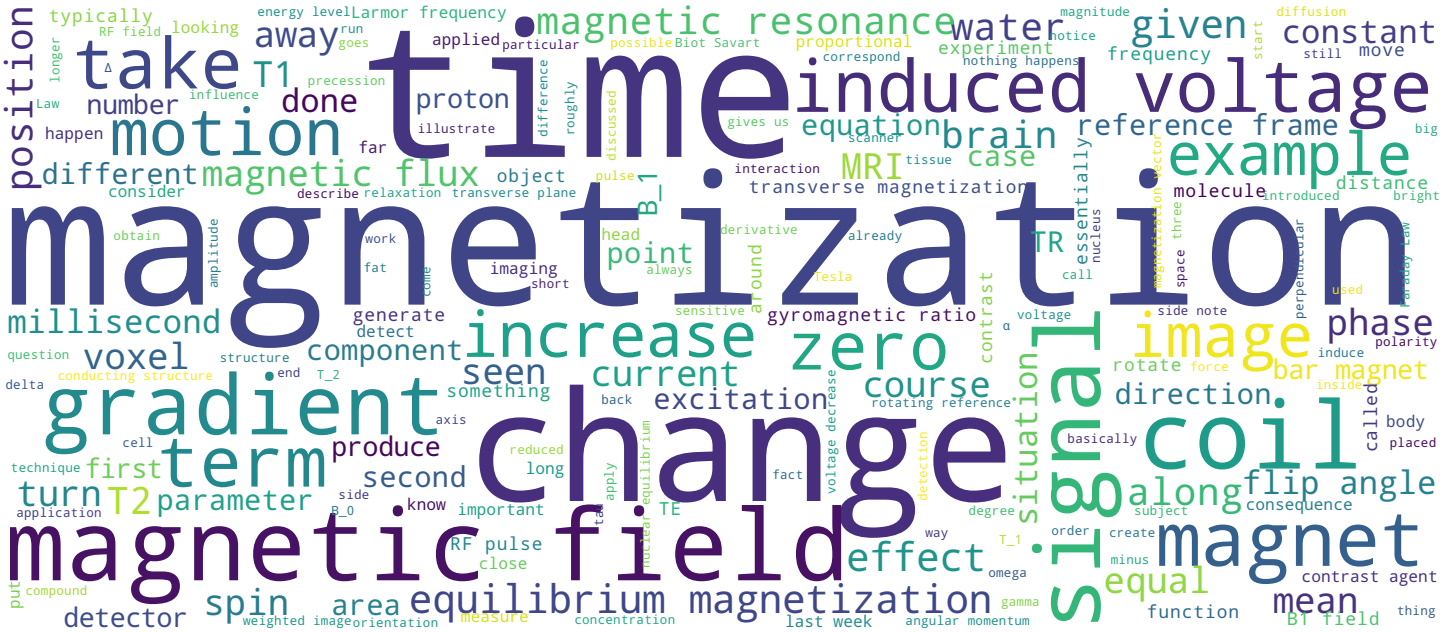
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

9.1 MR signal detection

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



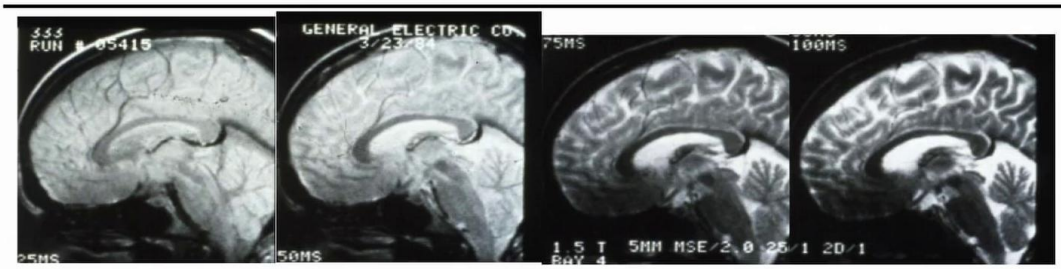
Search MOOC

Video

EPFL

MRI contrast depends on experimental parameters

I. Time after excitation TE



TE=25 ms 50 ms 75 ms 100 ms

9-2

Okay. In this week, we're going to talk about some features that are important for understanding the contrast mechanisms in magnetic resonance imaging. Now, there is an issue here that is, we have spent not much time on each of the imaging techniques, x-ray-based techniques. And there is something that is different with magnetic resonance and that is that the interactions between what we can manipulate on the scanner and how the image looks like, these interactions are far more diverse-- the mechanisms are far more diverse. And so, the point I want to make here is that, the contrast strongly depends on experimental parameters. So if we look at an image measured 25 milliseconds after the excitation, this is what it looks like. This is a sagittal cut through the head. We have, the nose is roughly here. The back of the head is here, so the head is a bit tilted. This is what the image looks like. If we look at it after 50 milliseconds, we have the appearance of the head like this. After 75 milliseconds and 100 milliseconds. Notice here how the appearance of the head considerably changes as we increase the time after excitation in intervals of 25 milliseconds. So this is one parameter that we can change.

