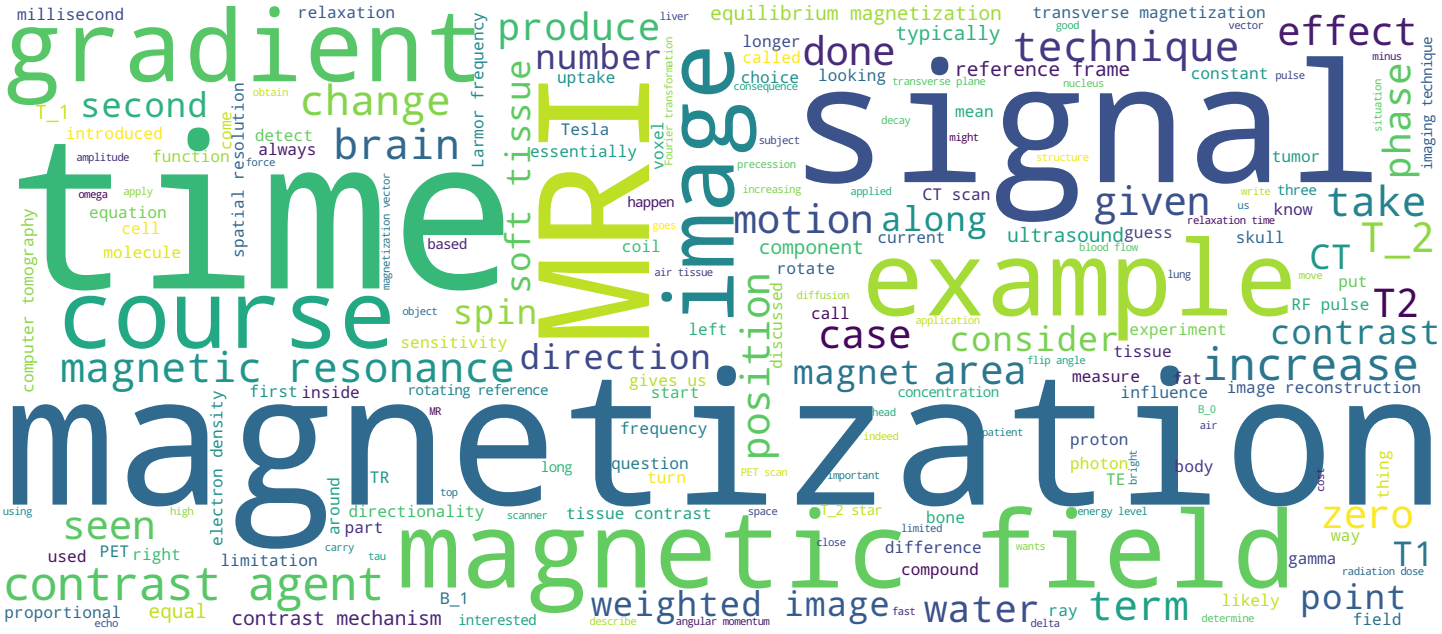
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

13.4 Overview and comparison of imaging modalities

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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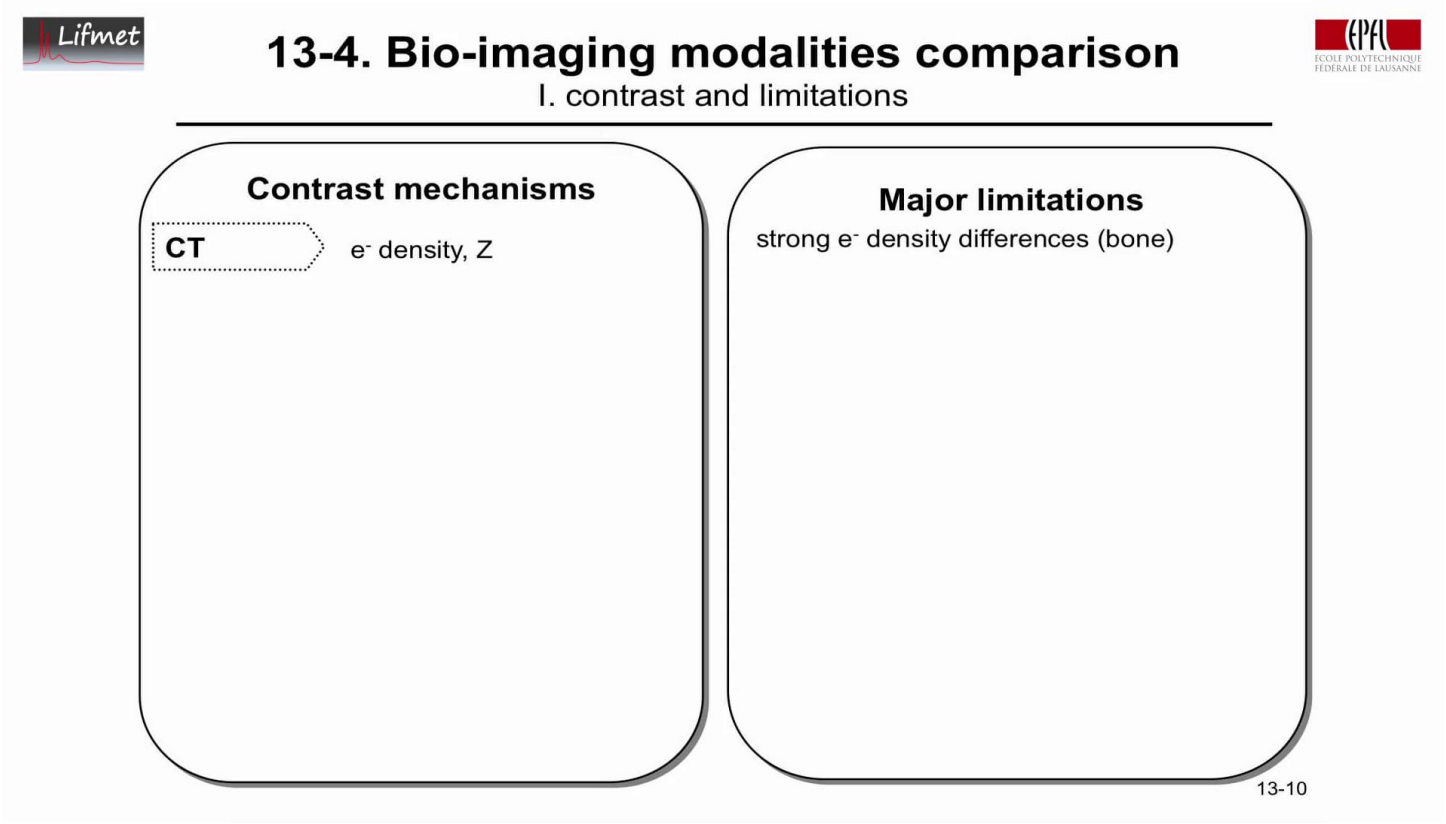
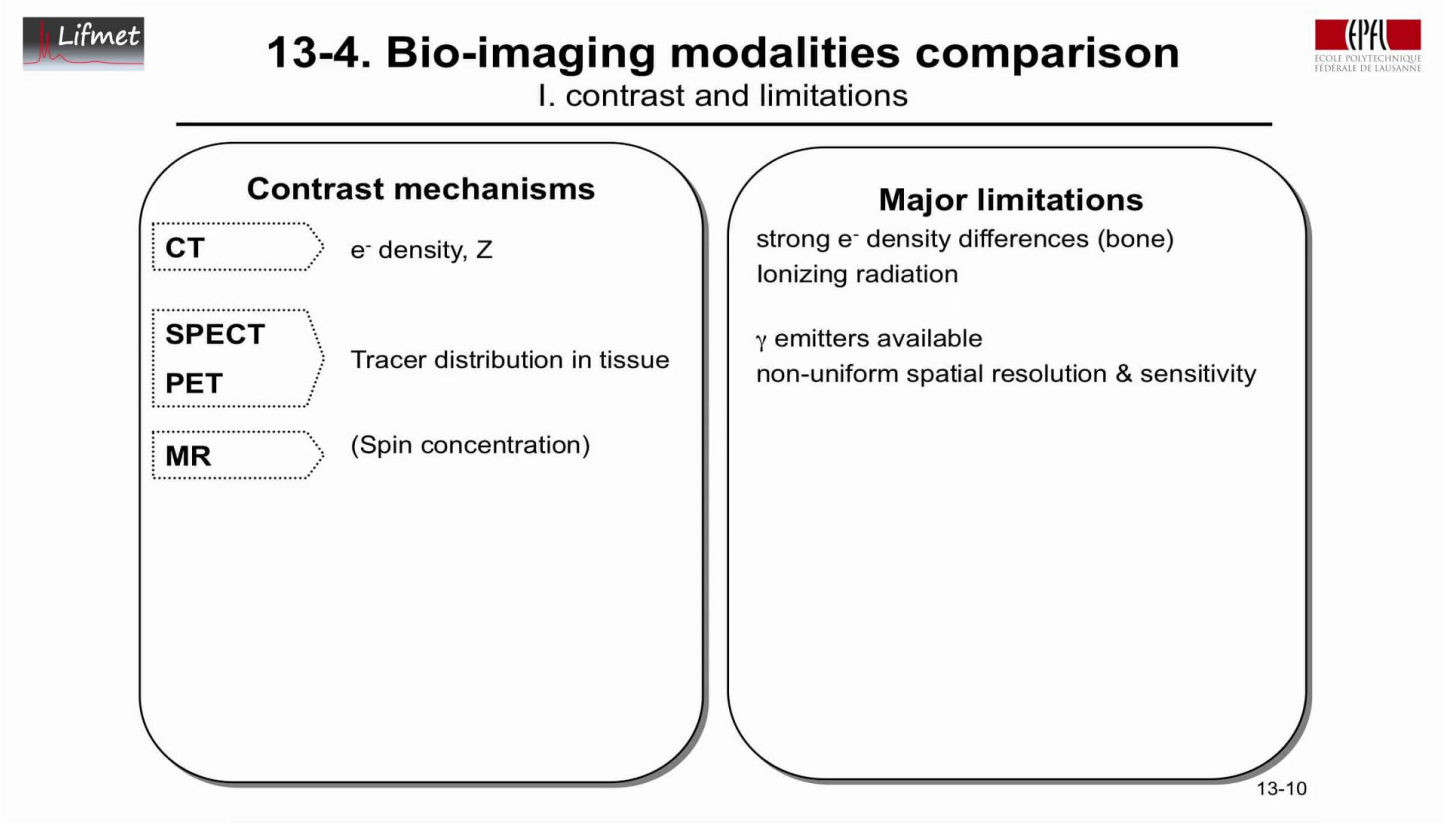


In this section I'd like to do a comparison of the bio-imaging modalities that we have treated in this course, both Part 1 and Part 2, put them in juxtaposition, so we have an easy overview of which imaging modality can do what. Now, there's a question that one always has: what is the best imaging modality? Did you guess it? Well, you might know that we are doing a lot of magnetic resonance imaging, so you might expect that the politically correct answer is MRI. Well, that is wrong. There is no such thing as a perfect imaging modality. And what's really important here is each one of them has its strengths and weaknesses, has its domains of application, and therefore is best used for certain applications. So I want to first discuss here, the contrast mechanisms and limitations. So on the left we'll have the contrast mechanisms, and on the right the major limitations for each of the techniques. Computer tomography, or X-ray, primarily has as its contrast mechanism, the electron density and the effective atomic number *Z*. What are its limitations? It is essentially limited to strong electron density differences-- so it's bone tissue or air tissue interfaces, where we have strong electron density variations.

