“REVEALING THE HUMAN BODY’S INNER SECRETS” – AN OVERVIEW OF POPULAR IMAGING MODALITIES

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Never Stand Still | Faculty of Engineering | Graduate School of Biomedical Engineering

Dr Mohit Shivdasani

Graduate School of Biomedical Engineering, UNSW

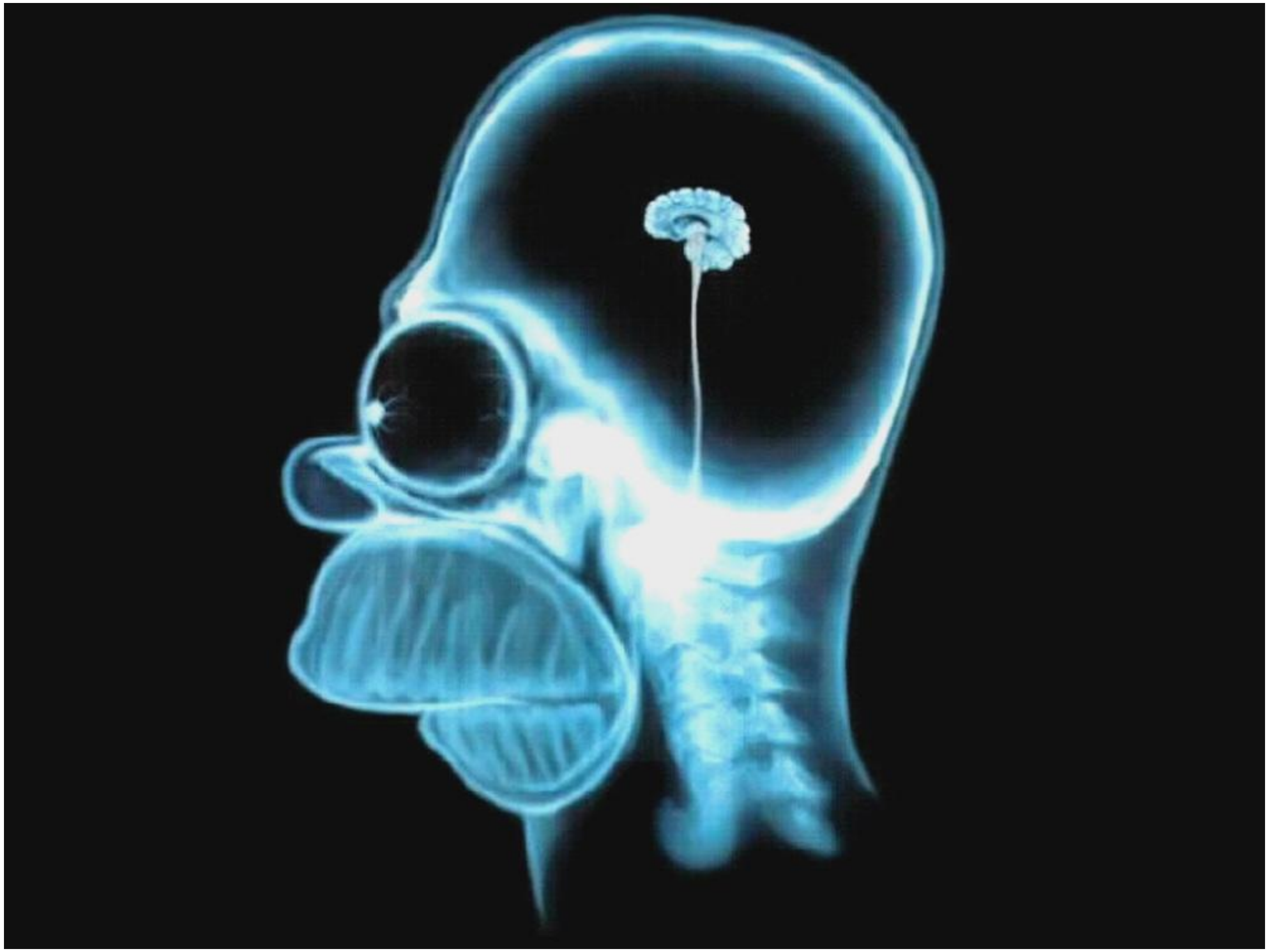
Little Bit About Me

- 2002 - Completed Bachelor of Biomedical Engineering in Mumbai, India
- 27th Feb 2003 - Came to Melbourne as an International Master's Student
- Dec 2003 - Completed Master of Electronic Engineering (Biomedical) from La Trobe University
- 2009 - Completed PhD in Auditory Neuroscience
- 2009-2017 - Worked at the Bionics Institute in Melbourne on developing a bionic eye for vision restoration
- Feb 2018 – Moved to Sydney and joined GSBmE … Research and Teaching – BIOM9660 (Bionics and Neuromodulation)

Why Am I Here Today?

- Semester 2, Third year of my degree – Interviewed for Industry Training
- Selected to Join GE Healthcare, Mumbai to Learn About Their Medical Imaging products
- Traveling to Various Imaging Centres/Hospitals on Service Calls (Not Alone!)
- Build Relationships With Clinicians/Doctors
- Filled Liquid Helium in MRI magnets!
- 6 months Flew By Quite Quickly

Why Do We Need Imaging



Unveil Secrets and Record Them Forever!