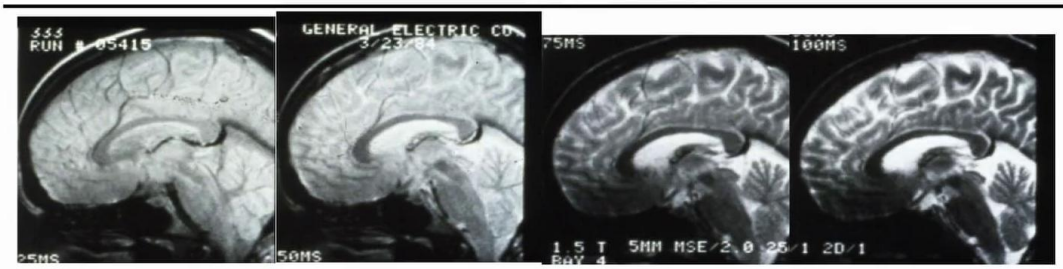
Notes

Summary

0m 04s

MRI contrast depends on experimental parameters

I. Time after excitation TE



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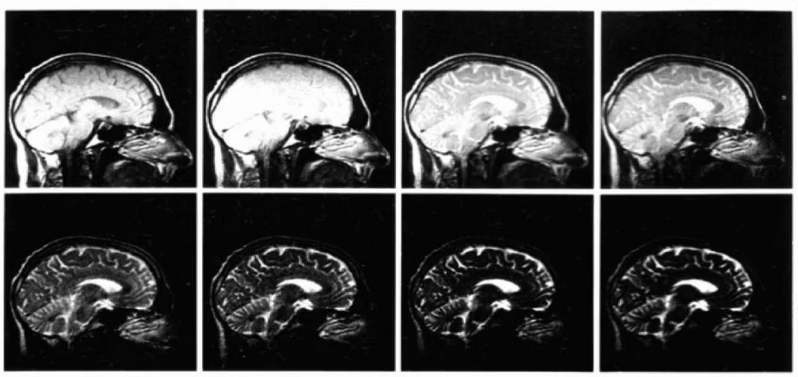


9-2

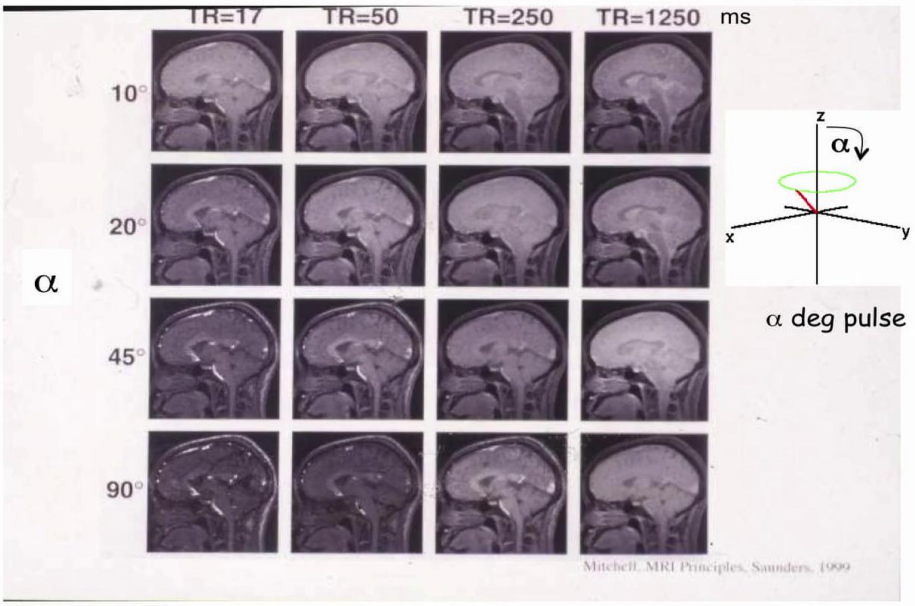
Here is another example of images as this parameter, time after excitation, is increased-- here very short, two very long. Here we can only see the fluid-filled spaces in the brain.

Notes

Summary

1m 35s

II. Flip angle α and time between excitations TR



9-3

The next parameters, actually, two parameters I want to look at is the *flip angle alpha*-- we've dealt with that last week, what this is. This is by how much we tilt the magnetization away from *z*. So we've taken equilibrium magnetization and we've tilted it away from the *z-axis* by this angle alpha, and now it precesses. And the other parameter is the *time between excitations TR*. We have, on the vertical access, the TR in milliseconds so this increases from 17 milliseconds to 1.25 seconds, and the flip angle increases from 10 to 90 degrees. What do we notice here? Well, we do notice that the image, as we increase the flip angle here, it becomes progressively darker. And as we increase the TR, the image becomes progressively brighter, there's more intensity. Here it's a very grayish image. Here it's essentially a black image. As a side note, the bright dots that we see here, these are actually blood vessels where magnetization is flowing into the image plane, but that's a side note. So here, in this matrix, we can see that the flip angle and the time between excitations TR, these two parameters have an interplay between each other and they manipulate the contrast also, quite substantially.

Notes

Summary

1m 49s

What do we know about MR so far ?

