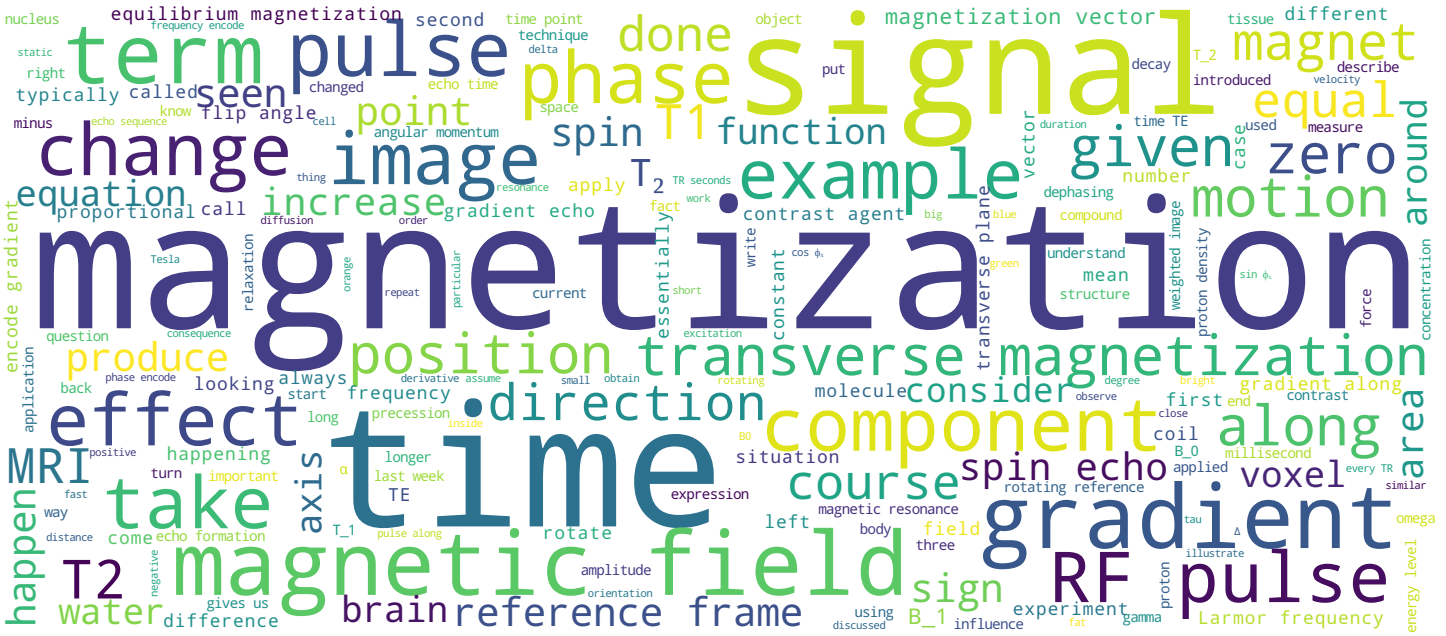
12.3 Spin echo formation

Fundamentals of Biomedical Imaging

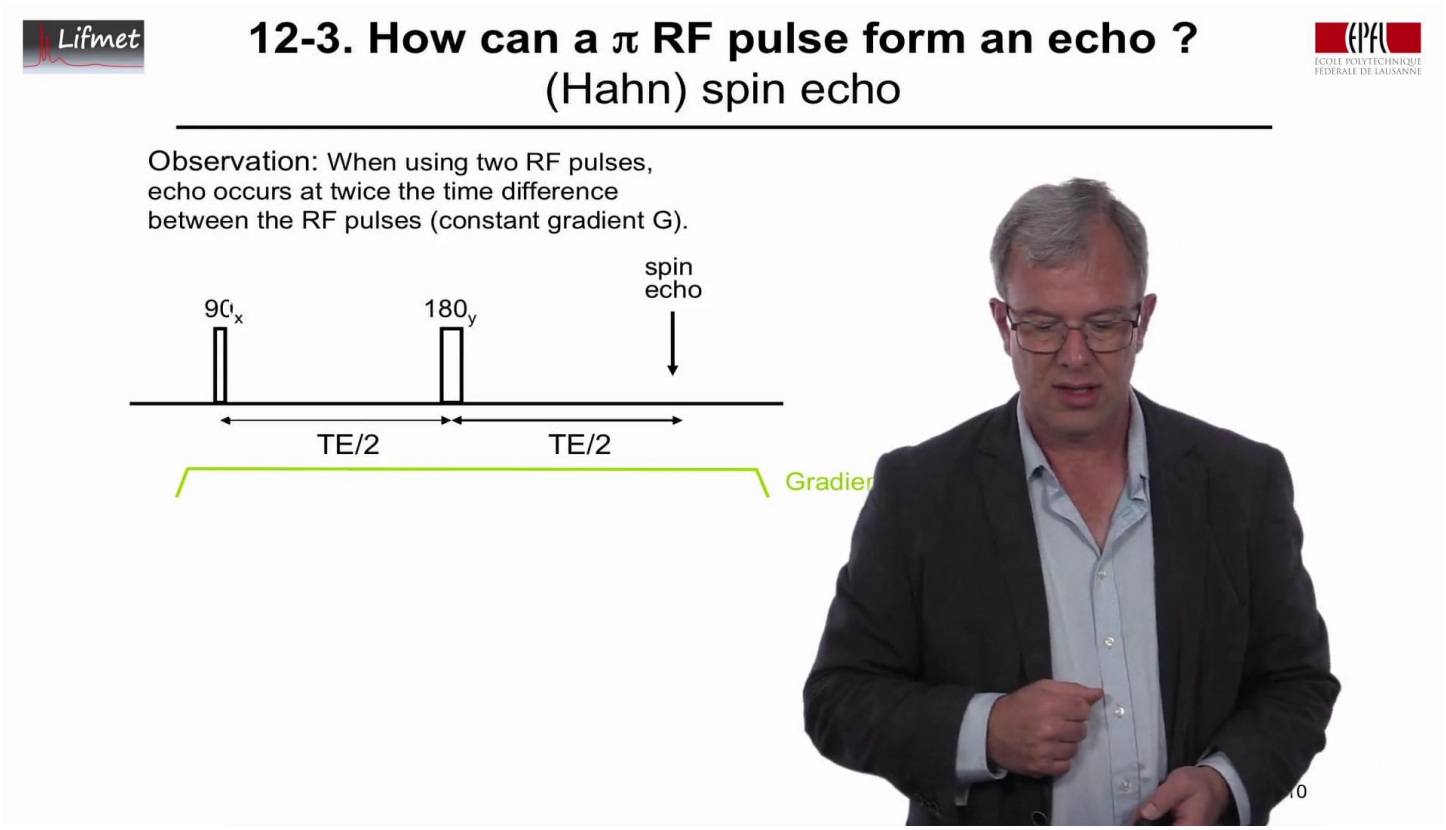
Prof. Rolf Gruetter



EPFL

12-3. How can a π RF pulse form an echo ?

(Hahn) spin echo



Okay, so spin echo, and this is actually a consequence of using two RF pulses. Irving Hahn observed this in the early '50s, that when using two RF pulses, then there is an echo observed at twice the time difference, and this happens in the presence of a constant gradient. You might ask, "In the 1950s, they did not have gradients; how come this was observed?" Well, actually, at the time, the quality of the magnets, as they were used, was so poor that they actually were like a... The B0 really was not constant, was not homogeneous, so there was a big gradient inside the magnet. So we'll look here at time. We'll now pretend that we've turned on the gradient along Y, and it is always on. So we'll just consider it is always on. We'll have a 90° pulse. This 90° pulse, the B1, is applied along the X axis, so it rotates the magnetization onto the Y axis. After a certain time, we will apply a gradient, an RF pulse of twice the duration, so it's a 180° pulse, but this time, around the Y axis. This time here, we will call this TE/2, and we're going to look at what's happening after another time TE/2. And at this point, actually, we will observe a spin echo.

