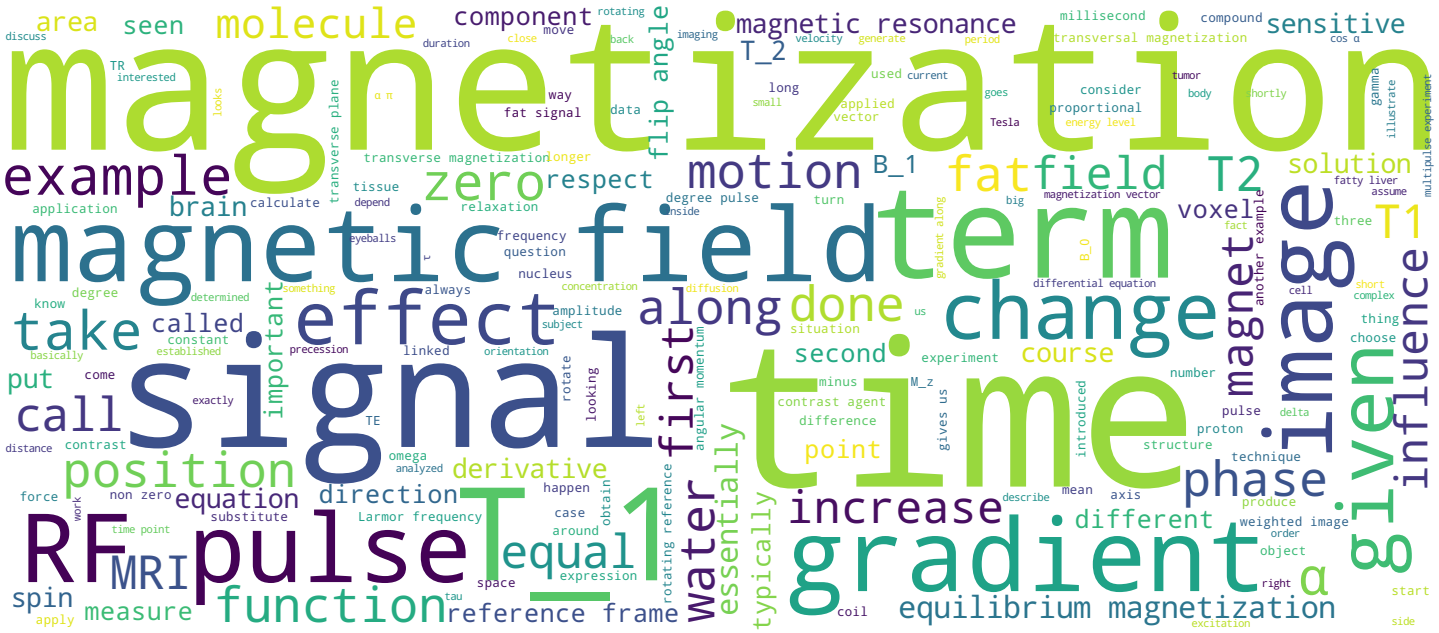
10.1 Effect of relaxation on magnetization

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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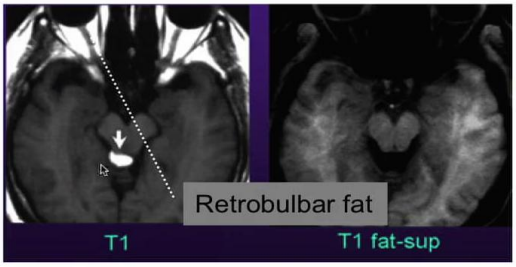
Fat and water in MRI: Examples



