CAP 5516
Medical Image Computing
(Spring 2025)

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UCF CENTER FOR RESEARCH IN COMPUTER VISION

Lecture 4: Introduction to Medical Image Computing (2)

Image credit: https://www.syberscribe.com.au/blog/the-ins-and-outs-of-medical-imaging/

Recap (X-ray vs. CT)

X-ray

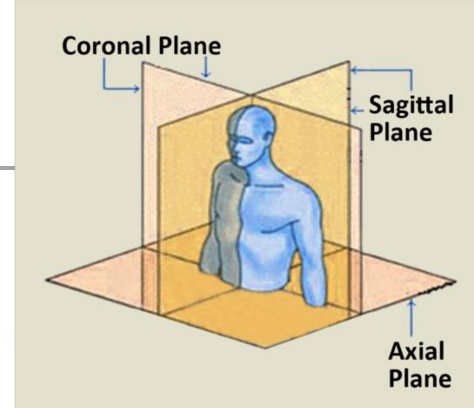
- **How it Works**: A single X-ray beam passes through the body, creating a 2D image (like a shadow).
- **Pros**:
  - Quick & widely available
  - Lower cost & lower radiation dose
- **Cons**:
  - Overlapping structures can hide details
  - Limited soft tissue detail
- **Use Cases**: First-line for fractures, chest/lung checks, basic skeletal exams

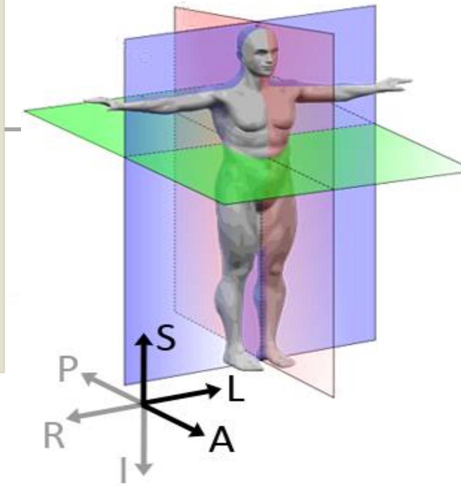
Recap (X-ray vs. CT)

CT

- **How it Works**: Multiple X-ray projections taken at different angles are reconstructed into cross-sectional (slice) images and 3D volumes.
- **Pros**:
  - Detailed, slice-by-slice view
  - Better soft tissue contrast
  - 3D reconstruction capability
- **Cons**:
  - Higher radiation dose
  - More expensive & larger equipment
- **Use Cases**: Trauma assessment, tumor detection, vascular imaging, surgical planning

3D View Terminology





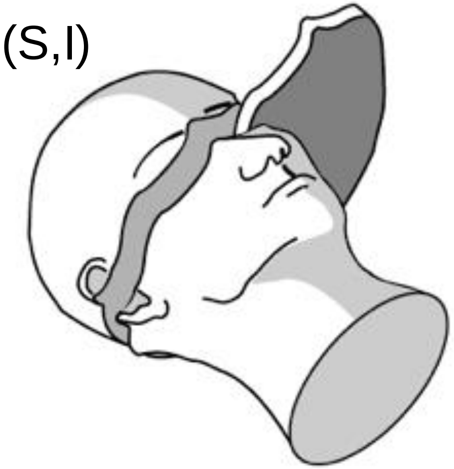
(L,R)

A Sagittal

(A,P)

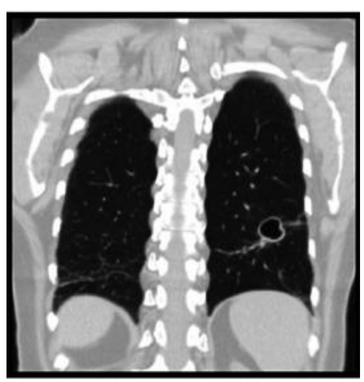
B Coronal

(S,I)



C Axial

Anatomical space
R: right
L: left
A: anterior
P: posterior
I: inferior
S: superior



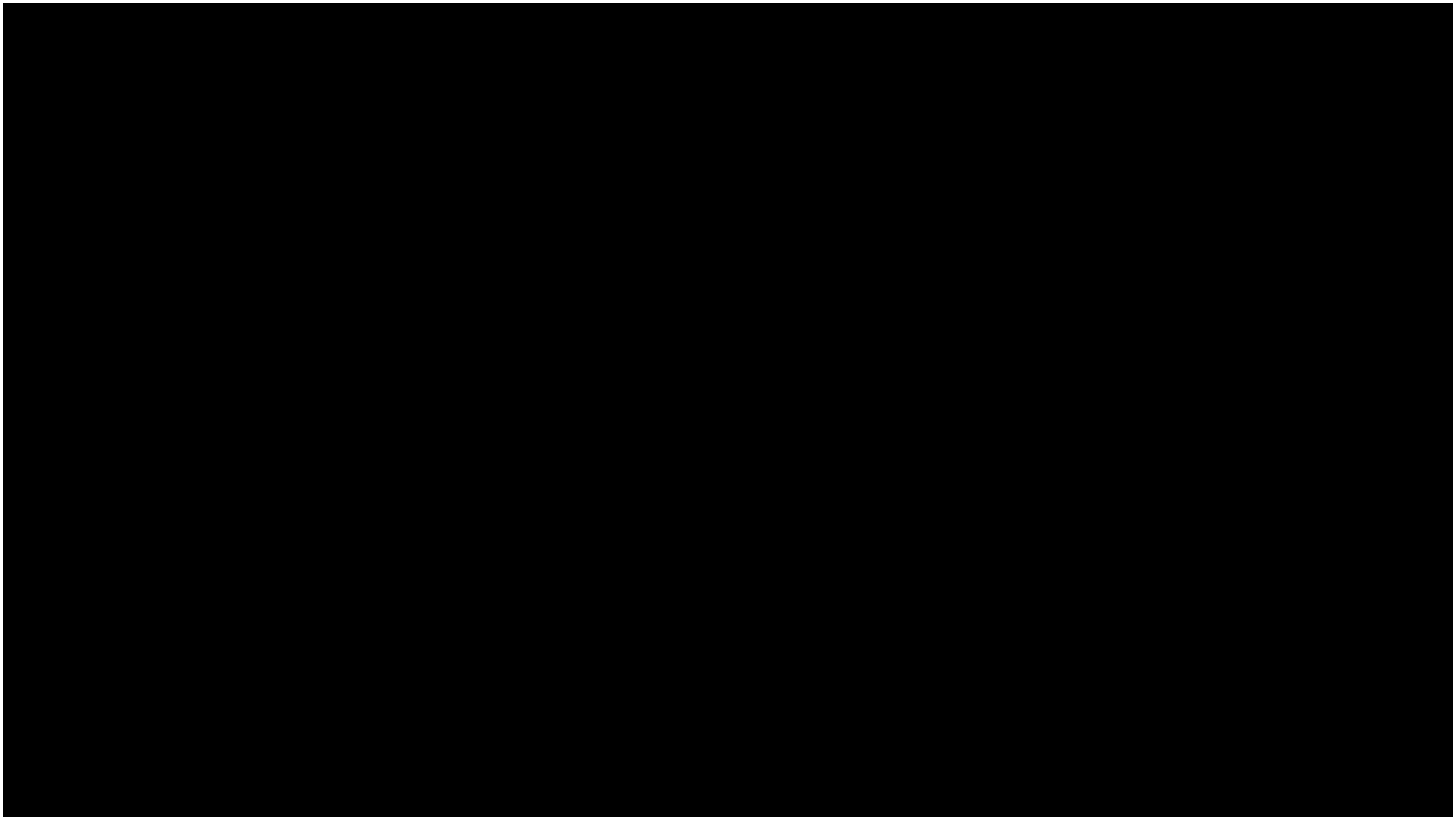
Magnetic Resonance Imaging (MRI)

- Magnetic Resonance Imaging (MRI) is a medical imaging procedure for making images of the internal structures of the body.

- MRI scanners use strong magnetic fields and radio waves (radiofrequency energy) to make images.

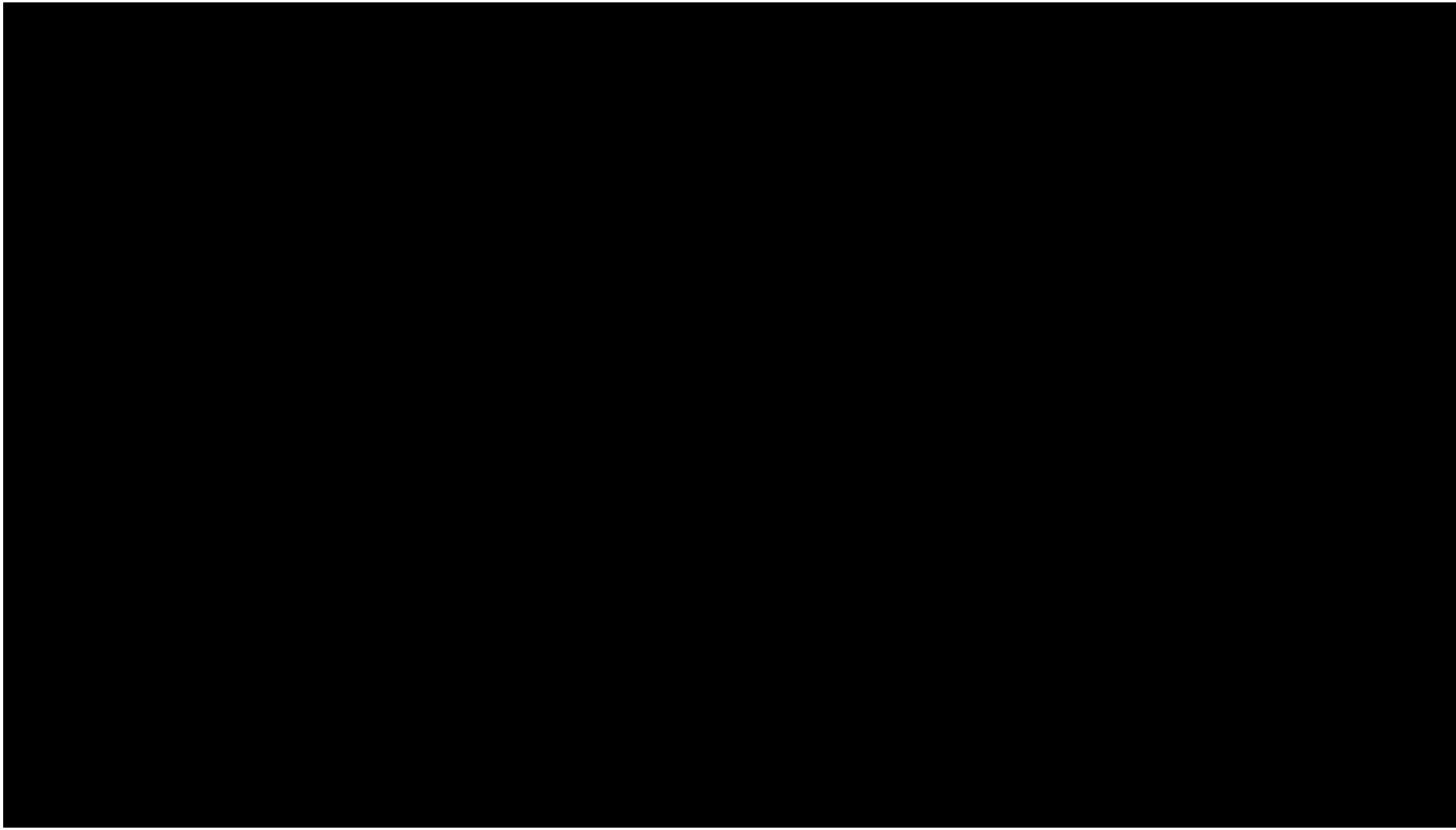
Source: https://assets.aboutkidshealth.ca/akhassets/BT_Neuro_MRI2_MEDIMG-PHO_EN.jpg?RenditionID=10

Magnetic Resonance Imaging (MRI)



Source: https://www.youtube.com/watch?v=E44W54z_Ykw

Magnetic Resonance Imaging (MRI)



Source: https://www.youtube.com/watch?v=1CGzk-nV06g&t=71s

The Basics of MRI

- **What is MRI?**
  - MRI (Magnetic Resonance Imaging) uses **strong magnets**, **radio waves**, and a computer to create detailed images of the body.
- **How does it work?**
  - The body is mostly water (H_2O), and water contains **hydrogen atoms**.
  - When placed in a strong magnetic field, hydrogen atoms in your body **align like tiny compass needles**.
  - A radio wave pulse “kicks” these hydrogen atoms, making them wobble (or resonate).
  - As they return to their original position, they release energy, which is detected to form an image.

The Basics of MRI

- **Why MRI Can Differentiate Tissues?**

1. **Water and Fat Content:**
    - Different tissues in the body contain varying amounts of **water** and **fat**.
    - For example:

        Muscles: High water content.