Need:

Nucleus with non-zero spin

Magnetic field B_0

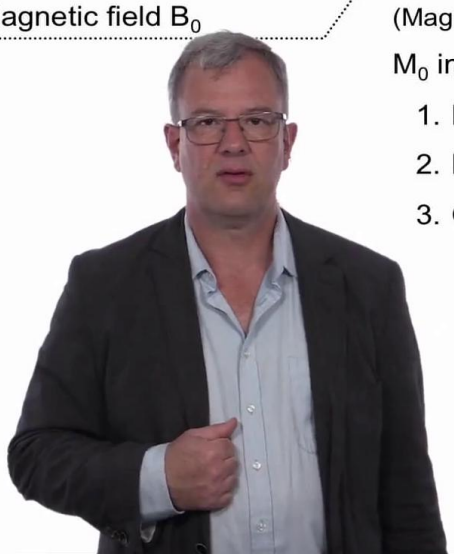
Get:

Nuclear (equilibrium) magnetization M_0

(Magnitude dictated by Boltzmann distribution)

M_0 increases with

1. Number of spins in voxel
2. Magnetic field B_0
3. Gyromagnetic ratio γ



9-4

So we're already at three parameters: time after excitation, time between excitations, and the flip angle. These three parameters, they're all under the control of the operator-- of the experimenter that we can change-- which can fundamentally alter the image contrast. So let's recap what we know about *magnetic resonance* so far. What we have seen is: We need a nucleus with non-zero spin so we have a magnetic moment, and we need an external magnetic field that's generated by our magnet. If we have these two ingredients, we put our subject into the magnet, then we get a nuclear equilibrium magnetization that builds up after a certain time. We can always picture you going to the magnet, and after a while, your body builds up this nuclear equilibrium magnetization. Its magnitude is dictated by the *Boltzmann distribution*. This equilibrium magnetization-- the thermodynamic nuclear equilibrium magnetization-- increases with the number of the spins in the voxel, the magnetic field *B-zero*, and the gyromagnetic ratio gamma. So these are three key elements: Number of spins in a voxel, gyromagnetic ratio gamma-- those are two parameters that we have limited control over.

Notes

Summary

3m 11s

What do we know about MR so far ?

Need:

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Magnetic field B_0

Get:

Nuclear (equilibrium) magnetization M_0

(Magnitude dictated by Boltzmann distribution)

M_0 increases with

1. Number of spins in voxel
2. Magnetic field B_0
3. Gyromagnetic ratio γ

Imaging ^1H in H_2O is most sensitive

Thermodynamic equilibrium magnetization M_0 is || B_0

$$\frac{d\vec{M}_0}{dt} = \vec{M}_0 \times \gamma \vec{B}_0 = 0$$

9-4

Gyromagnetic ratio we have no control over. Number of spins in a voxel, we can change the size of the voxel-- that can be changed. And the magnetic field is something we can experimentally alter. Now if we take all of these elements together... then our conclusion is that: Imaging of the proton-- that is, the hydrogen nucleus in water-- is the most sensitive. Our body is filled with water so we have a high number of spins. Water is present in concentrations of around 40, 50 molar in the body, so it's about 80 molar protons in our body. It has the highest gyromagnetic ratio, so imaging of the proton in water is the most sensitive way to do imaging. And that's for most practical purposes, but not all. We will essentially consider imaging of water in this course. We have seen last week that the thermodynamic equilibrium magnetization *M-zero* is proportional to *B-zero*. So if we look at the equation of motion, then the derivative of this equilibrium magnetization with time is equal to *M-zero cross gamma B-zero*. And, frustratingly, this term is zero so the consequence is that the equilibrium magnetization is along *z* and stays along *z*-- nothing happens.

Notes

Summary

4m 35s

What do we know about MR so far ?

Need:
Nucleus with non-zero spin
Magnetic field B_0

Get:
Nuclear (equilibrium) magnetization M_0
(Magnitude dictated by Boltzmann distribution)
M_0 increases with
1. Number of spins in voxel
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Imaging ^1H in H_2O is most sensitive

Thermodynamic equilibrium magnetization M_0 is || B_0

$$\frac{d\vec{M}_0}{dt} = \vec{M}_0 \times \gamma \vec{B}_0 = 0$$

M_0 does not precess

All this does not generate a measurable signal

9-4

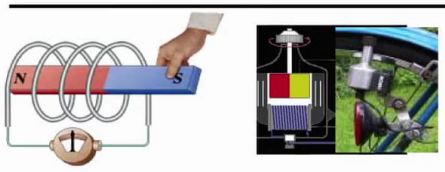
And if nothing happens, we cannot measure anything, so we need to induce some changes since all this that we have told you so far-- this does not generate a measurable signal, so we need to do something to be able to detect a signal from our nuclear magnetization. So we need to do something to the magnetization to generate a measurable signal because just leaving our subject in the magnet will not produce something that we can measure.

Notes

Summary

5m 57s

9-1. How is the MR signal detected ?



Faraday's Law of Induction

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Magnetic flux Φ_B

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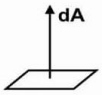