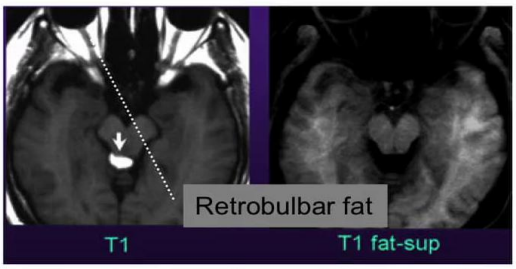
This week we are going to discuss an application of magnetic resonance that is dear to chemists and biochemists alike, but also has some applications in biomedical imaging. And I want first to start out with some of examples on the distinction of the magnetic resonance signal based on its chemical environment. And the prominent example of magnetic resonance imaging here is fat and water. So, if we take an image of the brain-- here are the eyeballs, this is a transversal cut, here is the midline-- this is a typical *T_1* waited image here. And then here the same image has been repeated, but through some manipulations the signal that arises from the fat has been eliminated, and we will discuss how this is being done. So we see the subcutaneous fat is gone. We also see that the signal behind the eyeballs here is eliminated. And this is due to the fact that behind our eyeballs we have the so called retrobulbar fat. So, in this image one has been able to eliminate the source of signal due to fat taking particular property. And so this bright region here, which could potentially be a tumor, is established here as containing a lot of fat and is most likely a lipoma.

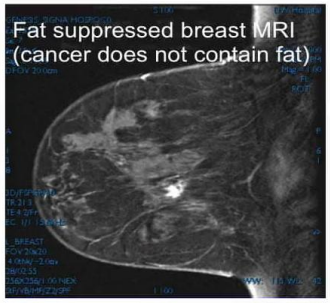
Notes

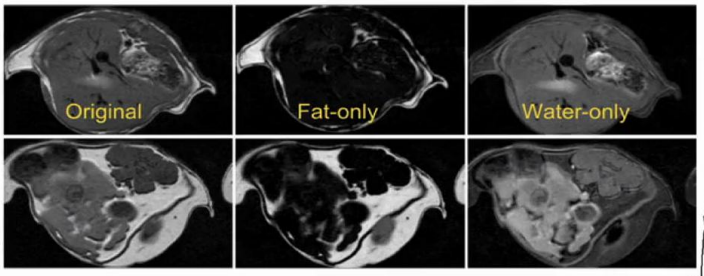
Summary

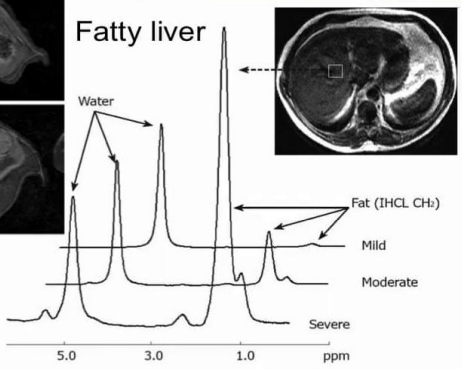
0m 04s

Fat and water in MRI: Examples









10-2

So, if you look at the body, then we have the original image, which is everything included, then one can generate an image that has only the the fat signal-- we see the fat signal here on the surface, this fat here or just the water-only signal. Or here, another example-- somebody who carries more fat. There is more fat here in this image, as illustrated here in the fat-only image and in the water-only image. The area which is rich in fat is not so intense. Here is another example-- this is MRI of the breast. We have a normal MRI of the breast here-- very bright images and then to distinguish between potential cancer tissue and fat signal which both would give up in this type of images bright signal-- the signal here was acquired with suppressing the signal from the fat. One sees a bright signal here, which is a potential cancerous lesion. Here is important to know that cancer typically does not contain a lot of fat signal. Here is an example from fatty liver. This is an area taken here from the liver, and one looks now at signal-- the water in these different cases of fatty liver is constant, and here on the side this extra peak here goes from mild to moderate to severe fatty liver. So this is an example of the way the data is analyzed to obtain biochemical information in vivo.

Notes

Summary

1m 36s

Why is NMR spectroscopy important for (bio)chemists ?