        Fat: High fat content.

        Bones: Very low water content (not well visualized in MRI).

2. **Relaxation Times:**
    - When hydrogen atoms “relax” after being excited by radio waves, they release energy at different rates depending on the type of tissue.

The Basics of MRI

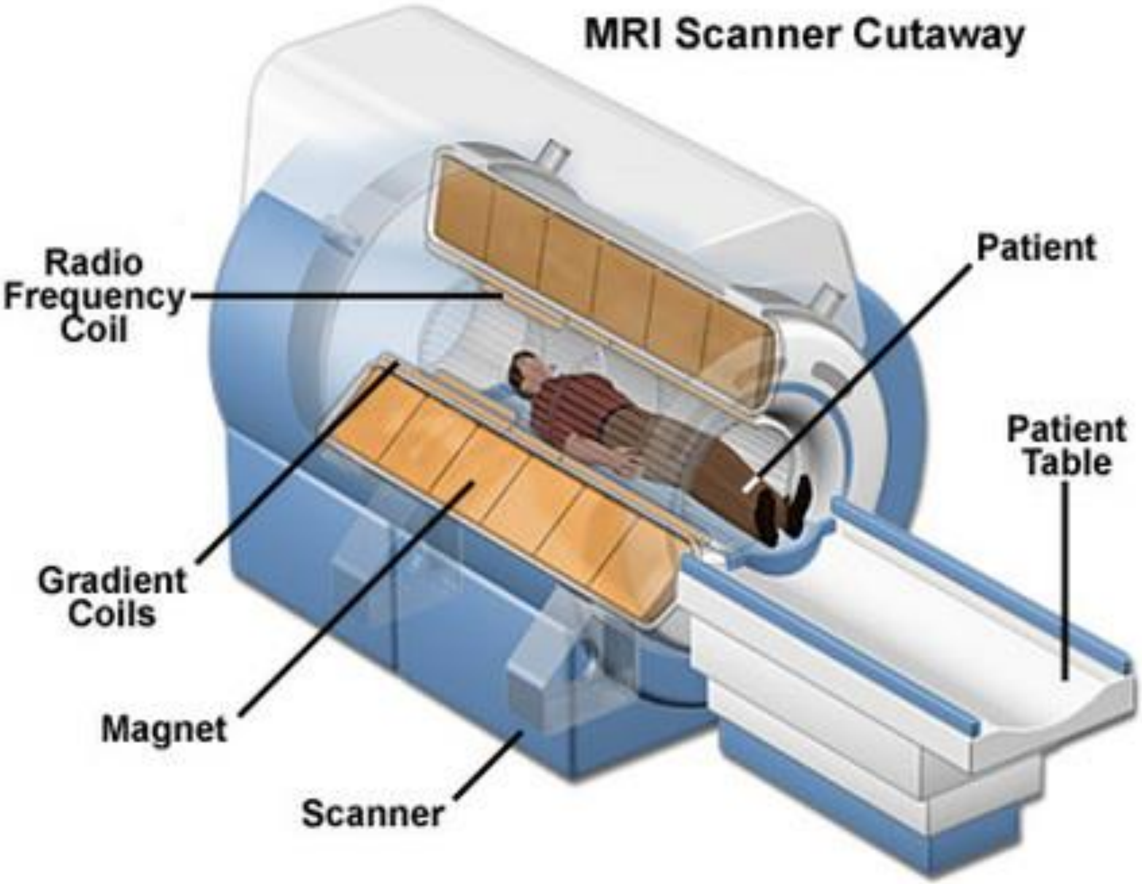
2. **Relaxation Times:**

- There are two key relaxation times:
  - **T1 Relaxation:** Measures how quickly hydrogen atoms realign with the magnetic field.
  - **T2 Relaxation:** Measures how quickly hydrogen atoms lose their coherence (or wobble out of sync).
- Different tissues have unique T1 and T2 properties, which create contrast in the images.

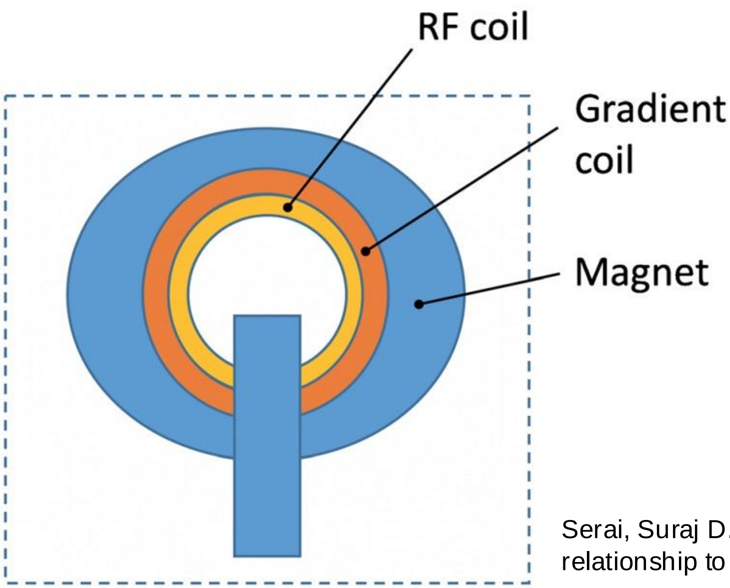
3. **Customizing MRI Signals:**

- By adjusting the MRI scanner settings, we can highlight specific tissues:
  - **T1-weighted images:** Fat appears bright; water appears dark (great for anatomy).
  - **T2-weighted images:** Water appears bright; fat appears darker (great for spotting inflammation or swelling).

MRI System Components and Functions



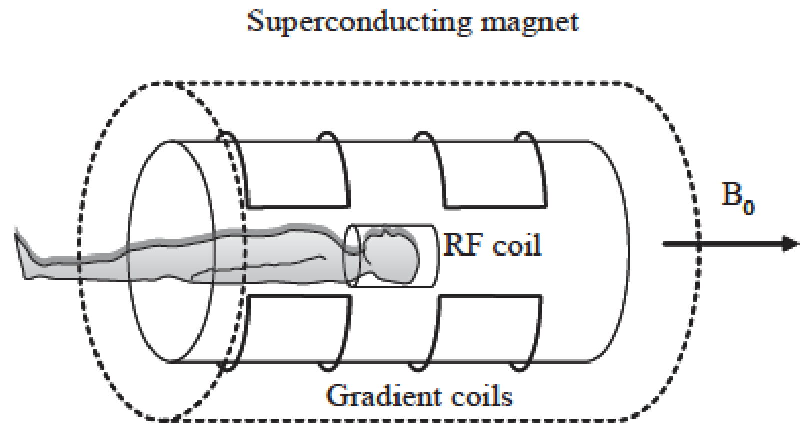
Source: https://snc2dmri.weebly.com/components--functions.html



Serai, Suraj D., et al. "Components of a magnetic resonance imaging system and their relationship to safety and image quality." Pediatric radiology 51.5 (2021): 716-723.

MRI System Components and Functions

- The **magnet** is the largest and most expensive component of the MRI scanner
- The strength of the magnet is measured in teslas (T). Clinical magnets generally have a field strength in the range 0.1–3.0 T, with research systems available up to 9.4 T for human use and 21 T for animal systems. The Earth's magnetic field is only 0.5 gauss. (1 tesla = 10,000 gauss)

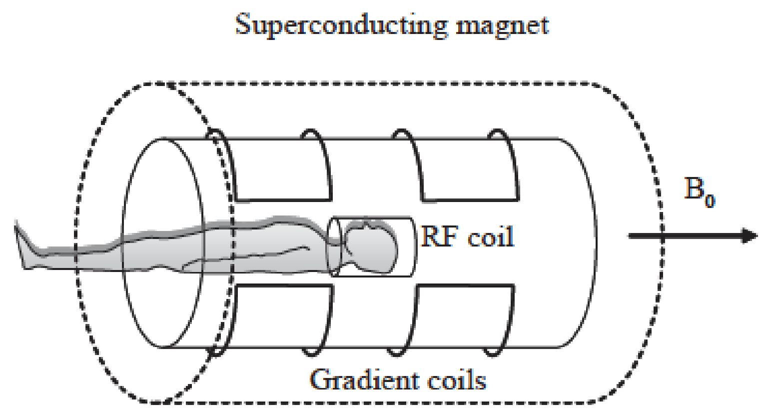


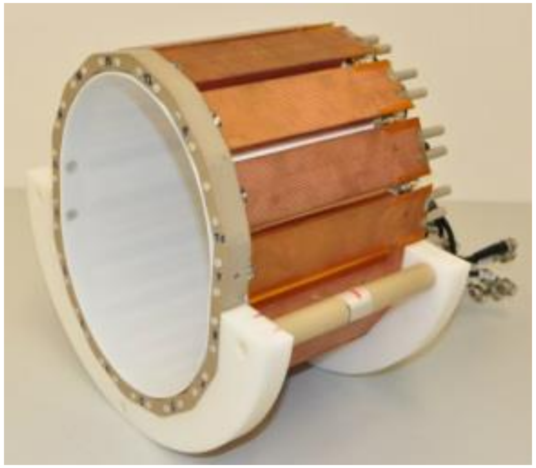
Source: https://stanfordhealthcare.org/medical-tests/p/pet-mri-scan.html

- Most clinical magnets are superconducting magnets, which require liquid helium to keep them very cold (temperatures below 10 Kelvin (−263 °C))

MRI System Components and Functions

- **Radiofrequency (RF) coils** are used to send RF pulses and receive the signal back from the patient's body.
- There are different coils located inside the MRI scanner to transmit waves into different body parts.

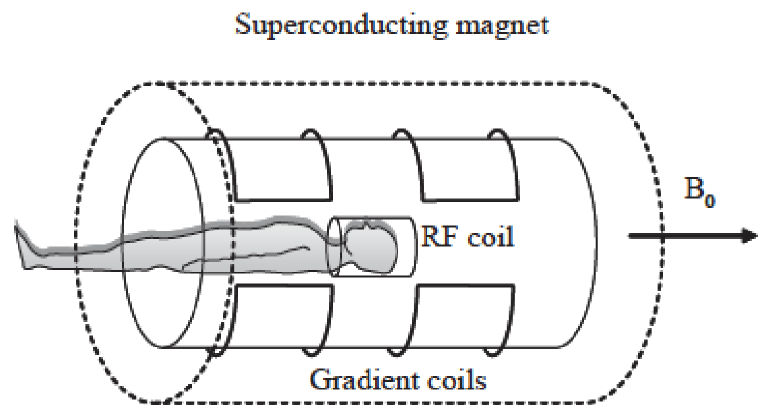


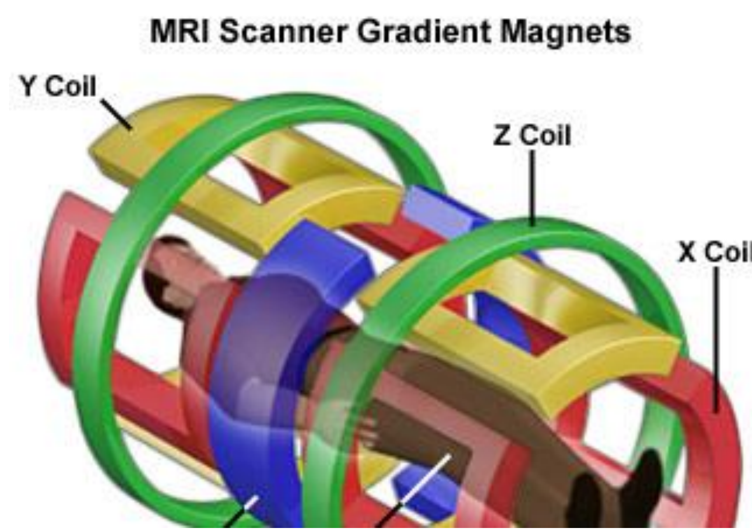


https://snc2dmri.weebly.com/components--functions.html

MRI System Components and Functions

- **Gradient coils** are used to spatially encode the positions of protons by varying the magnetic field linearly across the imaging volume. This allows spatial encoding of the MR signal.

