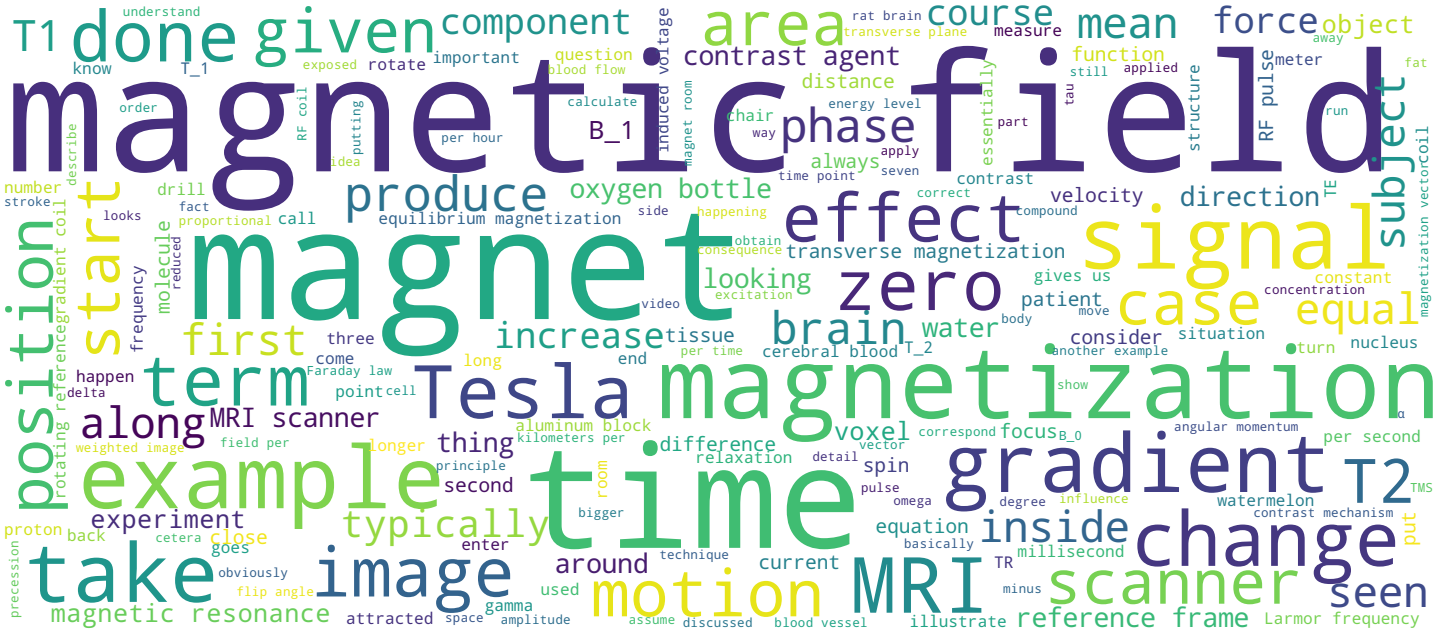
8.1 The multi-modal MR scanner

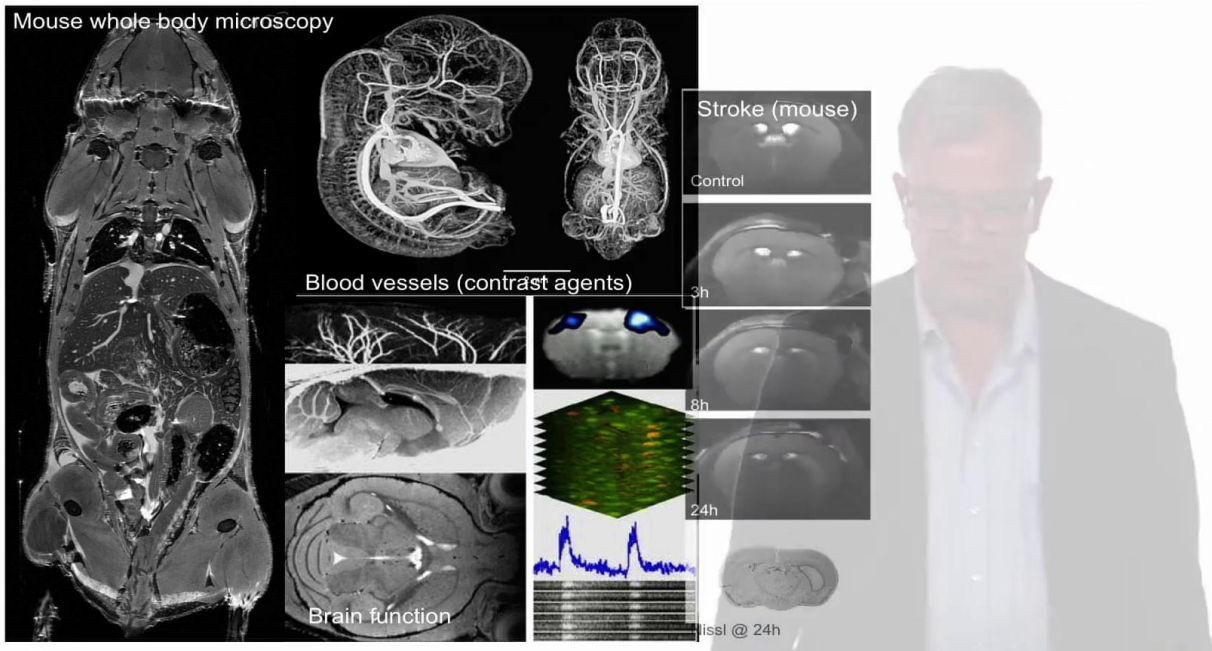
Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



