How long is a relaxation time?

At the end of our last section we already learned that it takes longer to climb a mountain than to ski down, which means that T_1 is normally longer than T_2.

Just to give you an idea: T_1 is about 2–10 times as long as T_2. Or in absolute terms in biological tissues: T_1 is about 300 to 2,000 msec, and T_2 is about 30 to 150 msec.

It is difficult to pinpoint the end of the longitudinal and transversal relaxation exactly. Thus, T_1 and T_2 were not defined as the time when relaxation has completed. Instead T_1 was defined as the time when about 63% of the original longitudinal magnetization was reached.

T_2 is the time, when transversal magnetization decreased to 37% of the original value. These percentages are derived from mathematical equations ($63\% = 1 - 1/e$; $37\% = 1/e$) describing signal intensity, but we do not want to go into more detail here. (However, we should mention that $1/T_1$ is also called **longitudinal relaxation rate**, and $1/T_2$ **transversal relaxation rate**.)

Previously, it was believed that measuring the relaxation times would give tissue characteristic results, and thus enable exact tissue typing. This, however, proved to be wrong, as there is

quite an overlap of time ranges. What is a long, what is a short relaxation time, and which tissues have long or short relaxation times?

Look at figure 23 – what do you see? You see somebody having a long drink, something liquid (representing water). When you go to your favorite bar, which is naturally crowded, as it is a popular place, and order a long drink, you have to wait quite a while to get your drink – T_1 is long. When you finally have your long drink, it also takes you a long time to drink it, so T_2 is also long. And we want to remember: water/liquids have a long T_1 and a long T_2.

Fig. 23: Liquids have a long T_1 and a long T_2.

Now, look at this gentleman in figure 24 getting a hamburger. These normally contain much fat, and will represent fat for us.

The hamburger is fast food, you get it fast, thus **fat** has a short T_1.

What about T_2? It takes some time to eat fast food because of the fat; however, you normally spend more time with your long drink, so fat has a shorter T_2 than water.

As **water** has a long T_1 and a long T_2, it is easy to imagine that "watery tissues", tissues with a high water content, can also have long relaxation times.

Interestingly enough, pathological/diseased tissues often have a higher water content than the surrounding normal tissues.

Fig. 24: Compared to liquids/water, fat has a short T_1 and short T_2.

What is T_1 influenced by?

Actually, T_1 depends on tissue composition, structure and surroundings.

As we have learned, **T_1-relaxation** has something to do with the exchange of thermal energy, which is handed over from the protons to the surroundings, the lattice. The precessing protons have a magnetic field that constantly changes directions, and which constantly fluctuates according to the Larmor frequency. The lattice also has its own magnetic fields.

The protons now want to hand energy over to the lattice to relax.

This can be done very effectively, when the fluctuations of the magnetic fields in the lattice occur with a frequency that is near the to Larmor frequency.

When the lattice consists of pure liquid/water, it is difficult for the protons to get rid of their energy, as the small water molecules move too rapidly.

And as the protons, which are on the higher energy level, cannot hand their energy over to the lattice quickly, they will only slowly go back to their lower energy level, their longitudinal alignment.

Thus it takes a long time for the longitudinal magnetization to show up again, and this means that liquids/water have long T_1s.

When the lattice consists of medium-size molecules – most body tissues can be looked at as liquids containing various-sized molecules, kind of like a soup – that move and have fluctuating magnetic fields near the Larmor frequency of the precessing protons, energy can be transferred much faster, thus T_1 is short.

This can again be illustrated by our hamburger and bicycle example: (see page 17) handing over hamburgers – i.e. energy – from one bicycle – proton – to the other – lattice – is easy and efficient, when both move with the same speed. With a difference in speed, the energy transfer will be less efficient.

Why does fat have a short T_1?

The carbon bonds at the ends of the fatty acids have frequencies near the Larmor frequency, thus resulting in effective energy transfer.

And why is T_1 longer in stronger magnetic fields?

As we heard in the beginning, the precession frequency depends on magnetic field strength, a relationship described by the Larmor equation.

If we have a stronger magnetic field, then the protons precess faster.

And when they precess faster, they have more problems handing down their energy to a lattice with more slowly fluctuating magnetic fields.

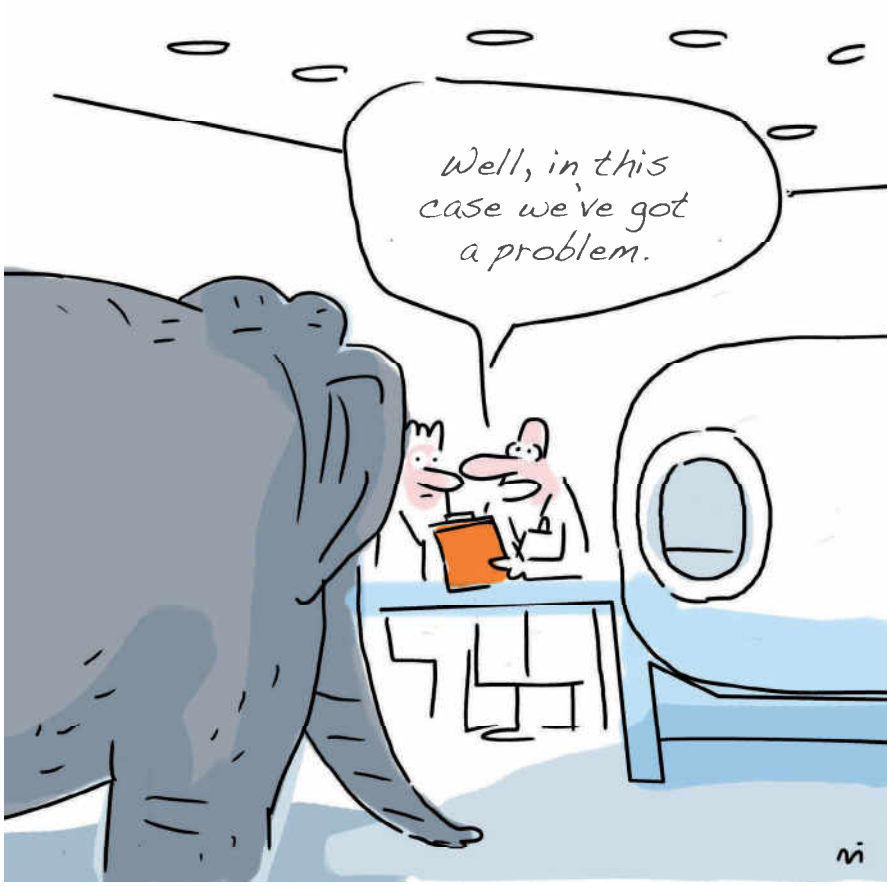
What influences T_2?

T_2-relaxation comes about when protons get out of phase, which – as we already know – has two causes: inhomogeneities of the external magnetic field, and inhomogeneities of the local magnetic fields within the tissues (see page 27). As water molecules move around very fast, their local magnetic fields fluctuate fast, and therefore kind of average each other out, so there are no big net differences in internal magnetic fields from place to place. And if there are no big differences in magnetic field strength within a tissue, the protons stay in step for a long time, before they dephase, and so T_2 is longer. With impure liquids, e.g. those containing some larger molecules, there are bigger variations in the local magnetic fields. The

larger molecules do not move around as fast, so their local magnetic fields do not cancel each other out as much. These larger differences in local magnetic fields consequently cause larger differences in precessing frequencies, thus protons get out of phase faster, T_2 is shorter.

This can be illustrated by the following example: imagine that you drive down a street with many pot holes. When you drive slowly (which is equal to the surroundings moving slowly and you are standing still), you will be bumping up and down in your car as it drives over each pot hole. The differences in the surroundings (the magnetic field variations) influence you considerably. When you drive very fast (which is the same as if the surroundings move very fast), you do not feel each single pot hole anymore. Before they have a major effect on you, you are already back at normal street level; thus their effect is averaged out, you are much less influenced by differences in the surroundings (the variations in magnetic field strength).

What does all this have to do with what we want to know? All these processes influence how your MR picture will finally look!



A brief review might be advisable:

- T_1 is longer than T_2.
- T_1 varies with the magnetic field strength; in stronger magnetic fields it is longer.
- Water has a long T_1, fat has a short T_1.
- T_2 of water is longer than the T_2 of impure liquids containing larger molecules.

An experiment ...