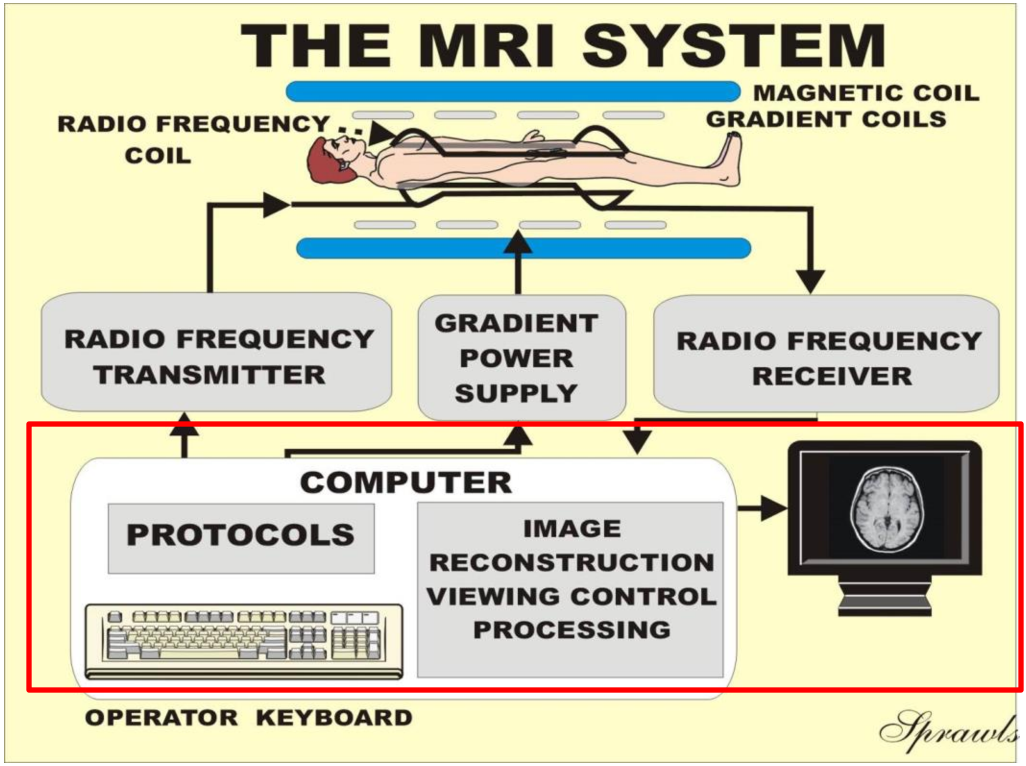




https://snc2dmri.weebly.com/components--functions.html

MRI System Components and Functions

- The multiple **computer systems** embedded in an MRI scanner have a range of functions
  - control the RF and gradient pulses
  - collect the data
  - process and display the generated image



http://www.sprawls.org/mripmt/MRI02/index.html

- More details about the basic physics for magnetic resonance imaging
  - Serai, Suraj D., et al. "Components of a magnetic resonance imaging system and their relationship to safety and image quality." *Pediatric radiology* 51.5 (2021): 716-723.
  - Currie, S., Hoggard, N., Craven, I. J., Hadjivassiliou, M., & Wilkinson, I. D. (2013). Understanding MRI: basic MR physics for physicians. *Postgraduate medical journal*, *89*(1050), 209-223.
  - Chavhan, Govind B. *MRI made easy*. JP Medical Ltd, 2013. Free online: https://rads.web.unc.edu/wp-content/uploads/sites/12234/2018/05/Phy-MRI-Made-Easy.pdf
  - Sprawls, Perry. Magnetic resonance imaging: principles, methods, and techniques. Madison, Wisconsin: Medical Physics Publishing, 2000. Online: http://www.sprawls.org/mripmt/index.html

- Lectures about MRI basics (Dr. Rasmus Birn, Univ. of Wisconsin – Madison)
  - MRI Basics Part 1 - Image Formation: https://www.youtube.com/watch?v=mBAIWAyNdz0&t=569s
  - MRI Basics - Part 2: Image Contrast: https://www.youtube.com/watch?v=KjuR5ahtIGs

MRI Sequences

- By varying the sequence of RF pulses applied & collected, different types of images are created

- The most common MRI sequences are T1-weighted and T2-weighted scans

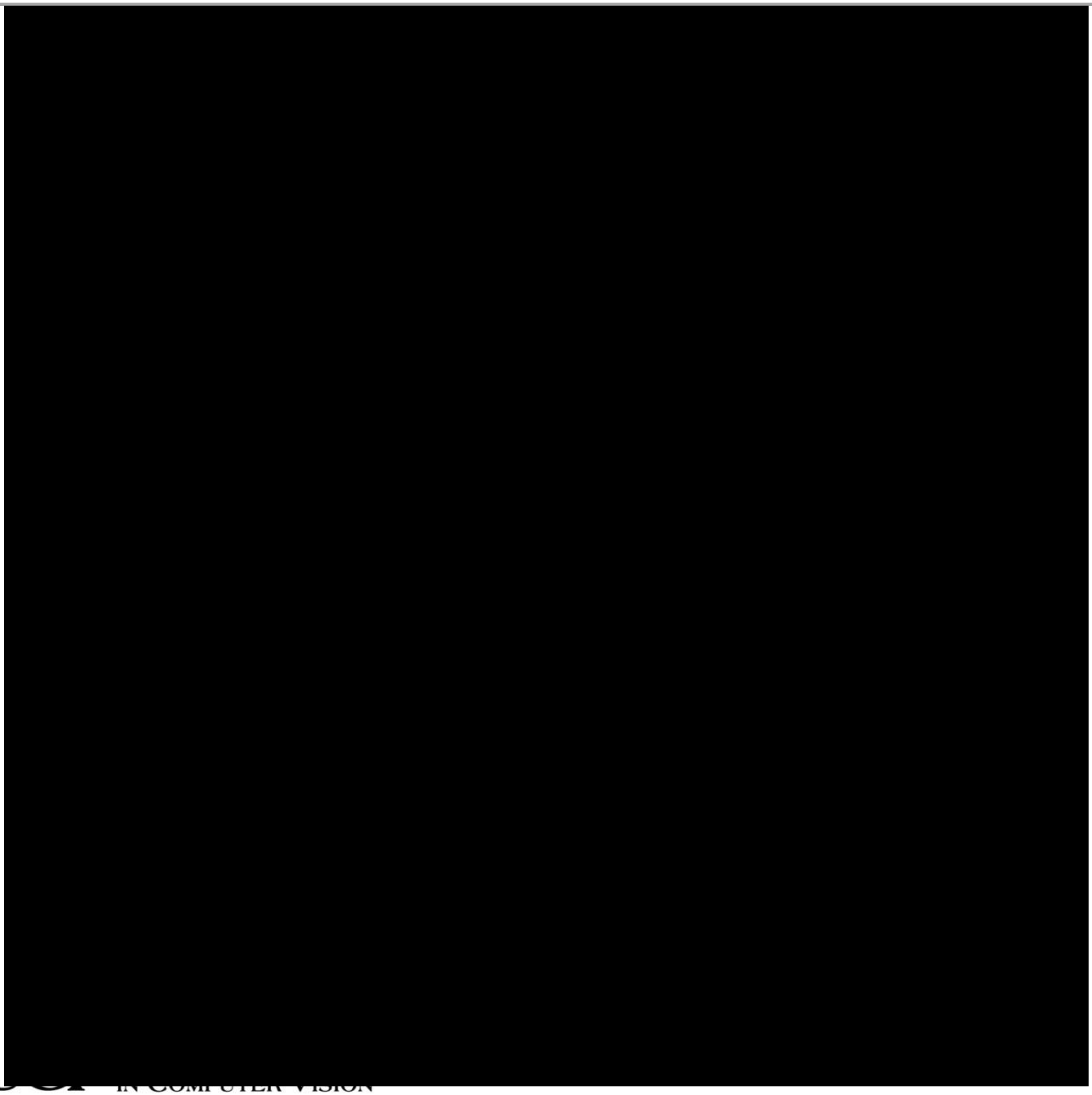
MRI Sequences

- Tissue can be characterized by two different relaxation times – T1 and T2.
- T1 (longitudinal relaxation time) is the time constant which determines the rate at which excited protons return to equilibrium. <u>It is a measure of the time taken for spinning protons to realign with the external magnetic field</u>.
- T2 (transverse relaxation time) is the time constant which determines the rate at which excited protons reach equilibrium or go out of phase with each other. <u>It is a measure of measures how quickly hydrogen atoms lose their coherence (or wobble out of sync).</u>

MRI Sequences

- **T1-weighted images** are produced by using short TE (Echo Time) and TR (Repetition Time) times. The contrast and brightness of the image are predominately determined by T1 properties of tissue.
- Conversely, **T2-weighted images** are produced by using longer TE and TR times. In these images, the contrast and brightness are predominately determined by the T2 properties of tissue.
- A third commonly used sequence is the **Fluid Attenuated Inversion Recovery (Flair)**. The Flair sequence is similar to a T2-weighted image except that the TE and TR times are very long. <u>It is designed to suppress the signal from free fluid, such as cerebrospinal fluid (CSF), making it appear dark.</u>

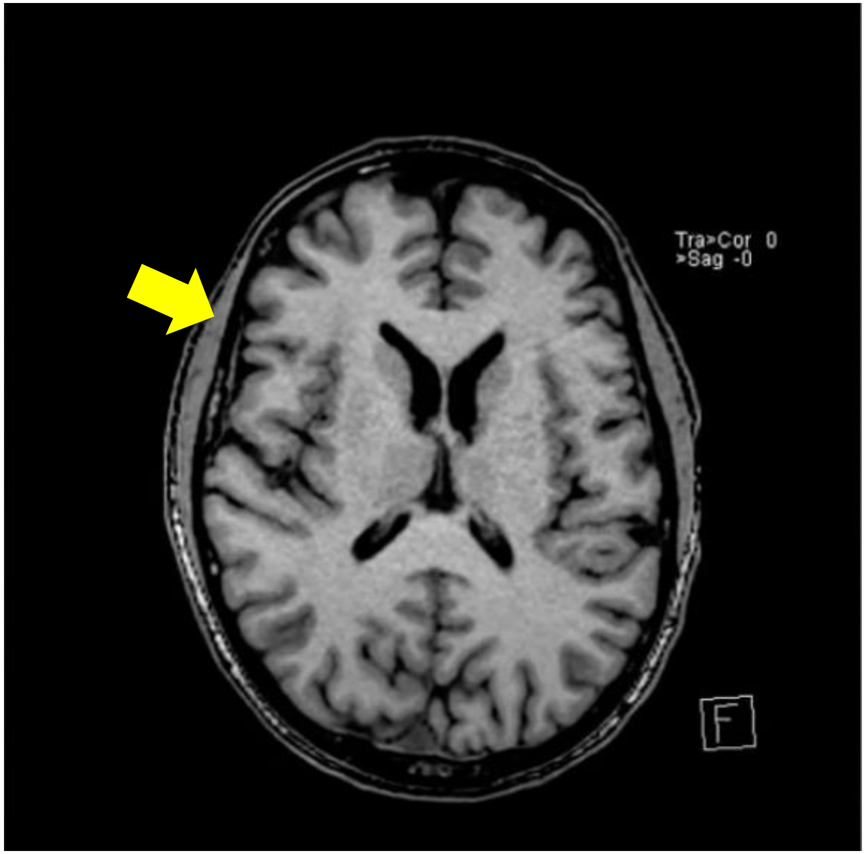
MRI Sequences



Source:
https://www.youtube.com/watch?v=Ue4gzUzlGNo

MRI Sequences (T1-Weighted Image)

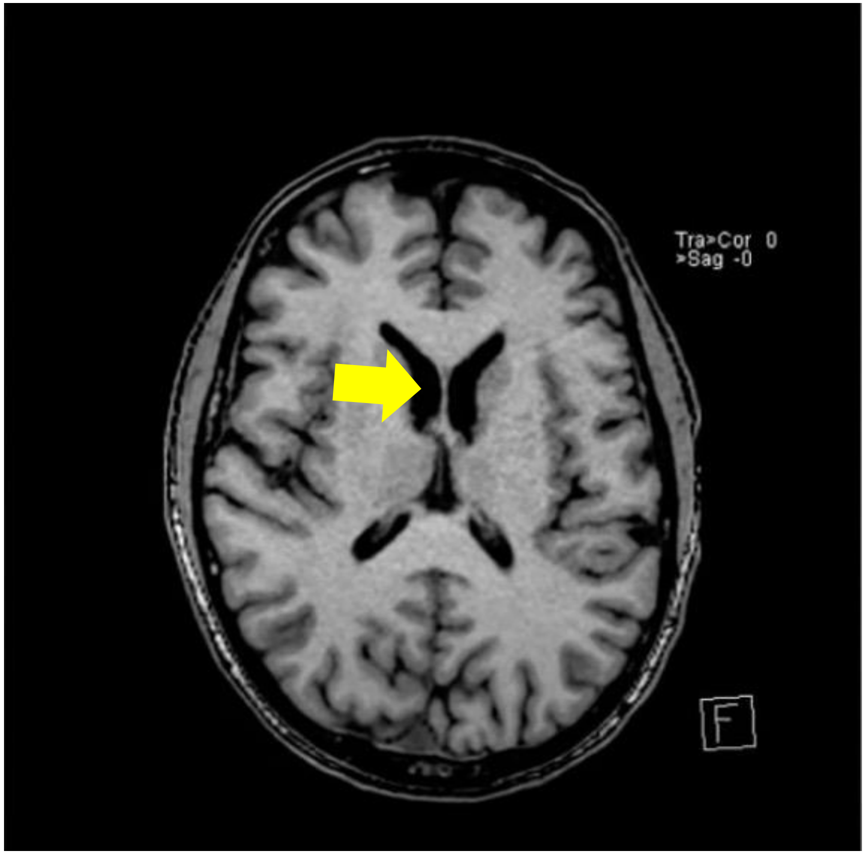
- Fat: Bright



Credit: Dr. David Nascene

MRI Sequences (T1-Weighted Image)