Notes

Summary

0m 03s

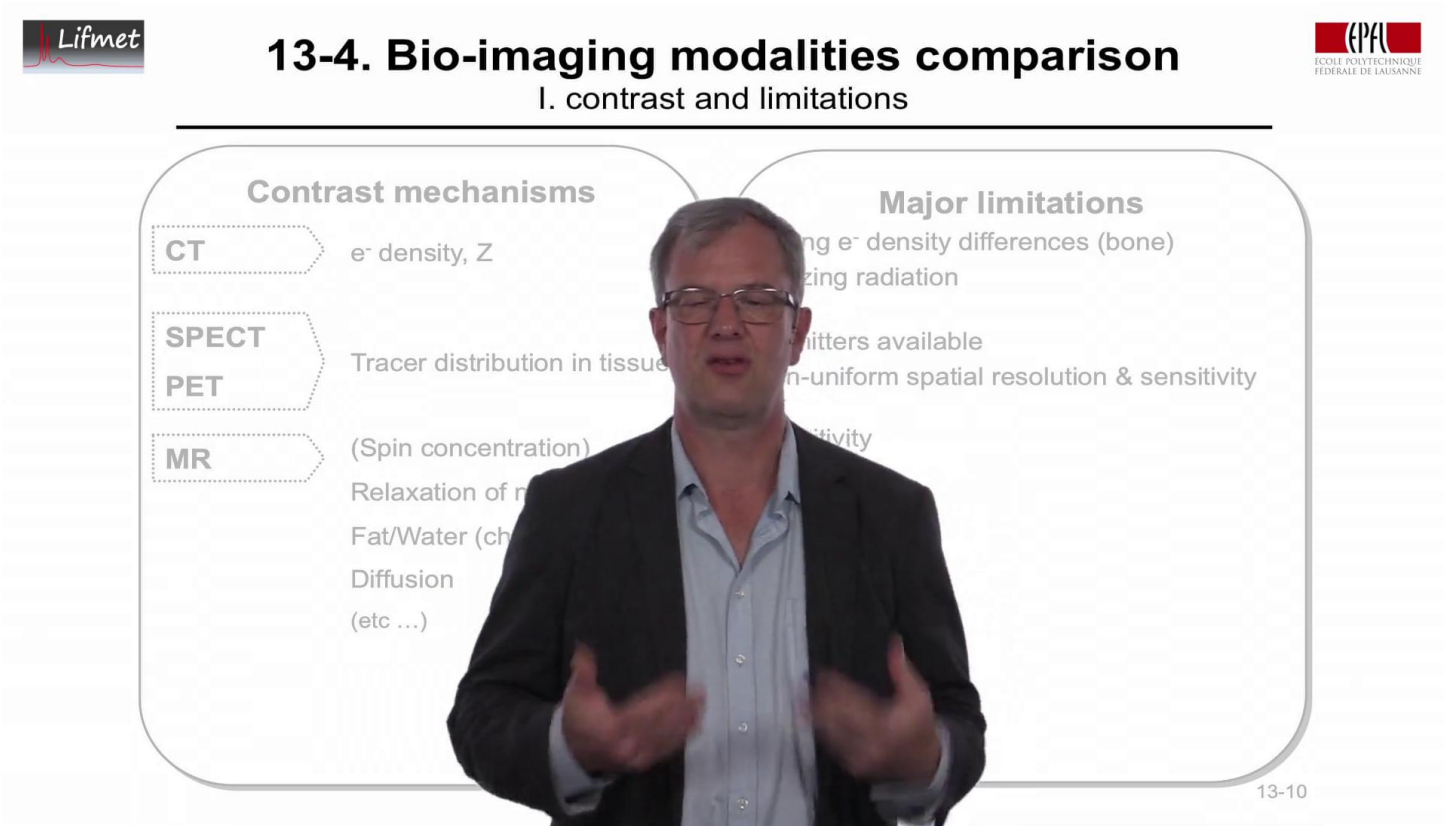


The other limitation is that it uses ionizing radiation. If we look at the emission computer tomography techniques-- SPECT, single-photon emitters, and PET, positron emitters-- the contrast mechanism here is the distribution of the exogenously-administered tracer in the tissue. So we administer a radioactive substance, a decaying substance, measure its radioactivity, measure that distribution of the radioactivity, in the tissue. These techniques are limited to the γ emitters that are available, and, in general, they don't have uniform spatial resolution and/or sensitivity; we have seen the impact of collimation on the spatial resolution for SPECT; we have also seen the impact of the scintillation crystal dimensions on spatial resolution of PET, and that sensitivity is not necessarily uniform either. How about magnetic resonance? Magnetic resonance is, the signal is proportional to equilibrium magnetization, so, in essence, physically it measures the spin concentration. I'm not putting it here as a contrast mechanism *fully*; it's in parenthesis because there is not a lot of contrast from the spin concentration-- that is, the concentration of water in tissue, per se.

Notes

Summary

1m 42s

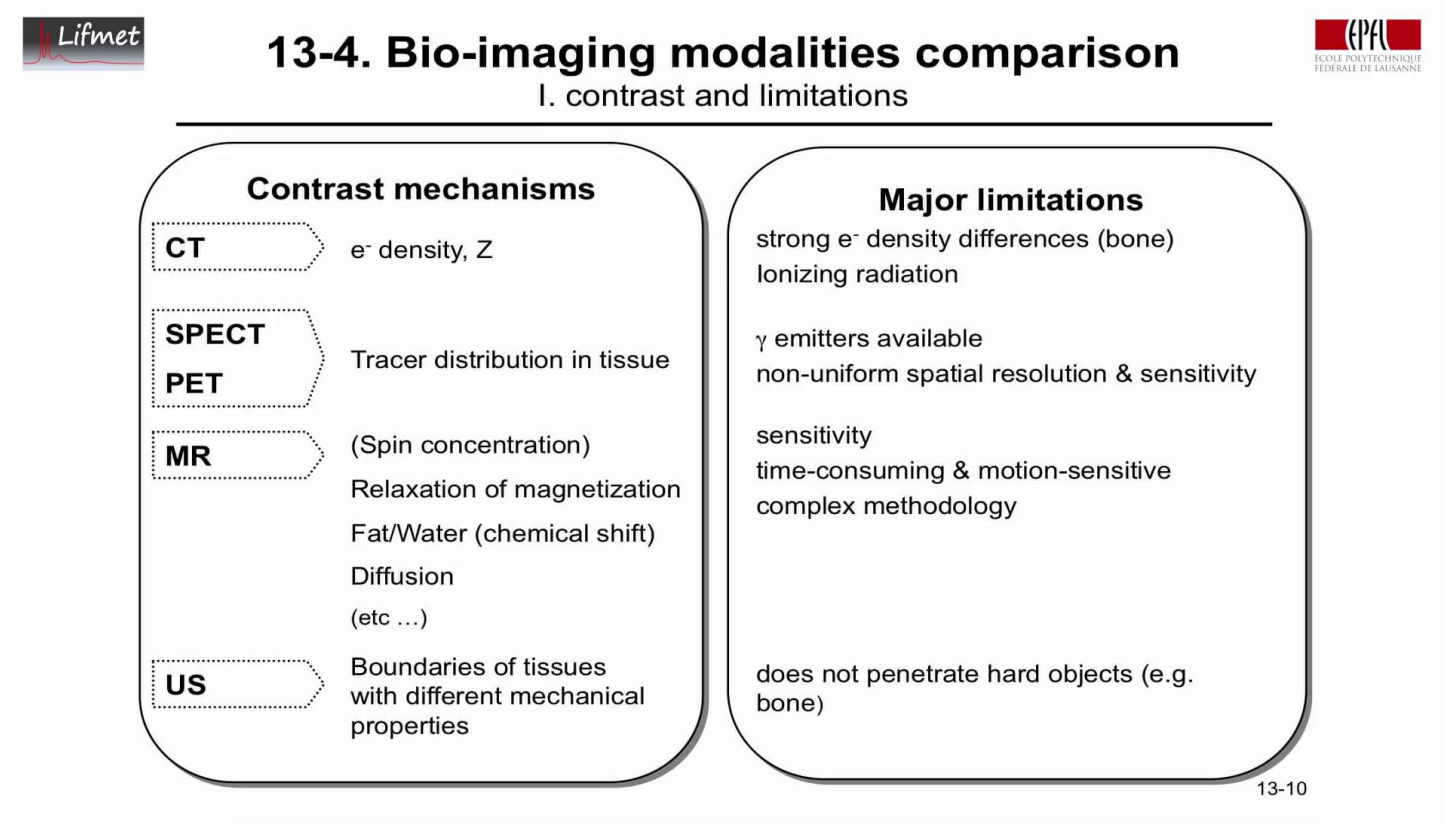


The major mechanism that we have discussed and that is being used are the relaxation processes-- the relaxation of magnetization is the major mechanism that produces contrast. We have also seen that with spectroscopy one can distinguish the chemical environment of the hydrogen nucleus in the tissue, and for MRI, the major application here is to distinguish whether the signal that one observes is due to fat or water, based on the chemical shift. We have also--that is this week--discussed the effect of motion and diffusion. So these are the major contrast mechanisms that we have discussed in this course. But I'll put *etc*. here-- there are, of course, many more contrast mechanisms for MRI that we have not discussed in this course. We have stuck here to some of the main features of mechanisms that contribute to contrast. There are, of course, many more that can be exploited in MRI. The limitation of magnetic resonance is its sensitivity. While we can imagine imaging a few picomolar of positron emitters in the body, a few picomolar of spins is not going to give us a measurable signal; we're stuck here with a low-sensitivity technique. This is compensated by using the signal of water with the Boltzmann distribution.