Why Do We Need Medical Imaging

Non-invasive visualisation of internal organs and tissues.

2D signal $f(x,y)$ – eg X-ray (radiography)

3D $f(x,y,z)$ – eg Magnetic Resonance Imaging (MRI) and Computed Tomography (CT).

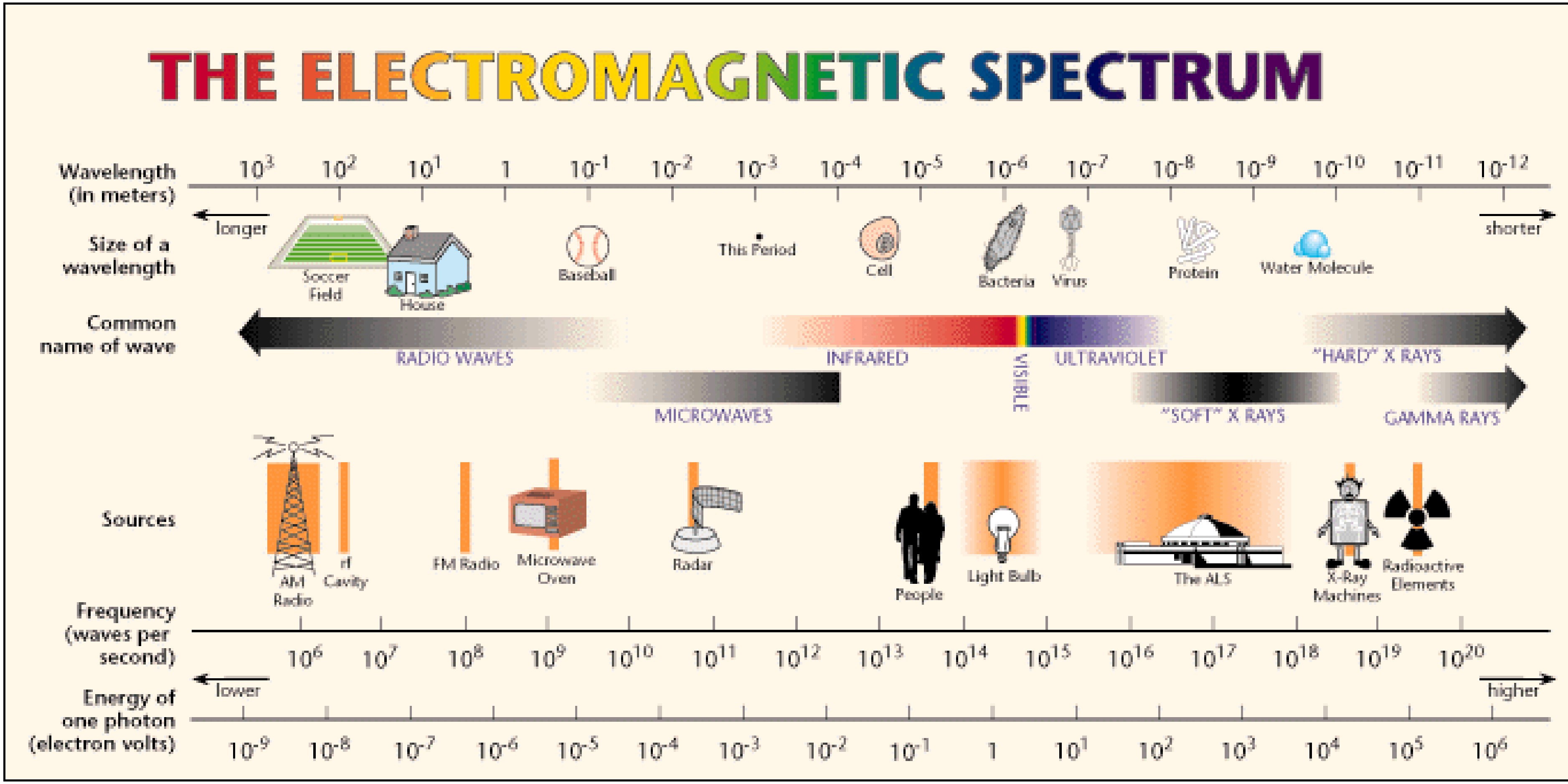
Catapulted By Discovery of X-Rays – 08/11/1895

Willhelm Conrad Röntgen
(Lover of Cathode Rays)

“So This is What Death Looks Like”