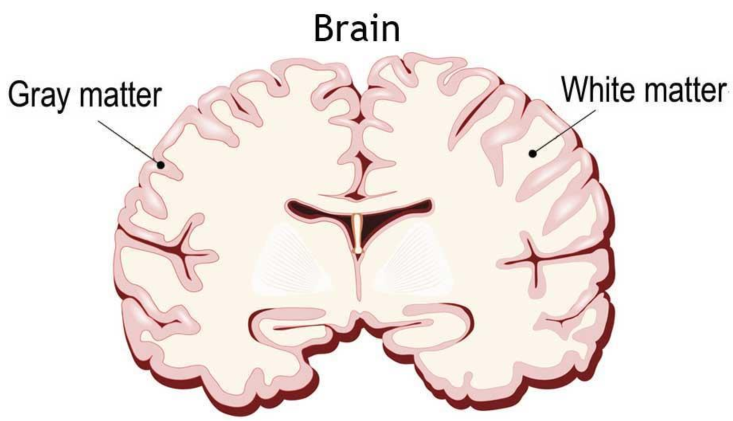
- Fat: Bright
- Fluid: Dark
  cerebrospinal fluid (CSF)

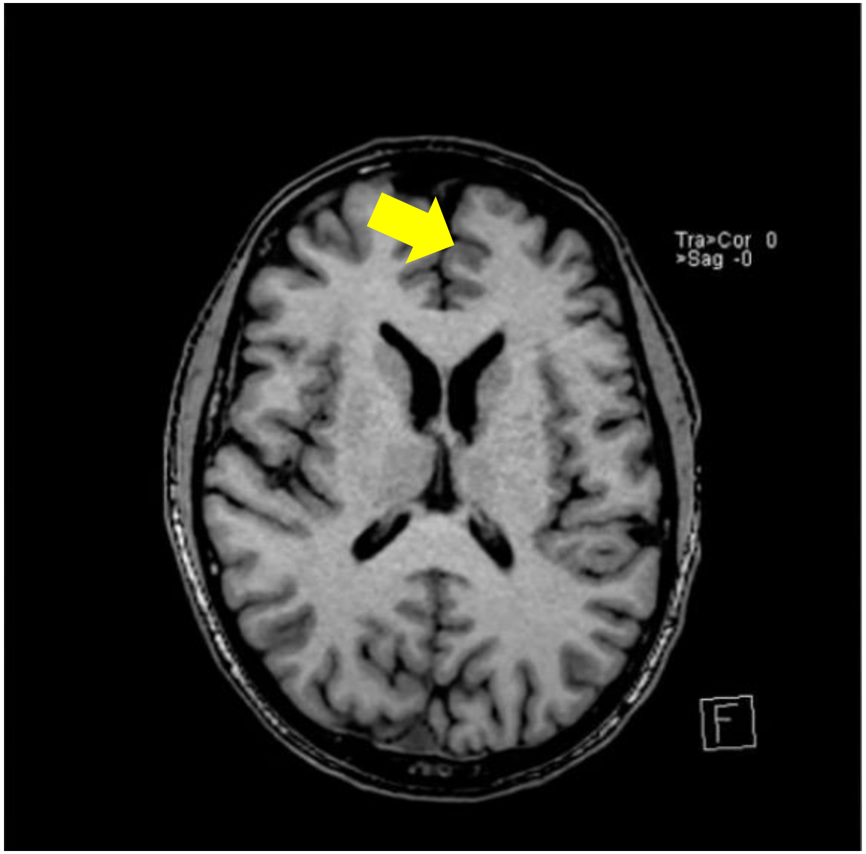


Credit: Dr. David Nascene

MRI Sequences (T1-Weighted Image)

- Fat: Bright
- Fluid: Dark
  cerebrospinal fluid (CSF)
- Gray matter is gray





Credit: Dr. David Nascene

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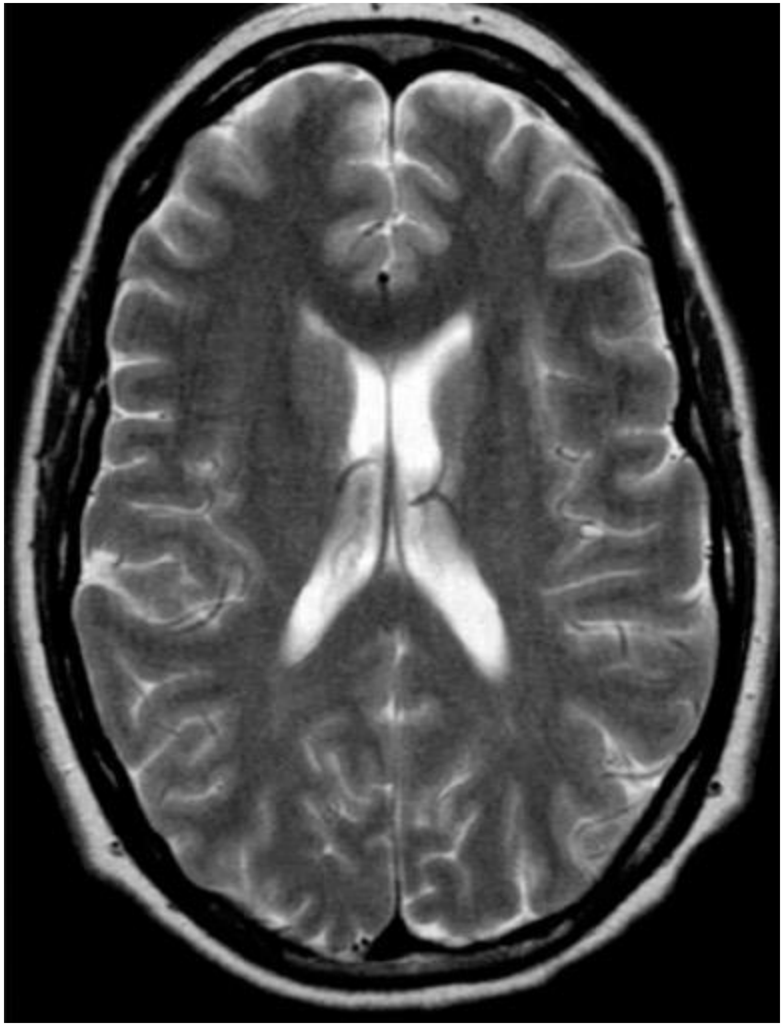
MRI Sequences (T1-Weighted Image)

- Fat: Bright
- Fluid: Dark
  cerebrospinal fluid (CSF)
- Gray matter is gray
- White matter is white

Credit: Dr. David Nascene

MRI Sequences (T2-Weighted Image)

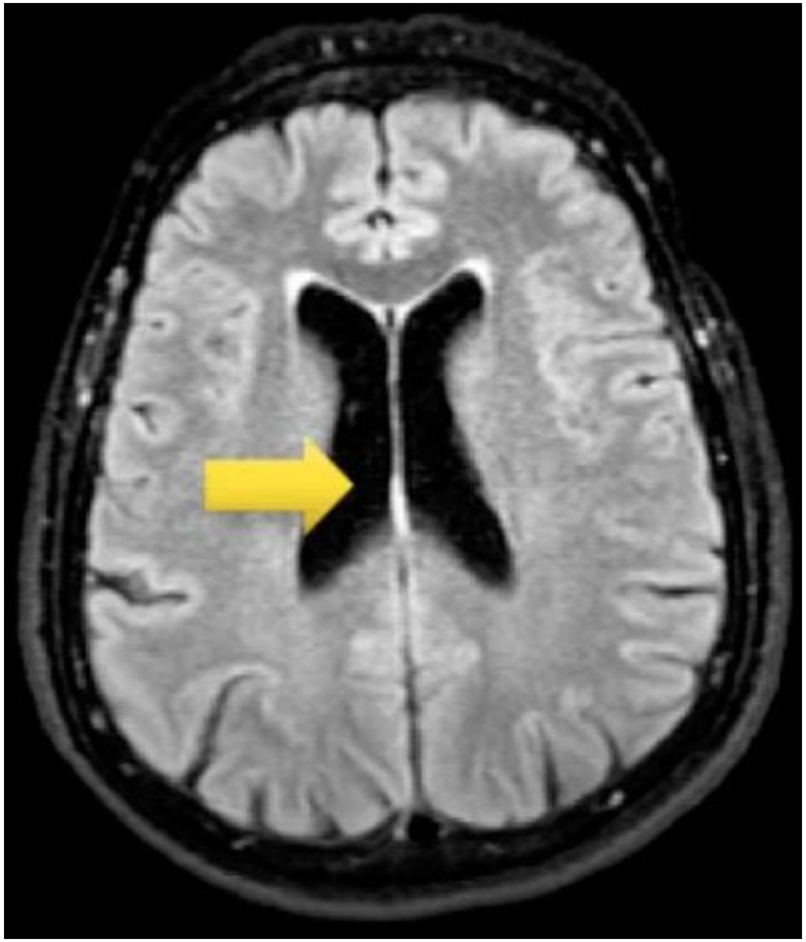
- Fat: Bright
- Fluid/CSF: Bright
- Gray matter: Bright
- White matter: Dark
- Good for detecting areas of **pathology**
  - Though FLAIR is more sensitive



Credit: Dr. David Nascene

MRI Sequences (FLAIR)

- FLuid Attenuated Inversion Recovery (FLAIR)
- Akin to T2-W with signal from free water (e.g. CSF) suppressed
- Most pathology exhibits bright signal on FLAIR



Credit: Dr. David Nascene

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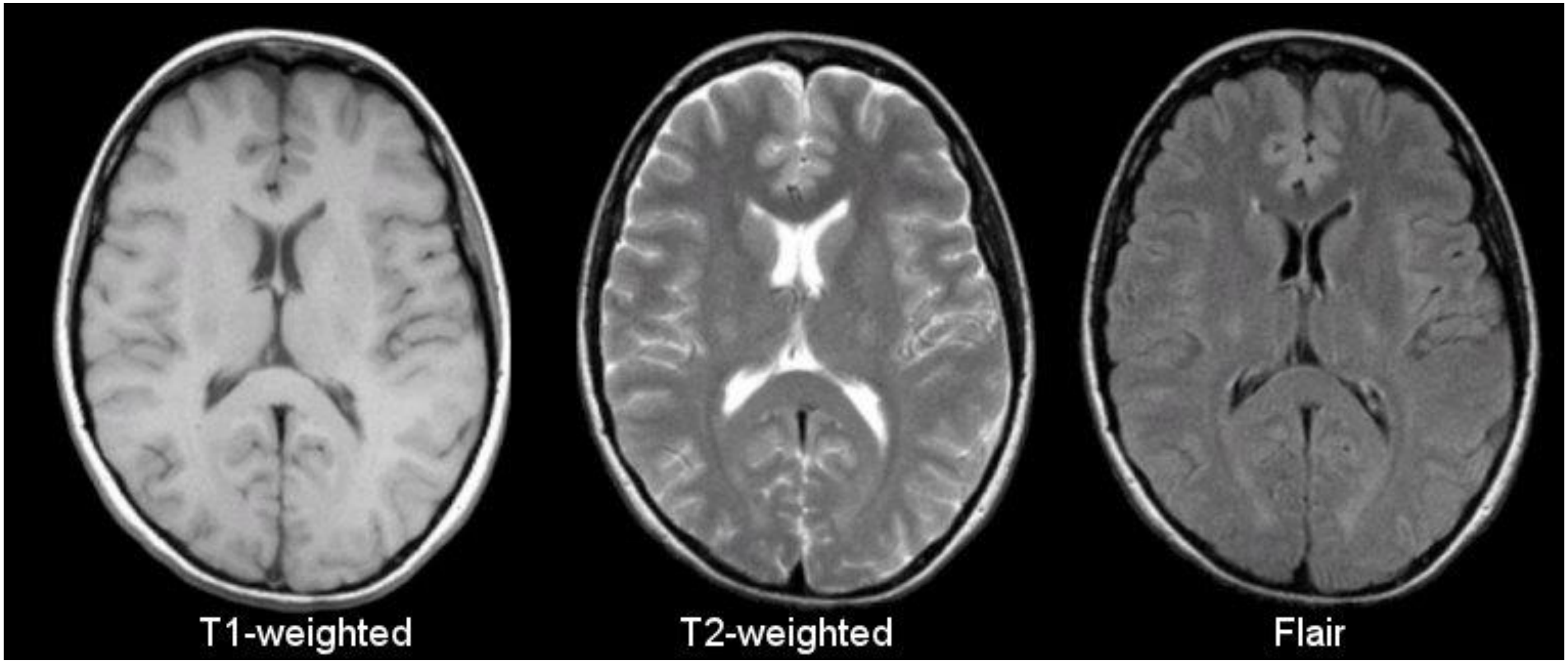
MRI Sequences (Comparison)



