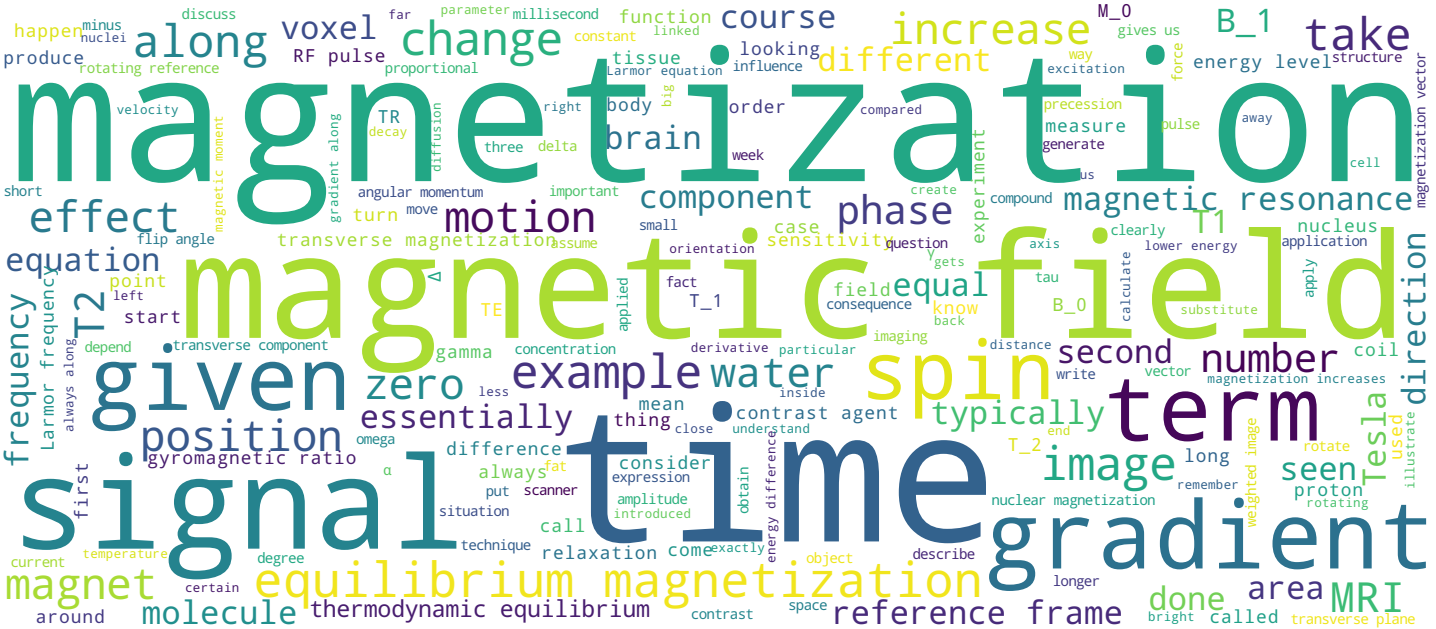
8.4 Sensitivity of MRI

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



EPFL

8-4. What are the essentials of Magnetic Resonance ?

nucleus & magnetic field

Nuclear equilibrium magnetization M_0

$$M_0 = (N_2 - N_1)\mu$$

$$N_2\left(1 - \frac{N_1}{N_2}\right)\mu = N_2\left(1 - e^{-\frac{\Delta E}{kT}}\right)\mu$$

$$\frac{N_1}{N_2} = e^{-\frac{\Delta E}{kT}}$$

$$e^{-x} \cong (1 - x)\ (x << 1)$$

By now we have learned quite a bit about magnetic resonance, and I want to recap the essentials, as we know them so far. We have a nuclear equilibrium magnetization *M_0* that develops. If you enter a magnet, your nuclei in your body will develop a nuclear equilibrium magnetization. This magnetization is given by the difference in the number of spins in the upper and lower energy level-- the difference between two times their magnetic moment. I will rewrite this equation here-- so, will write it in this form: I will have now *N_1 / N_2*, where we can use the Boltzman distribution. So, *N_1 / N_2*, the Boltzman distribution has been used here. And now what we will do is, we will use the linearization because we have said *Δ E / k T* is very small, so *e* to the - *x* can be approximated by *(1 - x)*, if *x* is very small compared to 1. And then with this linearization of the equation we have, the magnetization is given by this term here, and then I will substitute the *Δ E* with the term that we have seen previously, and this is now the nuclear magnetization, macroscopic equilibrium magnetization that we have.