Now let us perform an experiment

Look at figure 25, where you can see two protons, precessing around the z-axis. I hope you recall that the z-axis indicates the direction of a magnetic field line (see page 9). Instead of only these two protons, in reality there may be 8 pointing up and 6 pointing down, or 82 up and 80 down – there

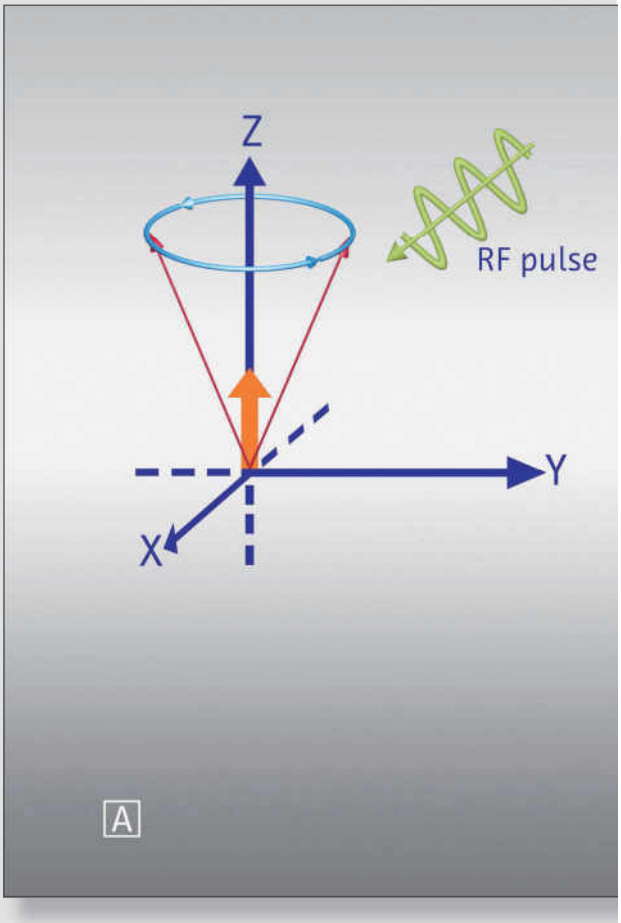


Fig. 25: If after the RF pulse the number of protons on the higher energy level equals the number of protons on the lower energy, longitudinal magnetization has disappeared, and there is only transversal magnetization due to phase coherence. The magnetic vector seems to have been "tilted" 90° to the side. The corresponding RF pulse is thus also called a 90° pulse.

shall only be two more protons pointing up.

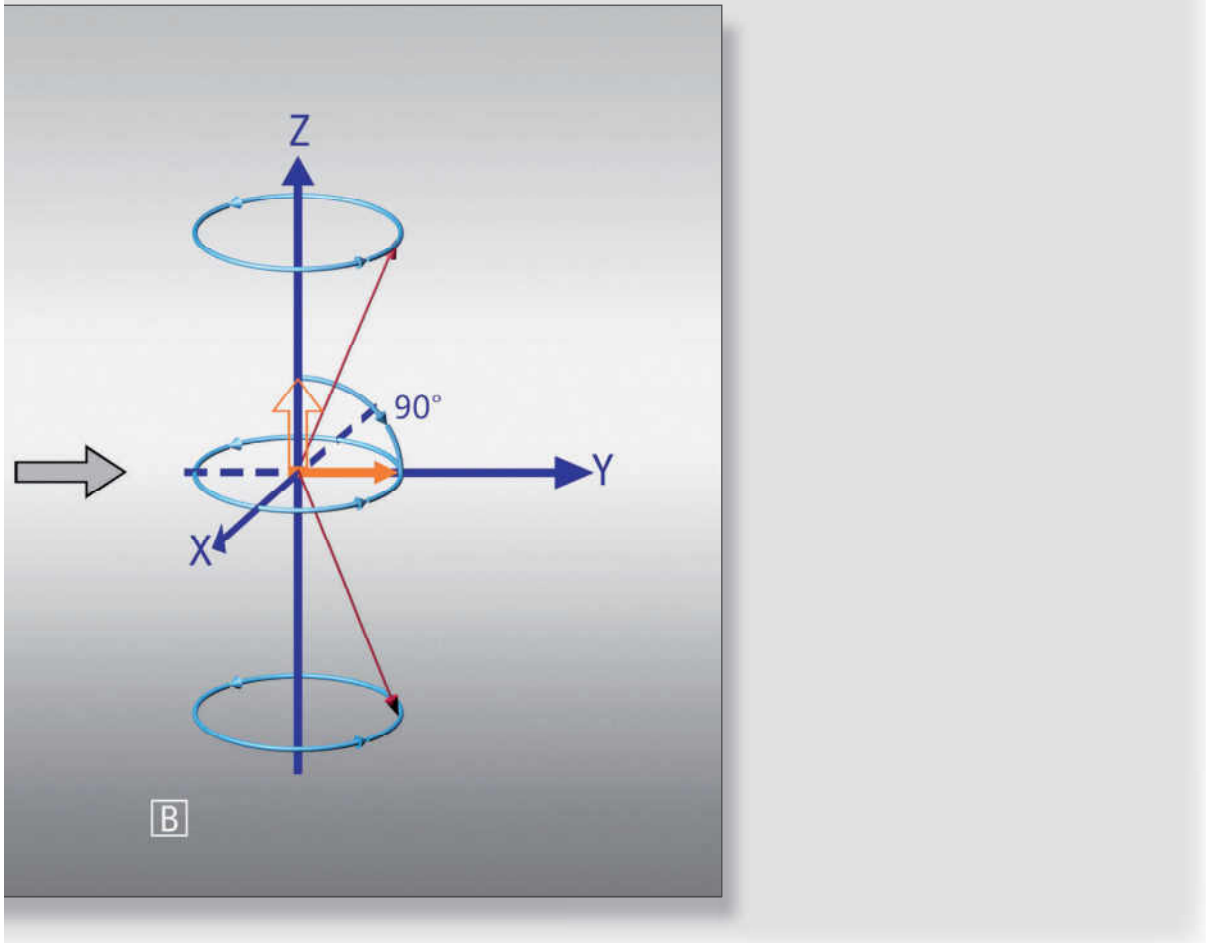
As we know, these are the ones that have a net magnetic effect because their effects are not cancelled out.

Now let us send in an RF pulse, which has just the correct strength and duration, so that one of the two protons picks up energy to go into a higher state of energy, i.e. points down/walks on its hands.

What will happen? The **longitudinal magnetization** (up to now resulting from two protons pointing up) will decrease, in our example to zero (one pointing up is neutralized by one pointing down). But: as both protons are in phase, there is now a transversal magnetization which had not been there before.

The RF pulse seemingly "tilts" the longitudinal **magnetic vector** 90° to the side.

Such an RF pulse is called a **90° pulse**. Naturally, other RF pulses are also possible, and are named accordingly, e.g. **180° pulse.**



To really understand this, let us look at another example. In figure 26A, we have 6 protons pointing up; we send in an RF pulse, which lifts 3 of them onto a higher energy level (B).

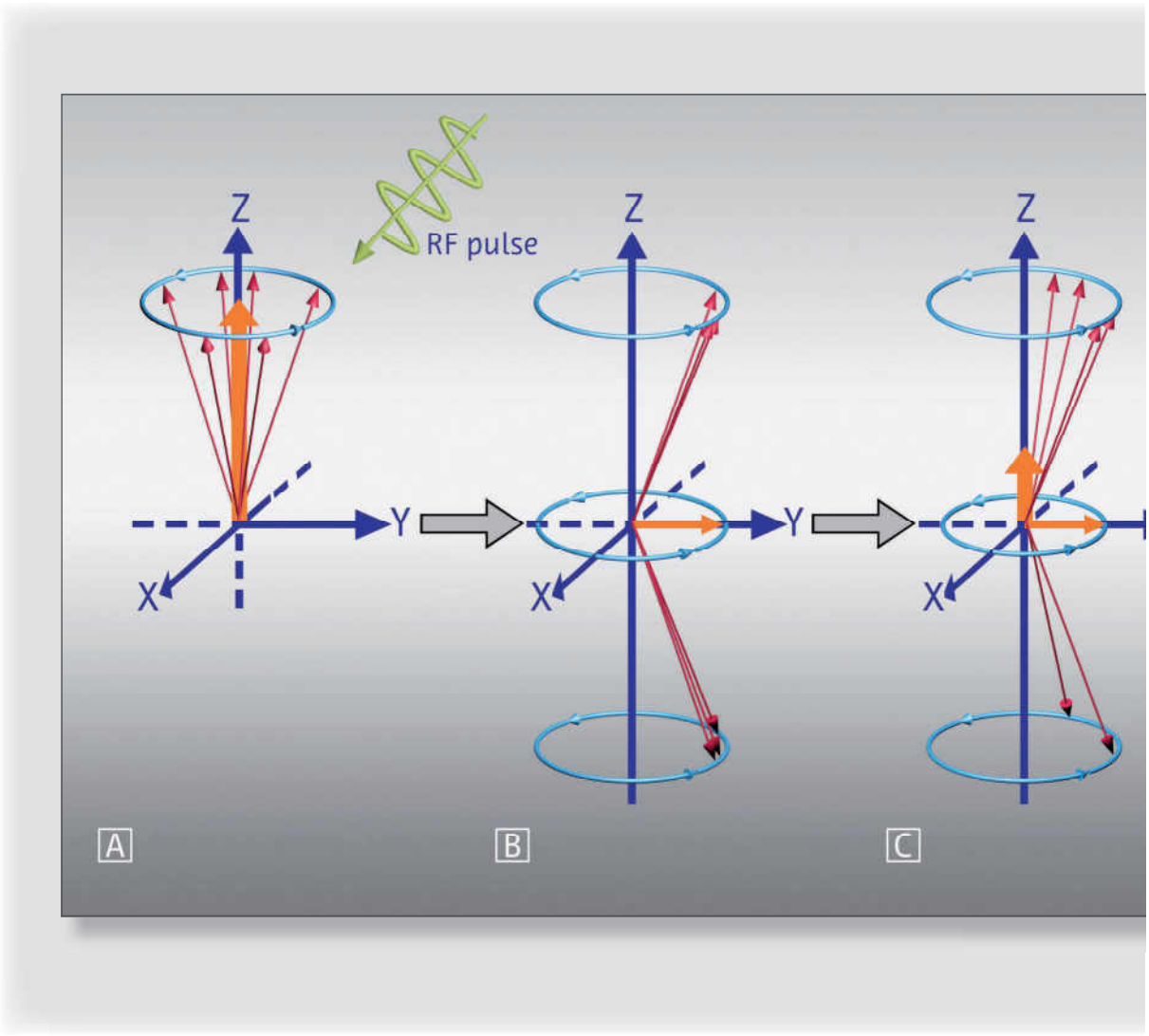
The result: we no longer have a longitudinal, but a transversal magnetization (again having used a 90° pulse).