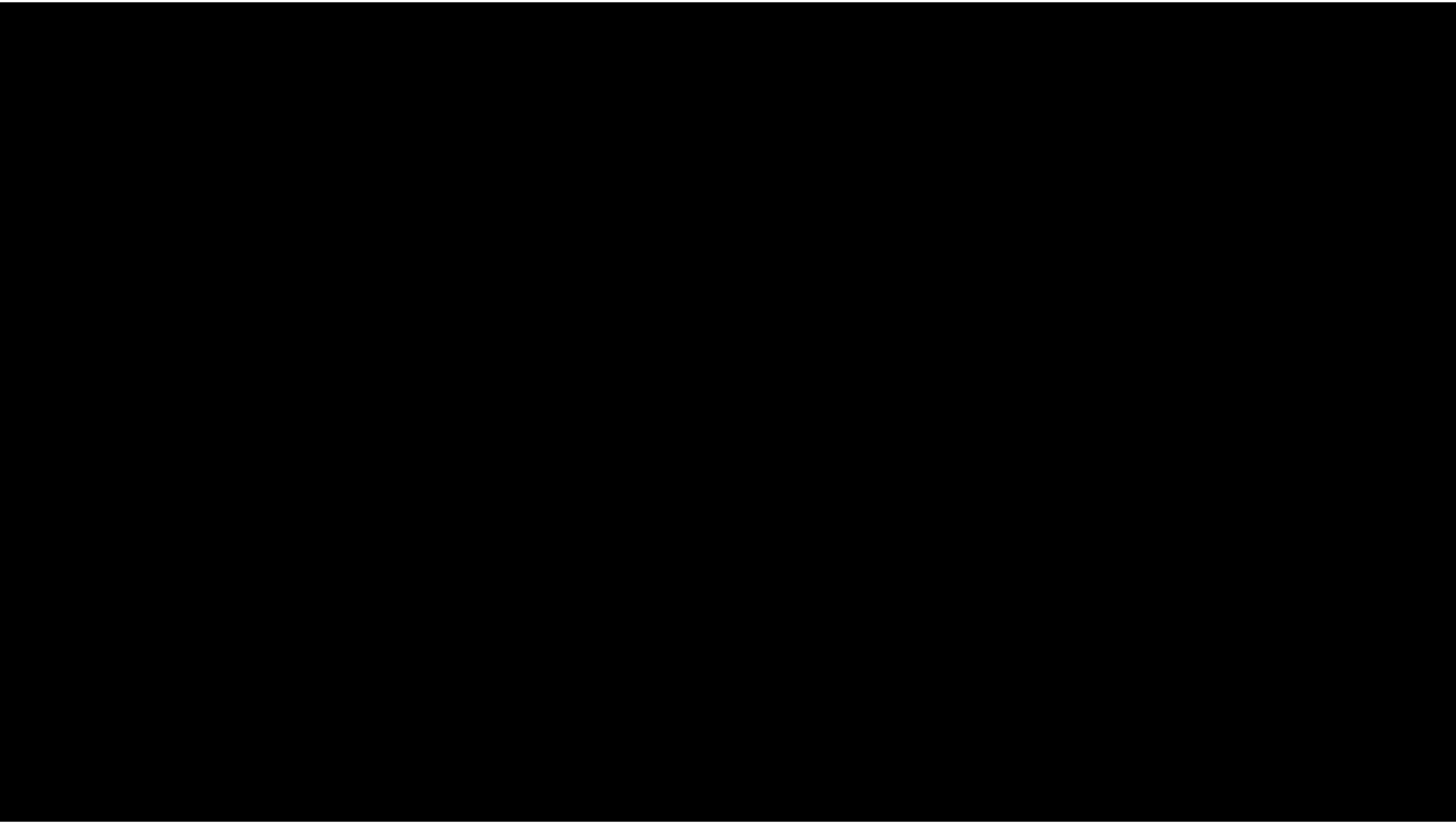
Tissue	T1-Weighted	T2-Weighted	Flair
CSF	Dark	Bright	Dark
White Matter	Light	Dark Gray	Dark Gray
Cortex	Gray	Light Gray	Light Gray
Fat (within bone marrow)	Bright	Light	Light
Inflammation (infection, demyelination)	Dark	Bright	Bright

https://case.edu/med/neurology/NR/MRI%20Basics.htm#:~:text=The%20most%20common%20MRI%20sequences,longer%20TE%20and%20TR%20times.

Appearance of common tissues on different MRI sequences

Tissue	T1-Weighted	T2-Weighted	FLAIR
Fat	Bright	Dark to Intermediate	Dark to Intermediate
Water/CSF	Dark	Bright	Dark
Fluid (Edema)	Dark	Bright	Bright
Gray Matter	Gray (Intermediate)	Light Gray	Light Gray
White Matter	Bright	Dark	Dark to Intermediate
Bone (Cortical)	Dark (Signal Void)	Dark (Signal Void)	Dark (Signal Void)
Muscle	Dark to Gray	Dark to Gray	Dark to Gray
Blood (Acute)	Dark	Variable (Depends on Phase)	Variable (Depends on Phase)
Pathology (e.g., Tumor, Edema)	Variable (Intermediate to Bright)	Bright	Bright

MRI Machine



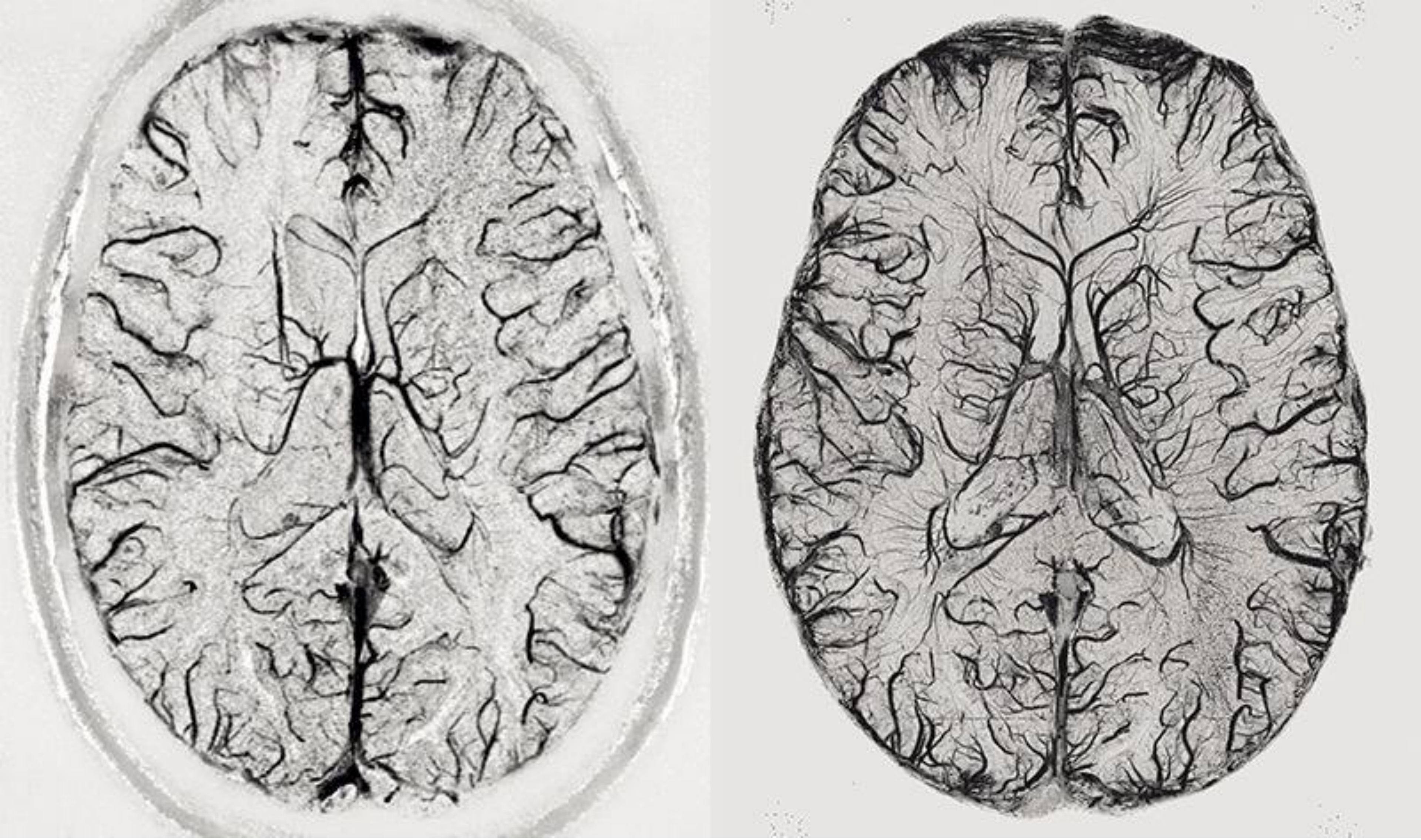
Source: https://www.youtube.com/watch?v=OBUeEfq6jEQ&t=1711s

Why MRI Machines Make Sounds

- **Gradient Coils Vibrate:**
  - Electric currents in gradient coils interact with the strong magnetic field, causing vibrations.
  - These vibrations produce the knocking, thumping, or buzzing sounds.
- **Different Sequences, Different Sounds:**
  - MRI sequences (T1, T2, FLAIR, etc.) use unique gradient patterns.
  - Faster sequences (e.g., EPI for fMRI) switch gradients rapidly, making louder, repetitive sounds.
  - Slower sequences have softer, less frequent sounds.
- **Gradient Strength and Speed:**
  - Stronger gradients = louder sounds.
  - Rapid switching = more frequent knocking or buzzing.

Safety in MRI

- MRI room has a strong magnetic field at all times, and it is strictly **prohibited to bring magnetic objects into MRI room.**
- In general, in preparation for the MRI examination, you will be **required to wear earplugs or headphones to protect your hearing** because many scanning procedures produce loud noises.



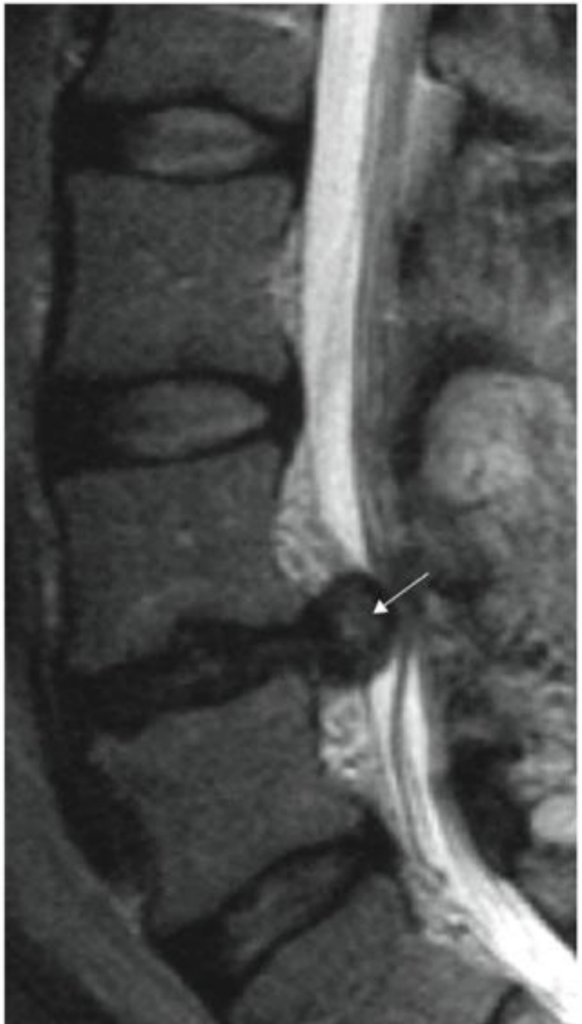
The brain of a volunteer is imaged using a 3-T (left) and 9.4-T (right) magnetic resonance imaging machine.Credit: Rolf Pohmann/Max-Planck-Institute for Biological Cybernetics (https://www.nature.com/articles/d41586-018-07182-7)

Nobel Prizes for MRI

- 1944: Isidor Isaac Rabi
  Physics (Measured magnetic moment of nucleus)
- 1952: Felix Bloch and Edward Mills Purcell
  Physics (Basic science of NMR phenomenon)
- 1991: Richard Ernst
  Chemistry (High-resolution pulsed FT-NMR)
- 2002: Kurt Wüthrich
  Chemistry (3D molecular structure in solution by NMR)
- 2003: Paul Lauterbur & Peter Mansfield
  Physiology or Medicine (MRI technology)