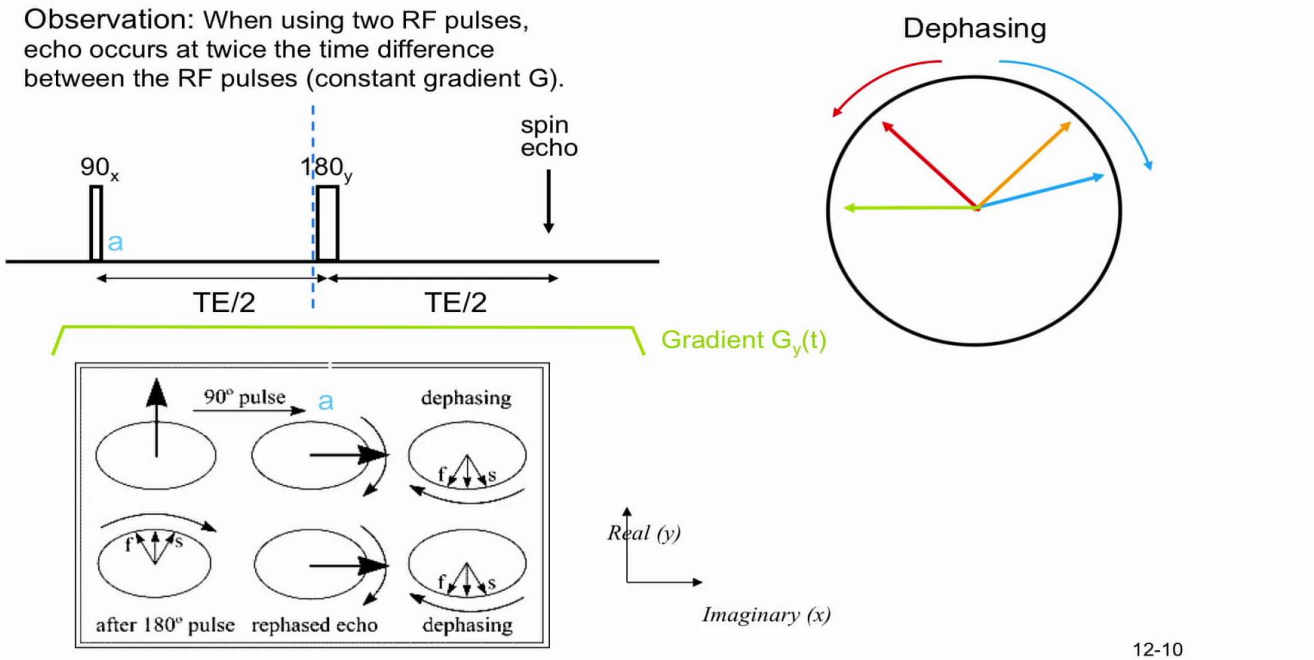
Notes

Summary

0m 04s

12-3. How can a π RF pulse form an echo ?

(Hahn) spin echo



12-10

So I'll take here the graphic What happens with the magnetization where, after the 90° pulse, we have the magnetization flipped into the transverse plane; it's along Y. So it's a 90° pulse along X. The magnetization is all in phase along Y. And now we're going to look at what's happening over time. And we're going to look at the magnetization vector in complex space, so the X magnetization component is, for example, imaginary, and the Y is real. It doesn't really matter what we're using here. So we have magnetization here, and I'll just draw four random magnetizations. They have different Larmor frequencies, and/or different signs of the Larmor frequency. All in, of course, the rotating reference frame. So after the 90° pulse, all the magnetization is collinear, and now, what happens during the time period is dephasing. We'll have two vectors going to the left, and two vectors going to the right, and this is what's happening during the first TE/2. So it's dephasing, depending on their position along Y, depending on... they will precess positive or negative, and with different Larmor frequencies. So after TE/2, we have these four magnetization vectors, that are spread out.

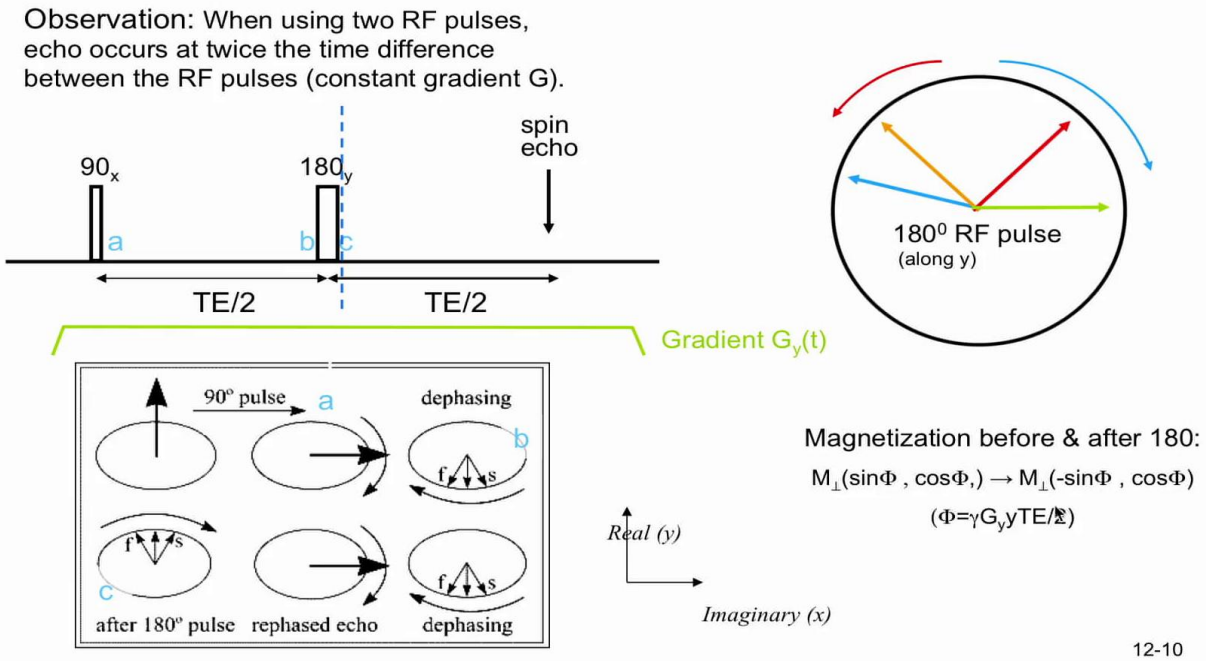
Notes

Summary

1m 25s

12-3. How can a π RF pulse form an echo ?