EPFL

Magnetic resonance of animal models



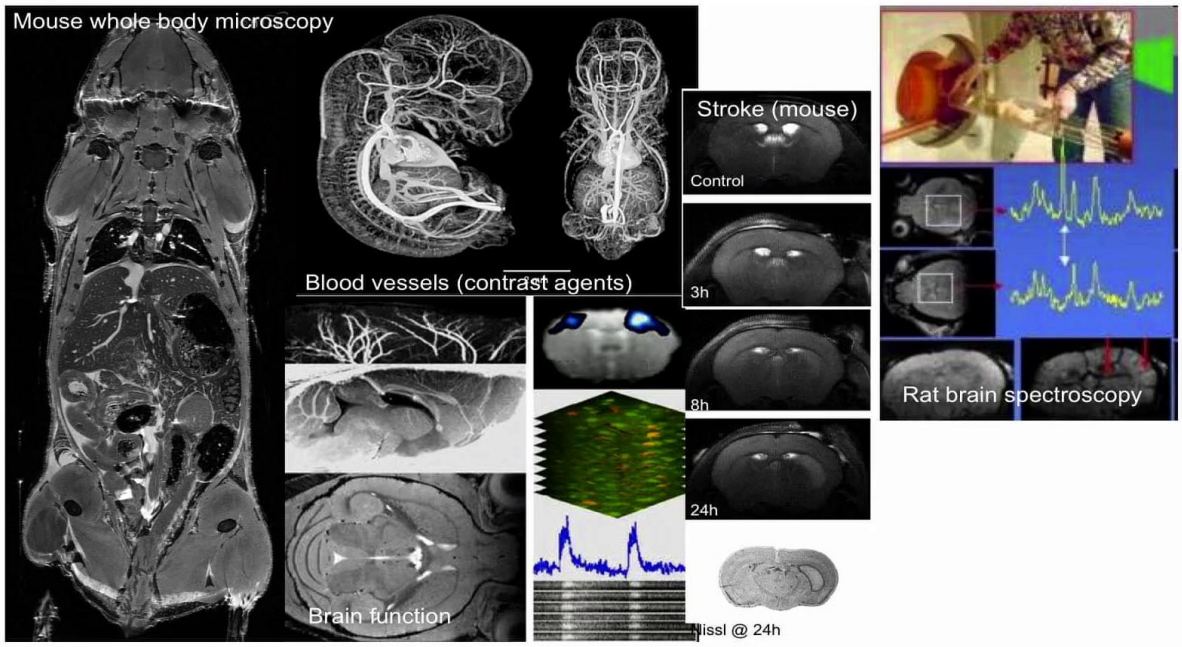
We are now, in this section of the course, Section 2., we are going to talk about magnetic resonance imaging. As you will see, this is distinctly different from the X-ray-based techniques that we have discussed in Part 1. I want to start now the introducing of the magnetic resonance of MRI. I want to start out with, first, some examples; of MRI. I want to start out with, first, some examples; we'll start with examples of animal models. I want to start out with, first, some examples; we'll start with examples of animal models. This is a high resolution scan, MRI scan, of a mouse. It's a whole body scan at very high resolution, and you can certainly appreciate all the fine details that are observable here, particularly, in the soft tissue. Here is another example of blood vessels, so here contrast agents were used to depict the blood vessels here in this mouse embryo. Another example here is brain function. We are looking at the vascular blood vessels inside the brain. Here's the brain, here's another brain scan, looking at the activity in the brain tissue that can also be done with MRI. Here's an example of a longitudinal study looking at a stroke in the brain; the development of the stroke.

Notes

Summary

0m 03s

Magnetic resonance of animal models



8-2

One can see some bright areas here the development of the stroke. One can see some bright areas here and this is the Nissl staining that shows the death of neurons-- that's done after the MRI scanning has been done. And finally, another example that one can look at is chemical compounds, here phosphorus-- phosphocreatine ATP, using spectroscopy of, in this case, the rat brain. phosphocreatine ATP, using spectroscopy of, in this case, the rat brain.

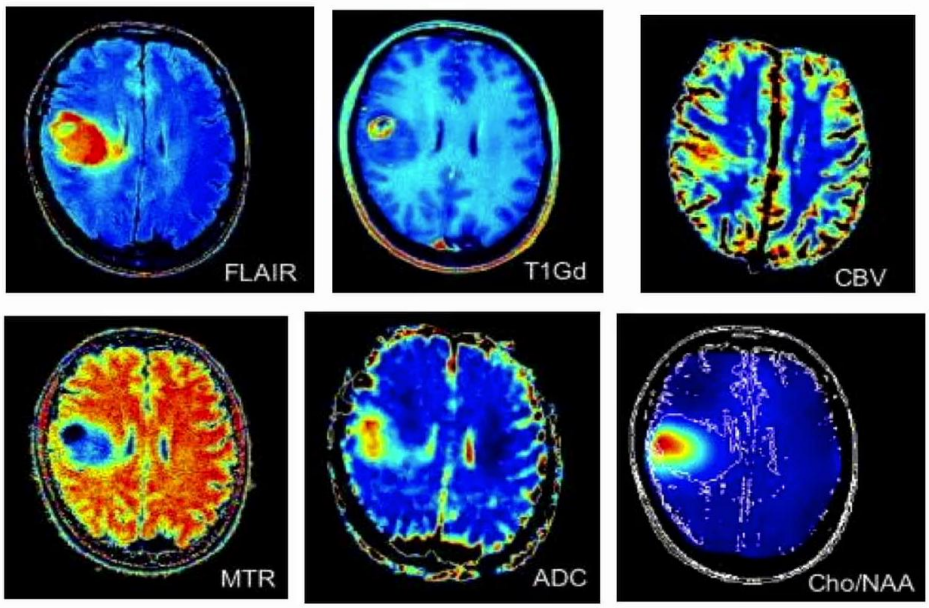
Notes

Summary

1m 27s

One magnet, many modalities (contrast mechanisms)