Clinical Use: Example

Use MRI to detect herniated disc



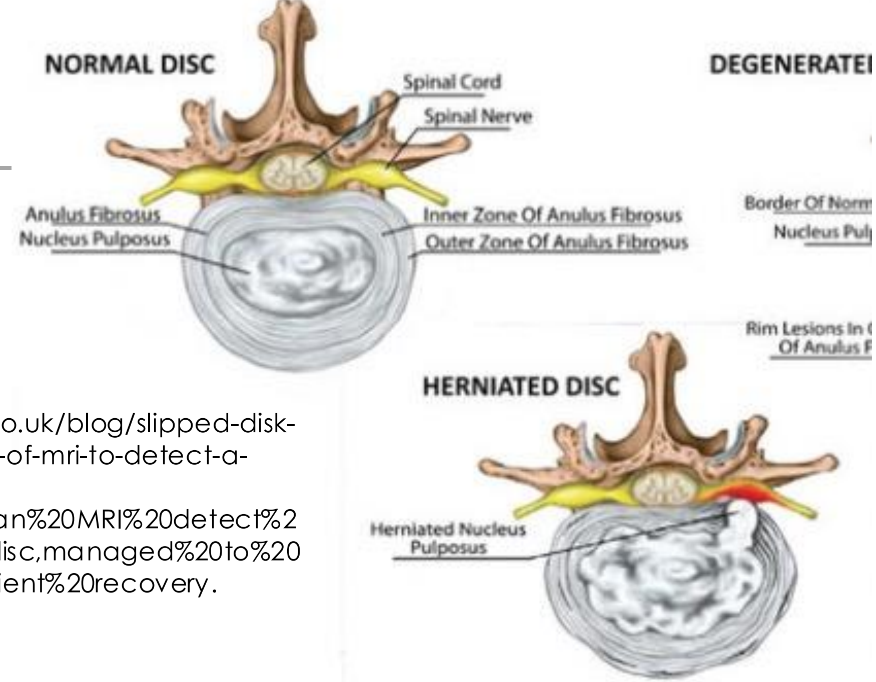
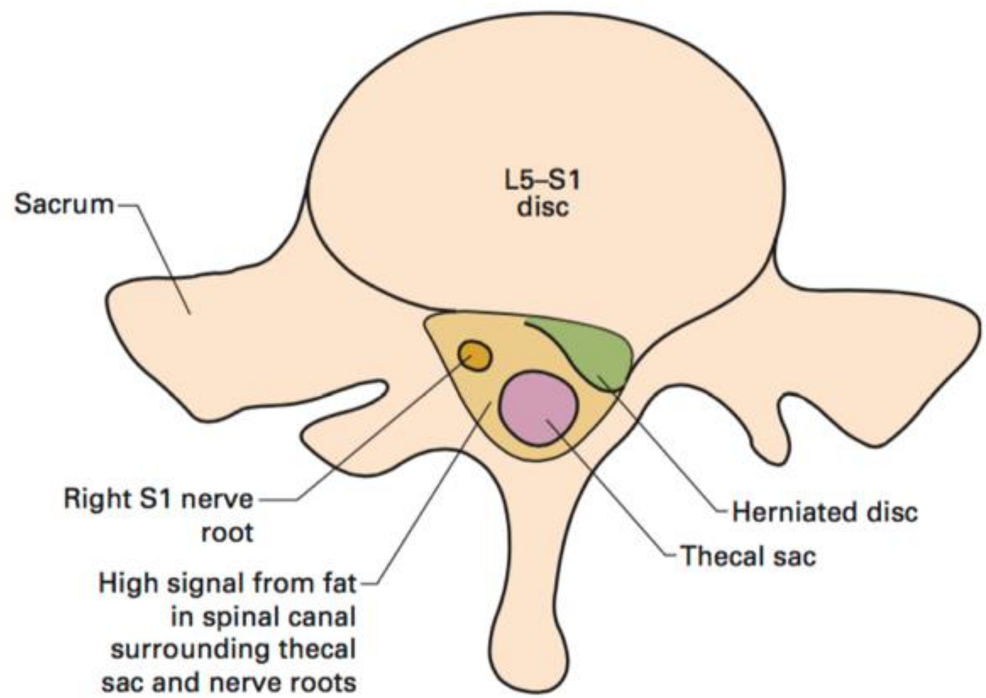
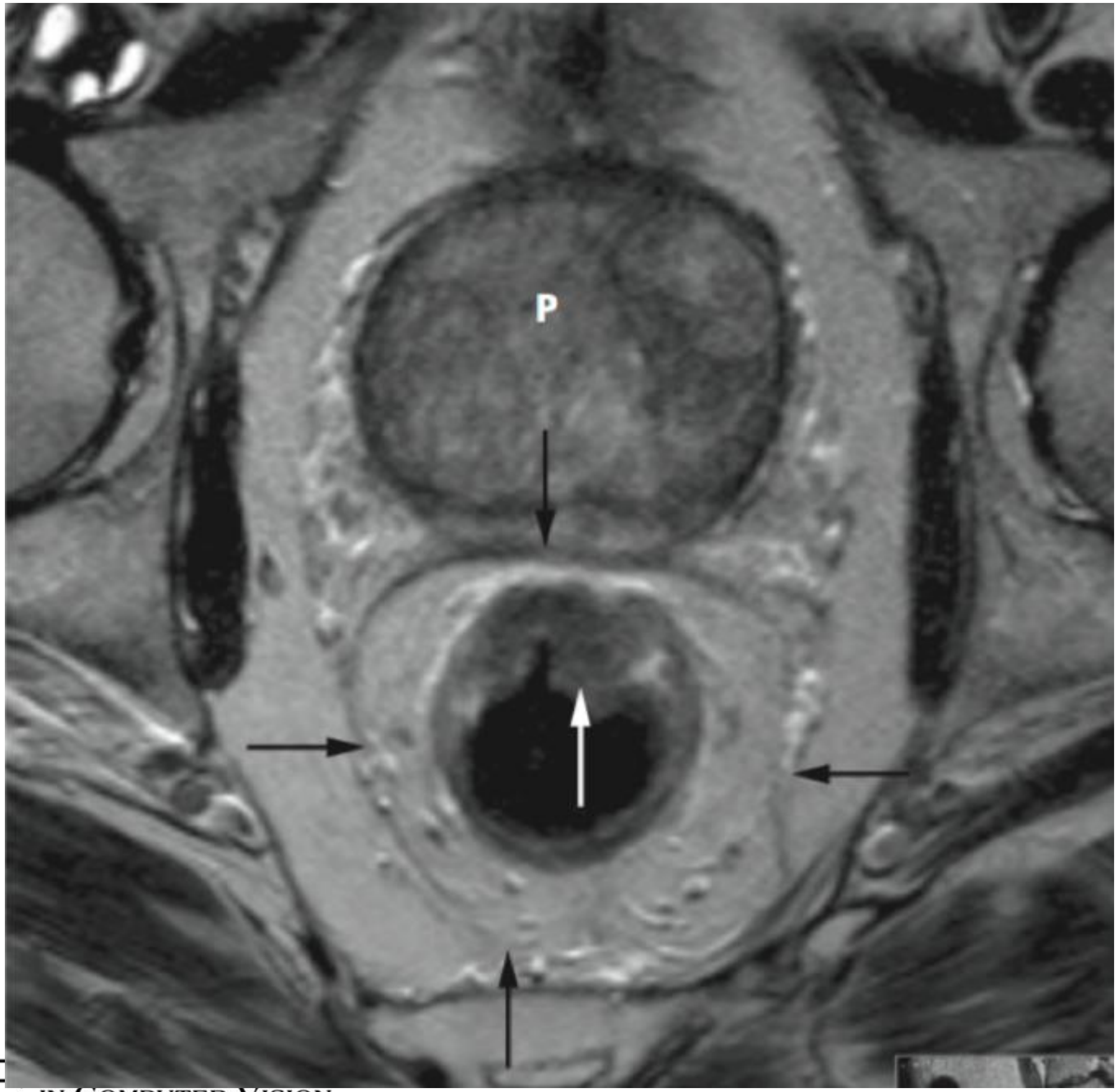


Image source: https://mriplus.co.uk/blog/slipped-disk-the-importance-of-mri-to-detect-a-herniated-disc/#:~:text=Can%20MRI%20detect%20herniated%20disc,managed%20to%20optimize%20patient%20recovery.



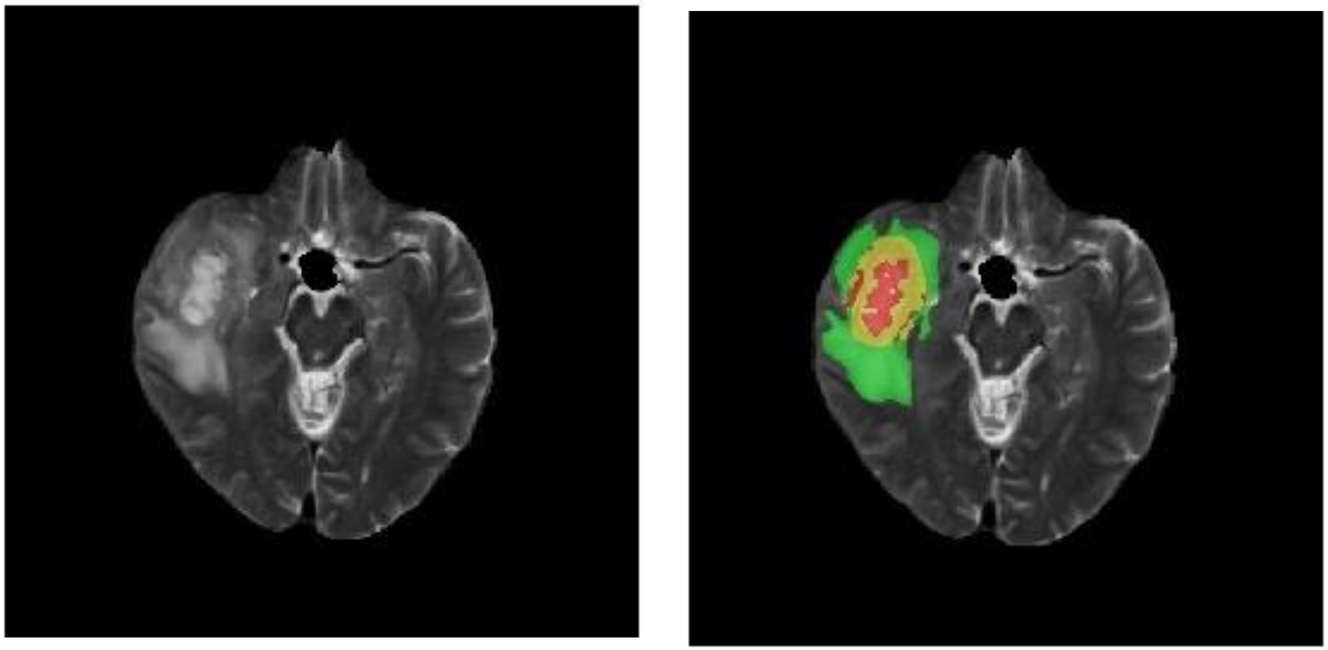
locate exactly the point on the spine that shows herniation

Clinical Use: Example



rectal tumor

Clinical Use: Example



Brain Tumor

Brain tumor

MRI vs. CT

Feature	MRI	CT (Computed Tomography)
Imaging Technique	Magnetic fields and radio waves	X-rays (ionizing radiation)
Best For	Soft tissues (e.g., brain, muscles, ligaments)	Bones, lungs, and dense structures
Radiation Exposure	No radiation (safe for repeated scans)	Uses ionizing radiation
Contrast in Images	Excellent soft tissue contrast	Better for visualizing dense structures
Speed of Scan	Slower (10–45 minutes)	Faster (a few minutes)
Noise Level	Loud, with knocking sounds	Quieter
Applications	Brain, spinal cord, joints, tumors	Bone fractures, lung disease, head trauma
Cost	Typically more expensive	Less expensive
Safety	Not suitable for patients with metal implants	Safe for most patients

Functional MRI (fMRI)

- Anatomical magnetic resonance imaging (MRI) provides excellent spatial resolution of head and brain anatomy.
- Functional magnetic resonance imaging (fMRI) is a technique for measuring and mapping brain activity that is noninvasive and safe.

Functional MRI (fMRI)

- Measures (primarily) brain activity through oxygen concentration in the blood flow.
- Relies on the fact that cerebral blood flow and neuronal activation are coupled.
- When area of the brain is active (in use), blood flow to that area also increases.
- fMRI is being used in many studies to better understand how the healthy brain works, and in a growing number of studies it is being applied to understand how that normal function is disrupted in disease (e.g. Alzheimer's disease).

https://my.clevelandclinic.org/health/diagnostics/25034-functional-mri-fmri

Functional MRI (fMRI)

Understanding MRI: What is functional MRI (fMRI)?

