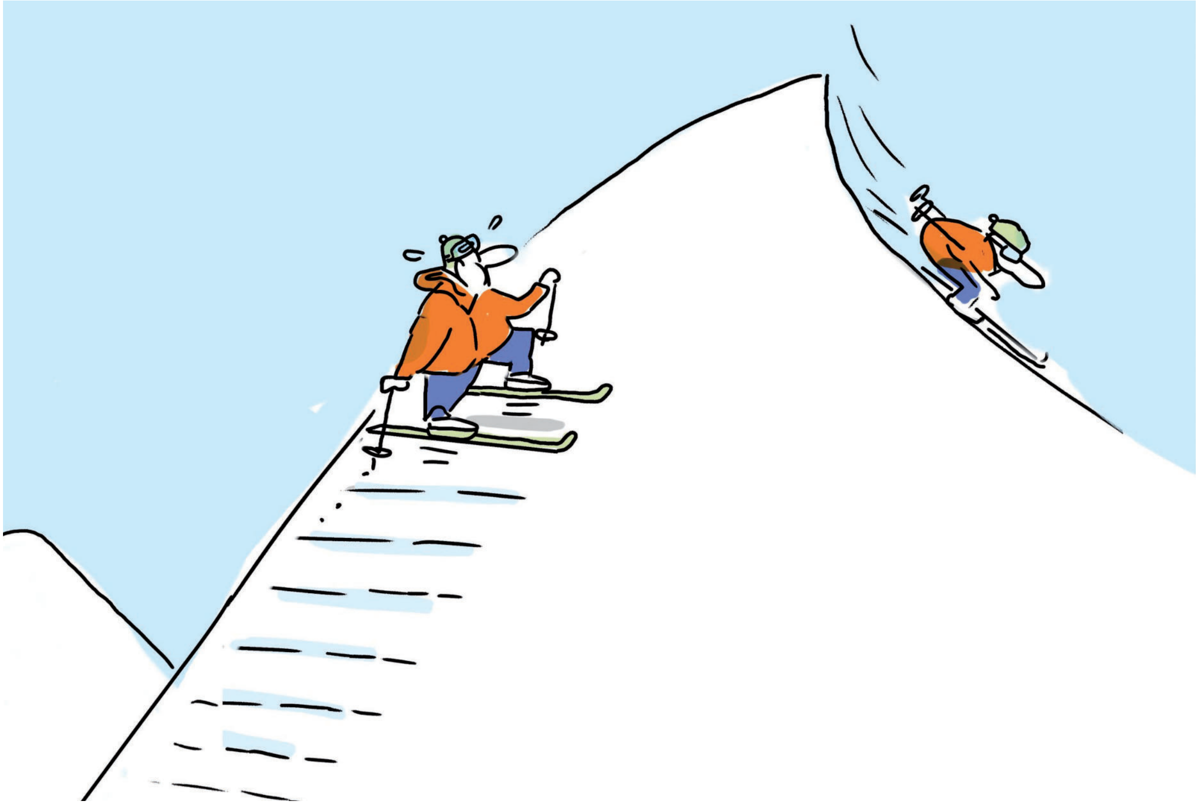


Fig. 21: If one plots transversal magnetization vs. time after the RF pulse is switched off, one gets a curve as illustrated, which is called a T_2-curve.



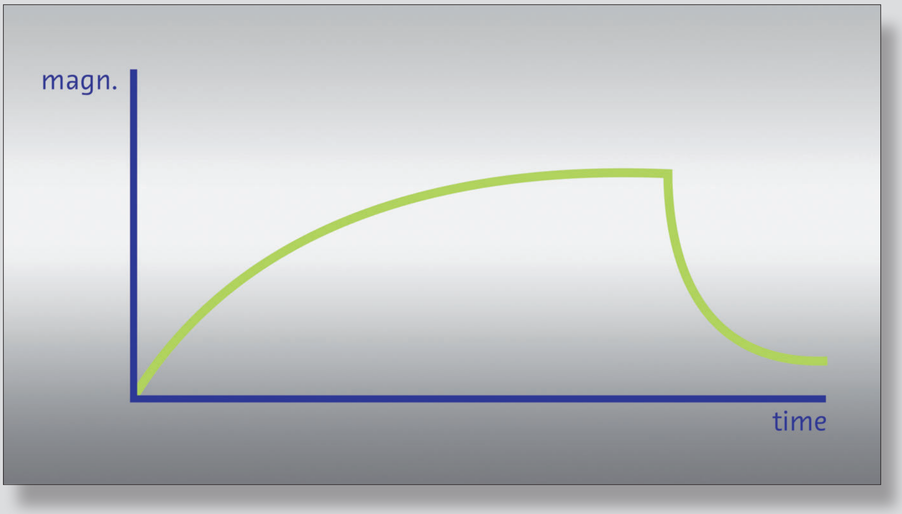


Fig. 22: Coupling of a T_1- and a T_2-curve resembles a mountain with a slope. It takes longer to climb a mountain than to slide or jump down, which helps to remember that T_1 is normally longer than T_2.

So, time for a review

We have learned:

- Protons are like little magnets.
- In an external magnetic field, they align parallel or anti-parallel.
- The lower energy state – parallel – is preferred, so a few more protons align this way.
- The protons perform a motion that resembles the wobbling of a spinning top.
- This motion is called precession.
- The precession frequency is dependent on the strength of the external magnetic field – a relationship which is described by the Larmor equation.

  The stronger the magnetic field, the higher the precession frequency.
- Protons “pointing” in opposite directions cancel each other’s magnetic effects in the respective directions.
- As there are more protons aligned parallel to the external field, there is a net magnetic moment aligned with or longitudinal to the external magnetic field.
- A radio frequency pulse that has the same frequency as the precessing protons, can cause resonance, transfer energy to the protons. This results in more protons being anti-parallel and thus neutralizing or cancelling more protons in the opposite direction.

  Consequence: the longitudinal magnetization decreases.
- The RF pulse also causes the protons to precess in synch, in phase. This results in a new magnetic vector, the transversal magnetization, which moves around with the precessing protons.
- When the RF pulse is switched off,

  – transversal magnetization decreases and disappears,

  – while longitudinal magnetization increases again.

  This longitudinal relaxation is described by a time constant T_1, the **longitudinal relaxation time**.

  The transversal relaxation is described by a time constant T_2, the **transversal relaxation time**.

  Longitudinal and transversal relaxation are different, independent processes, and that is why we discussed them individually (see figures 17 and 20).

This is what you should know by now.