Human brain



8-3

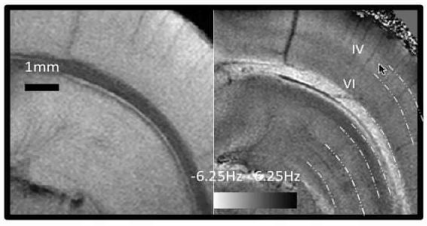
One thing-- and this is really an important message here-- is one thing that distinguishes MRI from the previous modalities, the other modalities, is it has one instrument, one magnet. But basically, it has many modalities built into it. Or, as we would call it, many different contrast mechanisms. Let me illustrate this with the human brain. We have here contrast mechanisms exploited that's called *FLAIR*. It highlights certain processes, typically from multiple sclerosis. Then we have here, a contrast agent application; Then we have here, a contrast agent application; we have here an image of cerebral blood volume changes; we have a mechanism called MTR that's Magnetization Transfer Ratio imaging; we have here an image of cerebral blood volume changes; we have a mechanism called MTR that's Magnetization Transfer Ratio imaging; We have diffusion, apparent diffusion coefficient or ADC that's being measured here-- this is all the same patient-- and finally, we have a biochemical measurement of choline to N-acetyl aspartate concentrations-- a map, showing changes here always in the same lesion. of choline to N-acetyl aspartate concentrations-- a map, showing changes here always in the same lesion.

Notes

Summary

1m 51s

One magnet, many contrasts
Rat brain



Phase imaging

8-4

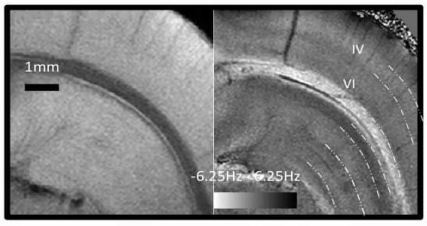
So, we take this, this has been all done in the same patient, pretty much in the same session, and we're obtaining six different views of the same process that's going on-- and this is exploiting the same principle, the same detection principle, the same instrumentation principle-- but there are many ways in which one can manipulate the contrast with MRI, and therefore, what is important to be stressed here, what I like to stress here, is we have one magnet and many modalities. We don't have an MRI as such. is we have one magnet and many modalities. We don't have an MRI as such. An MRI as such does not exist, and MRI comes always with a definition of what particular contrast mechanism is being imaged. Let me go on with the example of one magnet, many contrasts in the rat brain. We have phase imaging-- so we have a normal image here, this traditional image-- and if one looks at the magnetic field within the tissue, one can see the different cortical layers inside the brain. We can look at the distribution of glutamate, which is the major excitatory neurotransmitter in the brain.

Notes

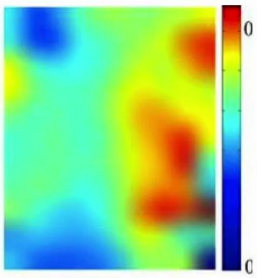
Summary

3m 04s

One magnet, many contrasts
Rat brain

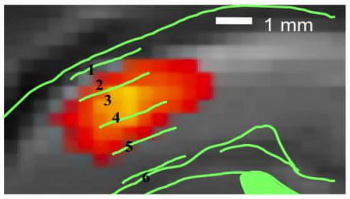


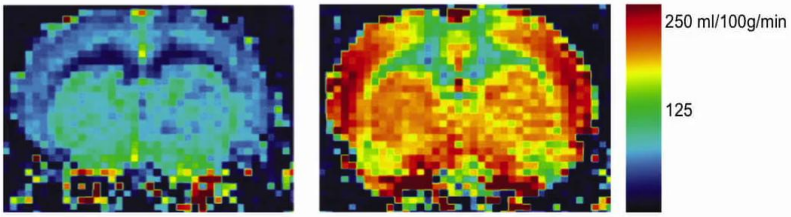
Phase imaging



Glutamate chemical shift imaging

Ca imaging using Mn-enhanced MRI





Cerebral blood flow using arterial spin labeling (rat, α-chloralose)

8-4

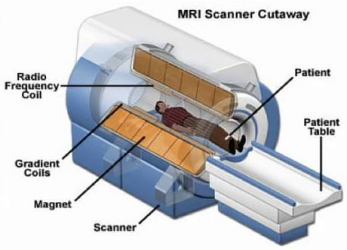
One can look at transport of calcium, by means of a tracer-- in this case it's manganese-- this is in response to activation, showing higher activity in cortical layer 3 and 4 upon a stimulation, upon a specific task. Or here, is finally an example of quantifying cerebral blood flow in the brain, using a technique called arterial spin labeling. of quantifying cerebral blood flow in the brain, using a technique called arterial spin labeling. This is in an animal anesthetized with α-chloralose. This is a normal animal, and this is an animal subjected to hypoglycemia, that is low blood sugars. So also here, not only in a human brain but also in the animal brain, we have many different contrasts that we can obtain, all with the same scanner and different depictions of what is going on, and these are just the examples for the brain-- this of course holds true for all the other organs as well.

Notes

Summary

4m 17s

8-1. What are the essential components of an MRI scanner ?



8-5

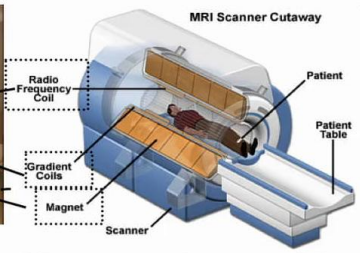
So then, what are the essential components of an MRI scanner? And I want to give out here a scheme that gives you an idea of what's inside an MRI scanner, and I will also highlight the aspects of the MRI scanner that we are going to deal with in this series of lectures. So here is a typical MRI scanner, again covered in a nice cover-- patients don't want to see the physics or the engineering-- and this is where you enter the magnet room as a patient; what you would typically see. and this is where you enter the magnet room as a patient; what you would typically see. So, what is inside the scanner? We have inside the scanner a magnet-- it's magnetic resonance, so there's a big magnet inside the scanner that's inside here. You are going inside the magnet. Inside the magnet we have gradient coils, RF coils, the patient table we can see here. This is the equivalent of this scanner for animal scans here; so we use this smaller opening-- as we've seen with all the other imaging techniques, when it comes to small animal imaging, rodent imagining, the dimensions of the scanner are being reduced, at least in terms of the hole.