MR: dA=constant

$\rightarrow \xi \propto dB/dt$

Lenz's Law

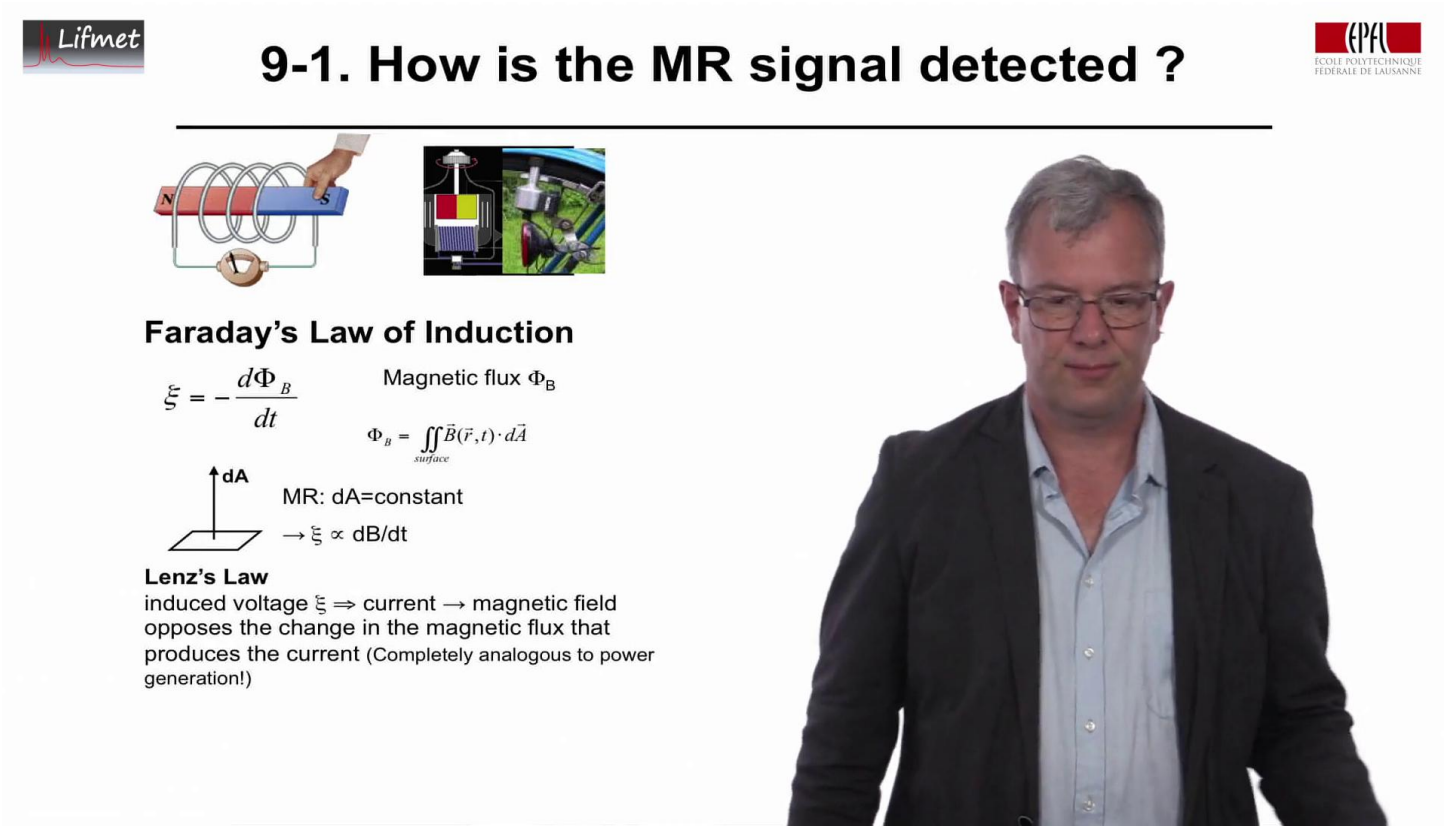
induced voltage $\xi \Rightarrow$ current $\rightarrow$ magnetic field opposes the change in the magnetic flux that produces the current (Completely analogous to power generation!)

So first, I want to talk about how the MR signal is being detected. What can we detect? And the essential principle that lies behind this is shown here. We have a magnetic dipole whose position varies in time and in that surrounding conducting structure there is an electric field being induced-- a voltage being induced. And all of this is simply Faraday's Law of Induction. *Faraday's Law of Induction* states that we get a induced voltage, it is given by the time derivative of the magnetic flux. The magnetic flux is given by the surface integral of magnetic field with the surface vector. So if we look at what this means: We have the *surface vector dA* here, it's perpendicular to the surface, and what we have in magnetic resonance, the surface is constant; we don't change the orientation, so this is a constant. And so, basically, the induced voltage in the coil that we have here is proportional to the change in magnetic field with time. We have *Lenz's Law* to consider that the voltage is induced voltage that produces the current-- This produces a magnetic field that opposes the change in magnetic flux. And this all is completely analogous to power generation whether we do this motion, or here in the bicycle...