Notes

Summary

3m 03s



This gives, however, then, again, a strong signal. The other part is, the measurement is time-consuming and motion-sensitive. It typically, for an image, takes a few minutes. It's very motion-sensitive-- compare this with CT where the image can be obtained in a few seconds. And another limitation is, it is of course, a complex methodology. We have so many different mechanisms that contribute to contrast-- that means we have so many different ways of manipulating the magnetization-- that this results, in the end, in a complex methodology that needs to be carefully mastered and controlled to produce reproducible results. Lastly, the ultrasound technique, which we introduced at the beginning of Module 1 of this course, it detects the boundaries between two tissues with different mechanical properties from the acoustic impedance. That is determining the creation of an echo. The down-side is that ultrasound does not penetrate hard objects-- so, not through bone. If you want to do an ultrasound of the brain, it is not easily done in adults. It is done in newborns where the skull is still open, this bone has not closed yet. Someone can put the transducer here on the top of the head and obtain an ultrasound of the brain in newborn babies.

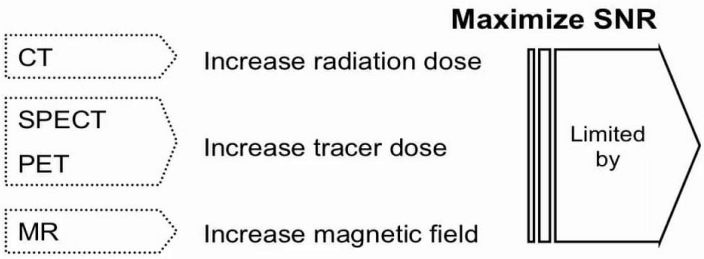
Notes

Summary

4m 38s

Comparison II

SNR, reconstruction, contrast agents



13-11

So, I want to continue with the comparison of the techniques here and first address the question, how do we maximize sensitivity? For computer tomography, this is actually relatively simply done-- we increase the radiation dose; we bombard the organ with more photons then we increase the sensitivity there. So we increase the radiation dose; practically, this is done by increasing the filament current and voltage. For the techniques SPECT and PET, we can increase the tracer dose-- so this will increase the number of radiotracers in the tissue and therefore increase the number of events, the photons, that one can detect. And, finally, for magnetic resonance, we can increase one parameter and that's the magnetic field. Remember, the sensitivity for magnetic resonance is determined by the equilibrium magnetization-- that's the strongest signal one can get-- and that is proportional to the magnetic field; that is the major factor with which one can experimentally increase the sensitivity. So, what are these increases limited by? In CT, essentially nothing, except for, in human application, the radiation dose-- we cannot just bombard our patient with unlimited amounts of radiation.

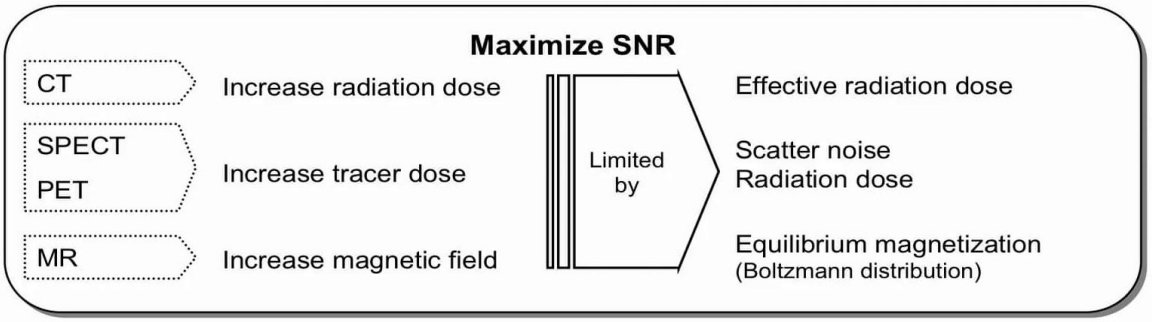
Notes

Summary

6m 11s

Comparison II

SNR, reconstruction, contrast agents



13-11

Same holds true for the emission computer tomography techniques like SPECT and PET; however, there is another effect-- even if you stay within the limits, as you increase the number of decays in the body, the probability of scattering increases and therefore the probability of random events increases, and therefore, the dose is limited by these kind of events; we have only a finite coincidence interval for PET, it cannot go for infinitely short coincidence intervals, and at some point the randoms and the scatter will take over the gains in sensitivity from increasing the tracer dose, and it goes down. So there is a optimum sensitivity that one can get. And magnetization? For MR, it is limited by the equilibrium magnetization due through the Boltzmann distribution. Those are the limits there. Now, we have to think of the cost or the implications of this: increase in radiation dose: increase in the filament current. That is just dialing up the current on the filament, so it's heating the filament more. Increasing the tracer dose is more expensive; we inject more molecules, [inaudible] have to synthesize more. Increase in the magnetic field--it's not just increasing the current in the magnet, it is actually building a new magnet, and this is very costly and not easily done. So it is a trend of our time that we go to higher and higher fields.

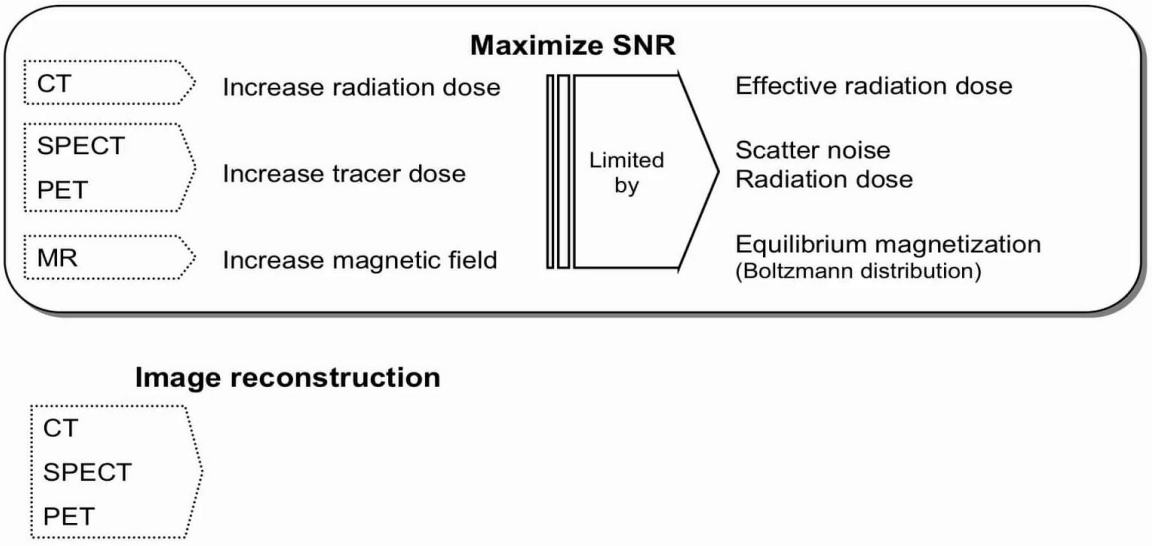
Notes

Summary

7m 41s

Comparison II

SNR, reconstruction, contrast agents



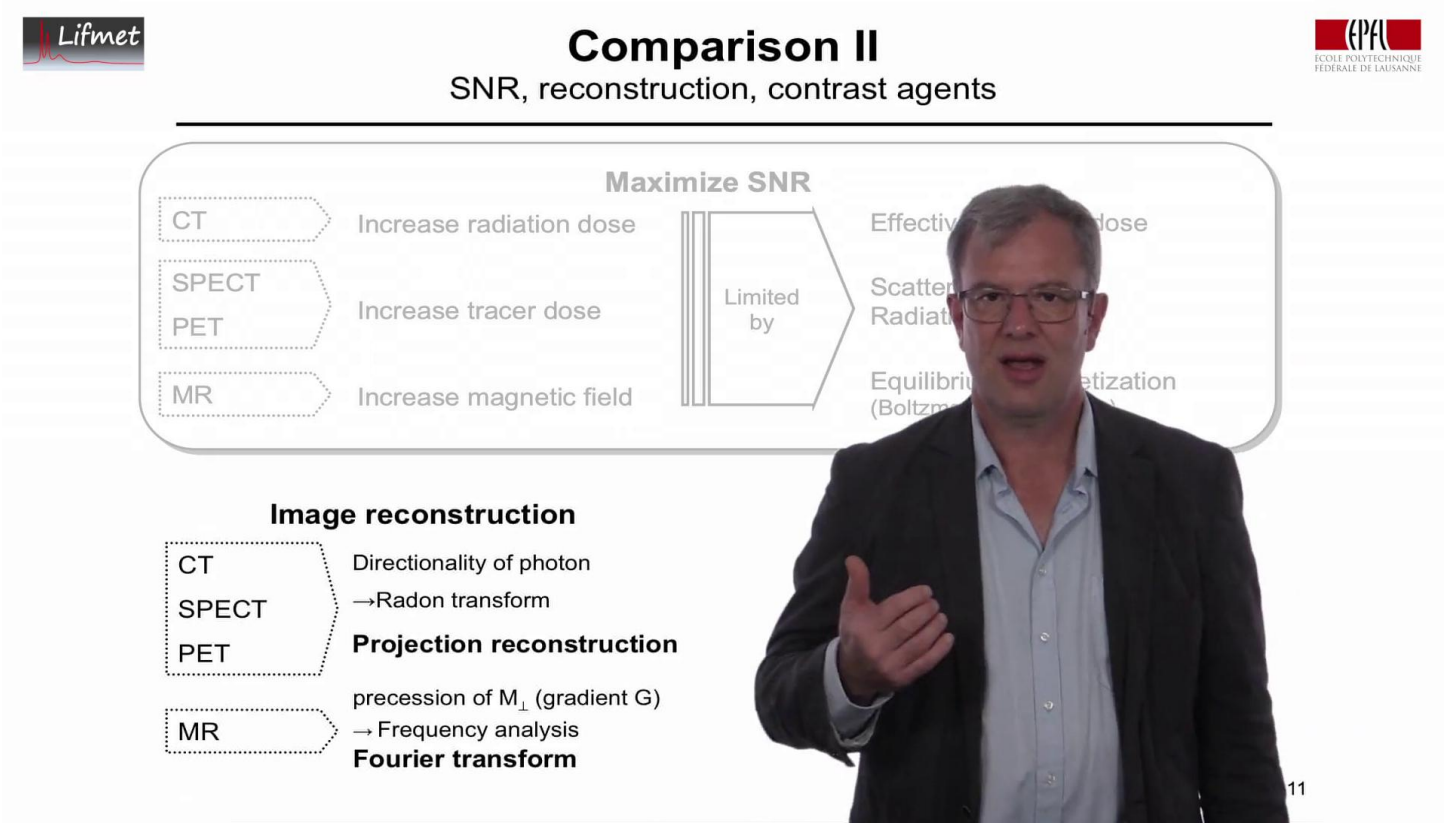
13-11

Now, what about the cost of these techniques? We had ultrasound, which is not on this list here because I excluded it; ultrasound is the cheapest modality of the modalities discussed. Then it's CT. Then comes SPECT for instrumentation purposes. The next more expensive technique is PET, if one neglects the cost of producing the isotopes. If you include the radiochemistry unit, that produces the isotopes on site, then you have to think of a cyclotron that you have to buy and maintain and a team of radiochemists-- that makes the cost different. If you can buy it from elsewhere then the scanner itself is a bit more expensive than the SPECT scanner. And, finally, MRIs are the most expensive instruments to buy. There the price increases with magnetic field. We have high-end academic or clinical MRIs at 3 Tesla, and some scanners now are available for human experimentation at 7 Tesla. So the cost goes-- as we have introduced the techniques in the course, the cost has increased. So, image reconstruction-- I want to look at how image reconstruction is done, summarize that. For CT, SPECT and PET, the image reconstruction depends crucially on knowing the directionality of the photon.