Notes

Summary

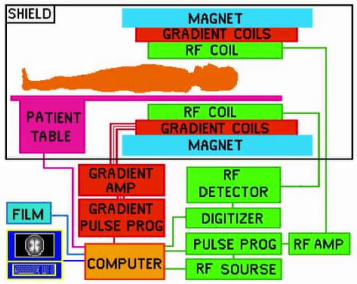
5m 22s

8-1. What are the essential components of an MRI scanner ?



It's a complex machine …

Cut-open in real life



Schematic depiction of all MRI components

8-5

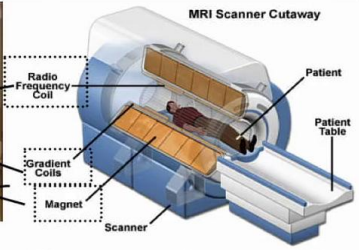
So, we have the magnet, which is here, and this is the magnet here; we have the gradient coils-- they are inside the cover, we will not see them as patients-- they would be here. And we have the radio frequency coil, which is this thing here, that pretty much looks like a bird cage laying flat, and it's actually called a *bird cage*. If we take a magnet, if we take the cover away, then we'll look at the open cut, then we can see quite a bit of engineering and physics behind this; a lot of copper, et cetera, that is the magnet when you cut it open. We don't see the magnet yet, we just see the insides, so that's the gradient coil system here. So, if we take the entire system, we plot it out, and we look at all the components, then we see lots of different components that are important in making a scanner operate and yes, it is a complex machine. However, we will not focus on *all* the aspects of what's involved in running an MRI scanner. We'll touch upon them where necessary to understand a few of the consequences, but we will not go into every detail. What we will focus on is the major elements of MRI, and that is the nucleus, we'll focus on the magnet, we'll focus on the RF coil, and we'll focus on the gradient coil.

Notes

Summary

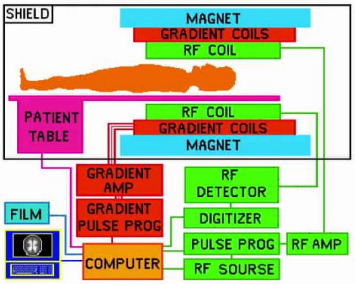
6m 32s

8-1. What are the essential components of an MRI scanner ?



Cut-open in real life

It's a complex machine …



Schematic depiction of all MRI components

This course focuses on the major elements of MRI :