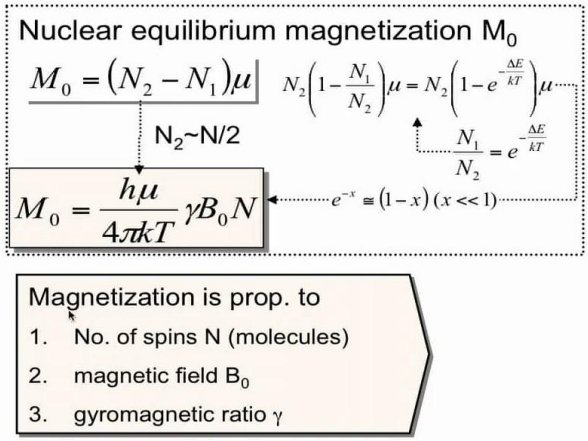
Notes

Summary

0m 04s

8-4. What are the essentials of Magnetic Resonance ?

nucleus & magnetic field



Now we will substitute for the fact that *N_2* is essentially half of all the spins-- this is to a very good approximation true, and then we obtain this expression here. So the magnetization is given by some constants of the system: Boltzman constant, temperature we can assume as constant, Boltzman constant, Planck's constant, the dipole moment and then we have gyromagnetic ratio, *B_0* and the number of spins. So this is the resulting relationship, and I will stress here-- it is good to understand this relationship, some dependencies here. And we have the magnetization here increases with the following terms: the number of spins-- so that is essentially the number of molecules. If we increase *N*, then the magnetization increases. If we increase the magnetic field, then the magnetization increases-- that's this term here *B_0*. If we increase the gyromagnetic ratio *γ*, then the thermodynamic equilibrium magnetization increases. So, taking all this together, for magnetic resonance imaging, which nucleus is the most favorable to look at? If we look at these three values here, we can control experimentally only one-- that's the magnetic field that's produced by the magnet that we construct.

Notes

Summary

1m 22s

8-4. What are the essentials of Magnetic Resonance ?

nucleus & magnetic field

Nuclear equilibrium magnetization M_0

$$M_0 = (N_2 - N_1)\mu \qquad N_2\left(1-\frac{N_1}{N_2}\right)\mu = N_2\left(1-e^{-\frac{\Delta E}{kT}}\right)\mu$$

N_2~N/2

$$\frac{N_1}{N_2} = e^{-\frac{\Delta E}{kT}}$$

$$M_0 = \frac{h\mu}{4\pi kT}\gamma B_0 N \qquad e^{-x} \cong (1-x)\ (x << 1)$$

$$\frac{d\vec{M}}{dt} = -\gamma \vec{B}_0 \times \vec{M}$$

Larmor frequency

$f_L = \gamma B_0 / 2\pi$

$\omega_L = \gamma B_0$

Convention in magnetic resonance:

Static magnetic field B_0 || z

Magnetization is prop. to

1. No. of spins N (molecules)
2. magnetic field B_0
3. gyromagnetic ratio γ

MRI:

^1H_2O !