What happens, when the RF pulse is switched off?

Two things happen: protons go back to their lower state of energy, and they lose **phase coherence**.

It is important to note that both processes occur simultaneously and independently. For the sake of simplicity, let us look at what happens step by step, and first focus on the **longitudinal magnetization**:

● After the RF pulse is switched off (figure 26C), one proton goes back to the lower energy state, result-



ing in 4 protons pointing up, and two pointing down. The net effect: we now have a longitudinal magnetization of "2".

- Then the next proton goes back up; now 5 protons are pointing up, and one down, resulting in a net longitudinal magnetization of "4" (figure 26D).
- After the next proton goes up, longitudinal magnetization equals "6" (figure 26E).

You surely have already noticed that the transversal magnetization decreases at the same time (figure 26C-E). Why? You should be able to answer this: After the RF pulse is switched off, the precessing protons lose phase coherence.

In figure 26B, all protons point in the same direction, but then increasingly get out of phase, and thus kind of fan out (figure 26C-E).

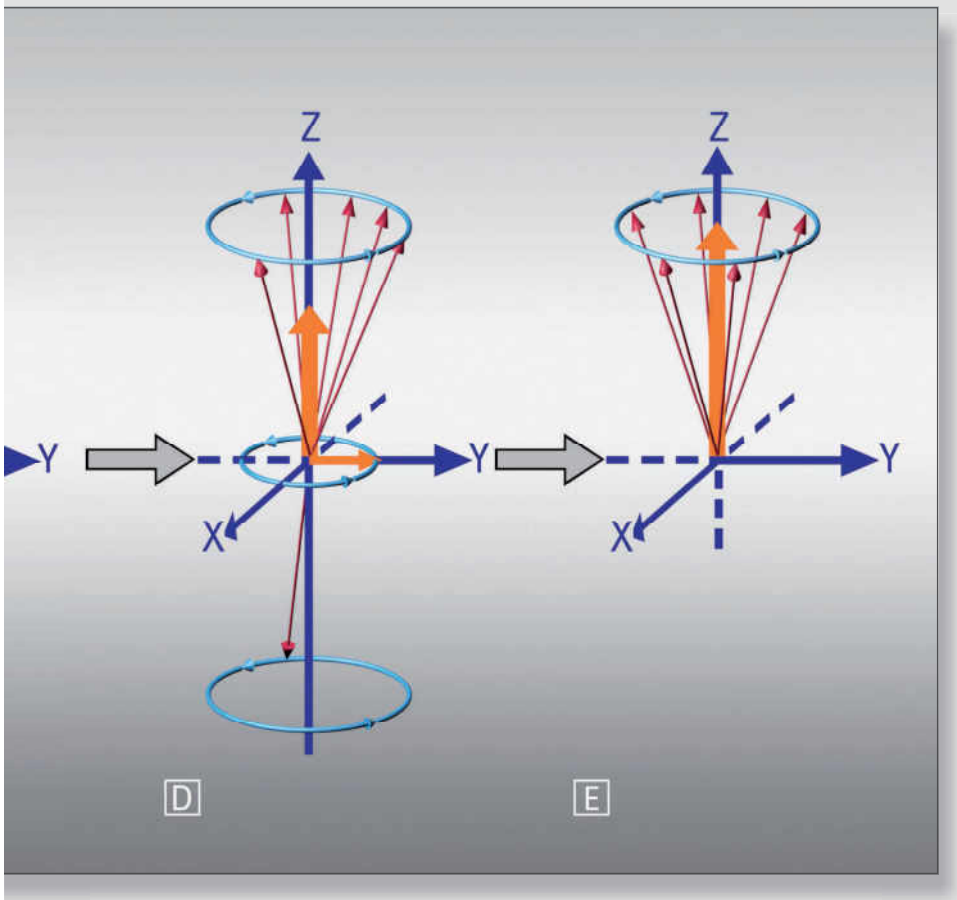
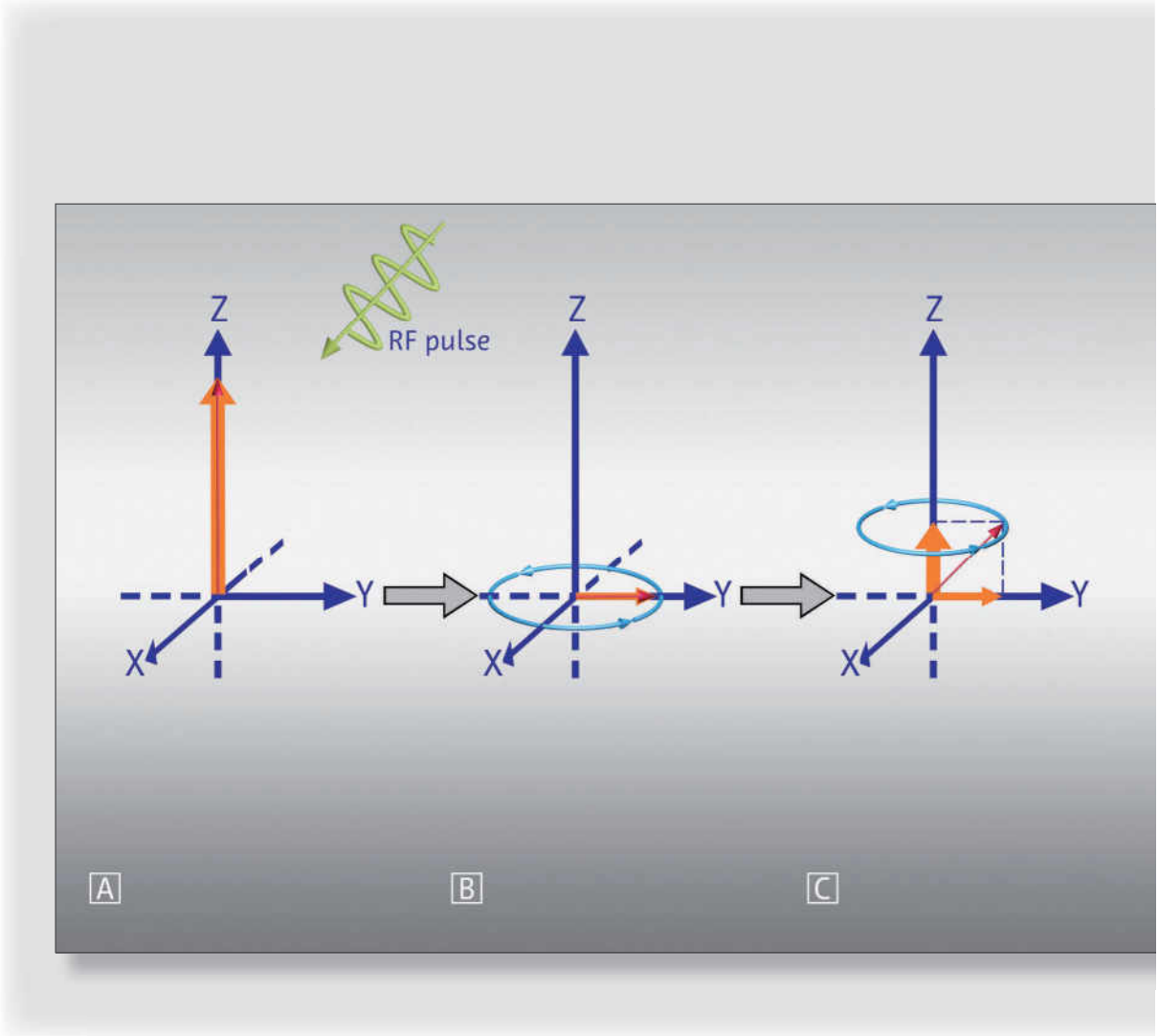


Fig. 26: (A) shows the situation before and (B) immediately after an RF pulse is sent in. The RF pulse causes the longitudinal magnetization (↑) to decrease, and with a 90° pulse as illustrated, it becomes zero (B). Protons also start to precess in phase (B), which causes the new transversal magnetization (→). After the RF pulse is switched off (C-E), longitudinal magnetization increases, recovers, and transversal magnetization disappears, decays. Both processes are due to entirely different mechanisms and occur independently, even though at the same time.