(Hahn) spin echo



So this is a situation *b* that we have here, just before the 180° pulse. They have spread out between fast and slow. And now, what we are going to do, is we are going to apply the 180° pulse along Y. So we're going to apply the RF pulse along the Y axis. What does this do? Did you see? Let's do it again. It flips the X component of the magnetization. An RF pulse that rotates around the Y axis will leave the Y component intact. We'll go back. This is before the pulse. And now, after the pulse, the X components have changed the sign for the vectors. So orange and blue on the right, red and green on the left, And now, red and green are on the right, and orange and blue on the left. The Y components are the same, but the X components have changed the sign. So this is the situation here, just after the RF pulse now. So if we look at what happens with the RF pulse, we only changed the X component, the sign, so that we have transverse magnetization, at a certain position, for any of the four magnetizations. We only changed the X components, so the X component changes sign. So now, the phase. And the phase can be the effect of the gradient here, so it's γ G_γ y TE/2.

Notes

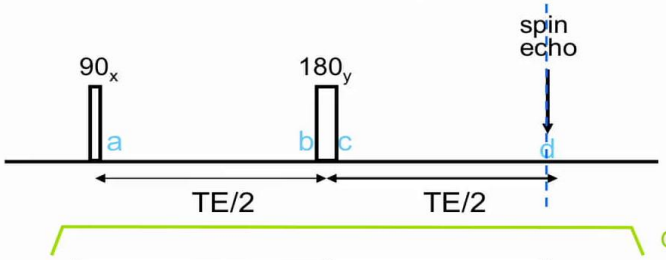
Summary

2m 51s

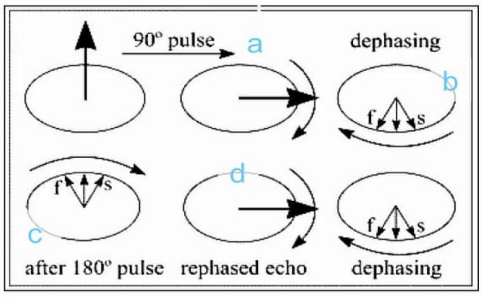
12-3. How can a π RF pulse form an echo ?

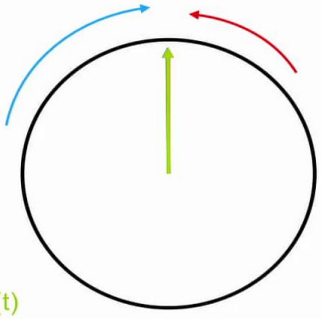
(Hahn) spin echo

Observation: When using two RF pulses, echo occurs at twice the time difference between the RF pulses (constant gradient G).



Gradient $G_y(t)$



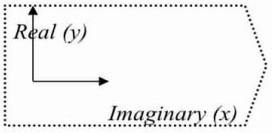


Rephasing

Magnetization before & after 180:

$M_\perp(\sin\Phi, \cos\Phi,) \rightarrow M_\perp(-\sin\Phi, \cos\Phi)$

$(\Phi=\gamma G_y y TE/2)$



$M_\perp e^{i\Phi} \xrightarrow{180^0 \text{ along } y} M_\perp e^{-i\Phi}$

12-10

So this is the duration, times the gradient, times γ, times the position, that gives us the total phase. And now, what we are going to do, we're going to look what happens from now on. And we remember blue and orange move faster in this direction. Red and green move in this direction. So if I go back, red and green moved in this direction. Blue and orange moved in this direction. So we're going to redo this, because they are going to keep their precession, orientation and speed, and as we do that, going from *c* to *d*, they continue to go with the same precessional frequency, but in the end, all the magnetization vectors will align themselves and be collinear again, and hence form an echo, and this is called a spin echo. So if we look at this in complex terms, so we have the transverse magnetization, we have this phase before the 180°, so the influence of the inhomogeneities here, before the 180°. The 180°, from this expression, we can also write the transverse mutation complex as a transverse, times $e^{-i\varphi}$. So it basically pretends as if the RF pulse does as if the inhomogeneity that has been applied is switching its sign here.