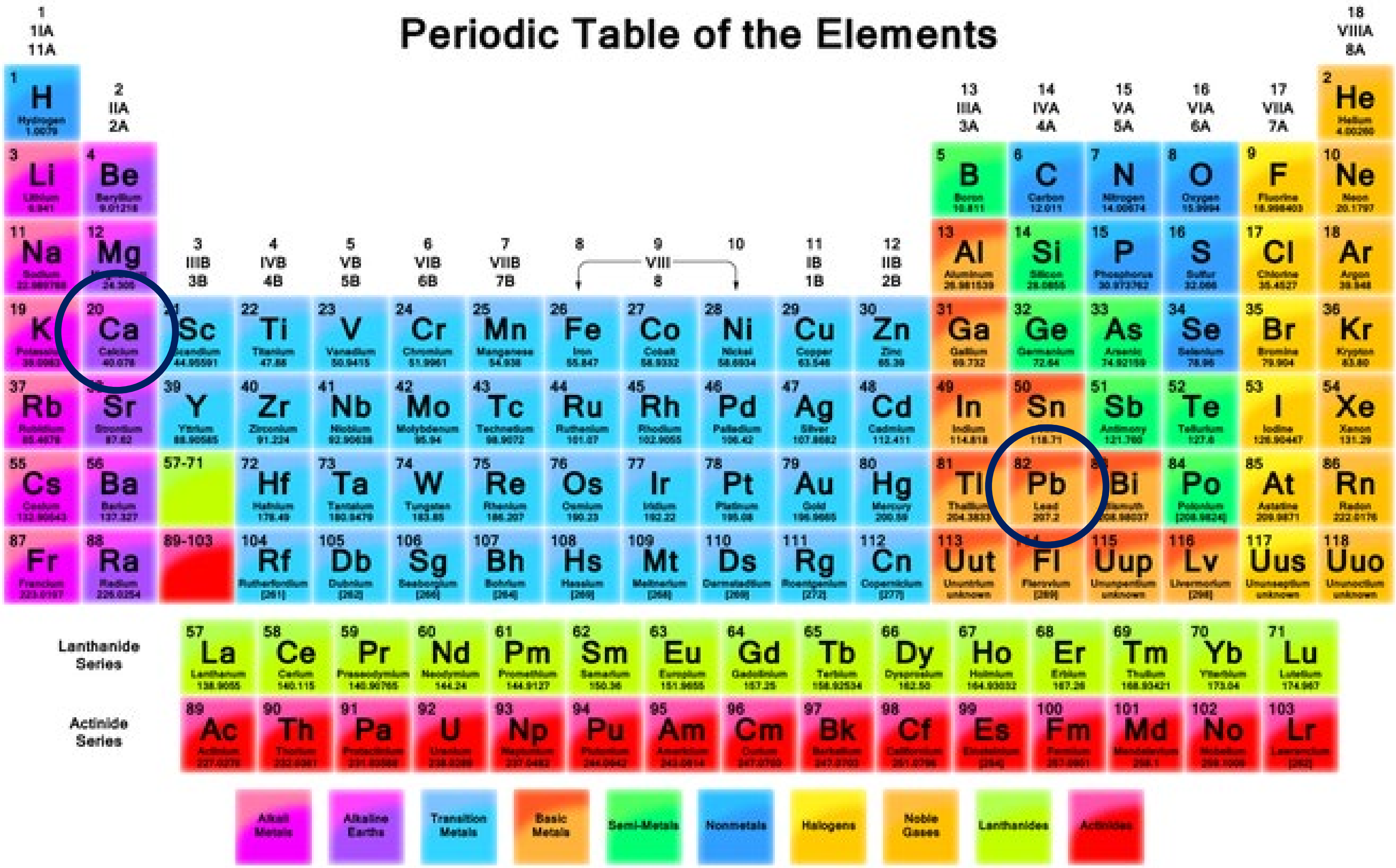
1901, Nobel Prize in Physics – Foundations of Modern Imaging

Where Do X-Rays Fit in With The Various "Waves" of Light



The Energy in Shorter Wavelengths Can be Pretty Phenomenal!

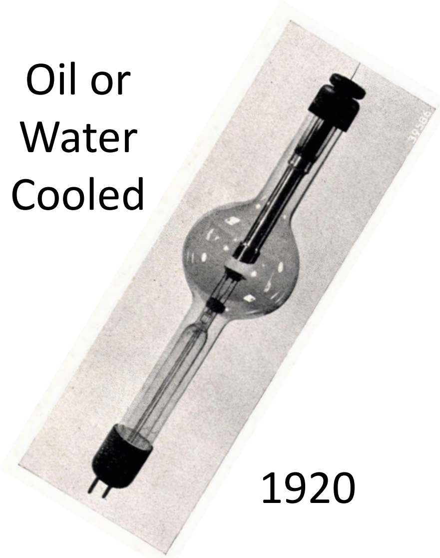
X-Rays Can Penetrate Matter (Well … Most Matter)