In figure 27, only the longitudinal and transversal **magnetic vectors** are depicted at corresponding times as in figure 26. These magnetic vectors add up to a sum vector (→).

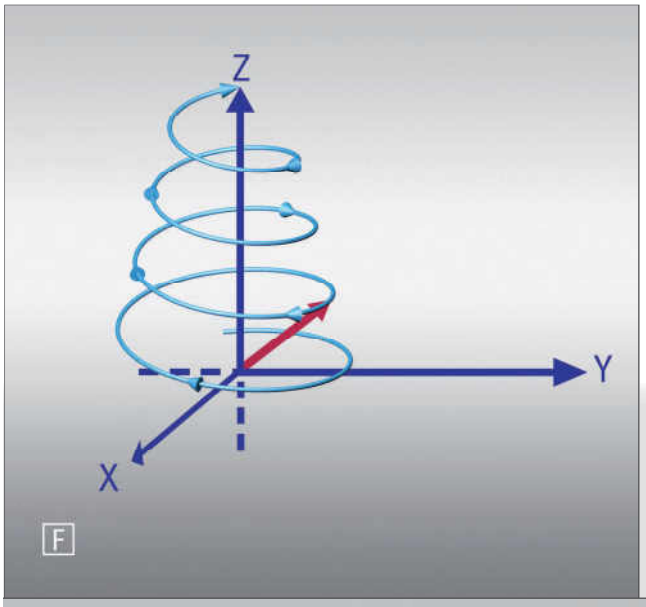
As you remember, vectors represent forces of a certain size and a certain direction. If you add up vectors pointing to different directions, you will come up with a direction that is somewhere in between, depending on the amount of force in the original directions. If we do the same with the longitudinal and the transversal vector, we get the **sum vector.**

This sum vector is very important, as it represents the total magnetic moment of a tissue in general, and thus can be used instead of the two single vectors, representing longitudinal and transversal magnetization separately. Our magnetic sum vector during relax-



ation goes back to a longitudinal direction, in the end equaling the **longitudinal magnetization.**

What we have to remember is that this whole system is actually precessing, including the sum magnetic vector. And thus – after the RF pulse is switched off – the sum vector will actually perform a spiraling motion (figure 27F).



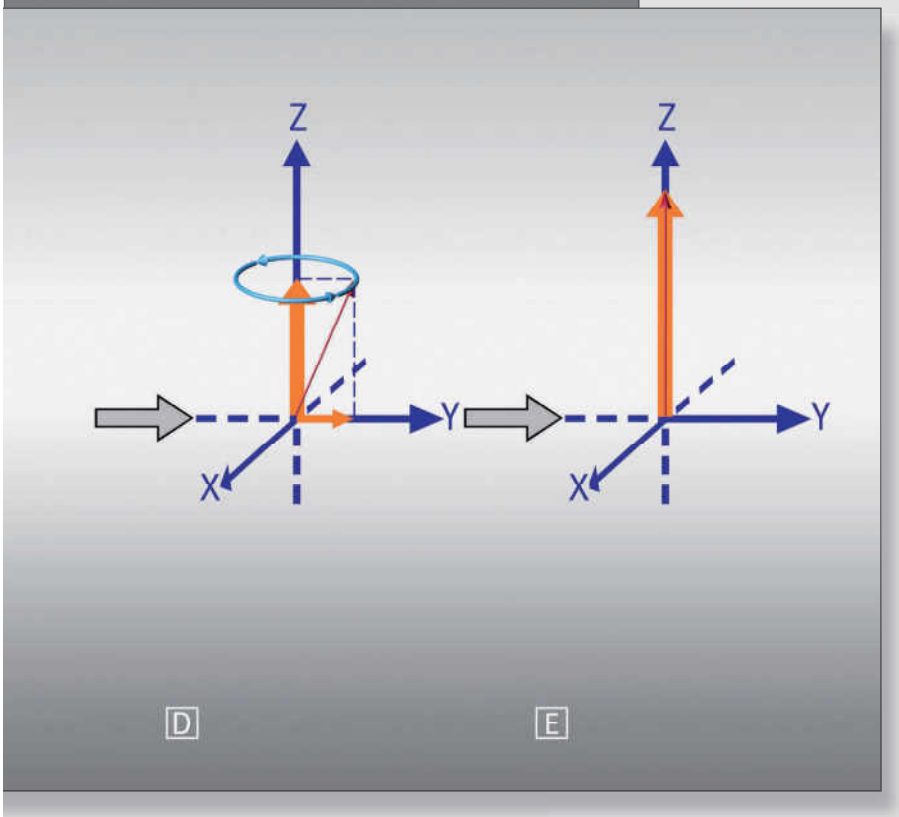


Fig. 27: In this illustration only the longitudinal and transversal magnetization vectors from our experiment in figure 26 are depicted. In (A) – before the RF pulse – there is only longitudinal magnetization. Immediately after the 90° RF pulse there is no longitudinal but new transversal magnetization (B), and this transversal magnetization vector is spinning around. With time this transversal magnetization decreases, while longitudinal magnetization increases (C-D), until the starting point with no transversal but full longitudinal magnetization is reached again (E). Transversal and longitudinal magnetization vectors add up to a sum vector (→). This sum vector performs a spiraling motion (F) when it changes its direction from being in the transversal (x-y) plane (no longitudinal magnetization) to its final position along the z-axis (no transversal magnetization).

I hope that you recall that a changing magnetic force/moment can induce an electric current, which is the signal that we receive and use in MR.

So if we put up an antenna somewhere (figure 28), we will get a signal as illustrated. This is easy to imagine, if you think of the antenna as a microphone, and the sum magnetic vector as having some kind of a sound-emitting device like a steam pipe at its tip. The further the vector goes away from the microphone, the less loud the sound. The frequency of the sound, however, remains the same because the **sum vector** spins with the precessing frequency (figure 29). So the

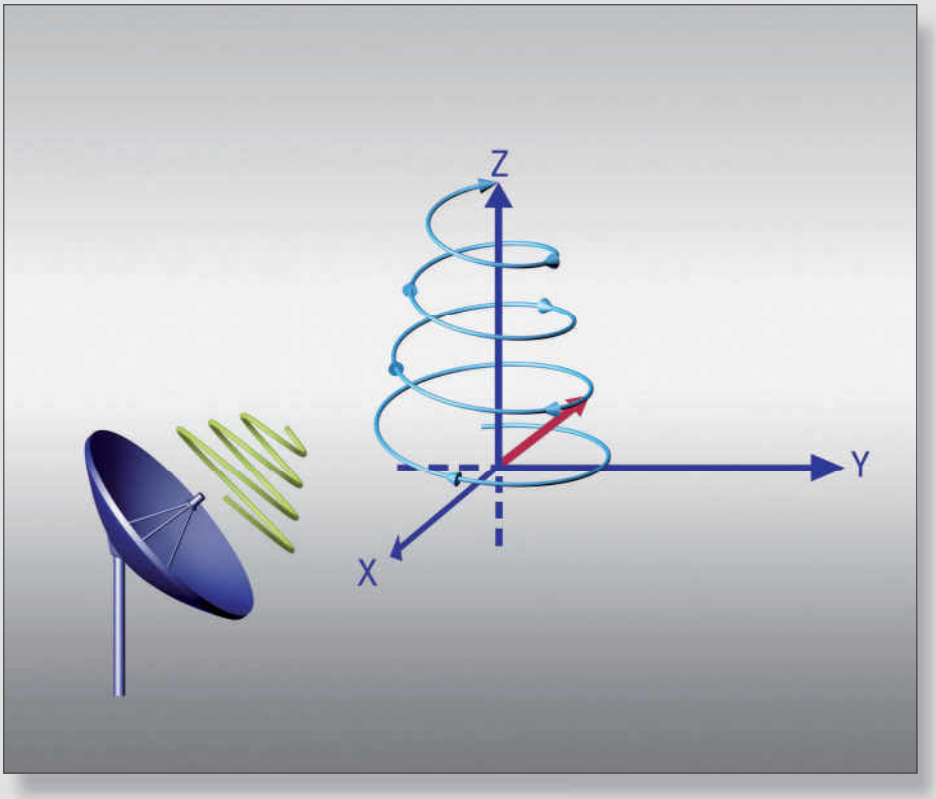


Fig. 28: For an external observer, the sum vector of figure 27F constantly changes its direction and magnitude, while it performs its spiraling motion. The sum vector induces an electrical current in an antenna, the MR signal. This is of greatest magnitude, immediately after the RF pulse is switched off, and then decreases.

signal from our experiment disappears with time, however, it has a constant frequency.

This type of signal is called a **free induction decay** signal, or **FID signal**.

By now it should be obvious that the magnetic vector directly determines the MRI signal and signal intensity by inducing electrical currents in the antenna. Instead of the terms "longitudinal" or "transversal magnetization", we can also use the term "signal or signal intensity" at the axis of our T_1- and T_2-curves.

This will hopefully become clearer, as you continue reading.