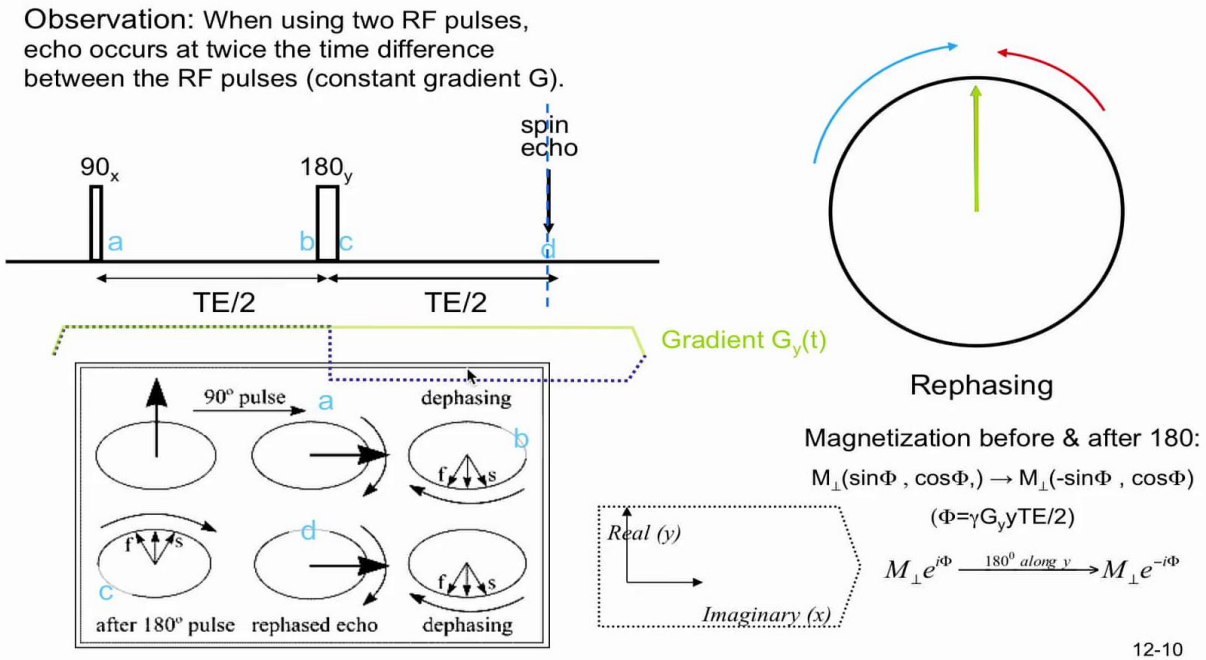
Notes

Summary

4m 18s

12-3. How can a π RF pulse form an echo ?

(Hahn) spin echo



This is, if you want to make the link to the gradient echo that we've discussed last week. And this week, then, your 180° pulse, in this scheme here, acts as if all the inhomogeneities that are static here are changing their sign in here. Of course, they're not doing it, but we can, to understand how this echo is done from this expression here, we can pretend as if this was happening. So it's a gedanken experiment. So this, in terms of phase evolution, it's as if the static gradient was with the 180°, was flipping its sign.

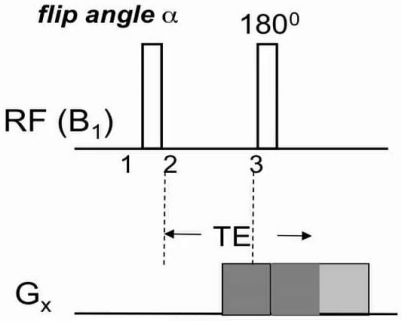
Notes

Summary

5m 44s

Spin echo formation revisited

Mathematical formulation



Magnetization at the time points specified:

1: $(0,0,M_z)$

rotated by α degrees (RF pulse):

2: $(0,M_z\sin\alpha,M_z\cos\alpha)\equiv(0,M_y,\ldots)$

[only consider M_{xy}, precesses with $B = +\gamma G_x x$

3: $M_y\ (\cos[(+\gamma G_x x)t], \sin[(+\gamma G_x x)t])$

$\equiv M_y\ [\cos(+\phi_x), \sin(\phi_x)]$

12-11

Okay, so I want to revisit the spin echo formation. We had a graphical argument why we have echo formation with a 90°, 180° pulse, and I want to take here a more mathematical approach. So we'll have the RF field. We'll do a flip angle α. We have a gradient along X. And we'll look at the time point 1. At the time point 1, we just have Z magnetization, so this is our magnetization vector. Then we rotate it by α degrees. So at this time point 2, we have the magnetization is M(z) sin α, and M(z) cos α. And now we'll just consider the terms of our components, so 0 and M_γ. We just have M_γ magnetization, because we're not concerned with the effect of the flip angle here. And now we'll look at just the magnetization in a transverse plane, which presents us now with a magnetic field that's given by γ G_x x. So here's our gradient, G_x. We have the echo time TE. We'll look at time number 3. So at time number 3, we have now a precession of the magnetization, so the X component increases with cosine, the Y component with sine, or vice versa. And so, we have expressed it here that the M_γ component's given by (cos ϕ_x) and (sin ϕ_x). Now the 180° pulse inverts the Y component of the magnetization, so M_γ becomes -M_γ at this point.