Nucleus with non-zero spin and high *gyromagnetic ratio* γ: ^1H

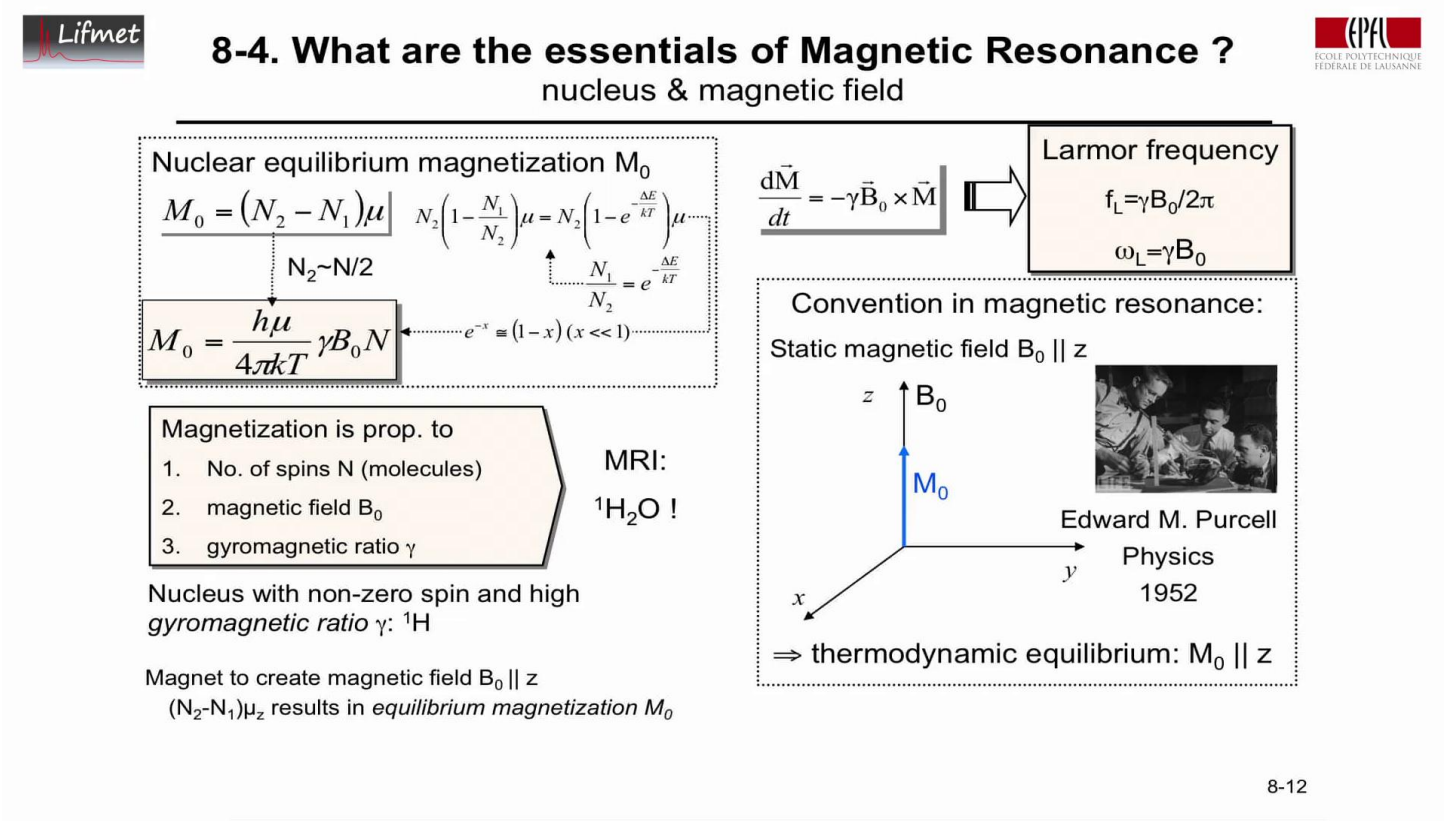
8-12

The number of spins is given by the organ under investigation, the gyromagnetic ratio by the nucleus. So we need to find a nucleus with a high gyromagnetic ratio and a high number of spins. And so this is essentially the hydrogen nucleus, H1 is the proton, has the highest *γ*, as we have seen before, and water is highly concentrated. Whether we like it or not, typically 80% of our body is water. So for MRI we are mainly focusing on imaging the hydrogen atom in water. So, we will take the Larmor equation here, and here I want to introduce the term that we have--from this we can glean-- the Larmor frequency, which is given by *γ B_0 / (2 π)*, that's in hertz, so it's a frequency; if we take angle velocity in radian per second then the *ω_L*, the Lamor frequency, is *γ B_0*. This we have to bear in mind. One thing that is non-negotiable in magnetic resonance is a convention about the reference system, the coordinate system. The static magnetic field *B_0* that we generate with our magnet the static magnet, the magnetic field generated by our scanner. That magnetic field is by definition always along *z*. We do not negotiate this convention--it is fixed.