Notes

Summary

9m 20s

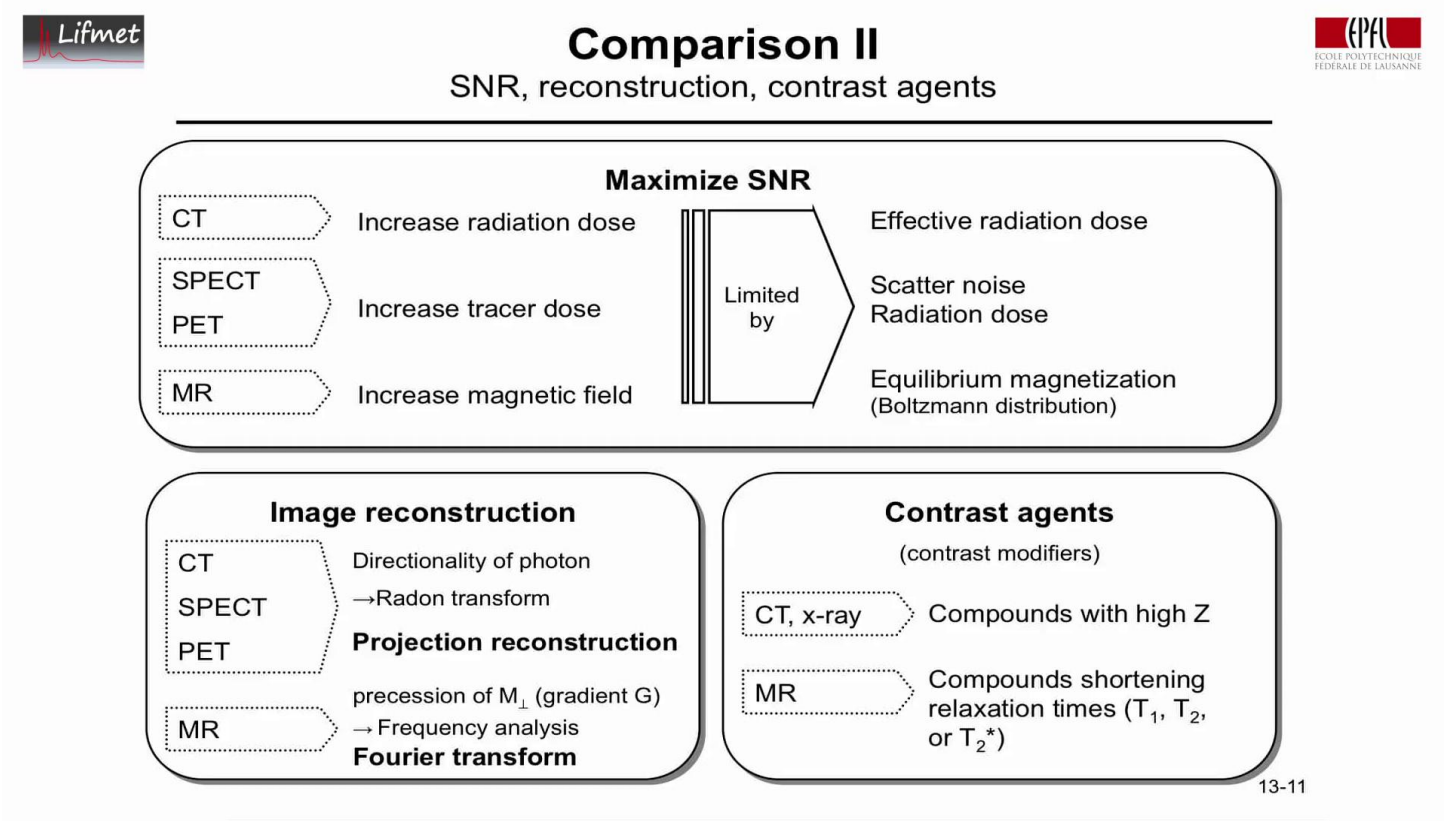


In CT it's done by the emission of the photon and the detection, this gives a line; together with an anti-scatter grid, this gives us the directionality of the photon--there it's defined. For SPECT we do collimation-- this defines the directionality of the photon. And for PET we have coincidence detection; from the simultaneity of events, the directionality of the photons are established. And we have seen, once we have the directionality of the detection process, of the photons, we can write the signal that is being measured in the form of a Radon transform, and once we have a Radon transform, we can use projection reconstruction to reconstruct the image. So for these techniques, projection reconstruction is a major method of image reconstruction. For magnetic resonance, the image reconstruction is based on a different mechanism, it's based on the precession of the transverse magnetization, under the influence of a gradient. So the precession frequency depends on position, and one does a frequency analysis of the signal that's being registered. A frequency analysis of the signal being registered basically means we're doing a Fourier transform.

Notes

Summary

10m 53s

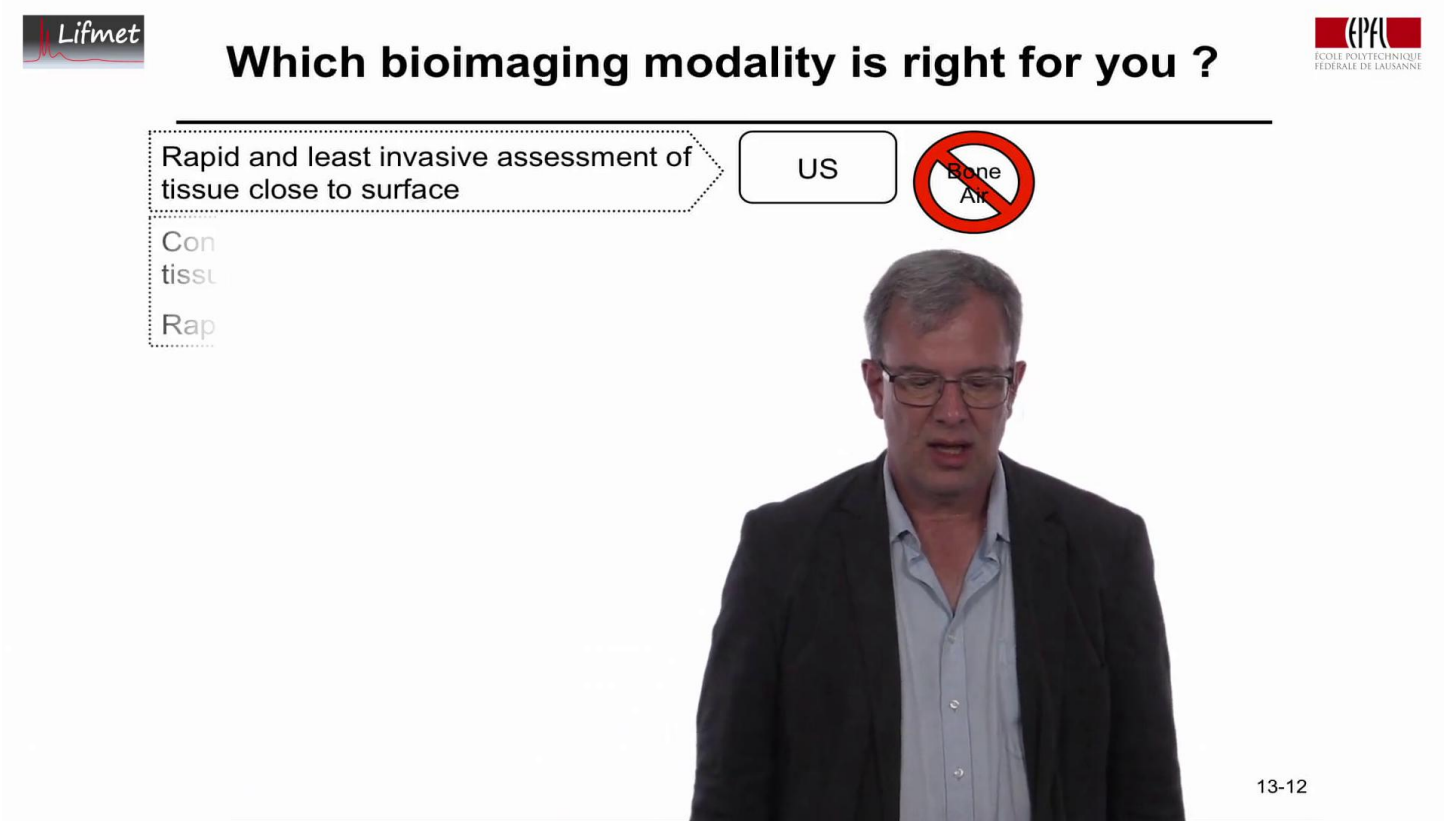


So while we have, for the X-ray techniques, projection reconstruction as the preferred image reconstruction approach, for magnetic resonance we have Fourier transformation which is the widely used gold standard in this technique. Finally, a word on contrast agents. As a reminder, contrast agents are substances that are injected into the body that change the contrast of the image modality. We've had, in CT and X-ray, the contrast agents are typically compounds with high *Z*. We have seen the example in Lecture 3 that just a few millimolar of a high *Z* component can produce a strong change in the linear attenuation coefficient. Most compounds that are used are iodine-based for CT, but we've also had the example of gadolinium. And, for magnetic resonance, the contrast agents are compounds that shorten the relaxation times, be it *T_1*, *T_2*, or *T_2 star*. There is no contrast agent that can prolong the relaxation time. The contrast agents in MR are typically lanthonides like gadolinium, they are molecules that are paramagnetic, they have unpaired electrons in the atoms. These unpaired electrons carry a magnetic spin, so they increase the fluctuation of the magnetic field and therefore, they can only do so by shortening the relaxation times. So these are the major contrast agents that we have discussed in this course.