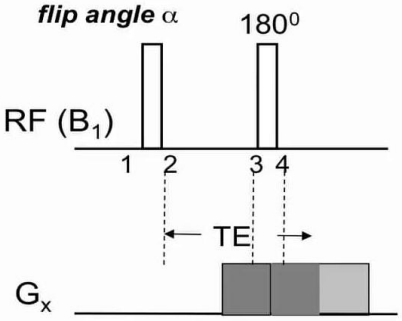
Notes

Summary

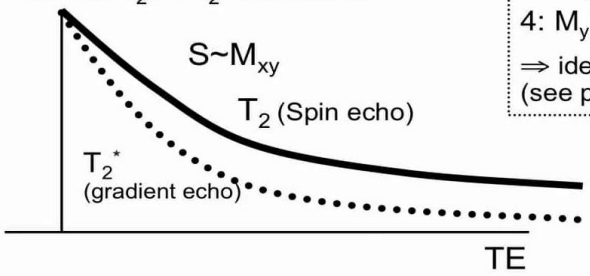
6m 21s

Spin echo formation revisited

Mathematical formulation



Signal S decays exponentially due to T_2 or T_2^* relaxation



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[only consider M_{xy}, precesses with $B = +\gamma G_x x$

3: $M_y\ (\cos[(+\gamma G_x x)t],\ \sin[(+\gamma G_x x)t])$

$\equiv M_y\ [\cos(+\phi_x),\ \sin(\phi_x)]$

180^0 pulse about x inverts y component of M_{xy} :

$M_y \rightarrow -M_y$

4: $M_y\ [\cos(+\phi_x),\ -\sin(\phi_x)] \equiv M_y\ [\cos(\phi_x),\sin(-\phi_x)]$

$\Rightarrow$ identical to the effect of a negative gradient (see previous lecture) $\rightarrow$ ***echo formation***