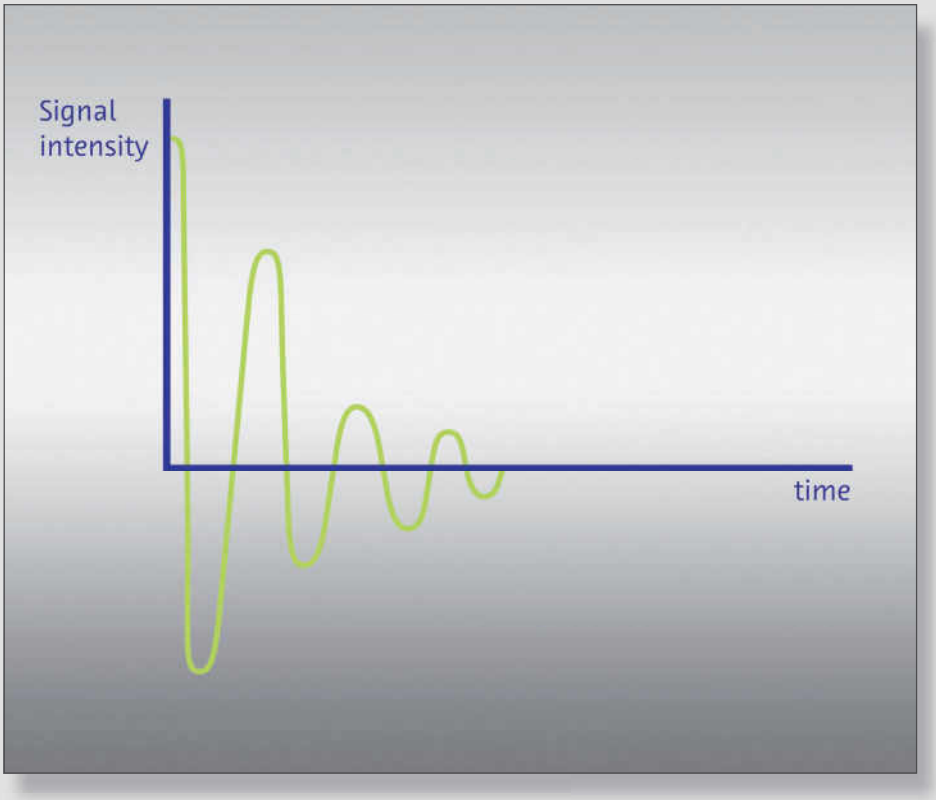


Fig. 29: The signal from our experiment in figures 26 to 28 disappears with time, however, it has a constant frequency. This type of signal is called a FID (free induction decay) signal.

Another experiment

Let us perform another experiment similar to the one illustrated in figure 30. As we want to concentrate purely on the magnetization, we can leave out the coordinate system. In figure 30A, we have two tissues, A and B, which have different relaxation times as we will see later. We send in a 90° RF pulse, switch it off and wait a certain time TR_{long} (we will explain later, why we use the term **TR**). Then we send in a second 90° pulse. What will happen?

As after the time TR_{long} tissue A and tissue B have regained all of their **longitudinal magnetization** (frame 5), the **transversal magnetization** after the second pulse will be the same for both tissues, as it was after the first RF pulse (frame 1). Tissue A cannot be differentiated from tissue B.

What if we do not wait so long from pulse to pulse? Let us look at figure 30B:

After the first pulse, an equally sized transversal magnetization is established in both tissues, which decreases after the pulse is switched off. At TR_{short} however, tissue A has regained more of its longitudinal magnetization than tissue B. When the second 90° pulse now "tilts" the longitudinal magnetization 90 degrees, the transversal magnetic vector of tissue A is larger than that of tissue B.

And when this vector of A is larger, it will reach closer to our antenna; thus the imaginary steam pipe at the tip of vector A will cause a louder, stronger signal in our "microphone", the antenna, than the vector of B.

The difference in signal intensity in this experiment depends on the difference in longitudinal magnetization, and this means on the difference in T_1 between the tissues. Using these two pulses, we can now differentiate tissue A from tissue B, which in our experiment was impossible, choosing only one 90° pulse or two 90° pulses that are a long time apart (after a long time, the differences in T_1 between tissue A and B no longer play a role in our experiment, because after that time the tissue B with the longer T_1 is back to its original state, too).

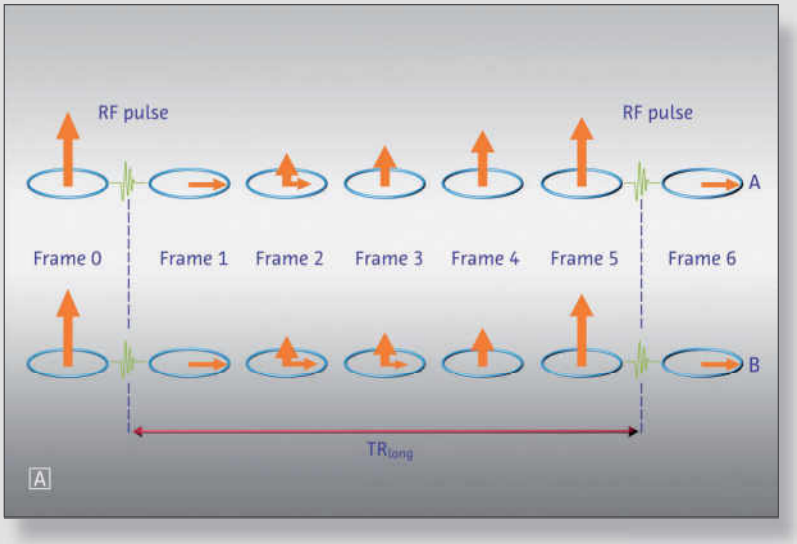


Fig. 30A

When we do not wait as long as in figure 30A, but send in the RF pulse after a shorter time (TR_{short}), like in figure 30B, longitudinal magnetization of tissue B, which has the longer T_1, has not recovered as much as that of tissue A with the shorter T_1. The transversal magnetization

When you use more than one RF pulse – a succession of RF pulses – you use a so-called **pulse sequence**. As you can use different pulses, e.g. 90° or 180° pulses, and the time intervals between successive pulses can be different, there can be many different pulse sequences. As we saw in our experiment, the choice of a pulse sequence will determine, what kind of signal you get out of a tissue. So it is necessary to carefully choose and also describe the pulse sequence for a specific study.

The pulse sequence that we used was made up of one type of pulse only, the 90° pulse. This was repeated after a certain time, which is called **TR = time to repeat.**

How did TR influence the signal in our experiment?

With a long TR we got similar signals from both tissues, both would appear the same on an MR picture, since the transversal magnetization was the same for both tissues. Using a shorter TR, there was a difference in signal intensity between the tissues, determined by their difference in T_1. The resulting image is called a **T_1-weighted image**. This means that the difference of signal intensity between tissues in that image, the **tissue contrast**, is mainly due to their difference in T_1. However, there is always more than one parameter influencing the tissue contrast; in our example, T_1 is just the most outstanding one.

What is a short, what is a long TR?

A **TR** of less than 500 msec is considered to be short, a TR greater than 1,500 msec to be long. As you may imagine or know already, we cannot only create **T_1-weighted images**, but also **T_2-weighted images**, and so-called **proton density (-weighted) images.**

This **proton density**, which is also called **spin density**, influences tissue contrast and can be explained quite simply: where there are many protons, we will have "lots" of signals. Where there are no protons, there will be no signal. We will read more about this later. The point is that by using certain pulse sequences, we can make certain tissue characteristics to be more or less important in the resulting image.

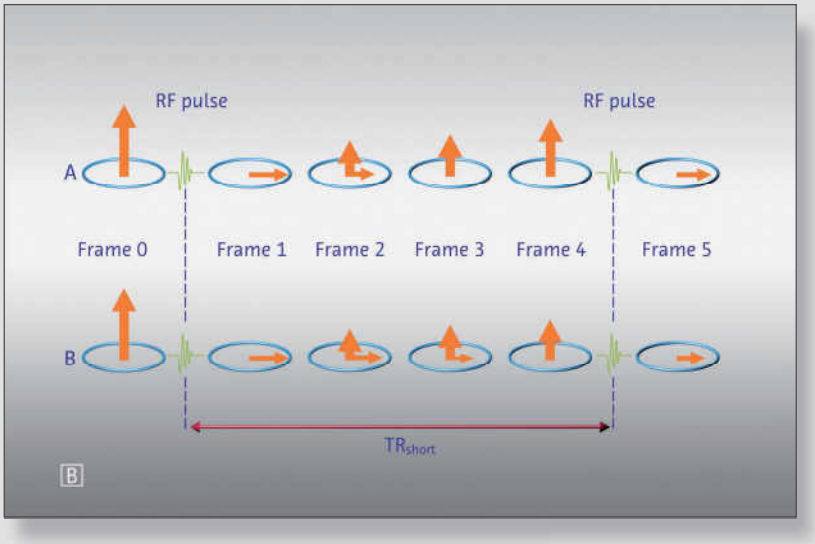


Fig. 30B

of the two tissues after the second RF pulse will then be different (frame 5). Thus, by changing the time between successive RF pulses, we can influence and modify magnetization and the signal intensity of tissues.

By choosing a pulse sequence, the doctor can be compared to a conductor of an orchestra (figure 31): he can influence the overall appearance of the sound (signal) by making certain instruments (parameters) influence the sound more than others. All instruments (parameters), however, always play some role in the final sound (signal).