Notes

Summary

12m 09s

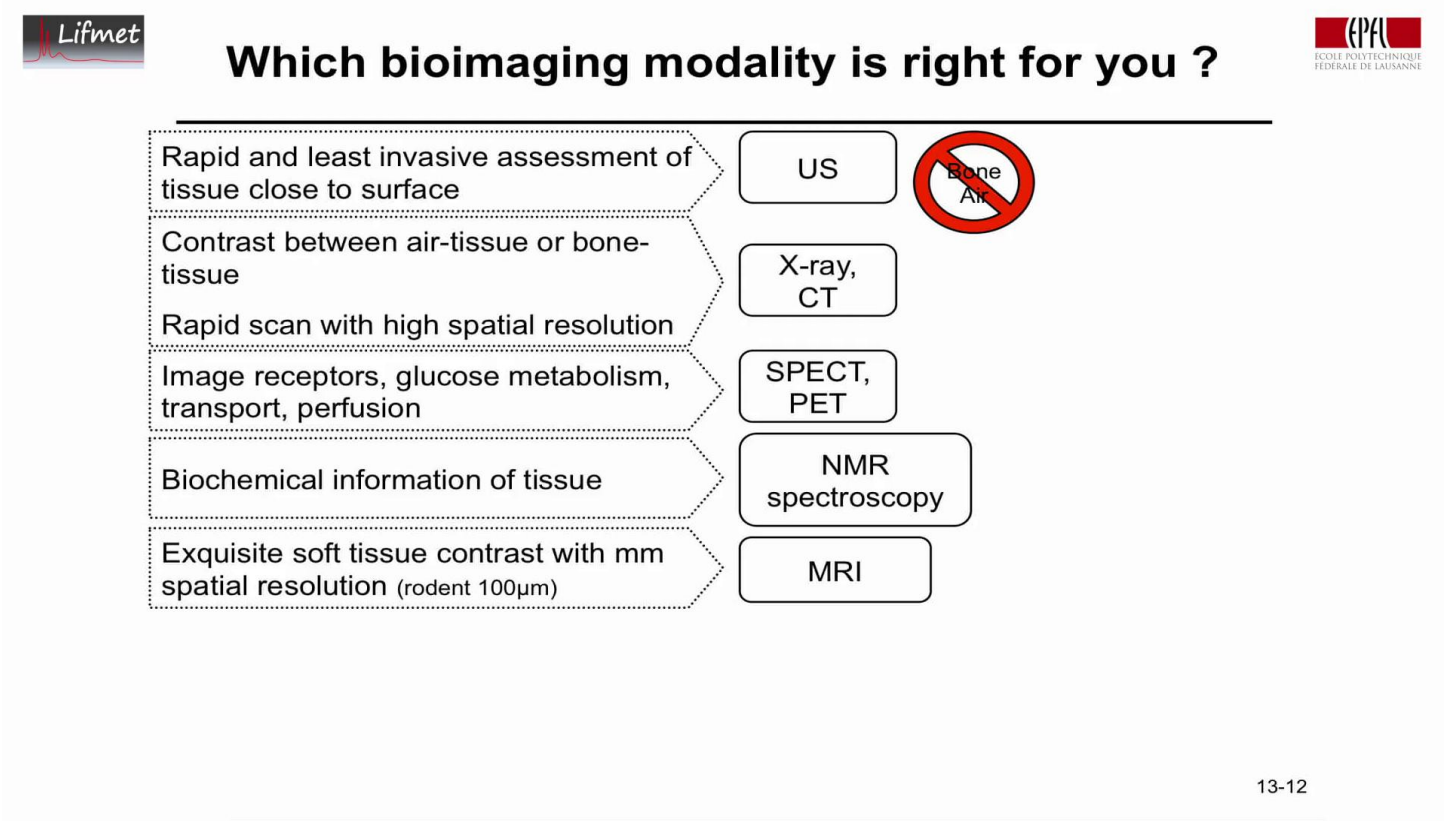


So now, what is the right bioimaging modality? This is a question that one is very often confronted with and it is useful to know some basic considerations. These are general considerations, they may vary in specific cases, but I've tried to do here a sort of a general chart to guide us a little bit on what we would consider. Well, if we want a rapid and least invasive assessment of a tissue that's fairly close to the surface-- so rapid, least invasive, least intrusive, nearly bedside, or bedside, and it's tissue close to the surface-- in this case, ultrasound is the technique that one would want to choose. There's a limitation though-- if, between the tissue that you're interested in, and the detector, the transducer-- if there is air or bone between, that creates artifacts, in that case it's not a good choice. I mention the air here because this is one of the major reasons why one uses the ultrasound gel on the transducer, put on the skin so that there are no air pockets in there that produce these artifacts. If one is interested in a rapid scan with high spatial resolution, and/or contrast between air tissue and bone tissue, then the technique to use is X-ray.

Notes

Summary

13m 50s

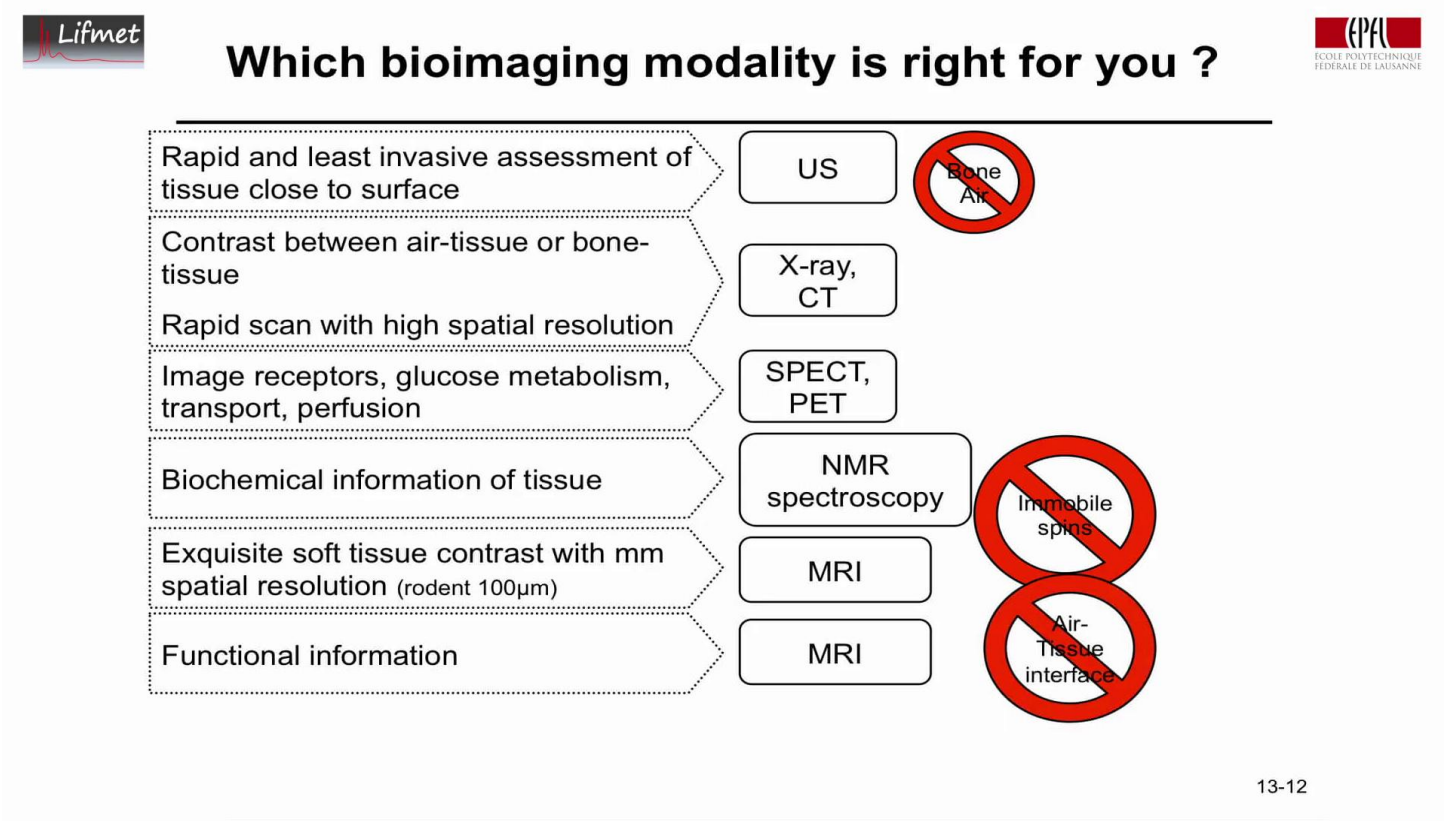


We've discussed here in the course the 2-D imaging technique, computer tomography. This can scan very rapidly and the primary contrast that's produced is between air tissue and bone tissue. Finally, if one is interested in metabolism, imaging receptors, glucose metabolism, transport and perfusion, then one has SPECT and PET as the techniques to be used here-- the metabolic imaging techniques and blood flow imaging techniques, the emission computed tomography, SPECT, and positron emission tomography techniques. If you'd like to know something about the biochemical information of tissue, then we have NMR spectroscopy, the chemical information that magnetic resonance provides can give us important insight into the biochemical composition of tissue, for example, in diagnostic MRI, the distinction between fat and water is very often used. If you would like to have exquisite soft tissue contrast with millimeter spatial resolution, in rodent's 100 microns, the exquisite soft tissue contrast, then MRI is your technique to use. Contrast this with X-ray-- it's fast, but the soft tissue contrast and what is between soft tissues, the electron density doesn't vary enormously, it is much more difficult to see.

