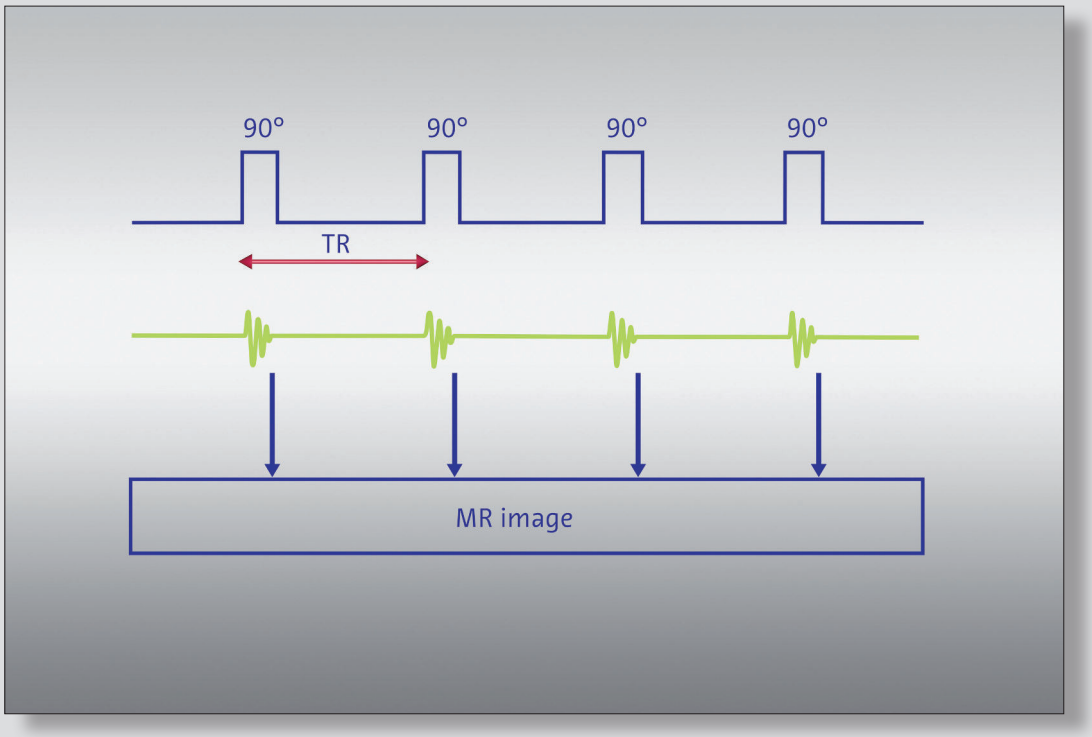

Fig. 51: Schematic illustration of the partial saturation/saturation recovery sequence.

Partial saturation/ saturation recovery sequence

We already heard about the term **pulse sequence**. Many different pulse sequences have been developed, and we should be familiar with their basic concepts. So let us take a look at them. Pulse sequences that use 90° pulses only, are the **saturation recovery pulse sequence** and the **partial saturation sequence** (figure 51) (which we have already discussed, but we did not give them a name).