- Nucleus
- Magnet
- RF coil
- Gradient coil

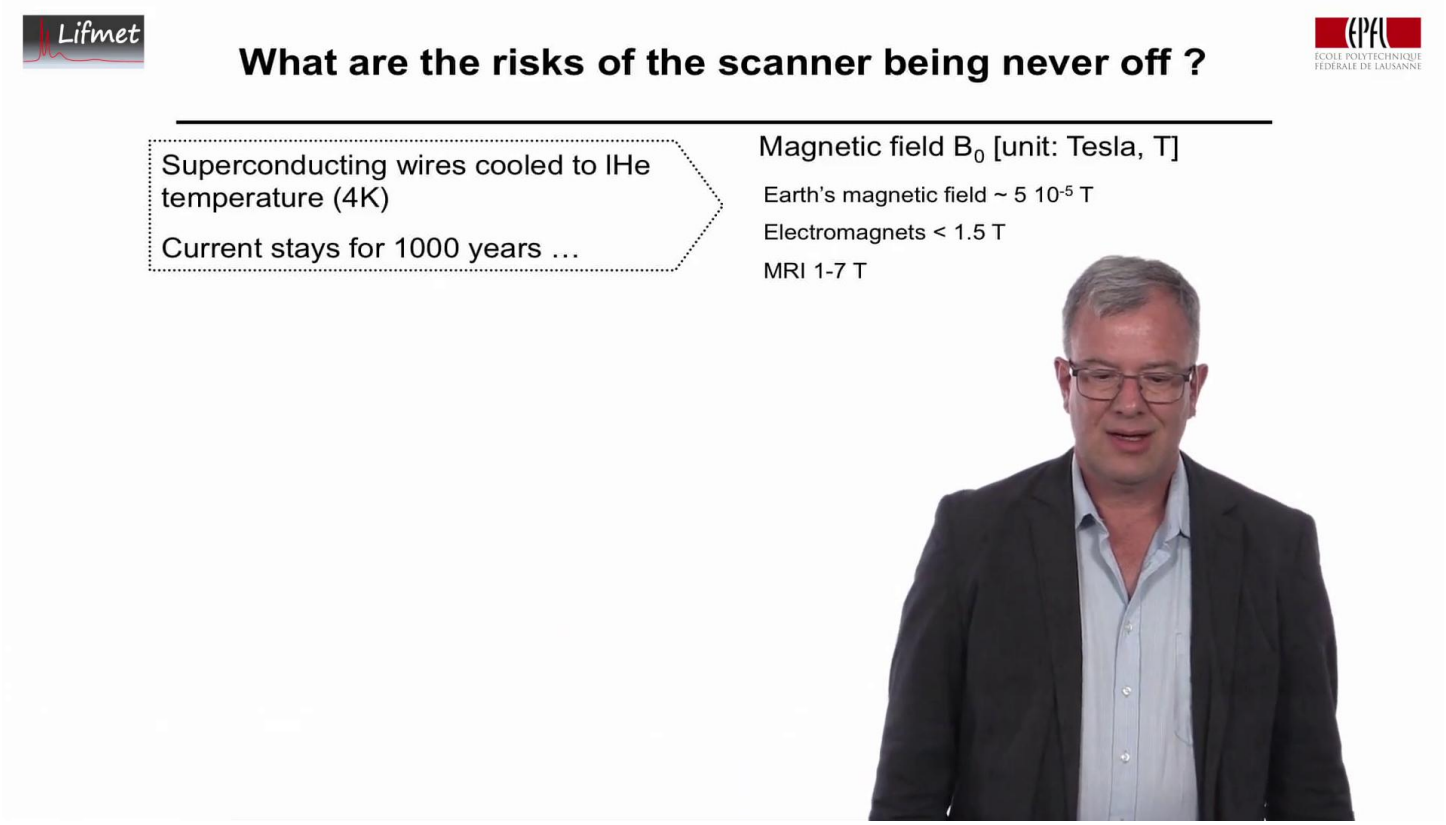
8-5

Those are the elements of this scanner. We will not focus on all the rest here, the addition, the important engineering, we'll not go into much detail for the purpose of understanding the fundamentals of MRI.

Notes

Summary

7m 59s



One thing with an MRI is it is a magnet, and that magnet is typically, in practice, always on. It is typically cooled by superconducting wires that are cooled to liquid helium temperature, so, 4 Kelvin; so it's cold inside there, and the current will stay in there for 1,000 years. As it is superconducting, the resistance of the wires is essentially zero, so the current will stay in there, and the magnet is never being off. So what are we looking at here-- what kind of magnetic field? [inaudible] the magnetic field generated by the MRI magnet. The unit here is *Tesla*. The Earth's magnetic field is roughly 5 times 10 to the minus five *Tesla*-- that's the magnetic field we're all constantly experiencing. Electromagnets-- so you take just the copper wire, winded like this, run a current through it-- you can produce such magnets, but they will have a limit of magnetic field strength that is for imagining purposes, typically below 1.5 *Tesla*. For MRI, what we are looking at is magnetic field strengths in the range of 1-7 *Tesla*. And this has a consequence: we have a powerful magnet, it is superconducting, so this powerful magnet is always on.

Notes

Summary

8m 18s

What are the risks of the scanner being never off ?

Superconducting wires cooled to lHe temperature (4K)

Current stays for 1000 years …

It's a powerful magnet …

Magnetic field B_0 [unit: Tesla, T]

Earth's magnetic field ~ 5 10^{-5} T

Electromagnets < 1.5 T

MRI 1-7 T

8-6

We cannot come into the room, and quickly turn it off-- unlike a CT scanner where we can turn off the X-ray tube and we won't have radioactivity being produced. [inaudible] spec scanner if we don't have traces in our bodies, we are not exposed to any radioactivity, but if you enter into a room with an MRI magnet you are entering a powerful magnet, and this requires some precautions that I want to illustrate now, that one has to be cautious around the magnet. You can't smell the magnetic field, you can't necessarily feel it, and so it can have some surprises in the observation, when being around the magnet without the necessary precautions, and that just explains why we are asking subjects, or visitors, that come close to the magnets, the take some extra precautions. So, let's look at this example here. In this video, what you are seeing is an aluminum block that's placed in front of the magnet on the patient bed. As the aluminum block is tipped over, it falls over. If you now look at the aluminum block placed inside the magnet, or close to the magnet-- so inside the magnetic field-- and as the aluminum block is tipped over, it falls very slowly.

Notes

Summary

9m 49s

What are the risks of the scanner being never off ?

Superconducting wires cooled to lHe temperature (4K)

Current stays for 1000 years …

It's a powerful magnet …

Magnetic field B_0 [unit: Tesla, T]

Earth's magnetic field ~ 5 10^{-5} T

Electromagnets < 1.5 T

MRI 1-7 T

8-6

What is happening here is that as the aluminum block falls, changes orientation, the magnetic flux in the aluminum changes, so we have Faraday's law of induction. So there are, because of the magnetic field, orientation across that block is changing, we have induced currents. These induced currents are producing themselves a magnetic field that counteracts the main magnetic field, and so, this produces a force that opposes the motion of the magnet. This principle is used in electromagnetic braking for example in the more modern hybrid cars, when we brake without using the physical contact, or in electrical trains. Here, in this example, what is being done here, is a tennis ball filled with nails-- nails are ferromagnetic, so they are attracted by the magnetic field-- and the person is letting go of the tennis ball filled with ferro magnetic nails, and it goes *tunk-tunk-tunk* into the scanner and then sticks to the side. What is happening here is the more critical effect-- that is, we have a ferromagnetic iron object that is exposed to a change in magnetic field, so if we have a difference in magnetic field across that object-- and therefore, it exerts a force on the object, and that object is being attracted such that it ultimately enters into the scanner.

Notes

Summary

11m 13s

What are the risks of the scanner being never off ?

Superconducting wires cooled to lHe temperature (4K)

Current stays for 1000 years …

It's a powerful magnet …

Magnetic field B_0 [unit: Tesla, T]

Earth's magnetic field ~ 5 10^{-5} T

Electromagnets < 1.5 T

MRI 1-7 T

8-6

The next example is a video surveillance camera of a friend of mine, who posted it on his YouTube channel. So you see the two gentlemen here were asked to enter the magnet room and put up a support structure, a frame, for putting some shelves, so one can put blankets and cushions, et cetera, into the room. Notice the one person who has in his hands a battery-operated drill. So they obviously want to do some drilling on this structure, or tightening some screws. As we are watching this video, you might notice at a certain time point that he is now without the drill, and as you are observing the two gentlemen they are now looking inside the magnet. So, what has happened? The drill has, most likely, some ferromagnetic components to it-- or at least the battery, batteries are typically ferromagnetic-- and as he was moving around in the room, he wasn't paying attention to the magnet that is in the back of the room, and as he got too close to the magnet, the magnetic field attracted the drill; he could no longer hold onto it, and it flew inside the magnet. In this case, there was nothing of major consequence happening-- the drill was removed and aside from the scare, nothing happened.