Notes

Summary

6m 27s

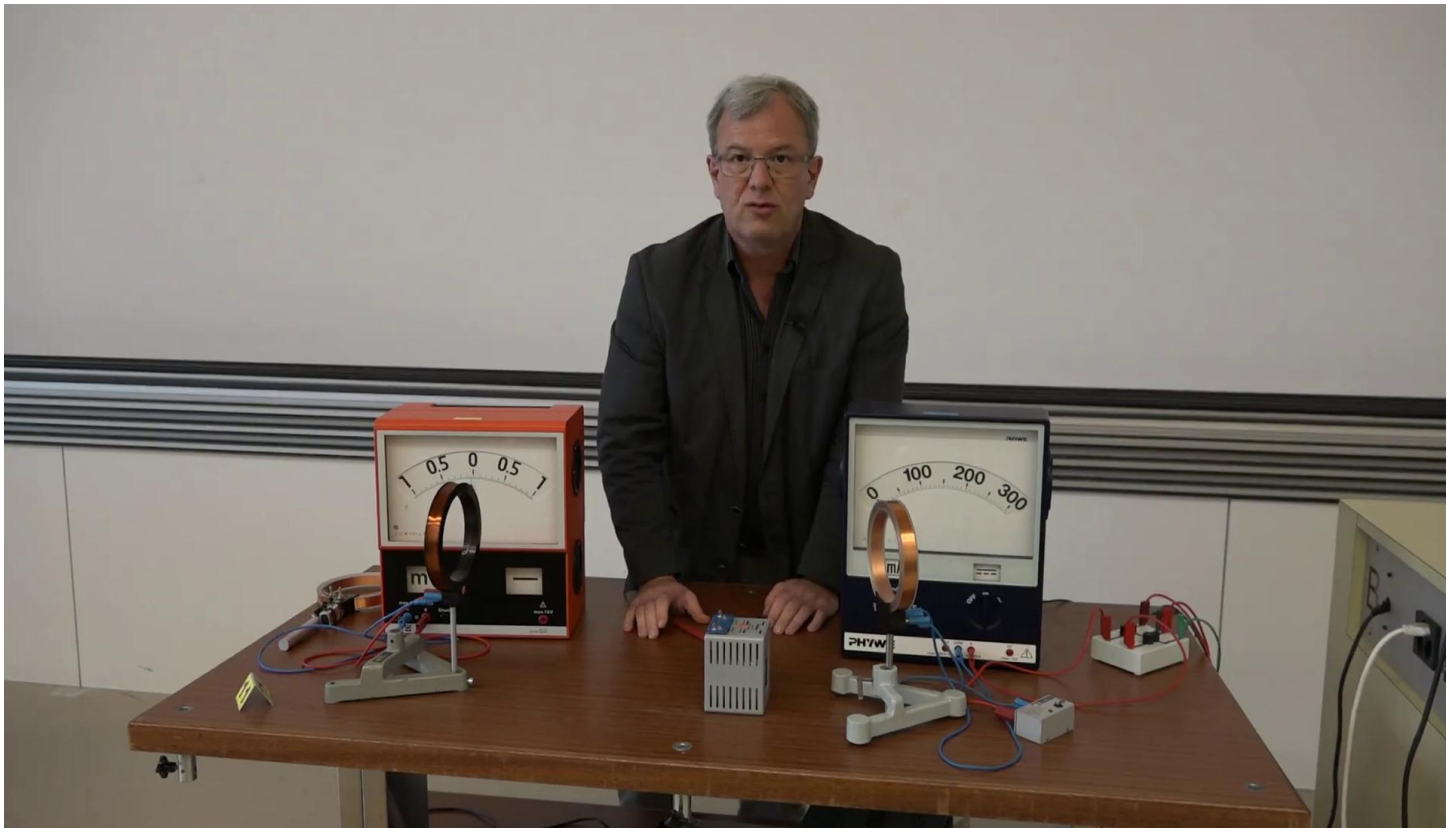


power generation for the light of the bicycle. And we'll demonstrate this in the following experiment. We'll take two situations to illustrate the generation of voltage with the change in magnetic flux.

Notes

Summary

7m 59s



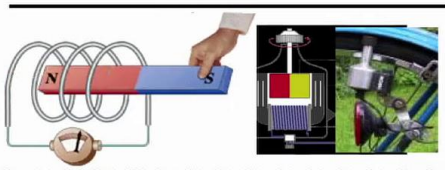
So in this coil I'll turn on the current and we'll see the induced voltage in this coil as we change the magnetic flux. I'll turn it on. We saw a little blip that's here on this side. And then if I move closer, the movement creates a change in magnetic flux on this coil over here. Likewise, I can take a bar magnet... and if I move that bar magnet here, I'll see, already, an induced voltage at this distance. If I'm further away, we don't see anything. And it gets really big if we're very close. And, of course, if I change the polarity, I'll change the polarity of the induced voltage here, so it goes from both sides as I turn around. We have similarly here with a magnet in here, I can demonstrate this in the following fashion: So if I move the magnet in here, depending on the motion, direction of the motion, the *flux sine* will have the LEDs that indicate the flow change. If I'm further out, nothing happens because now we're further away and with the *Biot–Savart Law*, this induces a lower voltage. So that's a demonstration of the distance effect of the change in magnetic flux on the induced voltage.

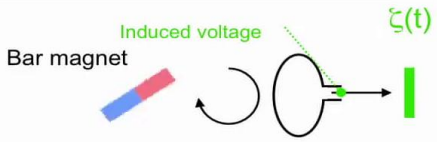
Notes

Summary

8m 20s

9-1. How is the MR signal detected ?





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Magnetic flux Φ_B

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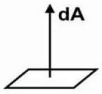


MR: dA=constant

→ ξ ∝ dB/dt

Lenz's Law

induced voltage ξ ⇒ current → magnetic field opposes the change in the magnetic flux that produces the current (Completely analogous to power generation!)