Let us go back to our experiment once more for a short repetition:

- With a certain type of RF pulse, we can cause the longitudinal magnetization to disappear, while a transversal magnetization appears. The "net magnetization" (the sum vector of longitudinal and transversal magnetization) is "tilted" 90° in this case (when we started, we only had longitudinal magnetization). The corresponding RF pulse is therefore called a 90° pulse.
- The transversal component of the net magnetization can induce a measurable signal in an antenna.

Fig. 31: The MRI doctor can be compared to a conductor: by choosing certain pulse sequences, he can modify the resulting signal, which is itself influenced by different parameters.

- Immediately after the RF pulse relaxation begins: transversal magnetization starts to disappear and longitudinal relaxation begins to reappear. The signal disappears.
- When we send in the second 90° pulse, the net magnetization is again tilted 90°, and we again receive a signal.
- The strength of this signal depends (among other things) on the amount of longitudinal magnetization we start out with. Do you remember the T_1-curve? The T_1-curve described the relationship between time (after an RF pulse) and the amount of longitudinal magnetization (figure 18).

When we wait a long time before sending in our second RF pulse, longitudinal magnetization will have recovered totally.

The signal after the second RF pulse will thus be the same as the one after the first pulse. However, when the second pulse comes in earlier, the signal will be different, since the amount of longitudinal magnetization at that time is less.

The difference in signal intensity

In figure 32, you can see the T_1-curves for brain and for cerebrospinal fluid (CSF). Brain has a shorter longitudinal relaxation time than CSF.

At the time 0, we have no longitudinal magnetization at all, and this can be the time immediately after our first 90° pulse. When we wait a long time before we repeat the 90° pulse (TR_{long}), **longitudinal magnetization** has pretty much recovered. The longitudinal magnetic vectors that will be "tilted" 90°, differ only to a small degree, so there will only be a small difference in signal intensity, i.e. tissue contrast between brain and CSF is small. If we, however, send in the second pulse after a shorter time, TR_{short}, the difference in longitudinal magnetization is rather large, so there will be a better **tissue contrast.**

And as we can see from the distance between the two curves, there is a time span where tissue contrast is most pronounced.

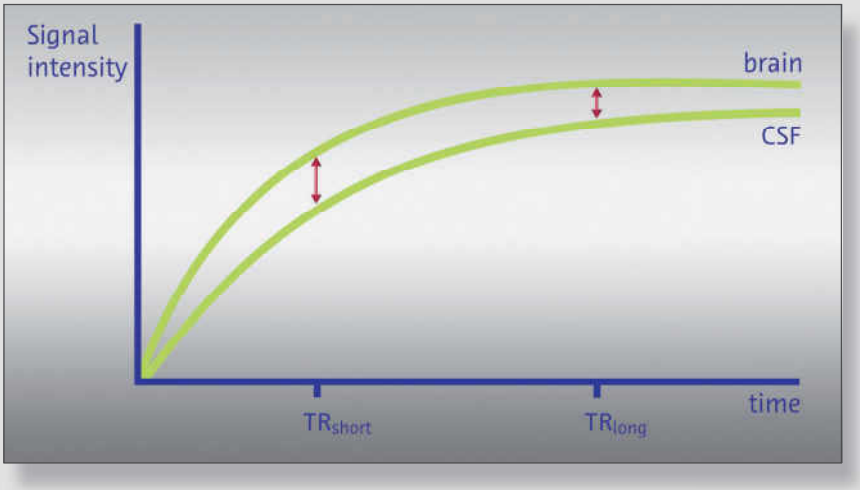


Fig. 32: Brain has a shorter longitudinal relaxation time than CSF. With a short TR, the signal intensities of brain and CSF differ more than after a long TR.

Why are the signals after a very long time TR between pulses not identical?

We have heard the explanation already. The signal intensity depends on many parameters. When we wait a long time, T_1 does not influence the tissue contrast any more, however, there may still be a possible difference in the **proton density** of the tissues in question.

And when we wait a very long time TR in our experiment from figure 32, the difference in signal is mainly due to different proton densities, we have a so-called **proton density-** (or **spin density-) weighted image.**

Now we have heard about T_1- and proton density-weighted images.

T_2-weighted images

How do we obtain a T_2-weighted image?

This is a little more difficult to understand. Let us perform another experiment, which is a little different from the ones before. First, we use a 90° pulse. The longitudinal magnetization is tilted, we get a transversal magnetization. What happens after this pulse, when we wait a short time?

You can surely answer this question without difficulty – if not, go back to page 27 before you continue to read.

After the pulse is switched off, longitudinal magnetization starts to reappear, the transversal magnetization, however, starts to disappear. Why does the transversal magnetization disappear? It is because the protons . . . lose phase coherence, as we learned earlier.

This is illustrated in figure 33 for three protons, which are almost exactly in phase as seen in (A) but increasingly spread out, as they have different precession frequencies (see B and C). The loss of **phase coherence** results in decreasing transversal magnetization and thus loss of signal. Now we will do something new: af-

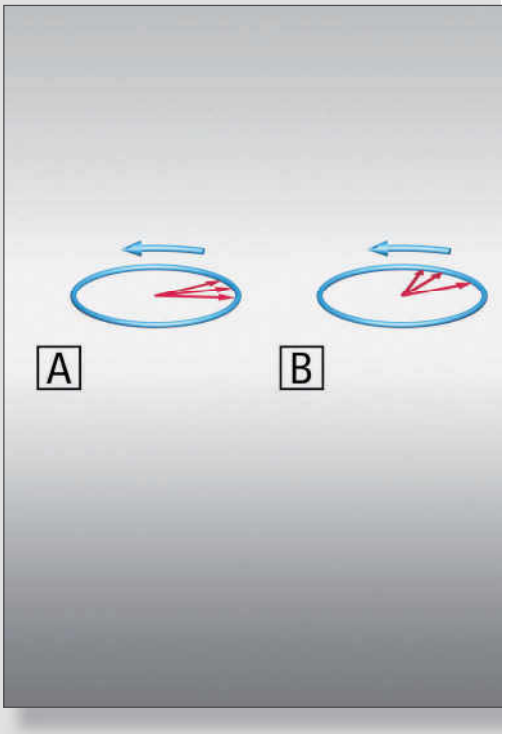


Fig. 33: After the RF pulse is switched off, the protons dephase (A-C). The 180° pulse causes them to precess in the opposite direction, and so they rephase again (D-F).

ter a certain time (which we call TE/2, half of **TE**, for reasons you will understand in a few minutes), we will send in a **180° pulse**. What happens?

The 180° pulse acts like a rubber wall; it makes the protons turn around, so that they precess in exactly the opposite direction, which is clockwise.

The result is that the faster precessing protons are now behind the slower ones. If we wait another time TE/2, the faster ones will have caught up with the slower ones (see figure 33F).

At this point in time, the protons are nearly in phase again, which results in a stronger transversal magnetization, and thus in a stronger signal again. A little later, however, the faster precessing protons will be ahead again, with the signal decreasing again.