Notes

Summary

3m 03s



So that is always along the magnetic field--it's along *z*. Then we have the equilibrium magnetization is also along *z*. The thermodynamic equilibrium magnetization is always parallel along *z*. And I want to give a great credit here to Edward Purcell, who discovered nuclear magnetic resonance and received the Nobel Prize for Physics in 1952. Quantum mechanics will tell you that the spin will never align with the magnetic field-- there is always a transverse component. However, the thermodynamic equilibrium magnetization is always along *z* and does not have a transverse component, and in the Appendix that we provide as *PDF* on this course the explanation is provided by the random phase approximation of equilibrium magnetization, so why there is no net transverse component of the magnetization at thermodynamic equilibrium. We need a magnet to generate a magnetic field that's along *z*. This results in a separation of the spins in the upper and lower energy level, which creates a thermodynamic equilibrium magnetization *M_0*. We will call the main magnetic field always *B_0*, and we will call the equilibrium magnetization always *N_0*.

Notes

Summary

4m 37s

8-4. What are the essentials of Magnetic Resonance ?

nucleus & magnetic field

Nuclear equilibrium magnetization M_0

$$M_0 = (N_2 - N_1)\mu \qquad N_2\left(1-\frac{N_1}{N_2}\right)\mu = N_2\left(1-e^{-\frac{\Delta E}{kT}}\right)\mu$$

$N_2 \sim N/2$

$$\frac{N_1}{N_2} = e^{-\frac{\Delta E}{kT}}$$

$$M_0 = \frac{h\mu}{4\pi kT}\gamma B_0 N \qquad e^{-x} \cong (1-x)\ (x << 1)$$

Magnetization is prop. to

1. No. of spins N (molecules)
2. magnetic field B_0
3. gyromagnetic ratio γ

MRI: ^1H_2O !

Nucleus with non-zero spin and high *gyromagnetic ratio* γ: ^1H

Magnet to create magnetic field B_0 || z
(N_2-N_1)μ_z results in *equilibrium magnetization* M_0
ΔE is small (~μeV)
⇒ **Non-ionizing e.m. fields**

$$\frac{d\vec{M}}{dt} = -\gamma\vec{B}_0 \times \vec{M}$$

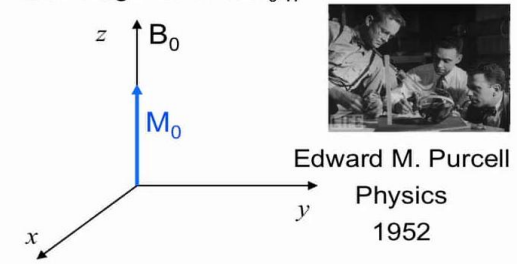
Larmor frequency

$f_L = \gamma B_0/2\pi$

$\omega_L = \gamma B_0$

Convention in magnetic resonance:

Static magnetic field B_0 || z



Edward M. Purcell
Physics
1952

⇒ thermodynamic equilibrium: M_0 || z

MR is safe, but insensitive

8-12

Now, if we look at the energy difference here, the *Δ E*, we find it is actually very small, and if you calculate this, you will find that this is on the order of micro-electron-volts. So, there is one consequence, we are using non-ionizing electromagnetic fields for magnetic resonance. So, that' good--that is different from the X-ray techniques. But given that this term here depends on the magnitude of the *Δ E* here-- this enters linearly, so as we increase the energy difference between the energy levels, we increase the magnetization-- there is also a consequence-- it is insensitive. So the following statement is certainly true: MR, magnetic resonance, is safe-- we are dealing with not ionizing radiation-- but it is insensitive. We cannot imagine to do an MR experiment with concentrations on the order of picomolar-- there are just not enough molecules there to produce a measurable nuclear magnetization that we can reasonably detect in the body.

Notes

Summary

6m 08s

How can the sensitivity be increased ?