Notes

Summary

15m 21s

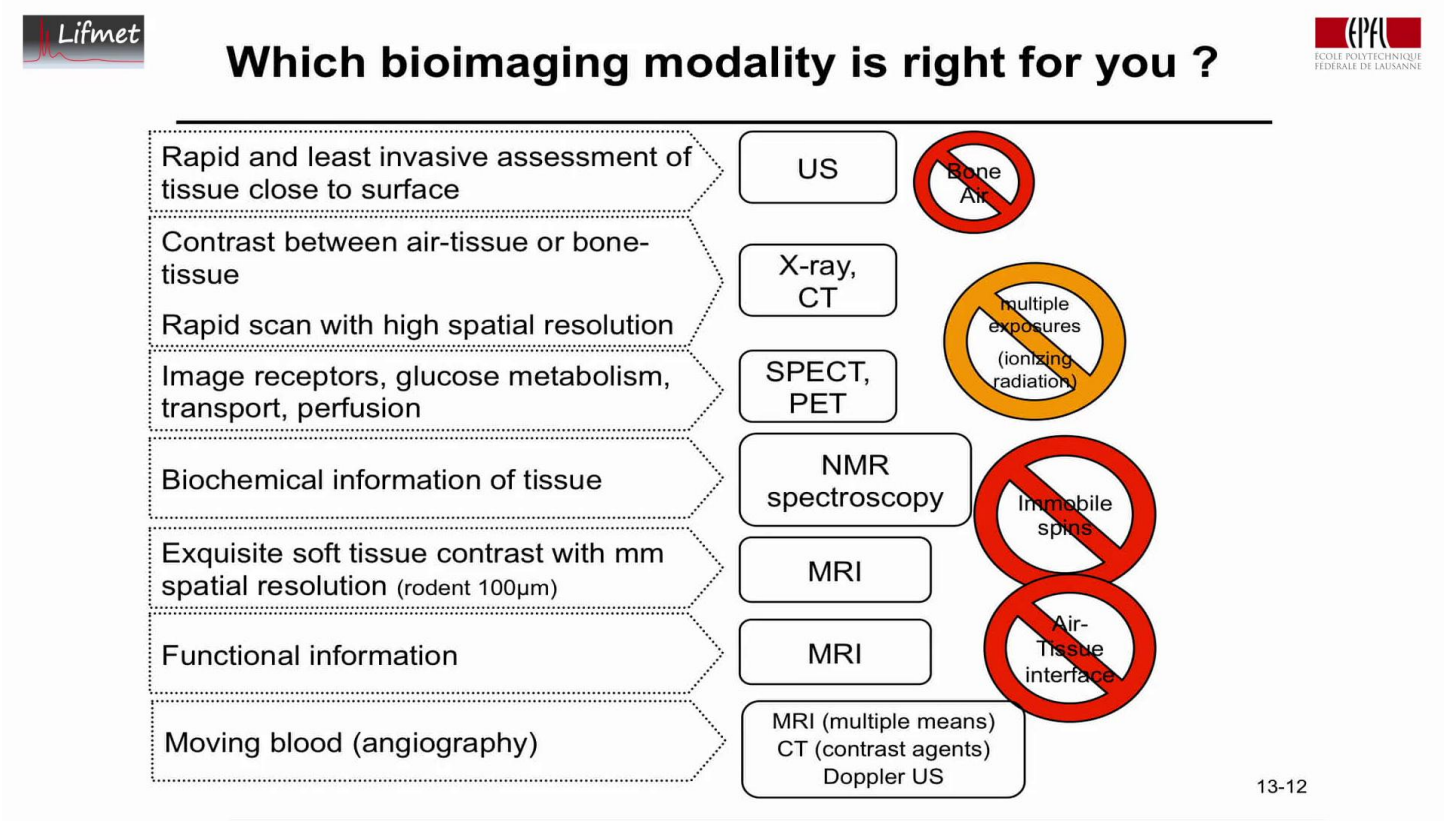


MRI there provides an abundance of contrast in the tissue. The limitation for MRI is that immobile spins, although they carry a magnetization, their magnetization, once it's excited, the transverse relaxation, be it *T_2* or *T_2 star*, is so fast that for practical reasons, it's very difficult, if not impossible, to reliably image. Some specialized acquisitions occur but as a general rule of thumb, it is not observable, so membranes, cell membranes, don't produce a measurable signal, although they carry a magnetization, and bones typically doesn't. So compare that to CT-- bone is the major contrast mechanism; in MRI, bone is not contributing to the signal. If one wishes to get functional information, then the technique to use here is MRI, particularly in the brain with functional MRI or BOLD fMRI-- we've discussed that. This is based on the deoxygenation of the blood vessels in the brain. It has, 25 years ago, replaced PET as the premier functional imaging technique, this is now being done with magnetic resonance imaging. This technique, *T_2 star*-weighted imaging, is not very applicable close to air tissue interfaces, so the sinuses in the head, the ear canals, these produce, on these images, signal fallouts, which are not easily recoverable.

Notes

Summary

16m 55s

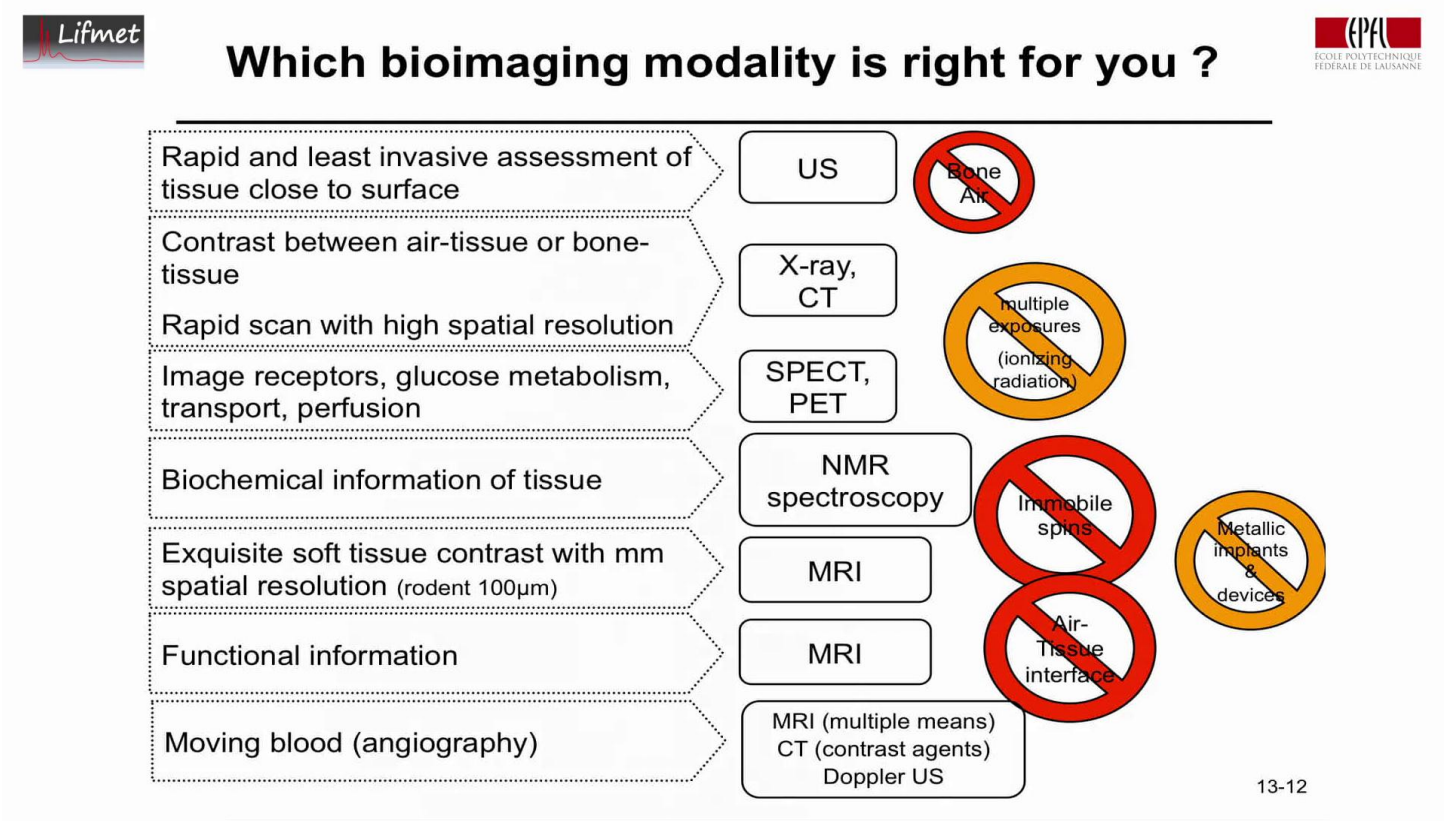


So it's hard to measure activation very close to these tissue interfaces, such as the nucleus accumbens in the brain, the olfactory bulb in humans-- in rats it's easier, the olfactory bulb is just sitting under the snout. And finally, if one wants to image moving blood-- that's angiography-- we actually have a number of techniques available. With MRI--I've given you in this week's lecture at the beginning an example of how MRI can encode moving blood. But there are multiple ways to do this aside from what I've shown you today. In computer tomography, one can depict the blood vessels with contrast agents and, of course, with Doppler ultrasound, we can also detect moving blood, and there, we can even do it in real time. So these are some rough charts. What is our interest? What is the preferred technology there? We have to consider some limitations for the X-ray techniques and that is multiple exposures limit it's applicability-- you do not want to go ten times a year into a CT scanner, if you're a healthy young volunteer. However, if the condition is life-threatening, it may matter less. I'll come with an example.

Notes

Summary

18m 35s

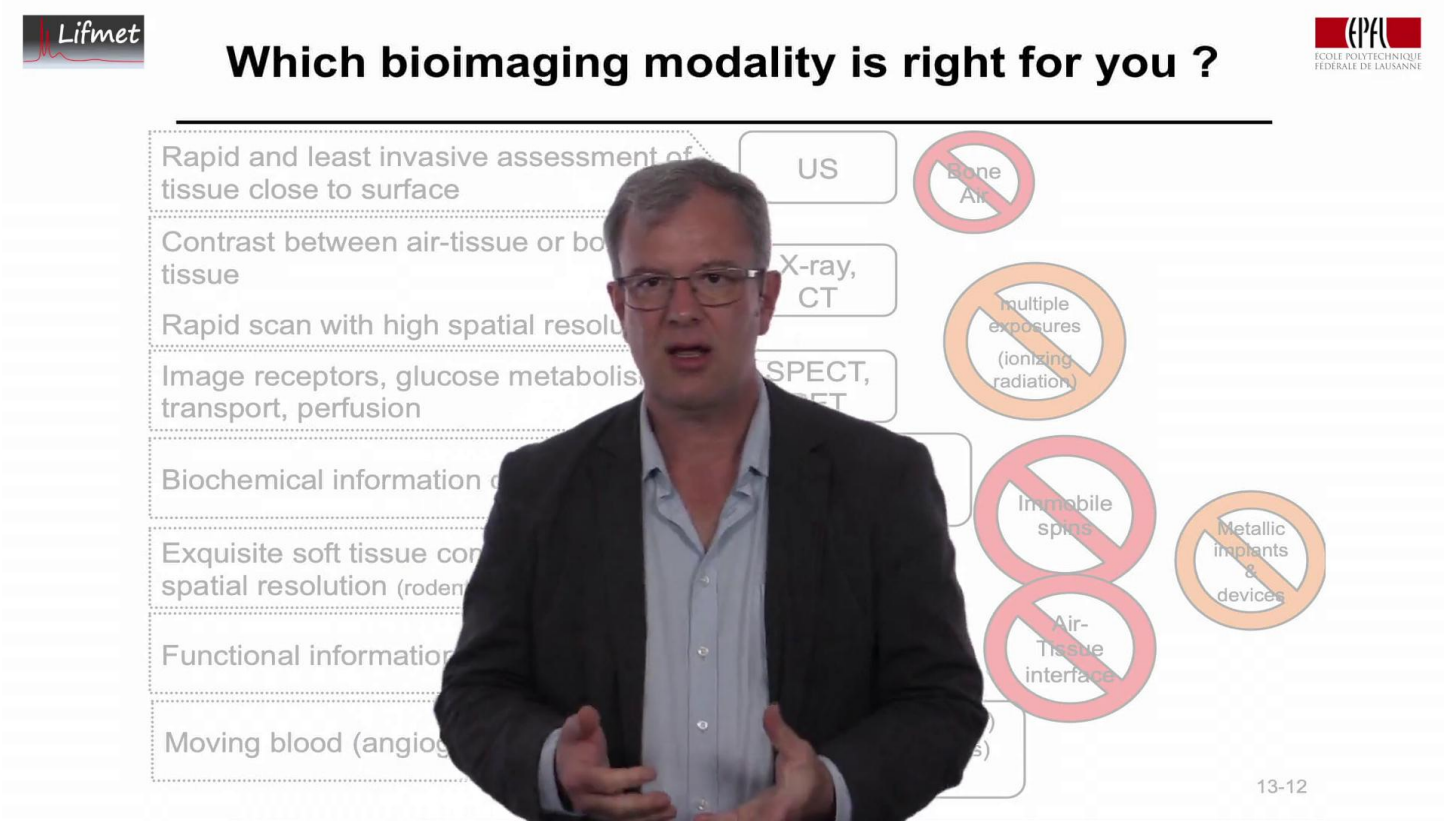


And for everything that has to do with magnetic resonance, we have to consider that we have a big magnet, if you carry a pace-maker, an insulin pump, a defibrillator, in your body, or metallic implants, then this is not the technique for you to be used. You're excluded from this technique.