Basically, the sequences are the same: they consist of two 90° pulses. The dif-

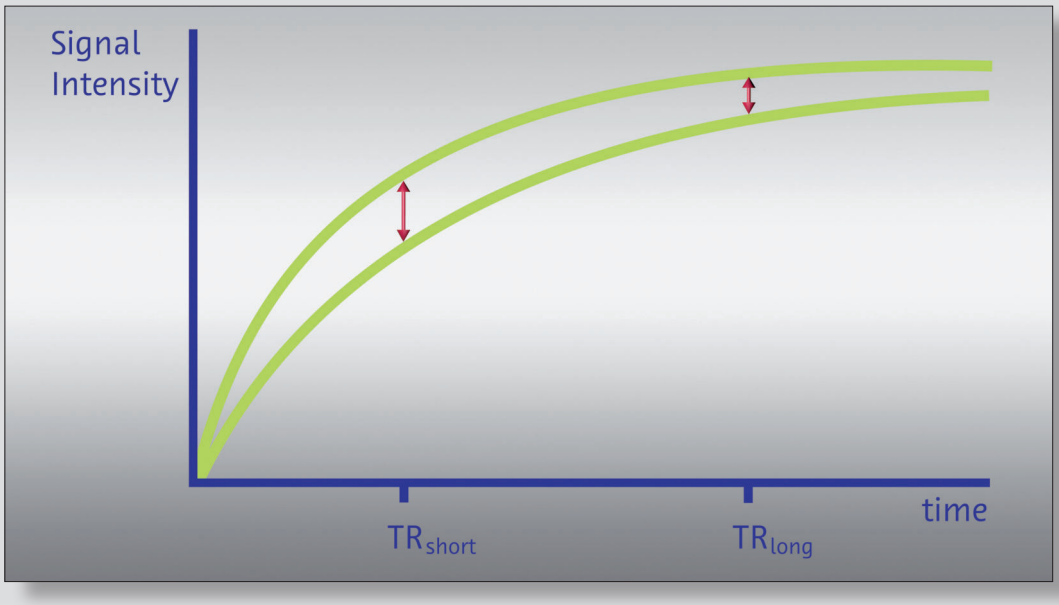

Fig. 52: Signal intensity of tissues having a different T_1 depending on the choice of TR: With a long TR, the saturation recovery sequence, image contrast is determined mainly by proton (spin) density. With a shorter TR, the partial saturation sequence, the resulting image is T_1-weighted.

ference is in the time interval between pulses, the TR (see page 45).

You can see the effect in figure 52 with the T_1-curves (going uphill!) of two different tissues. If we send in the second pulse after a long time, TR_{long}, both tissues will have regained longitudinal magnetization. With a TR_{long}, with the saturation recovery sequence (the protons have relaxed, are saturated), the signal is influenced by the proton density (Do you recall the stories with the short trousers and the long teas?). With a TR_{short}, with the partial saturation (protons have not relaxed), the T_1 becomes important for the signal intensity, so we get T_1-weighted images (figure 52).

Inversion recovery sequence

In contrast to the spin echo sequence that we have mentioned before (see page 57), the inversion recovery sequence uses first a 180° pulse which is then followed by a 90° pulse (figure 53).

What happens?

The 180° pulse turns the **longitudinal magnetization** in the opposite direction (all protons that were responsible for the net magnetic moment pointing up, now point down).

This is illustrated in figure 54 for two tissues with different T_1. The tissue with the faster longitudinal relaxation, i.e. the shorter T_1, is in the bottom row.

If we do not do anything else, the longitudinal magnetization will slowly go back up, like a ball that is thrown into water. To get a measurable signal, however, we need some transversal magnetization. And for this, we use

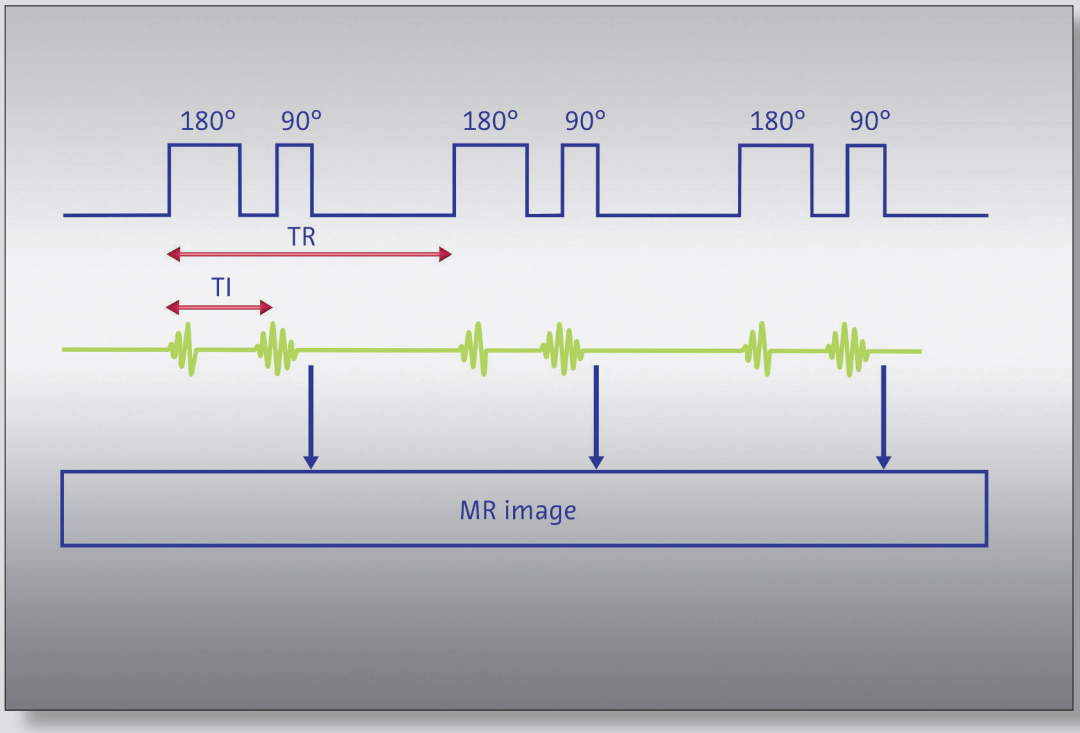

Fig. 53: Schematic illustration of the inversion recovery sequence.

the 90° pulse. The 90° pulse "tilts" the magnetization into the transversal (x-y-) plane, so it can be measured/received.