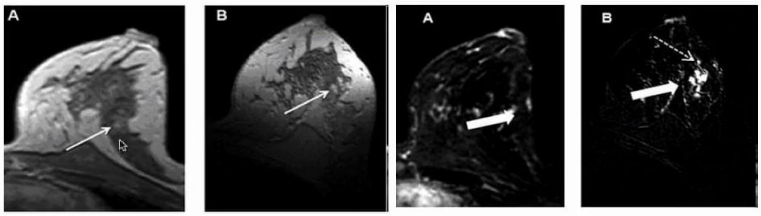
magnetic field strength B_0

MRI of the lower abdomen

MRI of the spine

fMRI of the brain (1.5 vs 4 Tesla)

MRI of the breast (1.5 vs 3 Tesla)



http://medicalphysicsweb.org/cws/article/research/38414

8-13

So therefore we would ideally like to increase the sensitivity, and how can we do that? We have seen just on the previous slide that the equilibrium magnetization depends on a number of factors that are given by the nucleus and some universal constants, and temperature, if course, which is more or less also given. So, the only parameter that is open for manipulation is the external magnetic field *B_0*. And here is an example of comparing a scan of the lower abdomen at 0.2 Tesla and 1.5 Tesla. If you look here, the image is grainy, and it gets much sharper here, at 1.5 Tesla. If we take the spine here, we have, again, 0.2 Tesla here-- grainy image--we see very nice details, but a very crisp image at 1.5 Tesla. So, comparing the image, the sensitivity at lower field and higher field, we notice a clear improvement in sensitivity. Here is another example-- that is brain function-- it's functional imaging-- we will discuss that in Lecture 12. This is a comparison of 1.5 with 4 Tesla-- clearly, the sensitivity increases substantially with higher magnetic field. Here we have an example of MRI of the breast. This is a standard MRI. We are seeing something here that is suspicious.

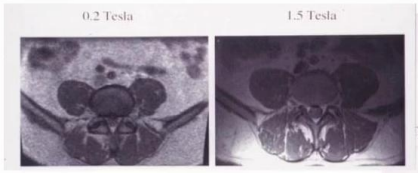
Notes

Summary

7m 14s

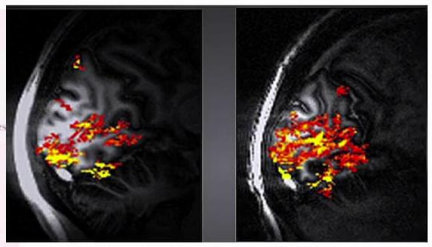
How can the sensitivity be increased ?

magnetic field strength B_0



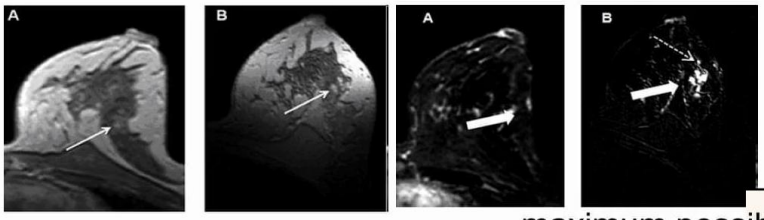
MRI of the lower abdomen

MRI of the spine



fMRI of the brain (1.5 vs 4 Tesla)

MRI of the breast (1.5 vs 3 Tesla)



http://medicalphysicsweb.org/cws/article/research/38414

maximum possible MR signal:

determined by

equilibrium nuclear magnetization M_0

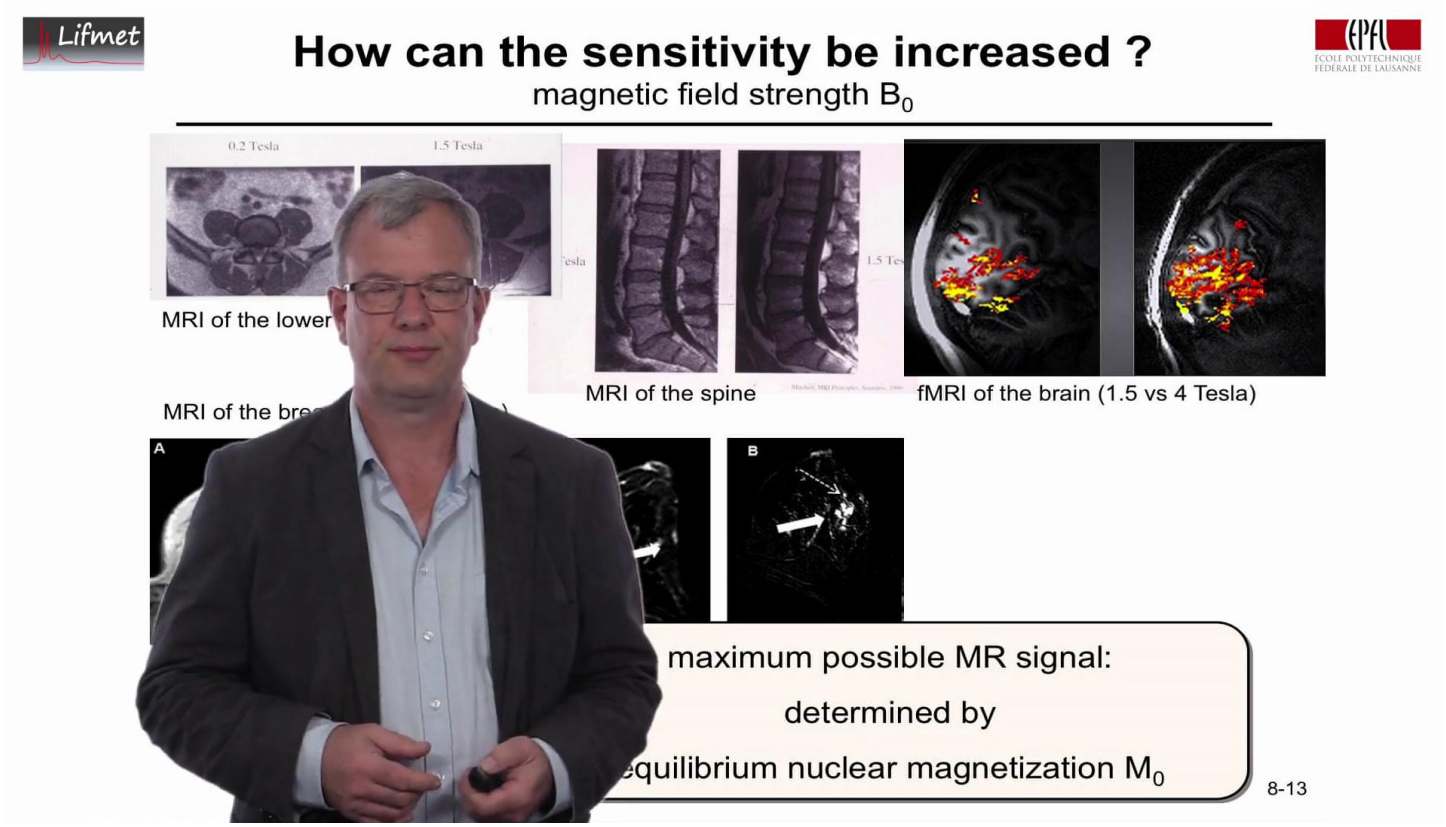
8-13

It's a bit clearer here, but this is a standard breast image, and here is a breast image with the fat signal removed-- we will discuss that in two weeks, how this is removed-- and then one can see clearly at 3 Tesla here compared to 1.5 Tesla. One can clearly see the potentially neoplastic lesion here, because the signal is not related to fat, so clearly an improvement in specificity with the higher magnetic field. Now, one thing that we need to remember for this course, this week and so on, the theoretically maximum possible MR signal is dictated by the equilibrium nuclear magnetization *M_0*.

Notes

Summary

8m 40s



This is a given of the system. We cannot go beyond that. So, any mechanism to generate contrast results in a reduction in magnetization. We will discuss in the weeks to come how this happens. So, we are limited by the thermodynamic equilibrium nuclear magnetization *M_0* in our sensitivity that gives us a maximum signal that is possible.

Notes

Summary

9m 28s