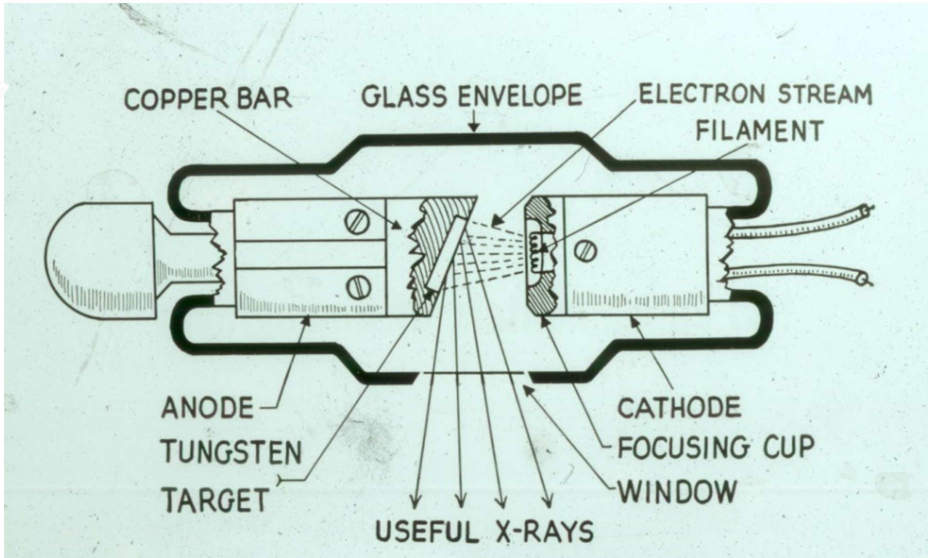
X-Ray Tube

- Energy converter
  - Electrical energy to X-Rays and Heat (undesirable by-product)
  - Special X-Ray Tube To Maximise Production
- High (Very High) Speed Cathode Rays Emitted From a Cathode (Super Heated Filament)
- Cathode Rays Strike “Big and Heavy Duty” Anode – Usually Tungsten (Heavy Metal, High Melting Point) & X-Rays Are Produced!