Biot-Savart Law

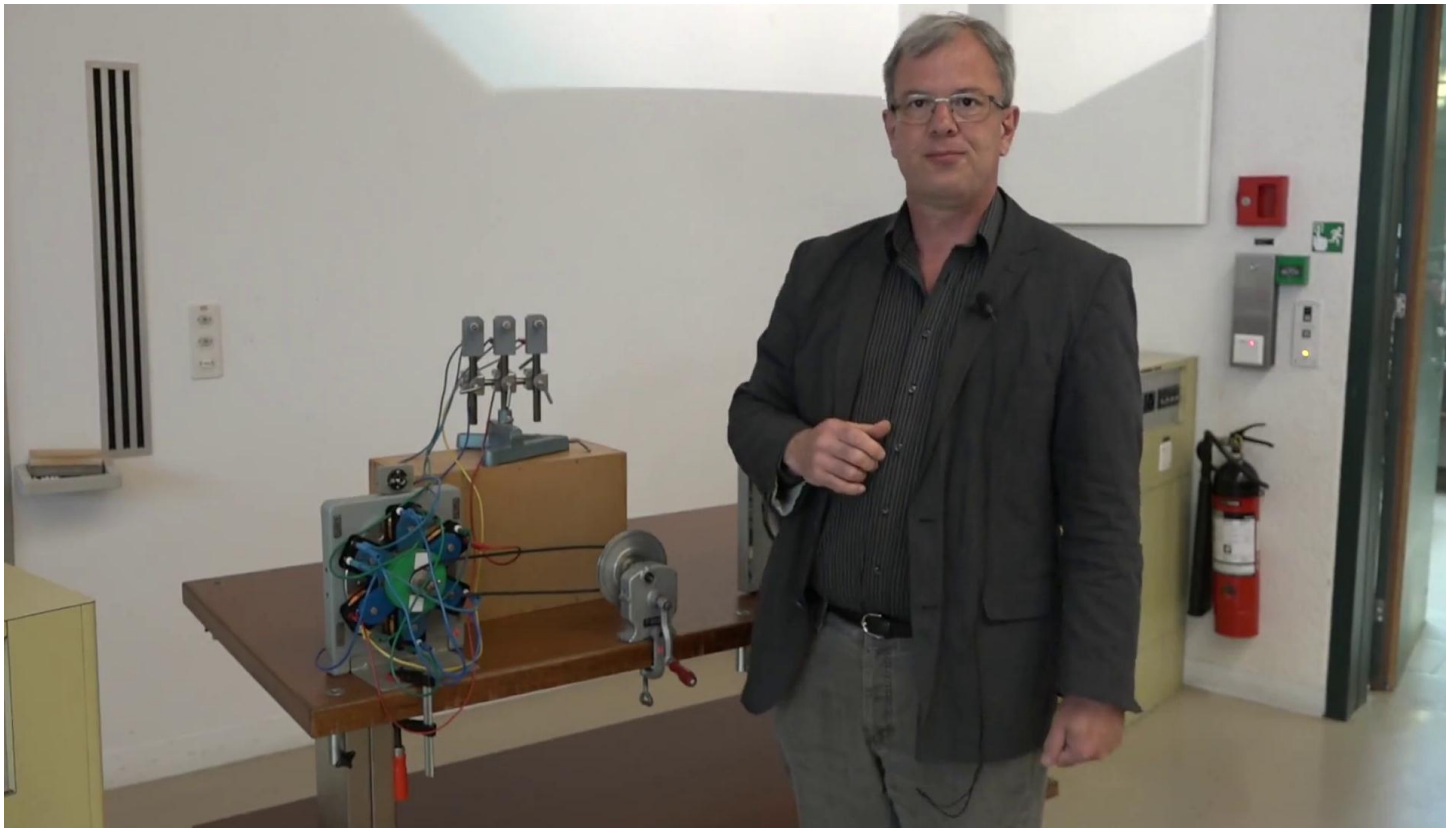
magnetic field falls off with r^{-2} $\vec{B}(\vec{r}) \propto \int \frac{\mu_0}{4\pi} I \frac{d\vec{l}\times\vec{r}}{r^3}$

Okay, now we also have to consider the law of *Biot-Savart* which basically says that the magnetic field produced by a current falls off with the distance squared, so it's one *over R squared*. There is the law of *Biot-Savart*. So these are the laws of electromagnetism that we're basing our observations on. And so, if we take the situation here, we'll take a microscopic bar magnet, we have the coil that picks up the change in magnetic flux, that converts it to a *emf*. And now we will look at what is the induced voltage in this coil. So the induced voltage is illustrated here with this bar, the magnitude. And now as I rotate this magnet, the voltage changes... periodically. Now, if I increase the distance of the magnet from the coil, what happens now? We have still the induced voltage, but due to *Biot-Savart's Law* here, we are getting a reduced induced voltage. And we will illustrate this interaction-- the distance dependence-- in a small experiment that we have prepared for you.

Notes

Summary

9m 38s



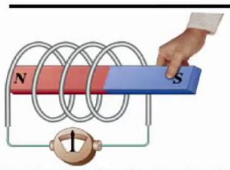
Okay, so what we have here is, we have coils, we have the magnet here in blue. The coil, as I turn it... as I turn it sufficiently large, it is moving the magnetic field. Therefore, the flux changes and that produces the current that lights the light bulb. This is one situation that does not correspond to what we have in magnetic resonance. The situation that we have in magnetic resonance is more like this one. Here we have the magnet, in green, and the coils that pick up the change in magnetic flux are around it. As I turn this, we will see the induced voltage by the light bulbs up here. So as I turn it, this is like the magnetization in magnetic resonance-- we have a change in magnetic field flux. This magnetic field flux is picked up by the coils and this produces induced voltage, and here, in this case, produces light, which, of course, we can't do with MRI.