Routine tool
- *Non-destructive* analysis of samples
  - » Wine in bottles
  - » Synthesis outcome control

Other applications
- Structure determination in solution
- Molecule dynamics
- Chemical reactions in situ

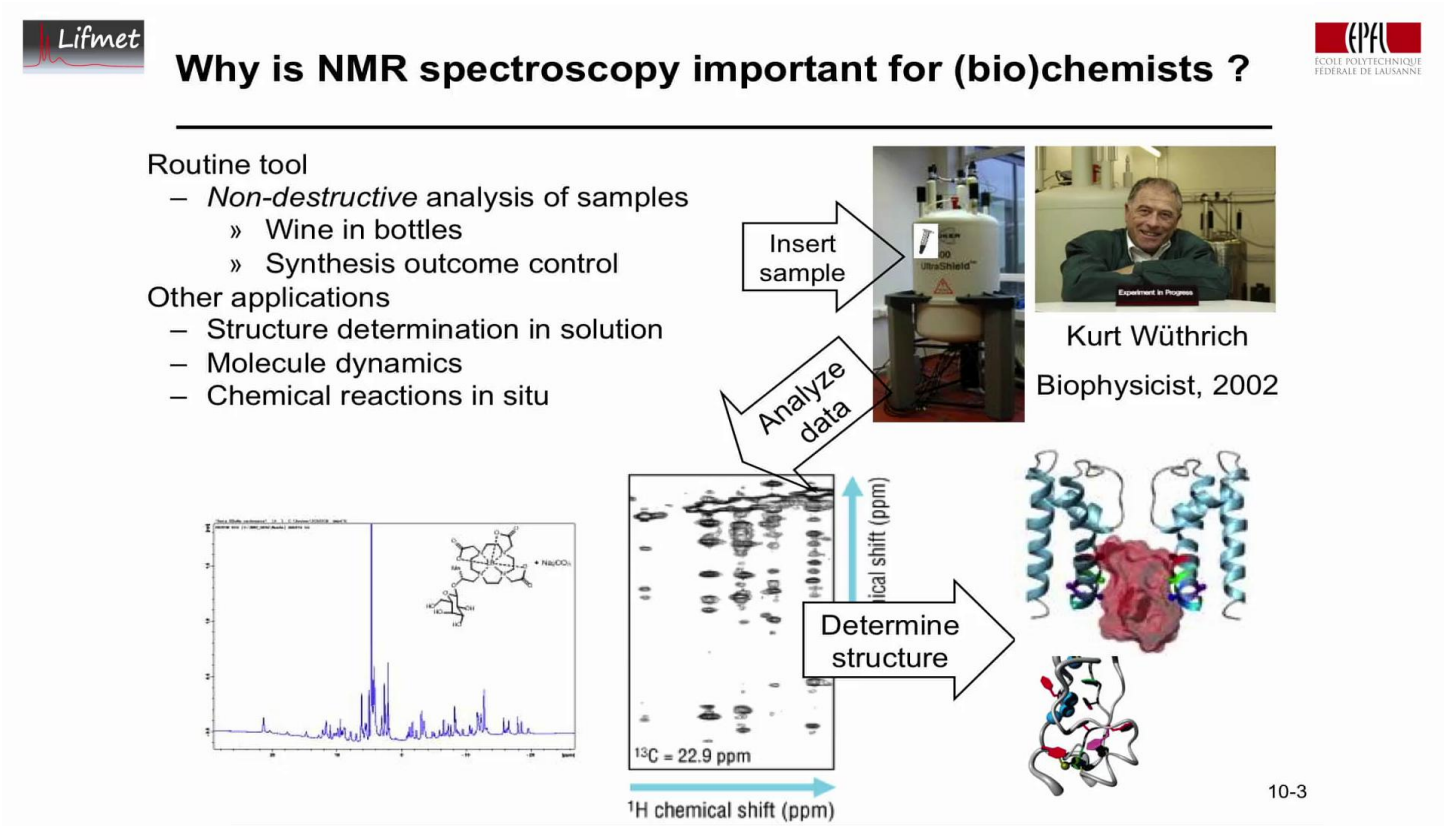
10-3

So, why is NMR spectroscopy so important for chemists and biochemists alike? It is actually so important that essentially any department of biochemistry or chemistry does have its NMR equipment. And the reason here is, it is a routine tool. It allows non-destructive analysis of samples. A more amusing example is to analyze the quality of wine in bottles. If you have an expensive wine, but you want to have quality assurance that this wine really is what it pretends to be, this can be done--you don't want to open the bottle of wine. Another example is, if you have spent several years in synthesizing in your compound, and you want to verify that the synthesis process has properly worked and your volume of your milligrams of the compound that has been synthesized you don't want to subject it to an analysis that's destructive, that destroys the molecules. Other examples include structure determination solution, so, since we are limited to soluble molecules, this allows to study the molecule structure in solution, molecule dynamics are accessible, since we have *T_1*, *T_2* and similar effects and also chemical reactions can be followed in situ. So, how is it done?

Notes

Summary

3m 08s



Well, typically the solution with a compound is put into an Eppendorf-- one needs some strong magnetic field, just like with by medical applications-- here the *z* axis is vertical that is a vertical bore NMR instrument, the sample is inserted, data is obtained, the data is analyzed, and here is an example of this complex molecule, and one now looks at different signals from this molecule, each corresponding to a different proton in the molecule. Or more complex here is the signal of protons, this is a 