Notes

Summary

12m 55s

However, in the context of medical application, this is a far more serious issue. And here is an illustration of an experiment showing the same effect, with a gas bottle, just an ordinary gas bottle, oxygen bottle, you have lots of oxygen bottles in the hospital. They are placing this bottle on the patient bed, and as you can see, on the patient bed, instead of putting a patient they are putting a watermelon as our subject inside the RF coil, where the head would be. The experiment that was here done, is to illustrate what happens if a magnetic object is being put too close to the magnet, when it starts to get attracted by the magnet, what then happens. Obviously, when it gets closer, as we've seen with the drill, or the nail-filled ball, as it gets close to the magnet, the difference in magnetic field creates a net force on the object. And the force as we see in this demonstration, accelerates this gas bottle, it accelerates it towards the watermelon. It has an impact on the watermelon, and the watermelon is being crushed. We see this at the end of the video, where they go to the back of the magnet and they show how much this watermelon has been crushed.

Notes

Summary

14m 37s

What are the risks of the scanner being never off ?

Superconducting wires cooled to lHe temperature (4K)

Current stays for 1000 years …

It's a powerful magnet …

Magnetic field B_0 [unit: Tesla, T]

Earth's magnetic field ~ 5 10^{-5} T

Electromagnets < 1.5 T

MRI 1-7 T

8-6

So, extreme caution is necessary with ferromagnetic objects, and this is particularly difficult in the medical context. This happened in the beginning of this millennium in the state of New York; that a subject, a cancer patient, for control purposes was being scanned. A nurse heard the word "oxygen bottle," went to the hallway, grabbed the oxygen bottle, walked with the oxygen bottle into the room; the oxygen bottle got attracted, and unfortunately, for the subject ..the subject was still in the magnet-- that created, of course, an unfortunate death of this subject. The difficulty here is, as medical professionals are trained to react in emergency situations, they are not all trained to work and live around the magnet, and so, the first response is to help the patient, and so, yes, you grab the oxygen bottle, you run into the room, and the oxygen bottle is being attracted; that's the situation here. It requires specific measures; the measures are to take off all magnetic things that we carry on ourselves, and in the case of a medical emergency, in an MRI scanner-- what one would do is actually, the first reaction, is to take the subject out of the magnet and out of the magnet room, and then only start coming in with medical equipment.

Notes

Summary

16m 21s

CPR is obviously fine, but one has to be extremely vigilant because we do not feel, we do not smell, we do not see the magnetic field. So, to give you an illustration, here's an example of a magnet, with a chair attached to it. This chair has obviously a lot of ferromagnetic material and you can see the quite considerable effort that it takes to remove that chair; it's a chair with wheels on it, so it somehow got too close to the magnet, was suddenly attracted, and *bang!* it went into the magnet. And you can appreciate from the effort that's being done how strong these forces are on the chair. And obviously, once one is away where the magnetic field doesn't vary a lot, then this force is substantially being reduced and we have less to consider. It really is a matter of the vicinity of the magnet, where the magnetic field changes very strongly. So this is a danger of MRI scanners. It's not a biological risk, it's a danger; it's just like walking up and down the stairs-- if you don't pay attention, you can fall and break your neck. Here we have to be around the magnet, we have to be cautious, making sure that ferromagnetic objects stay far away from our subject and from the scanner, and then, we are OK.