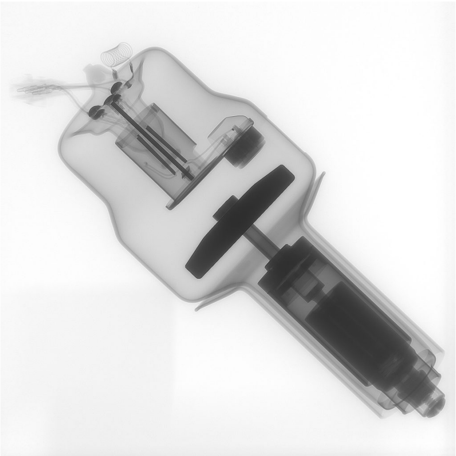
Oil or Water Cooled



1920

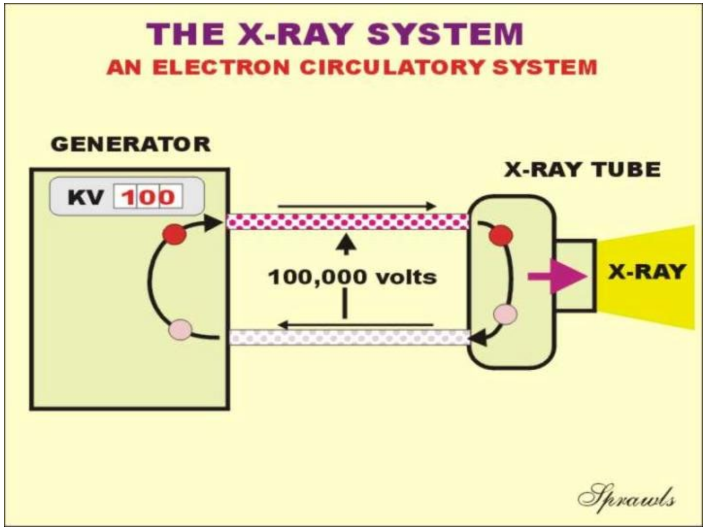


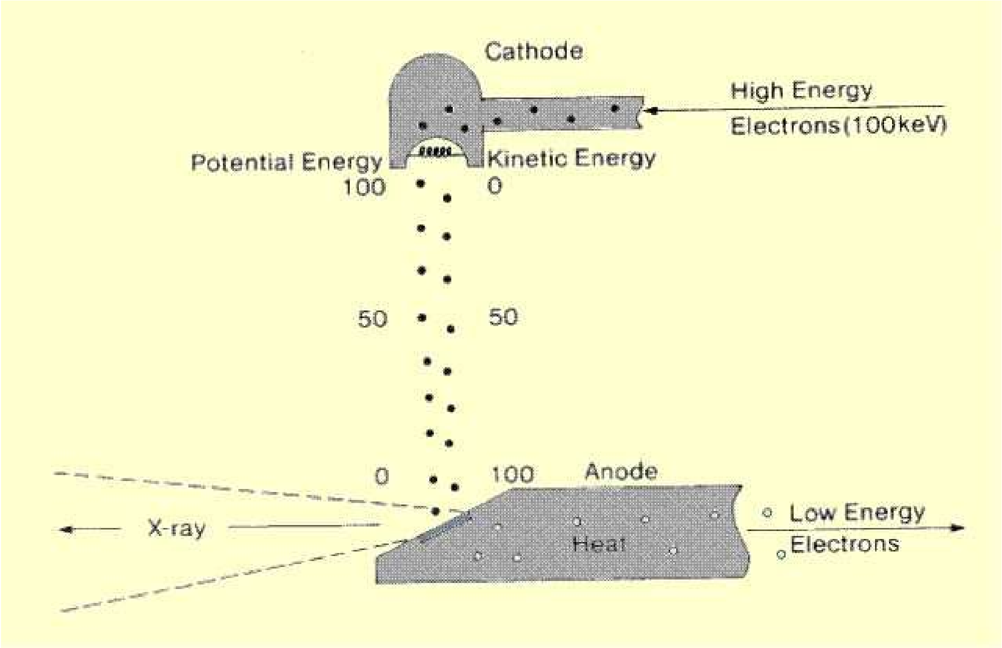
Rotating Anode

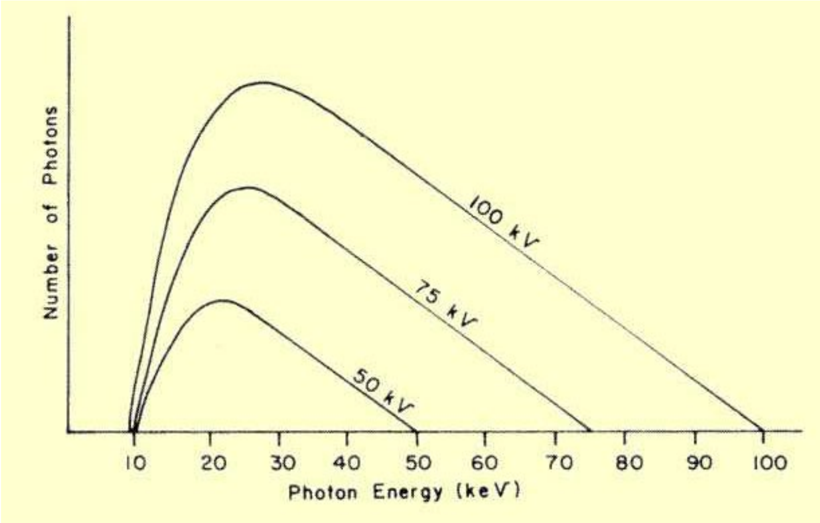


1960s - Today

The "Power Source"