2D plot [inaudible] what signals are linked to other signals here. I will come to that later. This typical data can be analyzed, and from that the structure can be determined. So here is the structure of a protein. One can see the core and four alpha helices here. Here is another example of a structure that's been determined with NMR. This work was pioneered by Kurt Wüthrich, a biophysisist from Zurich, who for his work received the Nobel Prize in Chemistry in 2002.

Notes

Summary

4m 34s

10-1. What is the effect of relaxation on M(t) ?

Bloch equations revisited

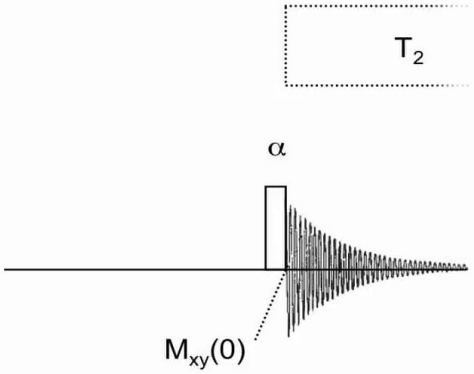
The effect of T_1 and T_2 on the signal :

flip angle $\alpha = \gamma B_1 \tau$:

$$M_z(t+\tau) = M_z(t)\cos\alpha$$
$$M_{xy}(0) = M_z(t)\sin\alpha$$

Effect of T_2

$$M_{xy}(t) = M_{xy}(0)e^{-\frac{t}{T_2}}$$



10-4

So, first, before I come to the chemical effects of how we can measure chemistry with nuclear phenomena-- that is nuclear magnetic resonance I want to dwell a bit into the effect of the relaxation on the magnetization. So, let's look at the effect of T_1 and T_2 on the signal. We have here time, we apply an RF pulse with flip angle *α*. The flip angle for such an RF pulse is given by *γ B_1* times its duration *τ*, and so the magnetization M_z after this RF pulse is given by the *z* magnetization before the RF pulse times *cos α*. The transversal magnetization after the RF pulse-- that would be here-- is given by the *z* magnetization before the RF pulse times *sin α*. So here this is the transversal magnetization at this time point, which we call *M_x_y (0)*. So, these are the effects of T_1 and T_2 on the signal, are given by the transversal magnetization, evolves now by this initial transversal magnetization with its exponential decay-- that's what we see here. And so, after the RF pulse the signal decays under the influence of *T_2* relaxation.

Notes

Summary

5m 51s

10-1. What is the effect of relaxation on M(t) ?