Notes

Summary

19m 52s

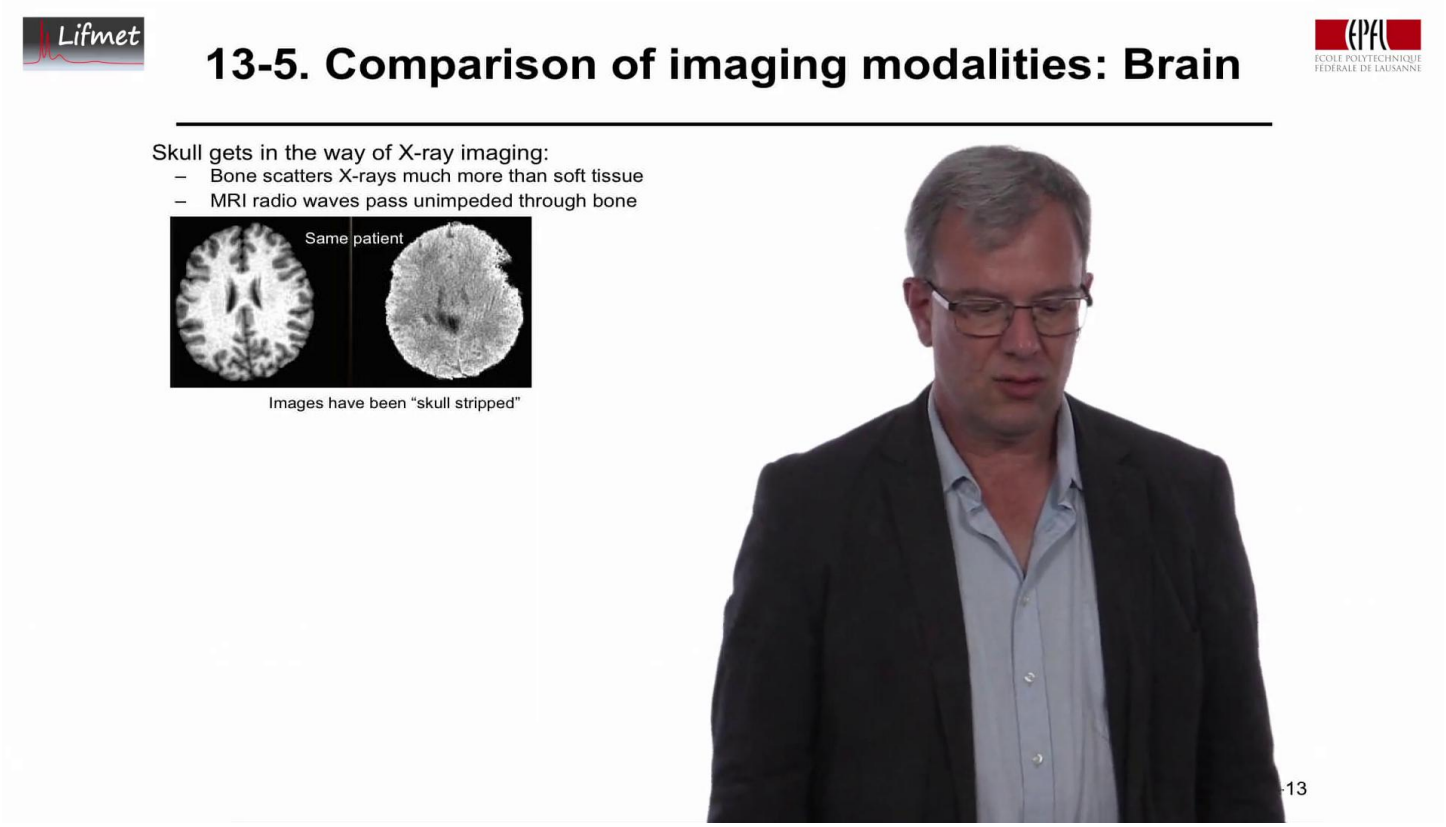


So consider, as an example, you have a subject that comes to the clinic. He's unconscious, probably had a stroke in the brain, and one wants to determine the extent of the stroke, for example, or whether it's indeed a stroke. Typically, one way to detect this is the mid-line in the brain is displaced in one direction. The person is an elderly person, you do not want to put them necessarily into an MRI unless you're absolutely sure there's no pacemaker or any metallic implant in the body-- the consequences are devastating. However, to just detect whether the mid-line is displaced in the CT there's sufficient contrast, this is done in a few seconds, it's also fast, gives you a fast assessment in this case. So there you would use-- even though the soft tissue contrast is not very good, it is sufficient to detect the medical question at hand. Likewise, if you have a tumor with a chance for treatment, and a PET or SPECT scan allows you to determine the area of the neoplastic cells-- that is the cells that multiply and divide-- you might have the choice between not being properly treated and dying, or the choice of being overexposed to X-rays, and *potentially* dying from cancer later, induced by the X-rays.

Notes

Summary

20m 11s



So in this case, the choice is a question of which one is worse, or the choice of the lesser evil, and one might want to stick with the CT techniques. So that's the overview of the techniques. In the next section I will just do a visual summary, with examples, of the imaging modalities in the course. Let's look at an example of the different modalities for the brain. If we look at the skull-- for X-ray imaging, the skull has a lot of electron density, calcium, so there's more scattering, it get's in the way of brain imaging. So it is not as good a technique. And so here we're looking at an image now, this image has been skull-stripped, now this is not what it implies, physically, it's not stripping the skull off the patient, it's stripping it by software means, so we don't see the signal from the skull, we're just looking at the soft tissue. And you can see on the left, we have exquisite contrast with the gray-white matter, and on the right, on the CT scan, it is essentially grayish for the same slice in the same subject, we're seeing not as much contrast on the CT scan.

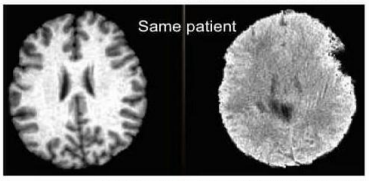
Notes

Summary

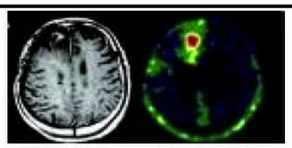
21m 44s

13-5. Comparison of imaging modalities: Brain

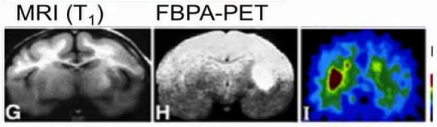
Skull gets in the way of X-ray imaging:
- Bone scatters X-rays much more than soft tissue
- MRI radio waves pass unimpeded through bone



Images have been "skull stripped"

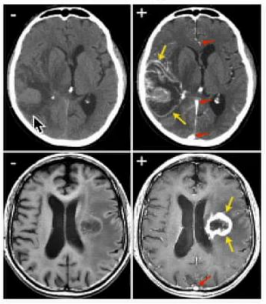


MRI (T_1) FBPA-PET



MRI (T_1) MRI (T_2) PET

Contrast agents



CT

MRI

13-13

Here we compare a PET scan on the right-- we have an area of high uptake, and on the *T_1*-weighted image, we're seeing here an alteration on the image here, and what the PET scan tells us, the location of where there is the uptake of this particular tracer, FBPA. Here's an example from a macaque brain, this is a *T_1*-weighted image of the brain-- we see some gyrification. This is a *T_2*-weighted image-- we see alteration here; this image is flipped, so we have here the uptake of the PET tracer corresponding to this area. Looking at contrast agents, we can see four images here. Take a few seconds and guess which one is the CT scan, which one is the MRI scan... Did you guess it? Guess which one has the contrast agent: which one is before, which one is after? Okay. So the top row is a CT scan-- we can see the bone very bright, the soft tissue contrast is not exquisite, on the MRI we see the fat and we have exquisite soft tissue contrast in the MRI. And we see, on the left, the pre-contrast agent administration-- so that's the native image, we see something is going on here-- now here on the MRI, the contrast agent tells us, at the periphery of this lesion, there's a lot of uptake for the contrast agent.

Notes

Summary

22m 59s

13-5. Comparison of imaging modalities: Brain

Skull gets in the way of X-ray imaging:
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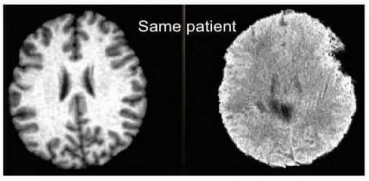
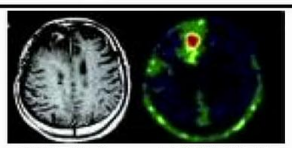
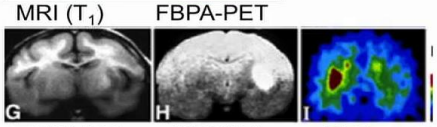


Images have been "skull stripped"

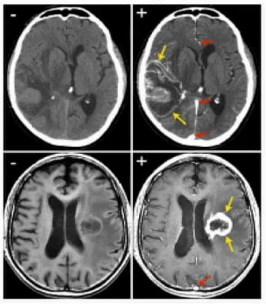


MRI (T_1) FBPA-PET



MRI (T_1) MRI (T_2) PET

Contrast agents

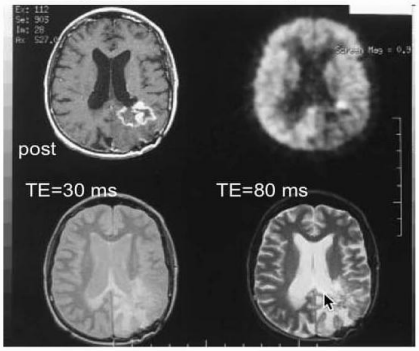


CT

MRI

pre post

High grade astrocytoma



13-13

Contrast agents for MRI are typically limited to the blood, so if we see uptake into the tissue, it means that that part of the blood-brain barrier has been ruptured-- these are, of course, brain scans-- and this is typically the zone where the aggressive cancerous cells are. The inside does not have much blood flow, so it's most likely a necrotic core. Likewise, here with the CT scan, one can see some alteration of the normal structure, and the one sees here, where the arrows point, the uptake of the contrast agent at the edge of the tumor-- this is where the blood-brain barrier has been ruptured, where there is vascularization and aggressive growth of cells. Here's an example of a high-grade astrocytoma. We have four different contrasts to consider: *T_1*-weighted image after contrast administration gives us here the rim of the tumor-- this is post-contrast; we have the *T_2*-weighted image, at 30 milliseconds, one sees something going on here-- at 30 milliseconds, 80 milliseconds very clear, that *T_2* in this area of the brain has been prolonged. A longer *T_2*--and *T_2*-weighted image bright means longer *T_2*-- a longer *T_2* means disruption of cellular membranes, of proteins and so on, there's less of that, the fluid content of the brain has increased.