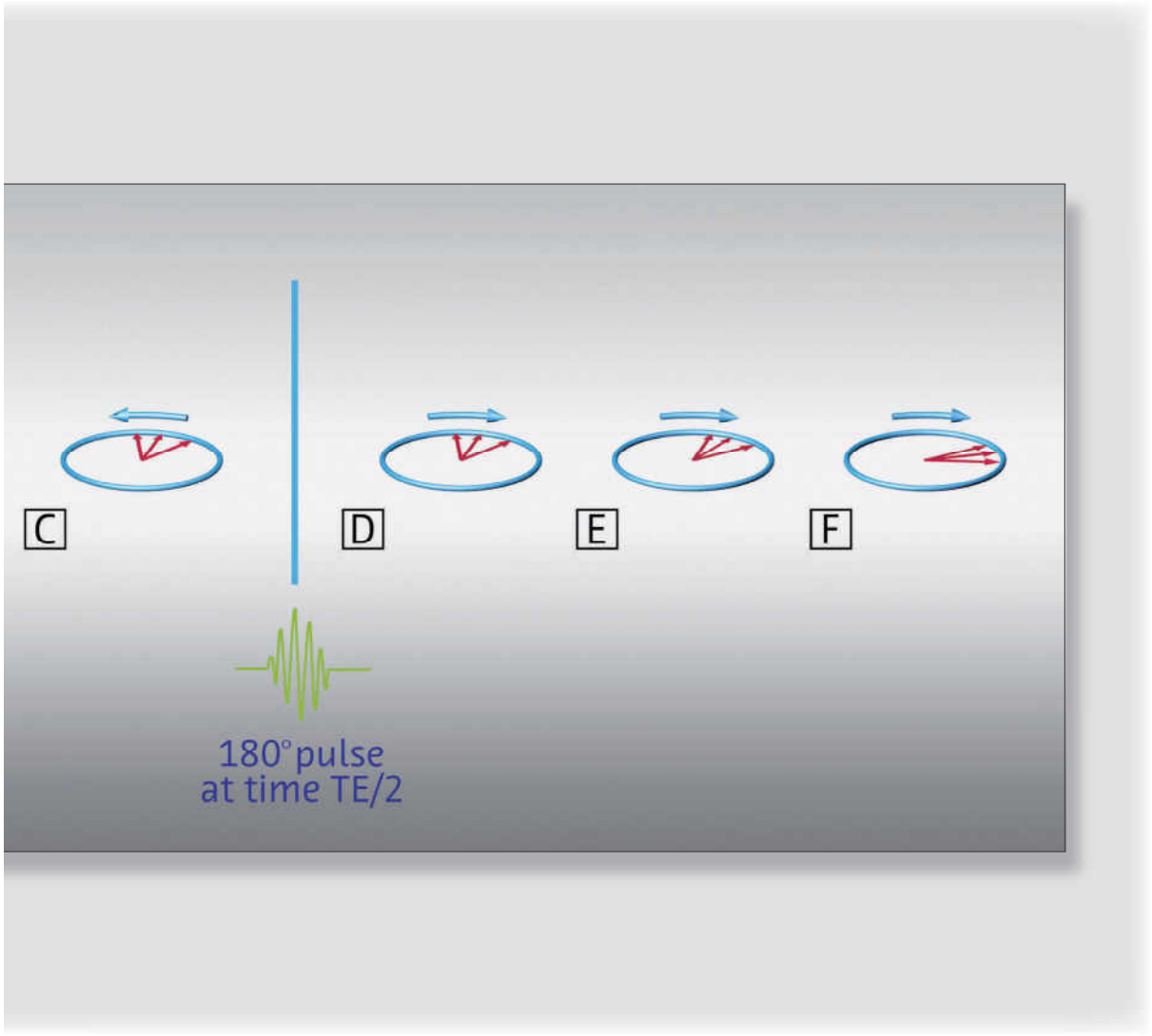


Fig. 34: When a hare and a tortoise run in one direction for a certain time, then turn around and run in the opposite direction with the same speed for the same time, they will arrive at the starting point at the same time.

To illustrate this: think about a race between a tortoise and a hare starting at the same line (figure 34). After a certain time (TE/2), the hare is ahead of the tortoise. When you make the competitors run in the opposite direction for the same length of time, they will both be back at the starting line at exactly the same time (assuming, that they run at constant speed).

In our experiment, the **180° pulse** acts like a wall, from which the protons bounce back, like a mountain reflecting sound waves as echoes. This is why the resulting strong signal is also called an echo, or **spin echo**.

After we have our signal, our spin echo, the protons lose phase coherence again, the faster ones getting ahead, as we have seen.

We naturally can perform the experiment again with another 180° pulse, and another and another ...

If we now plot time vs. signal intensity, we get a curve like in figure 35.

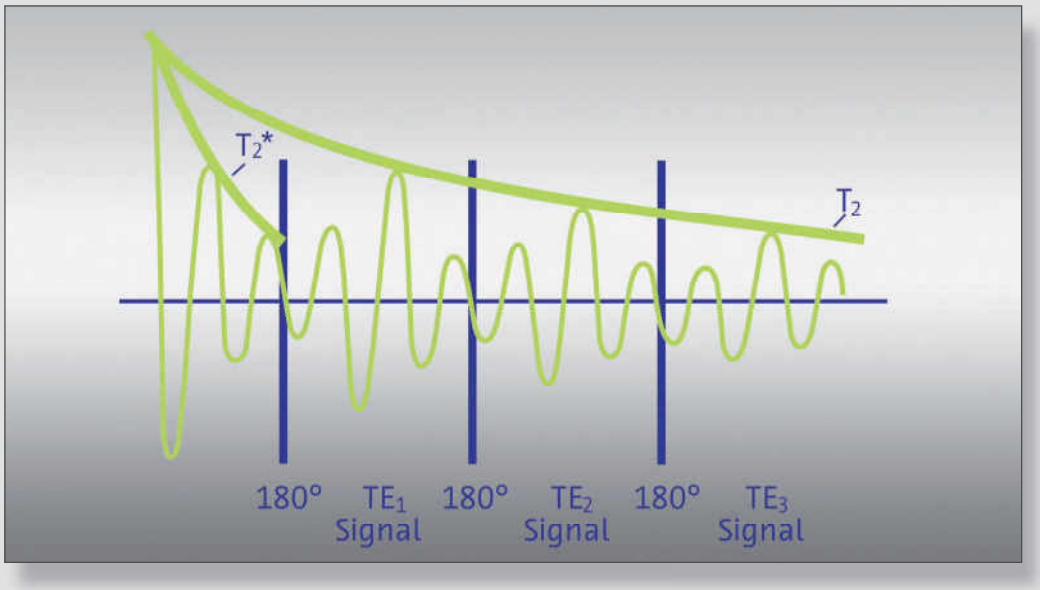


Fig. 35: The 180° pulse refocuses the dephasing protons, which results in a stronger signal, the spin echo after the time TE. The protons then dephase again and can be refocused another time by a 180° pulse, and so on. Thus it is possible to obtain more than one signal, more than one spin echo. The spin echoes, however, differ in intensity due to so-called T_2-effects. A curve connecting the spin echo intensities is the T_2-curve. If we did not use the 180° pulse, the signal intensity would decay much faster. A curve describing the signal intensity in that case is the **T_2*-(T_2 star)** curve, which is described in a little more detail on page 52.

From this curve we can see that the spin echo, the resulting signal, decreases with time. Responsible for this is the fact that our 180° pulse only "neutralizes" effects that influence the protons in a constant manner, and these are the constant inhomogeneities of the external magnetic field.

Inconstant inhomogeneities from local magnetic fields inside the tissue cannot be "evened out", as they may influence some protons before the 180° pulse differently than after the 180° pulse. So some of the protons may still be behind or in front of the majority of the protons that will reach the starting line at the same time. So from echo to echo, the intensity of the signal goes down due to so-called **T_2-effects**. A curve connecting the spin echo intensities is the **T_2-curve.**

May be we should illustrate this by an example: imagine two buses full of people, e.g. after a soccer or football game. They are standing at a starting line (figure 36). With two microphones, you record the signal (e.g. the singing from the crowd) that is coming from each bus. The buses leave in the same direction.

Listening to the singing of the crowds, i.e. recording the signal, you may recognize that one signal disappears faster than the other.

This can have two different causes: The difference in signal intensities, the difference in singing, may be due to differences in inherent properties of the two groups (internal inhomogeneities); may be in one bus, there are only the "party animals", who did not become tired as fast as the people in the other crowd.

Or . . . may be one bus is driving faster than the other (loss of signal would thus be due to external influences, the external magnetic field inhomogeneities).

To figure out what is actually the reason for the signal disappearing, you can make the buses turn around after a certain time TE/2, and have them drive back with the same speed also for the time TE/2. After 2 x TE/2 = TE, the buses will be back at the starting line. The signal intensity that you record with your microphone then depends only on inherent properties, i.e. how tired the crowds have become.

Let us have a look at our curve, when we plotted time vs. signal intensity sending in several 180° pulses (see figure 35). If you do not use a 180° pulse to neutralize constant external inhomogeneities, the protons will experience larger differences in magnetic field strength, when the RF pulse is switched off. Due to this, they will be out of phase faster, the transversal relaxation time will be shorter.

A curve describing the signal intensity in that case is the **T_2*- (T_2 star) curve.** The star distinguishes this shorter transversal relaxation time from the T_2 after the 180° pulse, which we have already talked about.

The corresponding effects are named **T_2*-effects**. These T_2*-effects are important with the so-called fast imaging sequences; we will hear about them later, and cover them in more detail in the book on "MR Buzzology".

In our example with the buses this would mean that we just record the signals, as the buses drive away. The signals vanish due to extrinsic (bus speed) and intrinsic (exhaustion of the passengers) properties under these circumstances (see figure 36).

The type of pulse sequence that we used in our experiment, is called a **spin echo sequence**, consisting of a 90° pulse and a 180° pulse (causing the echo). This pulse sequence is very important in MR imaging, as it is the workhorse among the pulse sequences, which can be used for many things. It is important to realize that with a spin echo sequence, we cannot only produce T_2-, but also T_1- and proton density-weighted images. We will get to that a little later.