Source: https://www.youtube.com/watch?v=4UOeBM5BwdY

Functional MRI (fMRI)

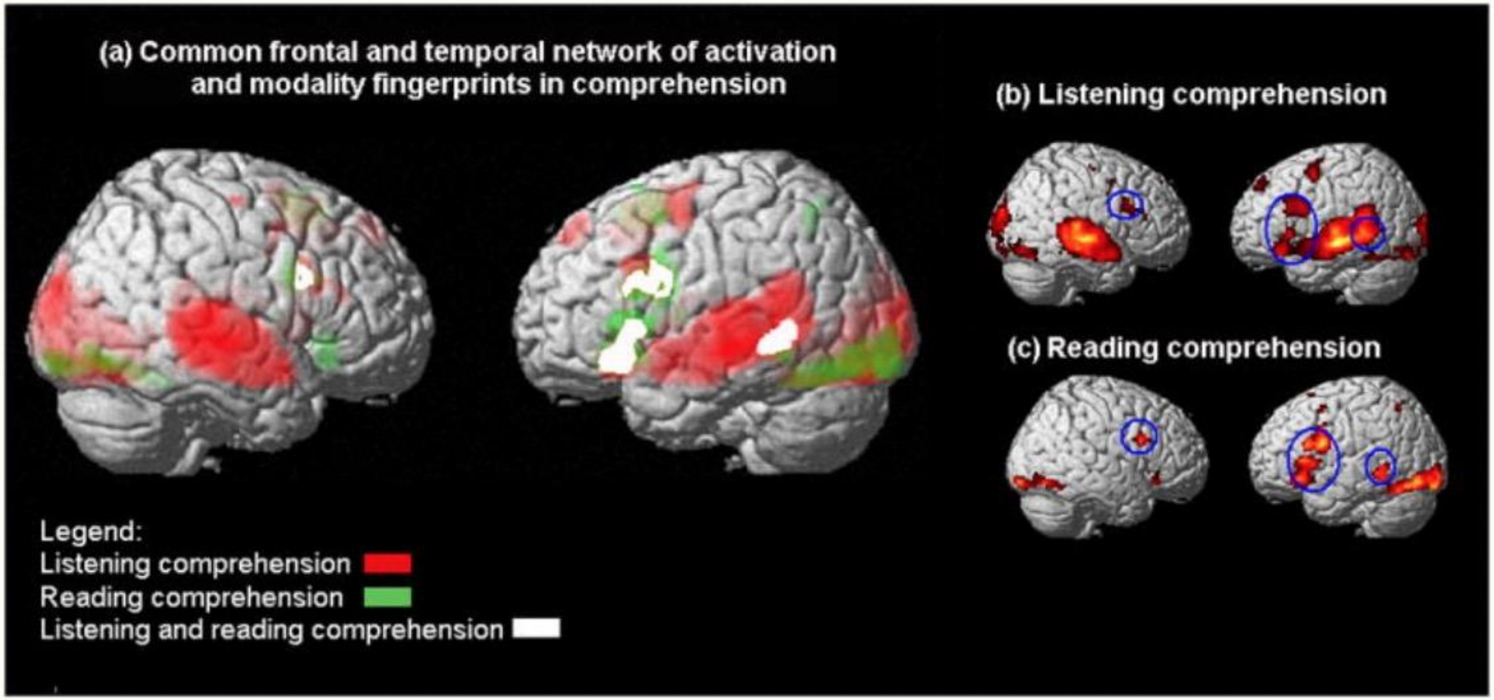
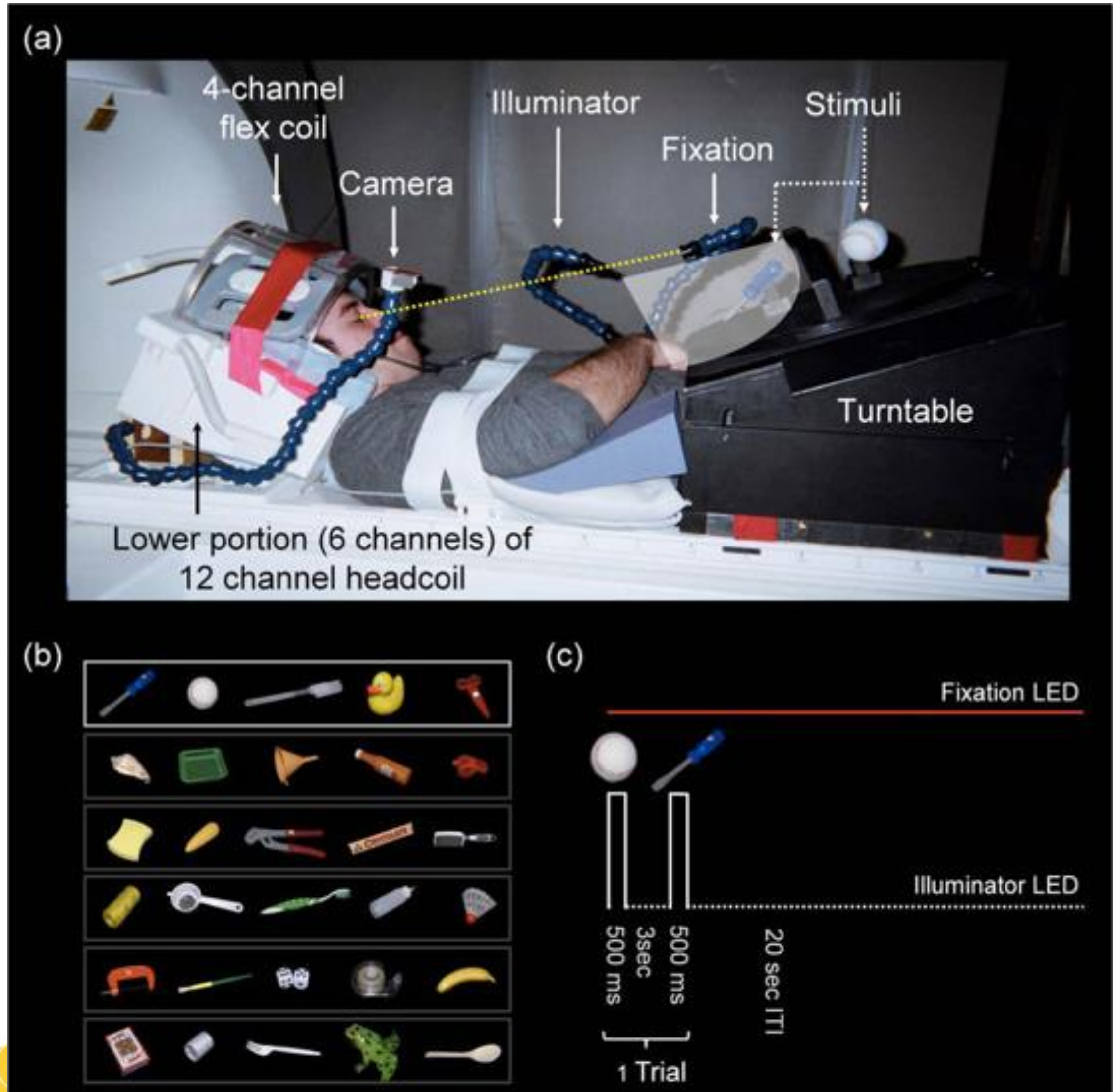


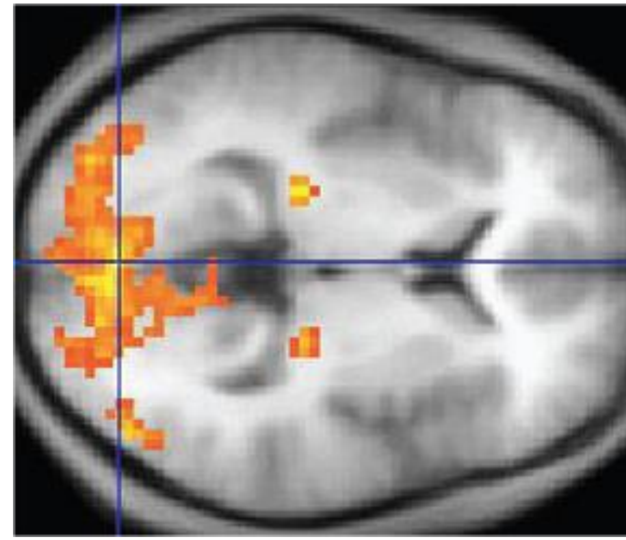
Figure 1

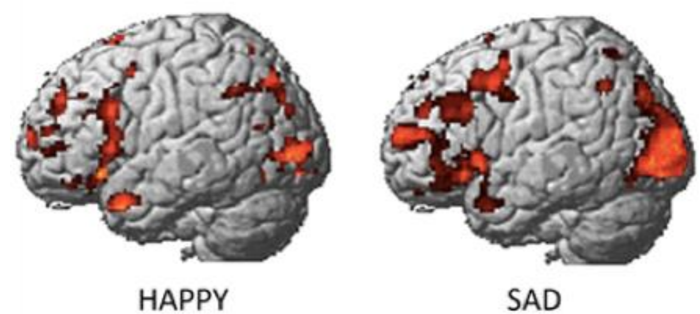
Cortical areas activated for listening and reading comprehension ($p < 0.001$, uncorrected; $T = 4.02$; extent threshold = 20 voxels; (a) illustrates the overlap of common subsets of cortical areas of activation for listening comprehension and/or reading comprehension contrasted with fixation (red = listening only; green = reading only; white = listening and reading), and shows the areas of activation (b) only in listening comprehension and (c) only in reading comprehension)

Buchweitz, Augusto, et al. "Brain activation for reading and listening comprehension: An fMRI study of modality effects and individual differences in language comprehension." Psychology & neuroscience 2.2 (2009): 111-123.

fMRI Settings







Active Regions

Applications of Functional MRI (fMRI)

- **Research Applications:**
  - Mapping brain functions (e.g., vision, speech, memory).
  - Studying mental health disorders (e.g., depression, anxiety).
  - Understanding learning and decision-making.
- **Clinical Applications:**
  - Pre-surgical planning for brain tumors.
  - Diagnosing conditions like epilepsy and stroke.
  - Studying neurodegenerative diseases (e.g., Alzheimer’s).
- **Emerging Uses:**
  - Studying the effects of meditation, exercise, and therapy.
  - Brain-machine interfaces.

Nuclear Medicine Imaging

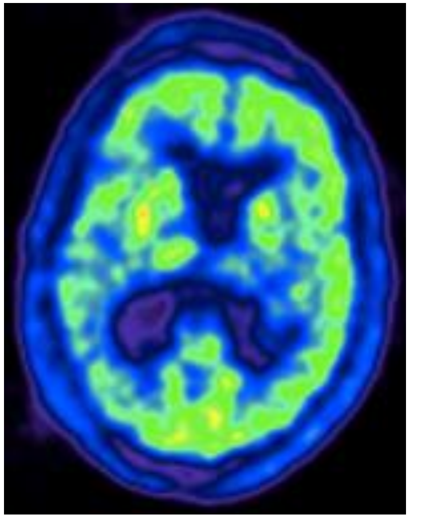
- Nuclear medicine is a medical specialty that uses radioactive tracers to assess bodily functions and to diagnose and treat disease.

- Specially designed cameras allow doctors to track the path of these radioactive tracers.