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma\Delta B$$

Unavoidable
(B_0 is never homogenous in space)
exploited in BOLD fMRI

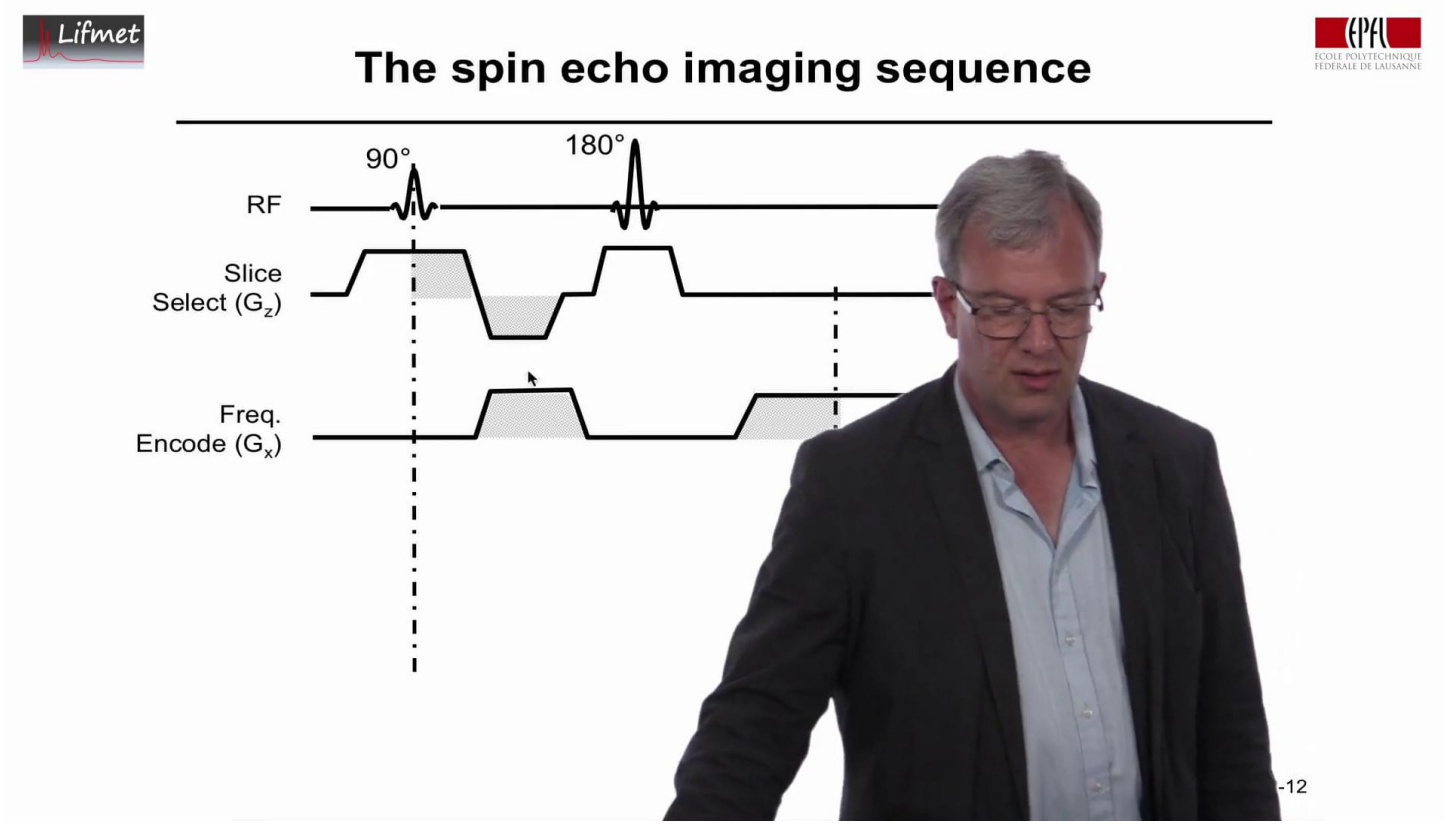
12-11

And so, we can now write this as M_γ [cos (ϕ_x) -sin (ϕ_x)], or M_γ [(cos -ϕ_x) and sin (-ϕ_x)]. So this is essentially identical to the effect of a negative gradient, like we have argued last week, and therefore, it produces an echo. So the signal decays, and in general, one considers that the signal decays exponentially, due to T_2 or T_2* relaxation. And what is the link between the two? So, if we have the transverse magnetization here, then we have T_2 -- that's the decay with T_2, -- and the decay with T_2*, with a gradient echo, is faster. T_2* is always shorter than T_2. So if we use gradient echo for refocusing, we have T_2* effects. If we use spin echo--90°, 180°-- then we have the T_2 effect. The two are always linked, due to the imperfect [magnetic] field in a given boxel-- this term is never exactly 0. And this is unavoidable in practice, since a magnetic field, in an object of finite dimensions, and complex anatomy, like we are, The B0 that is in the body is never perfectly homogeneous, however, this unavoidable effect is also exploited in BOLD fMRI like we have just discussed.

Notes

Summary

7m 56s



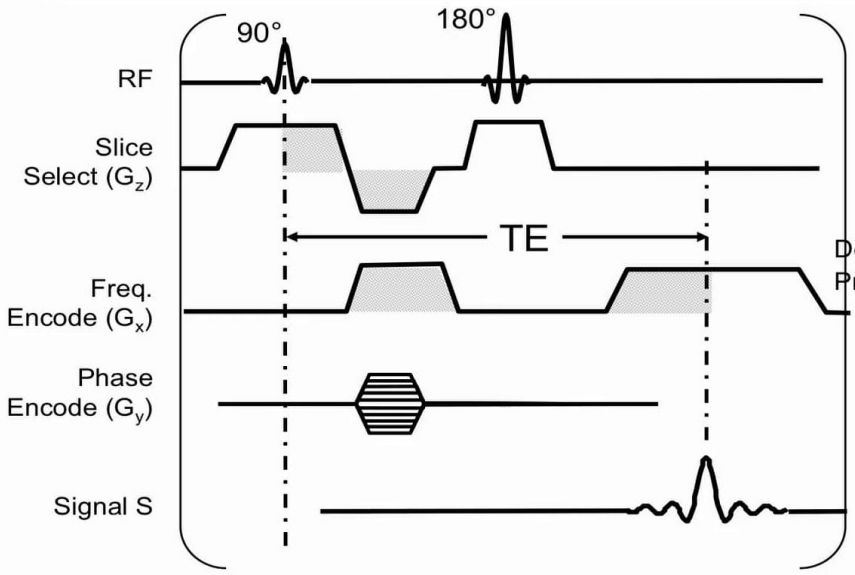
So now we come to the next imaging sequence, at the last one that I want to introduce here, in terms of spin physics. That's the spin echo sequence. So we have RF excitation of the slice, so this is just like we have had for the gradient echo. We have had the dephasing of the gradient, the rephasing of the gradient, and now we have the 180° pulse, and here the gradient is just placed symmetrically around the 180° pulse, as we have seen in the previous two slides, symmetric placement of a static gradient will produce no dephasing of the magnetization around a 180° pulse. For the frequency encode gradient, which here in this example, we'll presume it's along x, we have the dephaser. It's now before the 180° pulse, so now the dephaser has the same amplitude, or the same sign, as the frequency encode gradient, unlike the gradient echo when it was negative, beforehand, this is now positive, in the same direction as the frequency encode gradient. That has again to do with the fact that we have the 180° pulse in between. So this area, and the placement of the 180° pulses together, that defines the echo time TE for this sequence.