The signal that we get depends on the time between the 180°- and the 90° pulse, the time after the inversion by the 180° pulse; this time is thus called **TI = inversion time**.

The signal intensity in an **inversion recovery** image is dependent on T_1, which determines how fast the longitudinal magnetization goes back to its original value. So we get a T_1-weighted image – which is even more T_1-weighted than partial saturation recovery images.

Interestingly, when the 90° pulse is sent in when the longitudinal magnetization goes from negative to positive, i.e. is zero, the tissue does not give a signal! This may be useful when we do not want a tissue to show up in the image, e.g. when we want to suppress the fat signal – but let us not go into too much detail here.

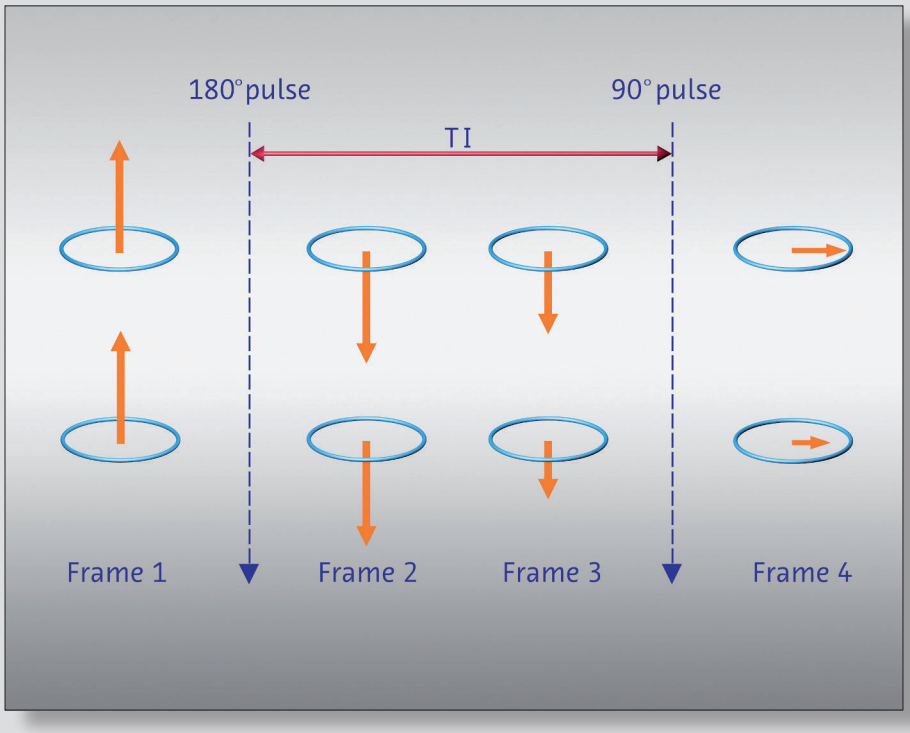

Fig. 54: The inversion recovery sequence uses a 180° pulse which inverts the longitudinal magnetization, followed by a 90° pulse after the time TI. The 90° pulse "tilts" the magnetization into the transversal (x-y-) plane, so it can be measured/received. The tissue in the bottom row goes back to its original longitudinal magnetization faster, thus has the shorter T_1. For the time TI which is illustrated, this results in less transversal magnetization after the 90° pulse.

Spin echo sequence

We have talked about the spin echo sequence in detail already.

It is composed of two pulses: a 90°- and a 180° pulse (figure 55).

You should be able to recall what happens by now: The 90° pulse establishes transversal magnetization, which immediately starts to decrease because the protons dephase. Some time (TE/2) after the 90° pulse, we send in a 180° pulse, which rephases the protons.

After the time **TE**, we get a strong signal, the **spin echo**. As we have heard, we can produce not only one, but several echoes using more than one 180° pulse. The disadvantage is, however that the signal becomes weaker and weaker.