Bloch equations revisited

The effect of T_1 and T_2 on the signal :

flip angle $\alpha = \gamma B_1 \tau$:

$$M_z(t+\tau) = M_z(t)\cos\alpha$$

$$M_{xy}(0) = M_z(t)\sin\alpha$$

Effect of T_2 $\quad M_{xy}(t) = M_{xy}(0)e^{-\frac{t}{T_2}}$

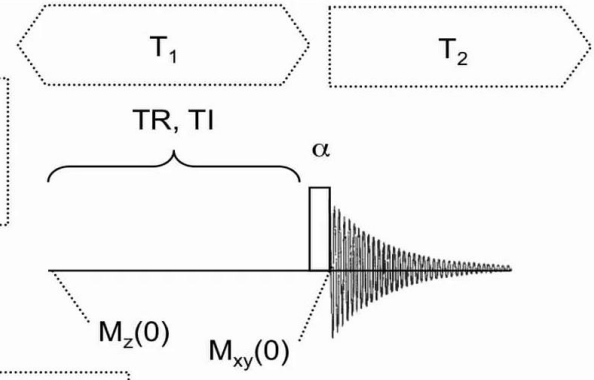
Effect of T_1 $\quad \frac{dM_z(t)}{dt} = -\frac{M_z(t) - M_0}{T_1}$

Longitudinal coherence

$$M_z(t) = M_0(1 - e^{-t/T_1}) + M_z(0)e^{-t/T_1}$$

$$M_z(0) = M_0 \cos\alpha$$

$$M_z(t) = M_0(1 - (1 - \cos\alpha)e^{-t/T_1})$$



Longitudinal coherence:

Effect of T_1 on signal depends on prior RF manipulations

10-4

Now, we call this, this *z* magnetization at time zero, then this period before the RF pulse, which we typically call the repetition time *T R* or *T I*, the time of inversion-- we will see shortly why this is called this way-- giving this time, we have the influence of T_1 relaxation. So. the effect of T_1 is given by this differential equation, the solution of which is given by this general equation here, and we call this equation also longitudinal coherence-- and we will see shortly why. So, if we're setting, *M_z(0)* is equal to this term here, then we substitute here the solution, we substitute this term here, and we obtain this solution here. We call this longitudinal coherence, because the effect of *T_1* on the signal, because we ultimately obtain the *M_z (t)*. The *M_z (t)* by the RF pulse is converted to transversal magnetization, which is being detected. So, the influence of *T_1* depends on prior RF manipulations. And this comes in the solution to our differential equation from this term here, which includes prior manipulations, that is, prior applications of RF pulses, that is, *B_1* fields, that have been done to the magnetization.

Notes

Summary

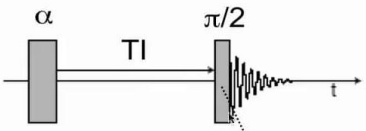
7m 16s

What are the optimal conditions to measure T_1 ?

Inversion recovery

Inversion-Recovery

Multipulse experiment with two RF pulses
Usual experiment to measure T_1 **($\alpha=\pi$)**



Converts M_z to M_{xy} (signal)

10-5

So, this is important here that what we do to the magnetization in terms of RF pulses, that influences on how *T_1* manifests itself on the signal. So, now I want to address the question under what optimal conditions are we most sensitive to changes in *T_1*? This is also a flip side of that is under what optimal conditions can one measure the influence of *T_1*. And here the term to introduce is *inversion-recovery*, and you will see shortly why it is called *inversion-recovery*. Essentially we are looking at this, say, application of two RF pulses-- it is the multipulse experiment-- and it is a traditional experiment which is used to measure the influence of *T_1*. So, we consider here an RF pulse of flip angle α, a certain time delay τ and then a 90 degree pulse. This time here we will call *T I*, or time after inversion. This 90 degree pulse, π / *2* pulse, it's sole function in this particular multipulse experiment is to convert the *z* magnetization, which is present right here, into transversal magnetization, because we want to measure the *z* magnetization, and *z* magnetization cannot be directly measured, so one has to go through the detour of converting it into transversal magnetization.

Notes

Summary

8m 50s

What are the optimal conditions to measure T_1 ?