Notes

Summary

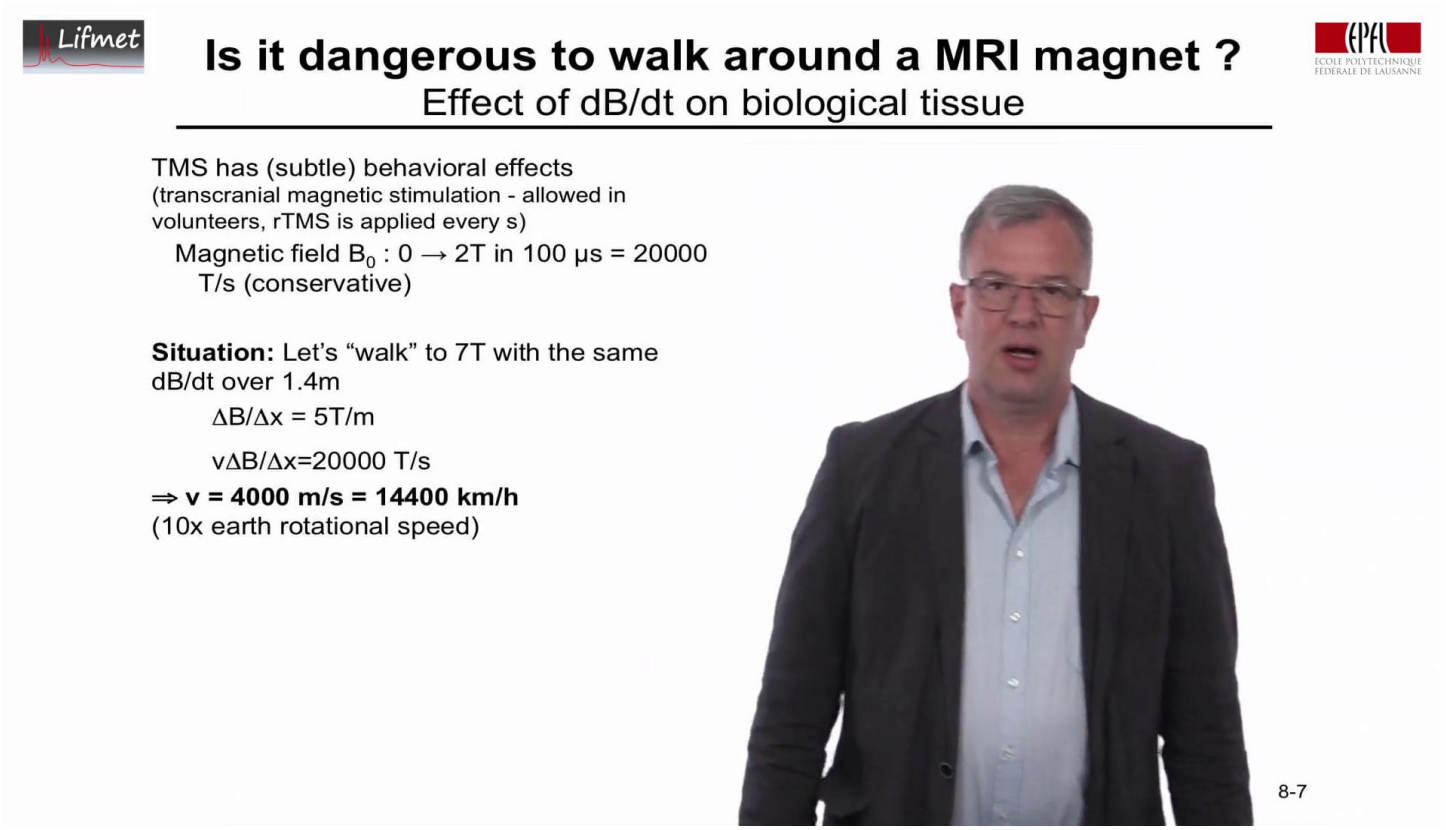
17m 59s

Another issue that I want to address is of some historical interest, especially with the perspective of Europe. But the question is-- let's say we forget about ferromagnetic objects and we're just ourselves walking around the magnet. The question is what kind of exposures of magnetic field changes can we subject ourselves to? I want to make here the example, by comparison, comparing the effects that we see with transcranial magnetic stimulation. Transcranial magnetic stimulation is a technique used in neuroscience to investigate the functioning of certain brain areas. It is allowed in healthy volunteers and these policies are applied quite frequently. I want to relate what we are-- if we move around the magnet, what this means in relation to TMS. Here's a TMS scanner; here's the coil that produces the magnetic field; the subject here. What is being done is one produces a magnetic field, *B_zero*, with this coil that goes from zero to two *Tesla* in roughly 100 microseconds. If we take a conservative estimate, this amounts to 20,000 *Tesla* per second change in magnetic field, dB/dt.