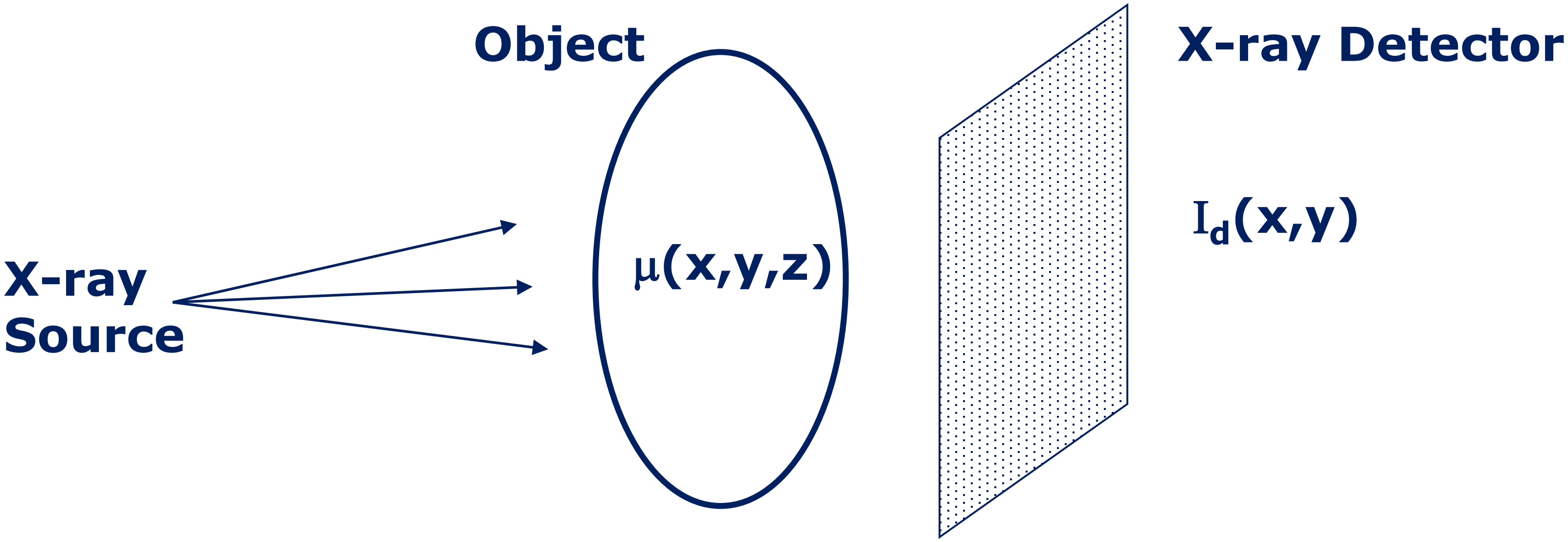


Energy And Number of X-Ray Photons Directly Proportional To Applied kV

Principles of X-Ray Projection

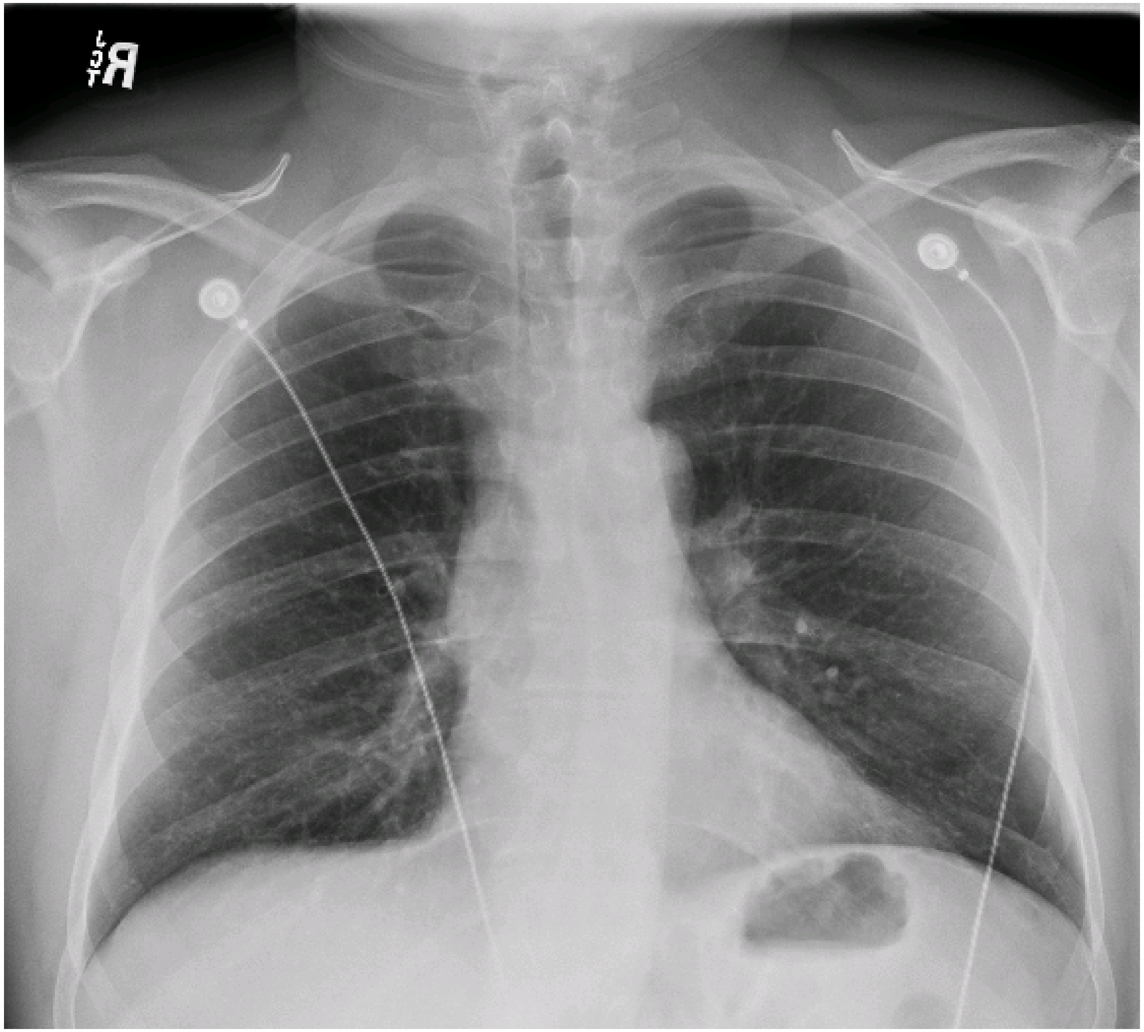
- Image records transmission of x-rays through an object – Different Objects Have Different "Radiopacity" To X-Rays

$$I_d(x,y) = I_0 \exp(-\int \mu(x,y,z)dl)$$



- The integral is a line-integral or a "projection" through object
- $\mu(x,y,z)$ – x-ray attenuation coefficient, a tissue property, a function of electron density, atomic number, thickness…