Notes

Summary

9m 35s

The spin echo imaging sequence



Derivation of signal $S \propto M_{xy}$:
Proton density $\rho \propto M_0$

$$M_{xy}(0) = \sin(90) M_z(0_-)$$

$$M_{xy}(TE) = M_{xy}(0) e^{-TE/T_2}$$

$$M_z(0_-) = (1 - e^{-TR/T_1}) M_0$$

12-12

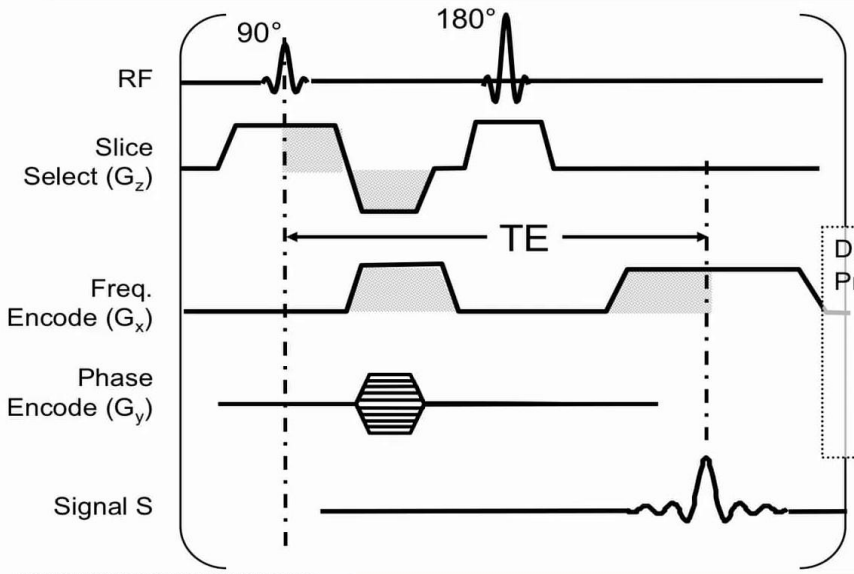
We have then the signal, the echo that is being recorded, and finally, we have the phase encode gradient, along Y in this particular example, applied for example here, which induces the phase encoding for the second dimension. This is, of course, applied every TR seconds, and so, this is what the spin echo sequence looks like. So very similar to the gradient echo, the fact that the 180° pulse is here changes the sign of the readout gradient, and the signal is now influenced by T_2, and not T_2*. So, if we look now at the signal, and the signal's proportional to the transverse magnetization, for proton density ρ, this is proportional to the equilibrium magnetization. Now we'll just consider 90° pulses here, so the transverse magnetization, at this point, is equal to Z magnetization just before the RF pulse, times sin 90°. At the time TE, the transverse magnetization is given by the transverse magnetization here, times e^{-TE/T_2}, and the Z magnetization just before the pulse, which is the last parameter that we need to understand here, is $1- e^{-TR/T_1} * M_0$. Those are the longitudinal coherence parameters for 90° pulse excitation and you can look that up in lectures 9 and 10, when we dealt with this situation.

Notes

Summary

10m 54s

The spin echo imaging sequence



Derivation of signal S ∝ M_{xy}:
Proton density ρ ∝ M_0

$$M_{xy}(0) = \sin(90) M_z(0_-)$$
$$M_{xy}(TE) = M_{xy}(0) e^{-TE/T_2}$$
$$M_z(0_-) = (1 - e^{-TR/T_1}) M_0$$

Repeated every TR seconds

$$S(TE,TR) \propto \rho(1 - e^{-TR/T_1}) e^{-TE/T_2}$$

12-12

So this is, for this 90°/180° sequence, the signal behavior. So as we repeat this every TR seconds, we have to acquire an image, we have to repeat it every TR seconds to produce a 2-D image. So our signal now becomes a function of the experimental parameter TE, TR. It is proportional to the proton density M_0 times e^{-}... this term here, that's longitudinal coherence, and this is the decay of the signal, due to T_2, for the spin echo sequence. And we'll work now through the basic contrasts. How do we take from this equation here, which has a number of terms, how do we produce the three basic contrasts, proton density, T_1-weighted imaging, and T_2-weighted imaging, that I introduced at the beginning?

Notes

Summary

12m 30s