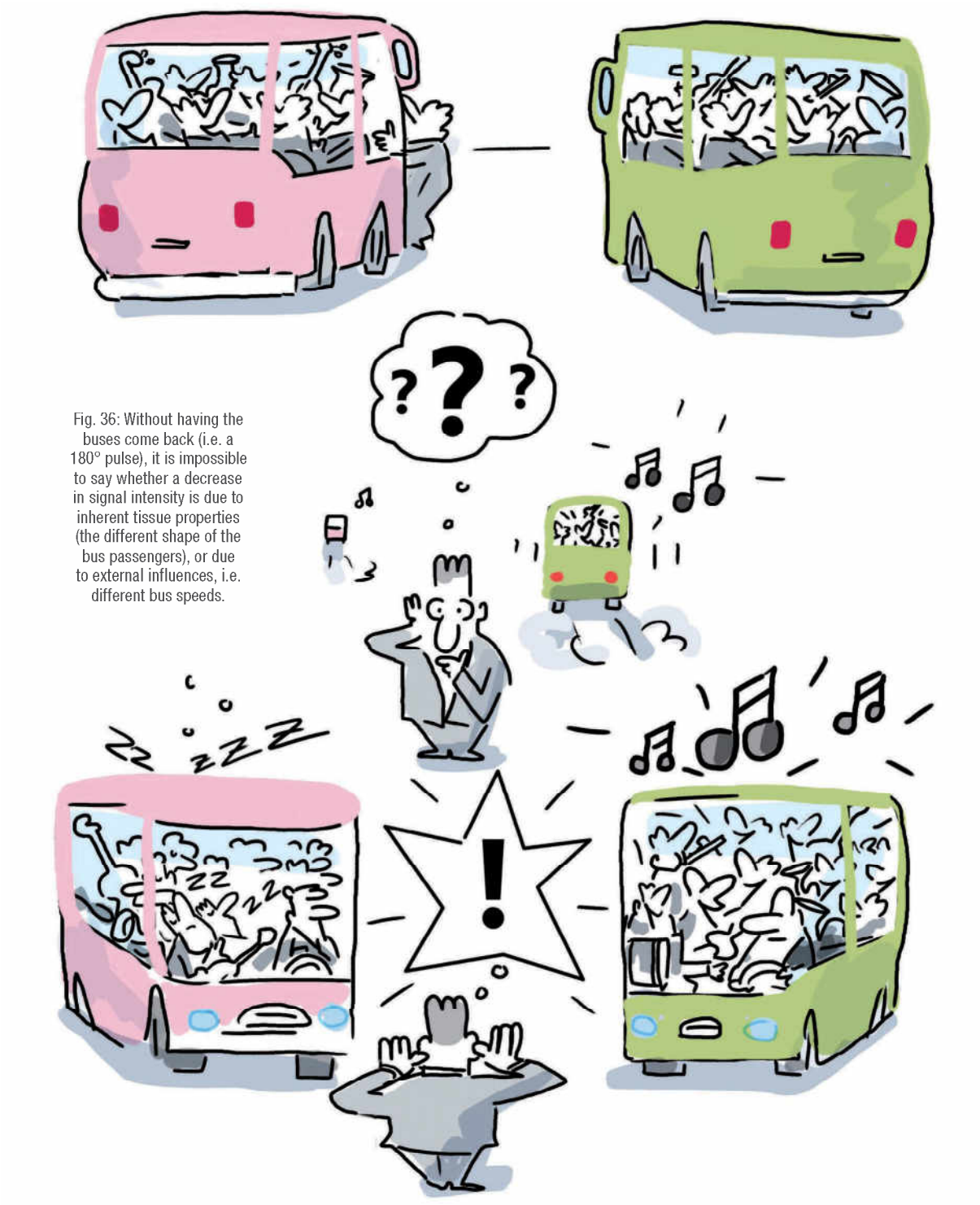


Fig. 36: Without having the buses come back (i.e. a 180° pulse), it is impossible to say whether a decrease in signal intensity is due to inherent tissue properties (the different shape of the bus passengers), or due to external influences, i.e. different bus speeds.

T_2-weighted images – a closer look

Let us first look at such a T_2-weighted sequence

What did we do? First, we sent in a 90° pulse, resulting in some transversal magnetization. Immediately after the 90° pulse, we have a maximum transversal magnetization. However, this transversal magnetization disappears, due to **T_2-effects**. How fast transversal magnetization disappears, can be seen from a **T_2-curve**; in figure 37, we have plotted T_2-curves for two different tissues, tissue A having a short T_2 (e.g. brain), tissue B having a long T_2 (water or CSF). The curves start at 0, which is the time immediately after the 90° pulse is switched off. When we wait for a certain time TE/2 to send in the 180° pulse, transversal magnetization will have become smaller. After waiting another time TE/2 (that is TE after the 90° pulse is switched off), we will receive a signal, the spin echo.

The intensity of this echo is given by the T_2-curve at the time TE. This time between the 90° pulse and the spin echo is called **TE = time to echo.**

The time TE can be chosen by the operator. And as we can see from the T_2-curve, TE influences the resulting signal, and thus also the image: the shorter the time TE, the stronger the signal that we get from a tissue. To get the best, strong signal, it may seem reasonable to use a short TE, because with longer TEs, signal intensity decreases. With a short TE, however, there will be a problem (figure 37).

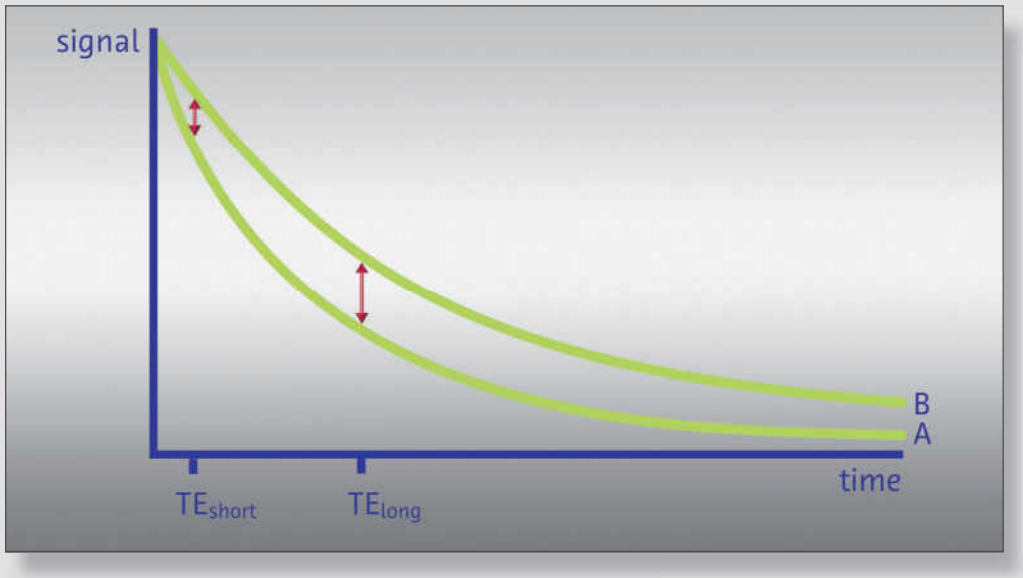


Fig. 37: T_2-curves for two tissues with different transversal relaxation times; tissue A has a shorter T_2 than tissue B, thus loses transversal magnetization faster. With a short TE (TE_{short}), the difference in signal intensity is less pronounced than after a longer TE (TE_{long}).

Let us have a look at two different tissues. Tissue B (water or CSF) has a longer T_2 than tissue A (brain).

Both T_2-curves in this example start at the same point. If we only wait a short TE, TE_{short}, the difference in signal intensity between tissue A and tissue B is very small, both tissues may hardly be distinguished, as there is hardly any contrast (which is the difference in signal intensity of tissues).

Consequence: with a short TE, differences in T_2 do not influence tissue contrast very much.

As both T_2-curves diverge with a longer TE, TE_{long}, the difference in T_2-curves, and thus the difference in signal intensity meaning **contrast**, is more pronounced in our example. So it might be reasonable to wait a very long TE; the resulting image should be very heavily T_2-weighted. But (and there is always a "but") if we wait longer, the total signal intensity becomes smaller and smaller. The **signal-to-noise ratio** becomes smaller, the image appears grainy.

An example to illustrate this signal-to-noise problem: when you receive a local radio station in your radio, this gives you a good signal, e.g. loud music and only little static noise.

When you drive out of town, the signal intensity of the radio station becomes weaker, and you will hear more static noise; and when you drive even further away, you may not be able to discern the music from the background noise. And this is the same for the MR signal: there is always some noise in the system, however, when the signal is strong, this does not matter much. However, the smaller the signal, the harder it is to differentiate it from the background noise.

Let us review some facts

We have learned:

- The spin echo sequence consists of a 90° and a 180° pulse.
- After the 90° pulse, protons dephase due to external and internal magnetic field inhomogeneities.
- The 180° pulse rephases the dephasing protons (sometimes the term spins is used interchangeably for protons), and a stronger signal, the spin echo, results.
- The 180° pulse serves to "neutralize" the external magnetic field inhomogeneities.
- Signal decrease from one echo to the next, when using multiple 180° pulses, is due to internal T_2-effects.
- By choosing different TEs (different times after the 90° pulse), the signal can be T_2-weighted in varying degrees – with very short TEs, T_2-effects have not yet had time to really show up.
- With longer TEs, the signal intensity difference between tissues will depend very much on their T_2s, their transversal relaxation time.
- With very long TEs, there should be even more T_2-weighting, however, signal intensity as such would be so small that at best it can just barely be distinguished from the background noise.

By the way: what is a short, what is a long TR or TE?

A short **TR** is one that is about as short as the smallest/shortest T_1 that we are interested in (remember: T_1 was a time constant, not a time that it takes for a tissue to regain its longitudinal magnetization!). A long TR is about 3 times as long as a short TR. A TR of less than 500 msec is considered to be short, a TR of more than 1,500 msec to be long (just to give you a rough idea). A short TE is one that is as short as possible, a long TE also is more than 3 times as long.

A TE of less than 20 msec is considered to be short, a TE more than 80 msec to be long.

Fig. 38: Schematic illustration of a spin echo pulse sequence.