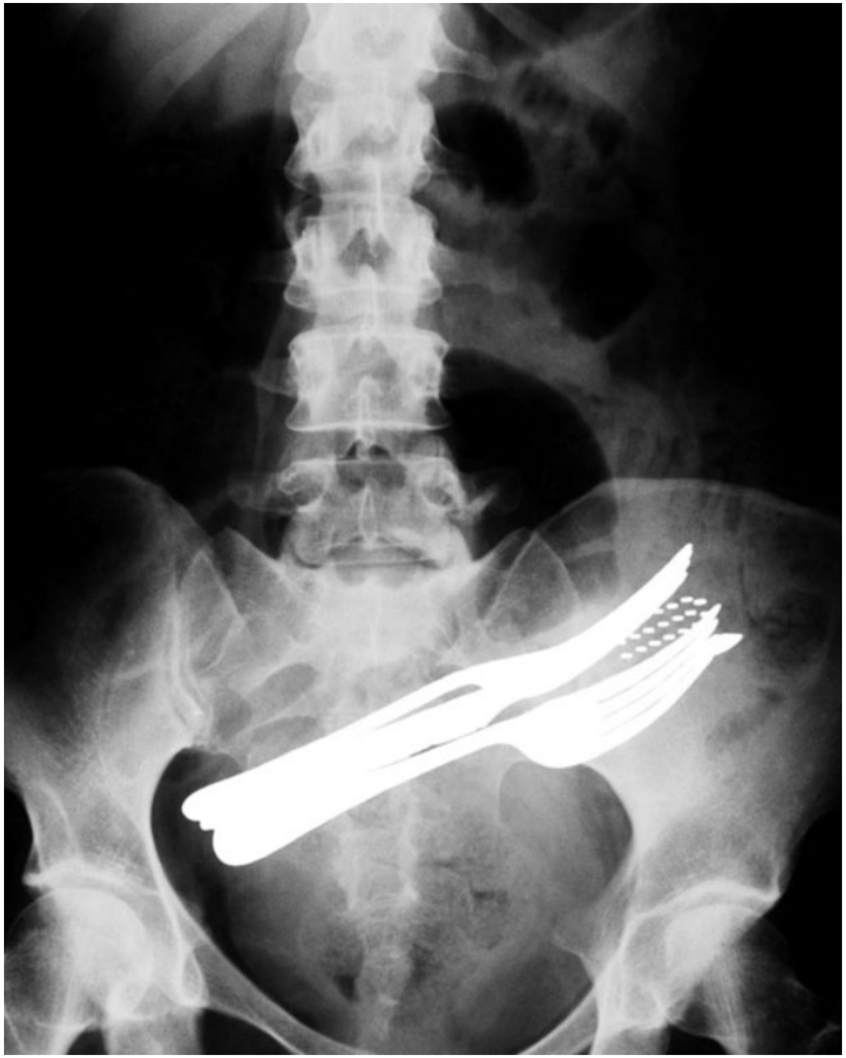
White – Absorbed, Black = Passed



Why You May Ask?

- All Tissues Have Different Absorption Capabilities – Atomic Number is the Key (Higher for Denser Tissue)
- Also X-Ray Energy Dependent; Higher Energy = More Penetration
- X-rays That Pass Through the Body to the Film (Outdated ….. Now it's all CCD!) = Black
- X-rays That Are Totally Blocked (not really possible in reality) Do Not Reach the Film (Detector) = White

What The _ _ _ _ Is That ….. ??



DESCENDING ORDER OF RADIOPACITY:

Metals >>>> Bone >>>>Nylon!! >>>> Soft Tissue >>>> Fat >>>> Air

We Live in An RGB World

X-Rays Don't Generate Colour!! Simply a Reassignment of Gray-Scales to Colour ….

What About Cartilage?

No Calcium So More Similar To Soft Tissue Rather Than Bone

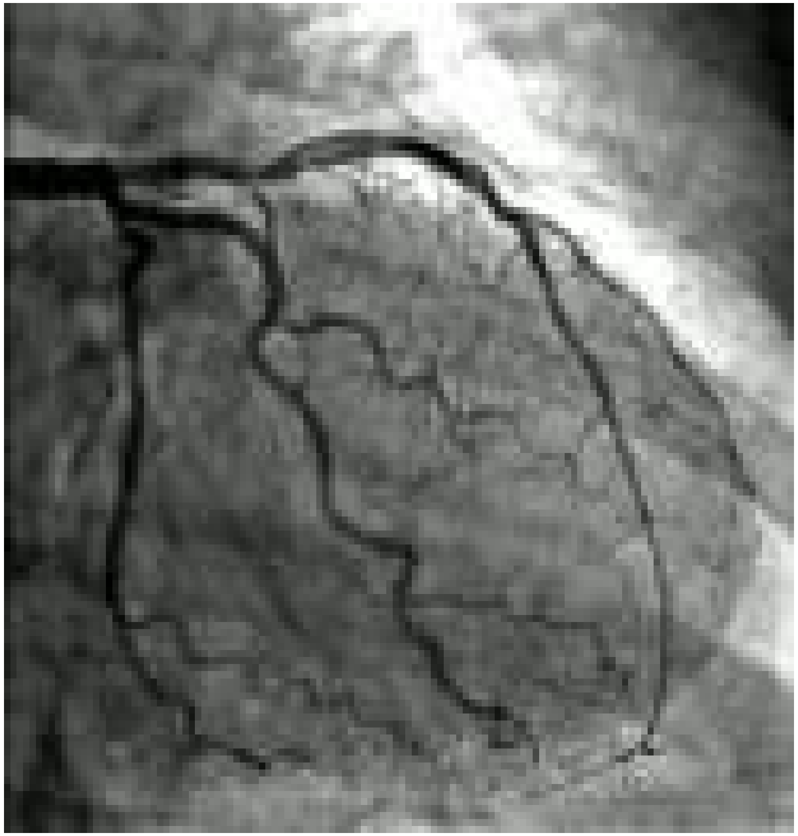
X-Ray With Contrast

- Radiopaque Agents Can be Introduced into Hollow Organs (eg Gastro-intestinal Tract and Blood Vessels) to Make Them Appear!