Nuclear Medicine Imaging – PET/SPECT

Key Modalities:

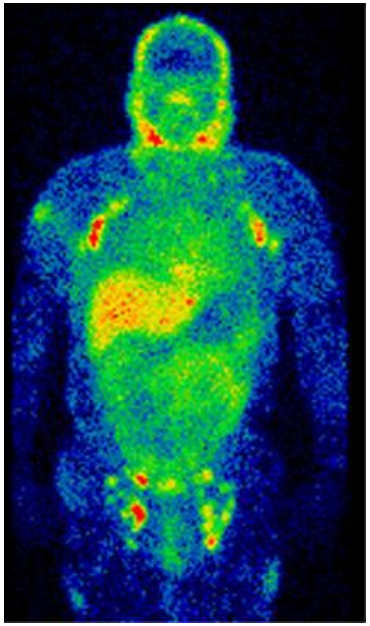
- **PET (Positron Emission Tomography):** Measures metabolic activity.
- **SPECT (Single Photon Emission Computed Tomography):** Measures blood flow and function.



https://www.nibib.nih.gov/science-education/science-topics/nuclear-medicine

Nuclear Medicine Imaging – PET/SPECT

- The tracer is radioactive, which means your body is exposed to radiation.
- This exposure is limited, however, because the radioactive chemicals have short half-lives. They breakdown quickly and are removed from the body through the kidneys.



https://www.nibib.nih.gov/science-education/science-topics/nuclear-medicine

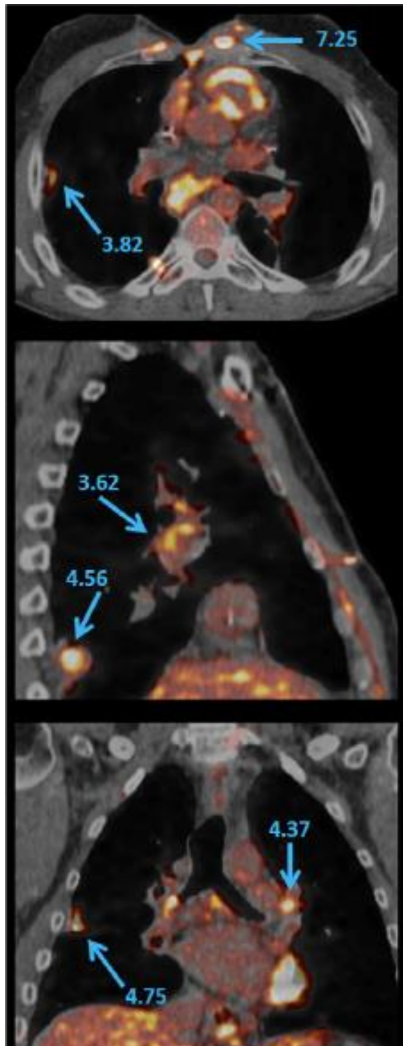
Nuclear Medicine Imaging – PET/SPECT

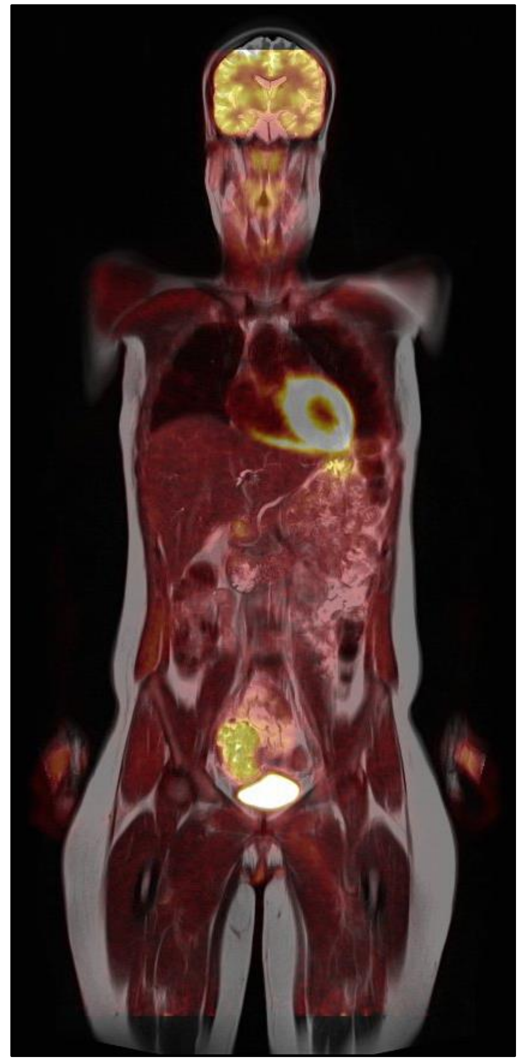
- The main difference between SPECT and PET scans is the type of radiotracers used.

Feature	**PET (Positron Emission Tomography)**	**SPECT (Single Photon Emission Computed Tomography)**
Radiation Type	Positrons (antimatter particles)	Gamma rays
Tracer Example	FDG (Fluorodeoxyglucose) for glucose uptake	Technetium-99m for blood flow
Resolution	Higher resolution	Lower resolution
Cost	More expensive	Less expensive
Applications	Cancer, brain disorders, cardiac function	Heart disease, bone scans, thyroid function

PET/CT and MRI/PET (Hybrid Imaging)

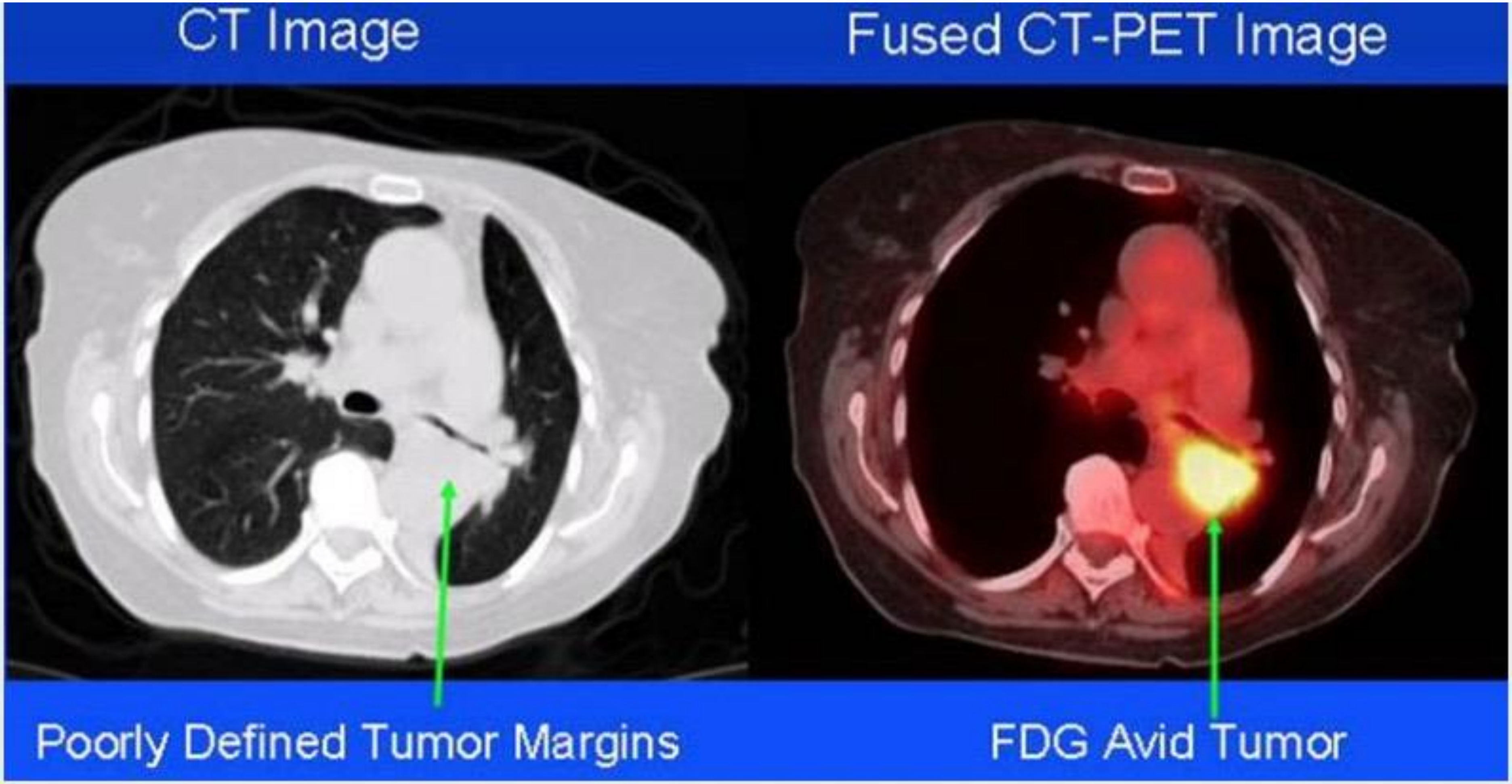
PET/CT





MRI/PET

Clinical Use of PET: Example



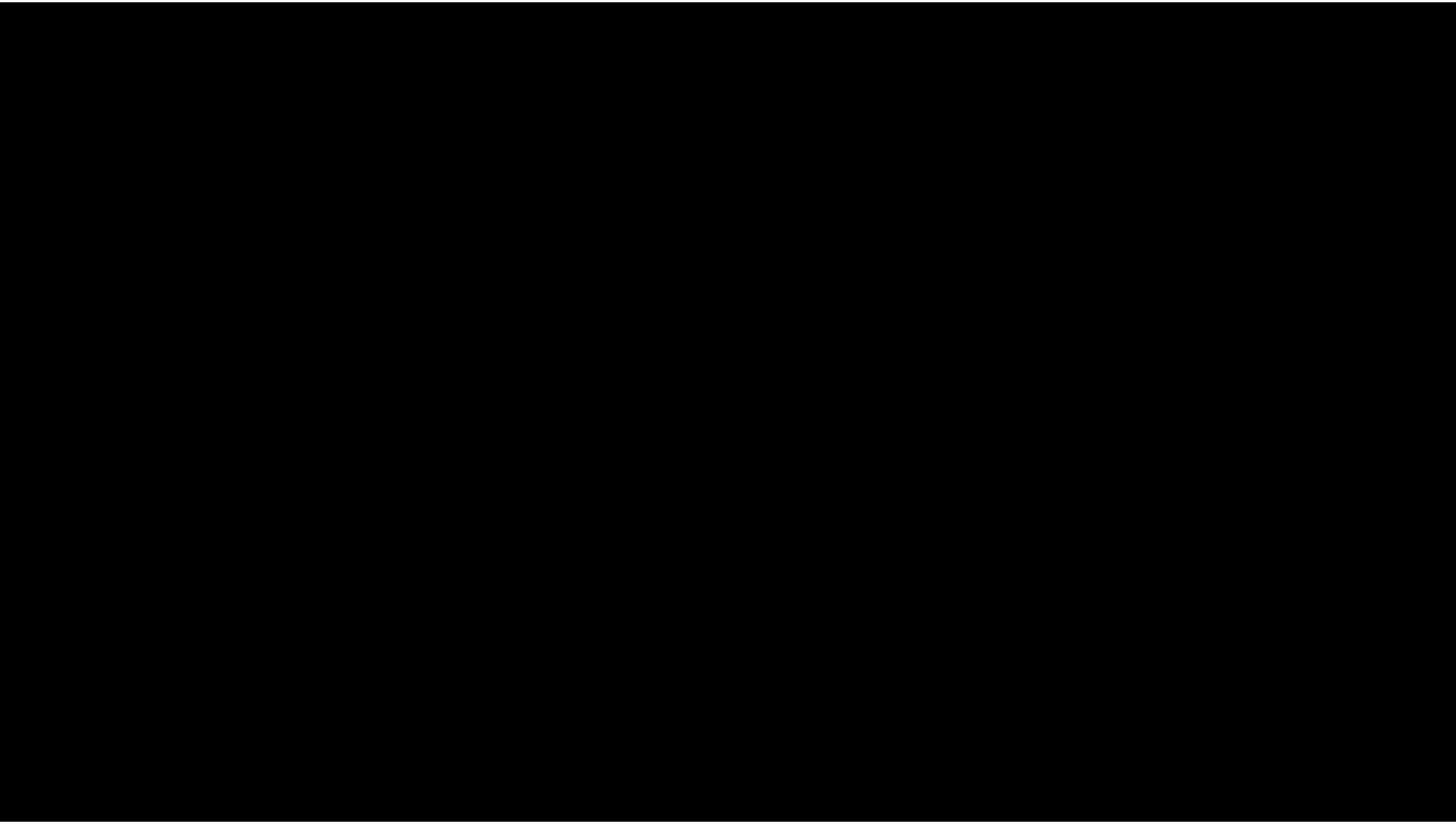
Fused CT-PET scans more clearly show tumors and are therefore often used to diagnose and monitor the growth of cancerous tumors.

https://www.nibib.nih.gov/science-education/science-topics/nuclear-medicine#:~:text=The%20main%20difference%20between%20SPECT,an%20electron%20but%20oppositely%20charged.

Serial and Simultaneous MRI/PET

Past

Now!



SPECT/CT Scan animation

Source: https://www.youtube.com/watch?v=2z_BBCVRD8Q

Nuclear Medicine vs. Radiology

- Nuclear medicine images organ function
- Radiology assesses anatomy

- Nuclear medicine uses radioactive drugs, injected into the patient’s bloodstream, images are then obtained based on the radioactive decay of the drug
- Radiology uses an external source of energy

Credit: Dr. Paulien Moyaert

- Demo of using ITK-Snap for visualizing MRI data

References and Slide Credits

- P. Suetens, Fundamentals of Medical Imaging, Cambridge Univ. Press.
- **ITK.org**
- **siemens.com**
- **slicer.org**
- MRI Made Easy (free, easy book): https://rads.web.unc.edu/wp-content/uploads/sites/12234/2018/05/Phy-MRI-Made-Easy.pdf
- https://www.nibib.nih.gov/science-education/science-topics/magnetic-resonance-imaging-mri
- https://case.edu/med/neurology/NR/MRI%20Basics.htm#:~:text=The%20most%20common%20MRI%20sequences,longer%20TE%20and%20TR%20times.
- https://my-ms.org/mri_basics.htm
- Some slides are adapted from Dr. Ulas Bagci's course materials