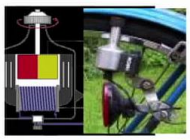
Notes

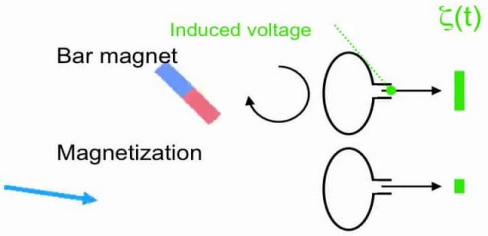
Summary

10m 56s

9-1. How is the MR signal detected ?







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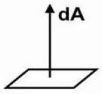

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induced voltage ξ ⇒ current → magnetic field opposes the change in the magnetic flux that produces the current (Completely analogous to power generation!)

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magnetic field falls off with r^{-2} $\vec{B}(\vec{r}) \propto \int \frac{\mu_0}{4\pi} I \frac{d\vec{l}\times\vec{r}}{r^3}$

Magnetic field of dipole decreases with distance :
ξ decreases with distance from magnetization

9-5

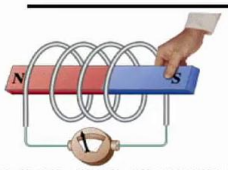
Okay, so we have seen with a physical bar magnet that when we change its orientation in a conducting structure, we induce a voltage, and as we move this away, we reduce the voltage. Now the link between a physical bar magnet and nuclear magnetization is that it is the same effect; it is still *Faraday's Law*. So we have a magnetization, so the role of the rotating bar magnet is taken by the magnetization. We have, again, our coil here and the induced voltage-- As the magnetization rotates, it creates a change in magnetic flux. The magnetic field becomes time-dependent here. This term is time-dependent, this term is constant, so we have a magnetic flux that changes with time, and this induces a voltage in the coil. And similarly to the bar magnet, the analogy here holds very well-- If the magnetization is further away from our conducting structure, then the induced voltage is substantially reduced. So if we take this together, then as we increase the dipole distance away from our conducting structure from this wire, then the induced voltage decreases. In other words, *dA emf*, the electromotive force, the induced voltage, decreases with distance from the rotating magnetization.

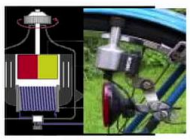
Notes

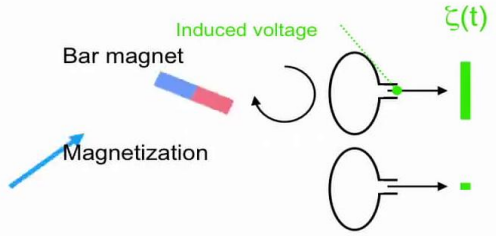
Summary

11m 55s

9-1. How is the MR signal detected ?







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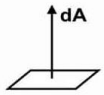

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Magnetic field of dipole decreases with distance : **ξ decreases with distance from magnetization**

NB. Generation of the RF field B_1

B_1 decreases with distance from RF coil (Biot-Savart)

9-5

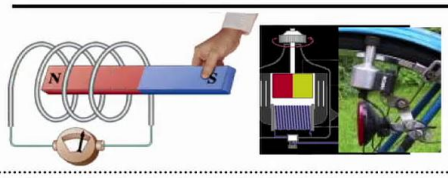
Now, on a side note, how do we generate the *RF field B* that we've discussed at the end of last week? And this works with the following principle: We have a coil here-- it's very often the same coil as we have here for detection-- we run a current through it and this current is applied on the coil. Now, this will just generate the linear polarized B1 field, but we can always consider any B1 field that's linear to be a superposition of counter-rotating circle of polarized B1 fields, and one of them is going to precess in the right frequency. So if we have this-- We have the current running in the coil, then, at this point, we will generate a B1 that is indicated here. If we are further away from the coil-- remember *Biot-Savart*-- then, in this case, the current, being still the same, but now the B1 field is reduced. So consequence is: The B1 field is strongest closest to the coil and decreases with coil distance. So the degeneration of the RF field is the inverse process of detecting the precession of the magnetization. Here, we run a current through the coil, this produces a B1 field that rotates, and this B1 field is the one that we have discussed at the end of last week.

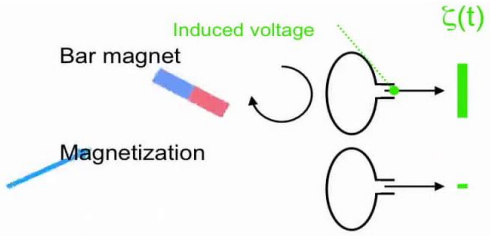
Notes

Summary

13m 21s

9-1. How is the MR signal detected ?





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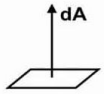

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NB. Generation of the RF field B_1

B_1 decreases with distance from RF coil (Biot-Savart)

9-5

Okay, so much for the theory. What are the consequences now for the fact that: As we are further away from the magnetization, or further away from our object of interest, either B1 or the induced voltage decrease.

Notes

Summary

14m 48s

What does an MR detector look like ?