Notes

Summary

19m 31s

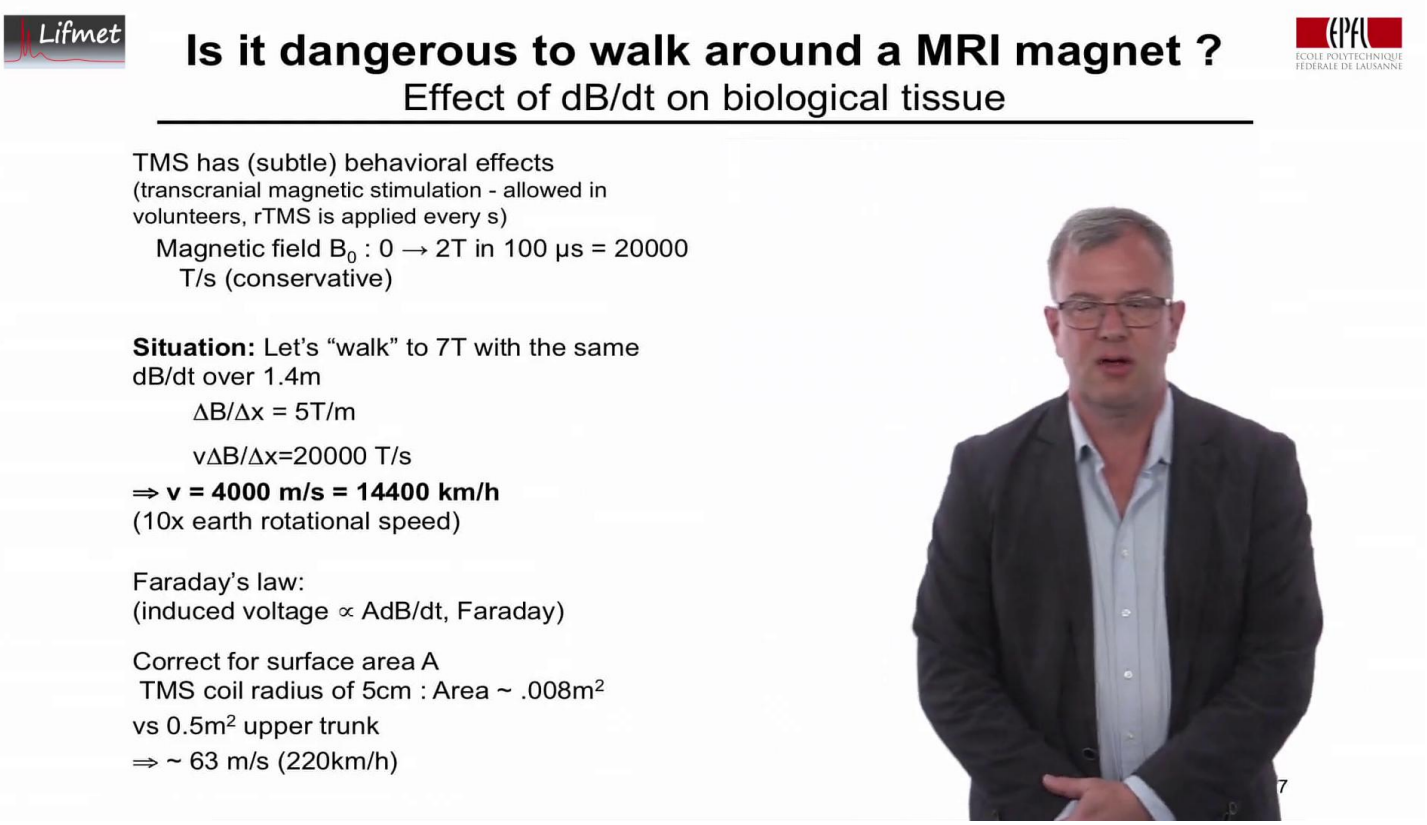


What I want to do with this calculation, just to give you an idea, to produce a similar change in magnetic field, how fast would we have to walk to a 7 *Tesla* scanner over a distance of 1.4.meters? We'll assume we go over 1.4 meters from zero to seven *Tesla*, and we want to expose ourselves to the same change of magnetic field per time. So we have a change in magnetic field per distance, which is 5 *Tesla* per meter, we have 7 divided by 1.4, so this gives us 5 *Teslas* per meter. We want to now have a change in magnetic field per time-- so that's velocity over distance-- that gives us per time times the change in magnetic field. We want this to be 20,000 *Tesla* per second. We can solve this, so we can calculate what velocity would we need to produce a magnetic field change of 20,000 *Tesla* per second. The calculation here, as you can easily verify, produces a velocity of 4,000 meters per second, or 14,000 kilometers per hour. This is essentially, ten times the Earth's rotational speed. That's a tremendous velocity. This is is very crude, and is, by no means, meant to be correct, but let's go a little bit into finer details.

Notes

Summary

21m 03s



And we'll look at Faraday's law in more detail. We have Faraday's law, which says the induced voltage is equal to the area times the change in magnetic field per time. So we're obviously having-- with the transcranial magnetic stimulation-- we're not having the same area exposed to the magnetic field as we have with our body, as we run towards the magnet, so we'll correct for the surface area. The TMS coil with a radius of 5 cm, we can calculate an area of.008 m2. We'll estimate that the upper trunk is roughly half a square meter of surface area-- we'll correct that; and then we are getting, from correcting for the fact that our area is bigger than the area of the TMS coil, to have the same induced voltage in our body, we are obtaining a velocity of 63 meters per second, or 220 kilometers per hour. So, if we run towards the magnet, and we go from zero to seven *Tesla* over a distance of 1.4 meters, we are going to be exposed in the upper trunk to voltages that correspond to those that we are exposed to in the brain with TMS at 220 kilometers per hour.

Notes

Summary

22m 31s

Is it dangerous to walk around a MRI magnet ?

Effect of dB/dt on biological tissue

TMS has (subtle) behavioral effects
(transcranial magnetic stimulation - allowed in volunteers, rTMS is applied every s)

Magnetic field B_0 : 0 → 2T in 100 µs = 20000 T/s (conservative)

Situation: Let's "walk" to 7T with the same dB/dt over 1.4m

$\Delta B/\Delta x = 5T/m$

$v\Delta B/\Delta x = 20000$ T/s

⇒ **v = 4000 m/s = 14400 km/h**
(10x earth rotational speed)

Faraday's law:
(induced voltage ∝ AdB/dt, Faraday)

Correct for surface area A
TMS coil radius of 5cm : Area ~ .008m²
vs 0.5m² upper trunk
⇒ ~ 63 m/s (220km/h)

Most B_0 is within the bore of the magnet
Don't start at 0 T, don't end at 7 T…
distance ~ 7m …
Max. equivalent speed can be several-fold higher …

8-7

What we have to consider is for most modern magnets most of the static magnetic field is actually within the bore of the magnet-- that is, within the structure-- so we actually, if we are on the outside, we can't even expose ourselves to the full 7 *Tesla*. That also means that most of the changes happening in there, we don't start at zero *Tesla*, we don't end at 7 *Tesla*. We have also the fact that the distance is more like 7 meters over which we approach the magnet, and not 1.4 meters. So, if we actually wanted to expose ourselves to the same effect around a magnetic field, then the equivalent speed to produce the same voltages as we have with TMS would be several-fold higher than 220 kilometers per hour. And, let's be honest, in reality, our speed is going to be already two orders of magnitude lower than what is here. So it is my opinion here that the considerations about motion around a static magnetic field-- around an MRI scanner-- are so low, the induced voltages are well beyond any concern that we should have and are having.

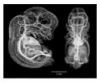
Notes

Summary

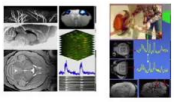
23m 55s

Credits (1/2)

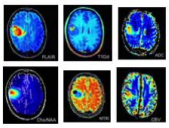
Mouse Imaging Centre
http://www.mouseimaging.ca/gallery/gallery_mri_mouse.html



Brad Smith
http://www-personal.umich.edu/~brdsmith/CreativeWork/Medical_Imaging/MouseVasc.html



ETH Zurich
http://www.nccr-neuro.uzh.ch/centers/c4



CNS Onco-radiology, Dr. Nasir Khan
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Functional MRI of calcium-dependent synaptic activity
Duong et al., Magn. Reson. Med. 2000; 43: 383

High-Field MR Imaging
Marques et al., Neuroimage 2009; 46: 345

Magnetic Resonance Spectroscopy
Mlynarik et al., Magn. Reson. Med. 2008; 59: 52

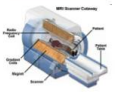
Notes

Summary

25m 18s

Credits (2/2)

The Moebius Project
http://www.jaynejubb.com/moebius/inhoud.html



National High Magnetic Field Laboratory
https://nationalmaglab.org/education/magnet-academy/learn-the-basics/stories/mri-a-guided-tour

MRI scan
https://tomographyblog.com/2008/01/

MRI Today
http://123mri-today.4t.com/about.html

MRI magic
https://youtu.be/fxC-AEC0ROk

Dangers of MRI
https://youtu.be/plvlEf7JsKo

How strong is an MRI magnet?
https://youtu.be/V9UJ6JAeVuE

Chair gets stuck in an MRI machine
https://youtu.be/4uzJPpC4Wuk

Drill being pulled into MRI scanner
https://youtu.be/-5S9jmr9-7w

NeuroStar TMS Therapy Treatment
https://youtu.be/G313g2FNyMg

Notes

Summary

25m 23s