What were the imaging parameters that influenced the MR signal in the spin echo sequences?

These were: **TE** = the time between the 90° pulse and the echo and **TR** = the time between two pulse sequences, i.e. from one 90° pulse to the next.

What did the TE and the TR do?

They determined how the resulting image was weighted: TE was responsible for the T_2-weighting, TR for the T_1-weighting.

If you cannot remember this or still are feeling unsure, please go back to pages 48 – 63 again.

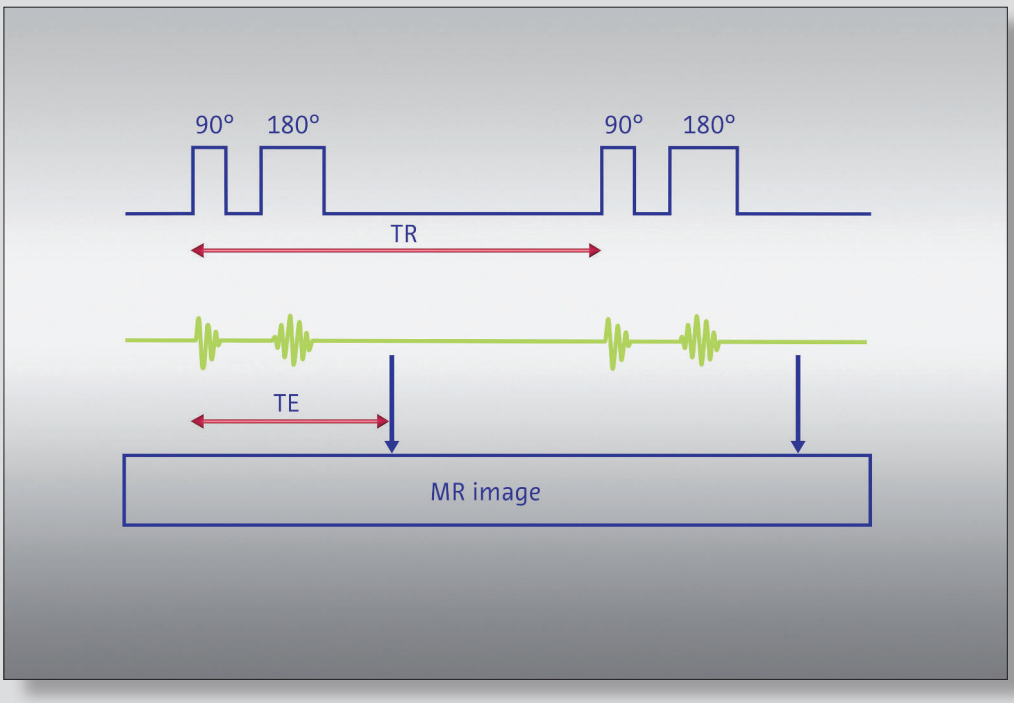

Fig. 55: Schematic illustration of a spin echo pulse sequence. This is repeatedly illustrated, as the spin echo sequence is so important.

Fast imaging sequences

What about those fast imaging sequences?

Normal imaging sequences take quite some time, during which it may be difficult for the patient to lay completely still. In addition, there is always some unavoidable motion, like respiration and heart beat. All these movements unfortunately decrease image quality.

To help with these problems, **fast pulse sequences** were developed, which take less time. Most of these have strange names such as FLASH (Fast – Low – Angle – Shot), or GRASS (Gradient – Recalled – Acquisition – at Steady – State). These sequences are very important nowadays in daily practice.

Here is just a rough outline – you can find more details in textbooks or the book "MR Buzzology".

As you may already have noticed, the TR is the most time consuming parameter of an imaging sequence (see also pages 57 and 83). It makes sense to shorten TR if we want to make imaging faster. And this is done in the fast imaging sequences.

But with a decreasing TR, there are some problems:

- Firstly, with a spin echo sequence we used a 180° pulse to refocus the dephasing spins. Unfortunately, we cannot use a 180° pulse for this purpose, when we do imaging with a very short TR: it requires some time to "produce" and to deliver a 180° pulse, and with a very short TR, there will not be enough time for that between the 90° pulses.
- Secondly, with decreasing TR, longitudinal magnetization will have recovered less and less between pulses (see pages 58-61), as we have already seen; so there is only very little longitudinal magnetization to be tilted by the next pulse, yielding very little signal.