RF Coil examples

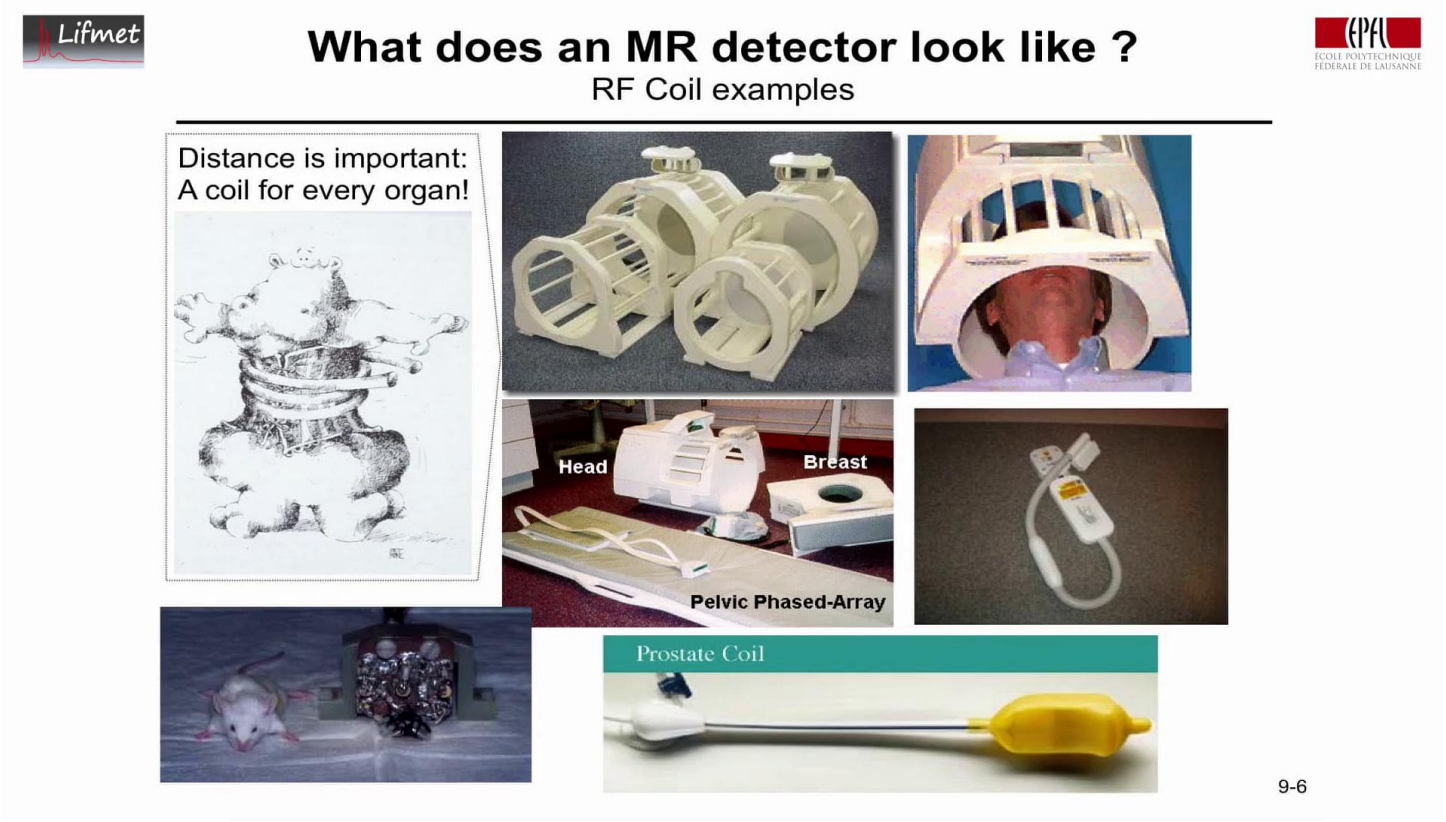
9-6

In other words, what does an *MR detector* look like? Well, since distance is so important, it implies that we have to optimize the coil geometry, the detector, so ideally-- and this is the physicist's view of things-- we'd like to put our object into our detector, and this detector should be as tight as possible. Clearly, the hippo here is not happy, it's not comfortable, this is not a situation that is ideal for comfort. So what this means-- It also means that our detector is not going to be a detector built for the human body and detect everything from the human body, but it means that we are going to have a detector for every organ of interest. Here's an example of detectors for the brain. They look like bird cages, and indeed, they are also called *bird cage*. Here's to give you an idea how the subject is placed. Here's a mirror for comfort, here's the subject's head, and here is the structure that detects and excites the magnetization. Here are three examples put together-- We have the head coil, again, we have a *breast coil* for breast MRI, and for a *pelvic phased-array*, it's a coil that's made for the lower abdomen.

Notes

Summary

15m 05s



Here, we have an *endorectal coil*-- it's a small coil-- and we have a prostate coil. A prostate is an important disease, so we want to be as close as possible with detecting our signal to the organ. You can imagine-- I'll leave that to your imagination to figure out where this coil is placed to be as close as possible to the organ. And here's an example with a rat. So for the rat brain-- Here's the rat, here's the brain, and here's the detector that's the coil that was placed on its brain for optimal sensitivity. Clearly, taking such a small subject into the detection of a brain coil or a head coil does not make sense at all because there, the conducting structures are too far away.

Notes

Summary

16m 22s

Credits

Creative Commons Animation
http://members.shaw.ca/len92/animations.htm

Creative Commons Picture
http://www.drawingnowparis.com

Átomo Núcleo (prótons + neutrons)
Dr. Magno Fernandes Junior
http://slideplayer.com.br/slide/8563280/

Notes

Summary

17m 13s