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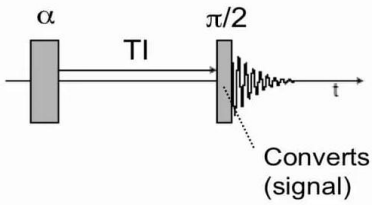
Inversion-Recovery

Multipulse experiment with two RF pulses
Usual experiment to measure T_1 **($\alpha=\pi$)**



Converts M_z to M_{xy} (signal)

Optimal choice of α for measuring T_1 ?

Use noise error propagation calculation (Lesson 1)

$$\frac{\partial M_z(t)}{\partial T_1} = \frac{t}{T_1^2}(1-\cos\alpha)e^{-t/T_1} \equiv F$$

Measured signal

$$M_z(TI) = M_0(1-e^{-TI/T_1}) + M_z(0)e^{-TI/T_1}$$

$$M_z(0) = M_0\cos\alpha$$

$$M_z(TI) = M_0(1-(1-\cos\alpha)e^{-TI/T_1})$$

10-5

So, that is the multipulse experiment we are going to consider. So, the measured signal is essentially *z* magnetization after this time period *T I*. This *z* magnetization is given here by the solution of the differential equation, where [inaudible] and here we have *M_z (0)*. *M_z (0) = M_0 cos (α)*, so we have waited a long time, we have equilibrium magnetization here, we apply now RF pulse *α*, and so the *z* magnetization at this time here is *M_0 cos (α)*. And we substitute this term here into this term, and this gives us this equation here, where we express the *z* magnetization as a function of this time *T I* here. Now, two things: What is the best choice of *α*, so what would allow us to produce the most sensitive experiment to changes in *T_1*? We will use the same approach that we discussed last week and we introduced in the first lecture in the first part of the course. It's the error propagation calculation. So, first we are interested in establishing how sensitive is our *z* magnetization, right here, at this point, just before the *π / 2* pulse, to changes in *T_1*.

Notes

Summary

10m 19s

What are the optimal conditions to measure T_1 ?

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Inversion-Recovery

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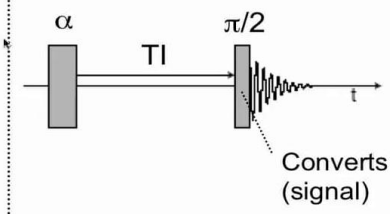

Converts M_z to M_{xy} (signal)

Optimal choice of α for measuring T_1 ?

Use noise error propagation calculation (Lesson 1)

$$\frac{\partial M_z(t)}{\partial T_1} = \frac{t}{T_1^2}(1-\cos\alpha)e^{-t/T_1} \equiv F$$

$$\frac{dF}{d\alpha} = 0 = \frac{t}{T_1^2}\sin\alpha e^{-t/T_1}$$

$\Rightarrow \sin\alpha=0 \Rightarrow \alpha=\pi$

Measured signal

$$M_z(TI) = M_0(1-e^{-TI/T_1}) + M_z(0)e^{-TI/T_1}$$

$$M_z(0) = M_0\cos\alpha$$

$$M_z(TI) = M_0(1-(1-\cos\alpha)e^{-TI/T_1})$$

10-5

That is, we calculate the derivative of *z* magnetization with respect to *T_1*. It gives us this expression here. Here is the *z* magnetization, we will take the derivative of this with *T_1*, and here we have not put *T I*, we just put just put a time *t*, and we call this function *F*. Now we want to know under what choice of *α* is this function maximal. So, we will take the derivative of this function with respect to *α* and will set that derivative to zero. This tells us at what point with respect to *α* is this function maximal. And here is the derivative, this id non-zero, this is non-zero, so we are interested in a solution, where *sin α = 0* And here we have two possibilities: *α = 0* or *α = π*. Now, *α = 0* is a silly experiment, because then basically we are not applying this RF pulse, the flip angle is zero. We will be just measuring equilibrium magnetization, and we are not sensitive to *T_1*, so the correct answer here is *α = π*. So, *α = π*, that is a 180 degree pulse or, as we have introduced earlier, two weeks ago, this is an inversion pulse and hence this experiment is called inversion, followed by recovery, and *T I* is called time of inversion.