These problems are solved as follows:

- We use a different way to refocus the dephasing spins: instead of a 180° pulse, we apply a **magnetic field gradient**. This means that an uneven magnetic field, a gradient field, is added/superimposed on the existing magnetic field.

The magnetic field gradient is switched on for a short time. This results in even larger magnetic field inhomogeneities in the examined slice. (The magnetic field inhomogeneities that already exist at that time are due to inhomogeneities of the external magnetic field, and the internal magnetic field inhomogeneities inside of the tissues, which we talked about earlier – if you do not remember this, go back to page 27 for a short recap).

Due to these larger magnetic field inhomogeneities, **transversal magnetization**, and thus the signal, disappears faster (protons dephase faster!). Then the magnetic gradient is switched off, and after a short time turned back on with the same strength, but in the opposite direction.

The faster moving protons now become the ones that move slowly, and vice versa (similar to what happens after a 180° pulse).

This results in some rephasing, and thus the signal increases again to a certain maximum, which is called a **gradient echo**. After this echo, the signal decreases again.

What to do about the second problem, the small amount of longitudinal magnetization with a short TR? The 90° pulse, e.g. in a spin echo sequence,

abolishes longitudinal magnetization; longitudinal magnetization, however, starts to recover immediately after the 90° pulse, depending on the T_1 of the tissue examined (if you have forgotten, see page 38). The trick with the fast imaging sequences is not to use a 90° pulse, but pulses that cause smaller "**flip angles**" (mostly in the range of 10°-35°).

With these flip angles smaller than 90 degrees, **longitudinal magnetization** is not totally abolished. Instead, there is always a substantial amount of longitudinal magnetization left, which can be "tilted" by the next pulse; this gives a reasonable signal even if the next pulse comes in after a very short TR.

As we have heard, a 180° pulse normally "neutralizes" the effects of external magnetic field inhomogeneities. The decay of transversal magnetization is then due to so-called **T_2-effects** (see figure 35).

When we do not use such a 180° pulse, the protons experience larger magnetic field inhomogeneities and get out of phase faster. Signal intensity decays faster, and in this case is due to so-called **T_2*-effects** (pronounced: T_2 star-effects), which has already been illustrated in figure 35.

Besides these T_2*-effects, other factors, e.g. the **flip angle**, influence signal intensity in the fast imaging sequences, which are also called **gradient echo sequences** for obvious reasons.

Here are some guidelines about gradient echo imaging:

- Larger flip angles produce more T_1-weighting.
- Longer TEs produce more T_2*-weighting.
- With fast scans, intense signals often come out of the vessels.

We save imaging time because
– with small flip angles we only need an **RF pulse** of short duration;
– we do not use a 180° refocussing pulse (which takes time to be generated and to take effect);
– we do not have to wait long TRs for enough longitudinal magnetization to reappear, as with small flip angles there is always a reasonable amount of longitudinal magnetization left after the initial pulse.

With these fast scans, it is possible to do imaging in a second or even less.

Well, time to repeat and take a break.

Partial saturation and saturation recovery sequences use 90° pulses. TR is relatively short with partial saturation and relatively long with saturation recovery.

While saturation recovery yields proton (spin) density images, the images are T_1-weighted with partial saturation.

- A spin echo sequence has a 90° pulse, which is followed by one – or more – 180° pulses, to rephase the dephasing protons resulting in one – or more – spin echoes. This sequence can give proton density-weighted, T_1-weighted, or T_2-weighted images. This is determined by the imaging parameters which are chosen (TR, TE).
- In the inversion recovery sequence, a 180° pulse is followed by a 90° pulse, resulting in T_1-weighted images.
- Fast imaging sequences use flip angles that are smaller than 90°, and so-called gradient echoes. Image weighting is also determined by the specific type of sequence and the imaging parameters chosen.

About imaging time

As we have just seen, fast imaging sequences decrease **imaging time**.

Is there any other way to decrease this time? What does actually determine the **imaging time**?

For MR imaging with normal pulse sequences, this can be easily calculated; the **acquisition time (a.t.)** is:

a.t. = TR x N x N_{ex}

This looks a little complicated but it isn't really. Let us start at the back. N_{ex} is the number of excitations. What does that mean?

For certain reasons, it is necessary to use not only one signal measurement, but to repeat the measurement several times. As the MR signal coming out of the patient is very weak, it may be good to add up signals from several measurements, to take several "**averages**", to get a good quality image.

Actually, what you get is an image with a better signal-to-noise ratio.

Naturally, imaging time increases with every additional measurement.