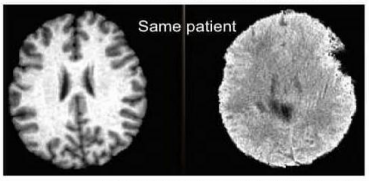
Notes

Summary

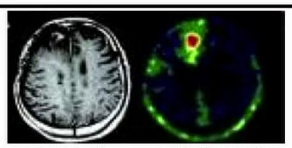
24m 29s

13-5. Comparison of imaging modalities: Brain

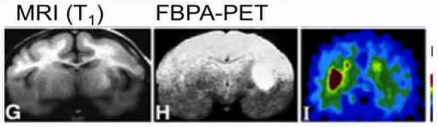
Skull gets in the way of X-ray imaging:
- Bone scatters X-rays much more than soft tissue
- MRI radio waves pass unimpeded through bone



Images have been "skull stripped"

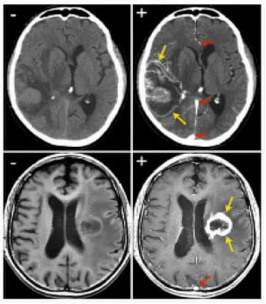


MRI (T_1) FBPA-PET



MRI (T_1) MRI (T_2) PET

Contrast agents

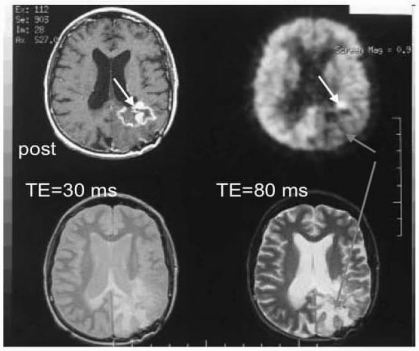


CT

MRI

pre post

High grade astrocytoma



13-13

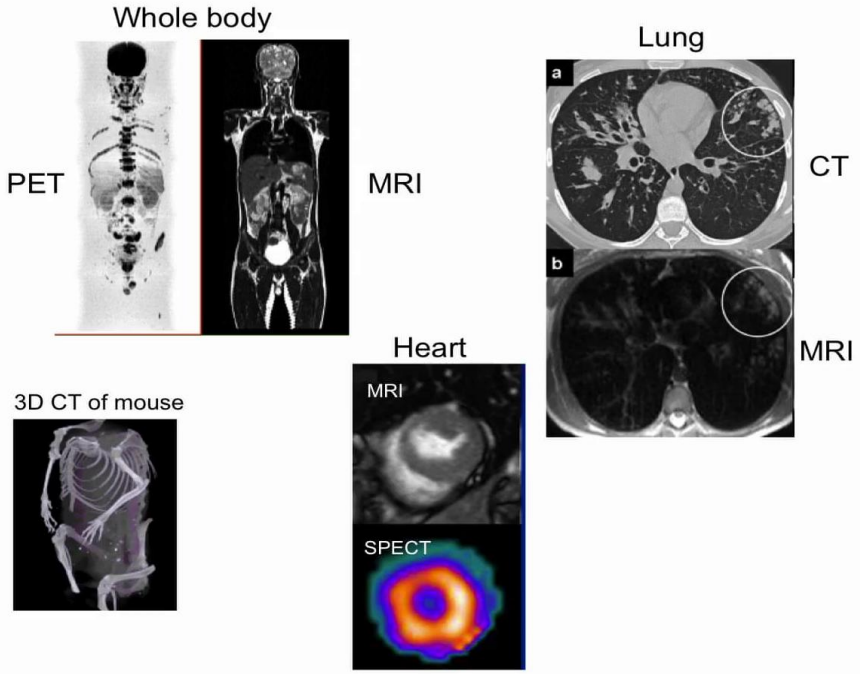
This is a hallmark of tumors but it's also a hallmark of edema, so these two cannot be distinguished. Well, we see here, there's a diffuse hyperintensity in this area, all over the area, we see there is a rim of high-uptake of the contrast agent, there's the vascularization, and, if one now includes the FDG-PET scan, one can see the uptake of glucose at this point. This is the point where the cells are that have a high glucose metabolic rate, they are most likely the cells that one wants to get out to stop the proliferation and the growth of the tumor. Most likely, what we have in here, inside here, is necrosis and we can indeed see there's very little uptake of glucose at this point. The rest that shows up bright on the *T_2*-weighted image, hyperintense-- like I said, it's a reduction of relative presence of membranes and so on-- is most likely a reflection of edema-- so it's peritumoral edema-- that creates the increase in *T_2* in this image, most likely. So the arrow here highlights the area where one would go for, say, surgical or radiotherapy treatment.

Notes

Summary

25m 58s

Comparison of modalities: Body



13-14

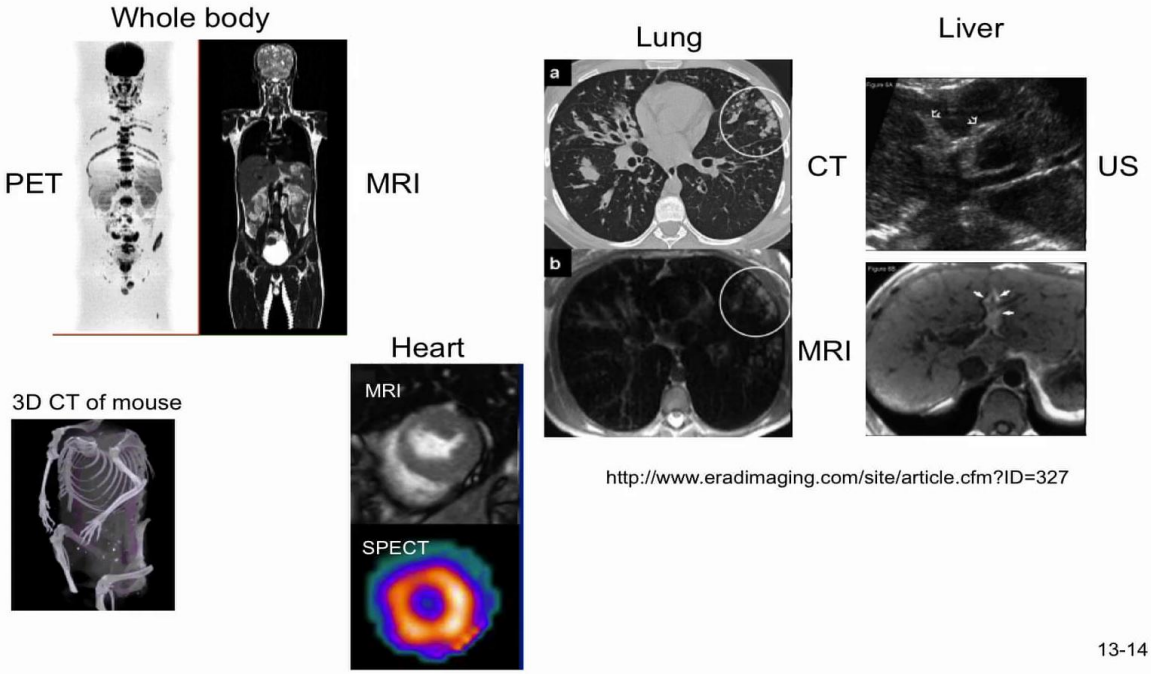
Now, I want to give some final examples from the body. This is a whole body PET scan, on the left, and a whole body MRI scan; they are clearly different contrast-- MRI being soft tissue, PET, depending on the tracer that one uses, one traces a different process. Here's a higher resolution-- a 3-D CT of a mouse. We can see the skeleton very nicely depicted, grayish is the contrast of the other things, but the skeleton depicts very nicely in three dimensions. SPECT images of the heart measuring heart perfusion on the bottom-- so this is indicating a perfusion in the muscle-- this in the MRI is the muscle and the bright area here, that's the ventricle filled with blood; that's what we're pumping roughly every second through our circulation. That's the job of the heart. Here's an example of the lung-- it's a cystic fibrosis example-- we have on the top: can you guess what modality that is? We can see bone, we can see the ribcage, so it is CT, and on the bottom we have MRI. And we can see here in this case that there is something inside the lung that shouldn't be there-- the lung should just be air. So it should not be detectable with MRI and with CT, and this is, in this case of cystic fibrosis, is a major complication of this disease.

Notes

Summary

27m 11s

Comparison of modalities: Body



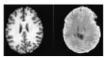
Some of you might have had pneumonia-- when you have pneumonia, very often there is a chest X-ray being performed just to determine to what extent there is fluid accumulation in the lung, which you have to cough out in the course of the disease. And the final example I want to show here is the liver--this is an ultrasound. The liver is, of course, there's no bone impeding the image to deliver, so ultrasound's a good technique, and there is also MRI here. This is a typical structure of a liver lobe-- this is the front of the belly, here's the spine, and there is some hyperintensity in the liver, so that can also be used for MRI, and ultrasound is, of course, much faster in this case.

Notes

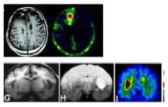
Summary

28m 40s

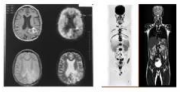
Credits



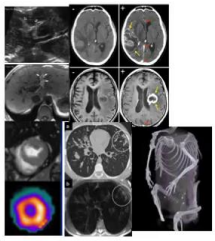
“Neuroimaging with MRI : some of the things we can see”, Robet W. Cox, 2007
http://slideplayer.com/slide/3280316/



Creative commons pictures



Millensys Vision Tool 3D view
http://www.millensys.com/products/oncology/3dview_petct/index.html



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So I wanted to give you some examples of different techniques, by example, by showing the images, to put ourselves in the context of these image modalities that we have seen in this course. And this concludes the entire course. Thank you very much. I hope you have enjoyed it.

Notes

Summary

29m 27s