Notes

Summary

11m 44s

What are the optimal conditions to measure T_1 ?

Inversion recovery

Inversion-Recovery

Multipulse experiment with two RF pulses
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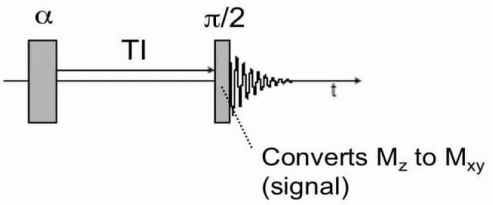


Measured signal

$$M_z(TI) = M_0(1 - e^{-TI/T_1}) + M_z(0)e^{-TI/T_1}$$

$$M_z(0) = M_0 \cos\alpha$$

$$M_z(TI) = M_0(1 - (1 - \cos\alpha)e^{-TI/T_1})$$

Optimal choice of α for measuring T_1 ?

Use noise error propagation calculation
(Lesson 1)

$$\frac{\partial M_z(t)}{\partial T_1} = \frac{t}{T_1^2}(1 - \cos\alpha)e^{-t/T_1} \equiv F$$

$$\frac{dF}{d\alpha} = 0 = \frac{t}{T_1^2}\sin\alpha e^{-t/T_1}$$

$\Rightarrow$ $\sin\alpha=0 \Rightarrow \alpha=\pi$

$$M_z(TI) = M_0(1 - 2e^{-TI/T_1})$$

Optimal t=TI to detect changes in T_1 ?

$$\frac{dF}{dt} = 0 = \frac{1}{T_1^2}(1 - \cos\alpha)e^{-t/T_1} - \frac{t}{T_1^3}(1 - \cos\alpha)e^{-t/T_1}$$

$$0 = \frac{1}{T_1^2}(1 - \cos\alpha)e^{-t/T_1}\left(1 - \frac{t}{T_1}\right)$$

TI = T_1

10-5

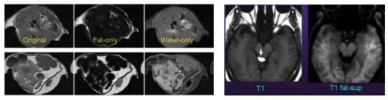
So, in this particular case we have now the *z* magnetization as function of *T I*. It's given by the equilibrium magnetization times *(1 - 2 e ^ T I / T_1)*. Next question is: What will be the proper choice of time *T I* here to detect changes in *T_1*? So, we want to choose the *T I* such-- we have established that *α* is 180 degrees-- we want to choose *T I* such that we are most sensitive to changes in *T_1*. So, we will take this function here and we will calculate now the derivative of this function with respect to time. Here we did it with respect to *α* to find the optimal *α*, now we will do it with respect to this time *t* here, which is our *T I*. This is a chain rule, we get this expression here, we simplify the terms--this is non-zero, this is 2, this is non-zero, so the term in the bracket has to be zero, and we are finding that the optimal inversion time *T I* to be sensitive to changes in *T_1* is, if we choose *T I = T_1*.

Notes

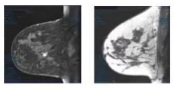
Summary

13m 07s

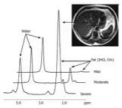
Credits



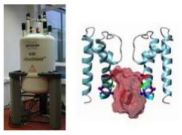
MRI
http://www.medscape.com/viewarticle/405305_2



Breast MRI
http://perimastologias.blogspot.ch/2011_10_01_archive.html



Advances in the treatment of nonalcoholic fatty liver disease
Sanjeev R Mehta et al., World J. Gastroenterol. 2008; 14:3476



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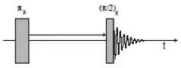

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This is again not surprising-- we have an exponential function and, again, in an exponential function, as you increase, you are not sensitive here, you are not sensitive here somewhere in the middle, and it turn out that you are most sensitive exactly when this time equals to *T_1*.

Notes

Summary

14m 18s