- Contrast Agent Must Be:
  - Inert
  - Non-toxic
  - Not be absorbed or retained by the body
  - Easily excreted

- Conventional (Invasive) Coronary Angiography – Large Catheter Threaded Through Groin or Waist Artery into Heart and Contrast Dye Injection

Catheter Laboratories (Cath-Lab)



"Intra-Operative Monitoring of Structures"

Can X-Rays Be Viewed in 3D?

YES THEY CAN !!!!

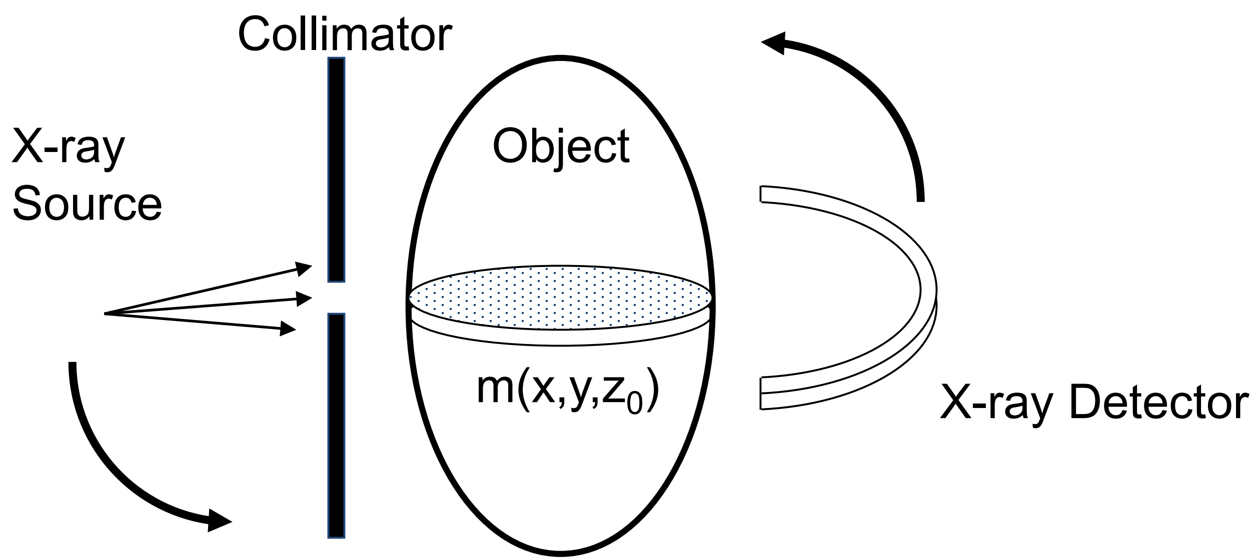
IT’S CALLED

<u>C</u>OMPUTED **<u>A</u>**XIAL **<u>T</u>**OMOGRAPHY

(A CAT SCAN)

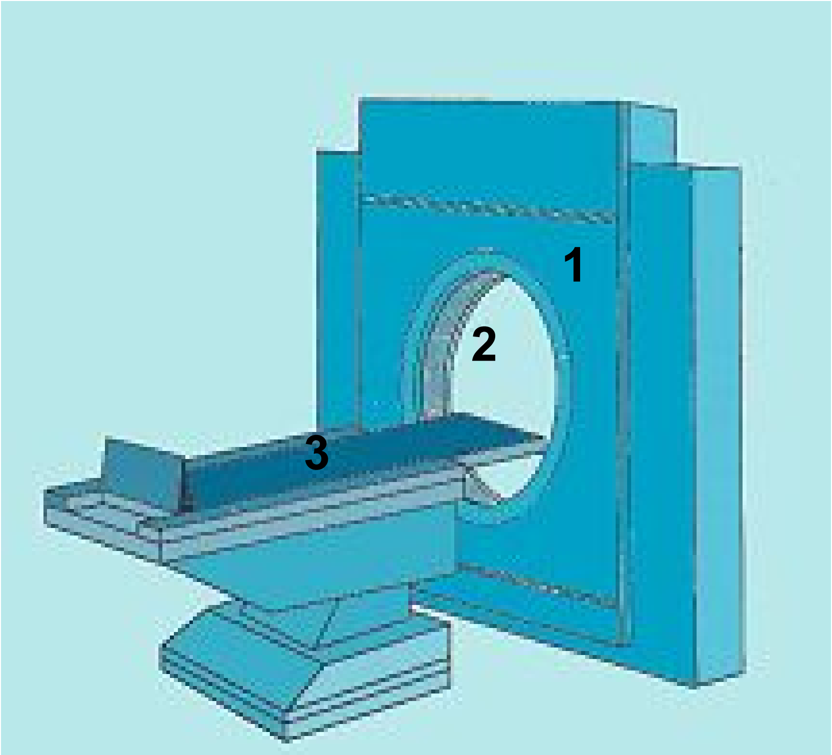
Principles of CT

- Uses X-rays, But Exposure Limited to a Slice by a Collimator
- Source and CCD Detector Rotate Around the Object (2D Projections from Many Angles)
- Takes Serial Pictures Synthesized by a Computer
- Re-construct to 3D!



Principles of CT

One Slice At a Time

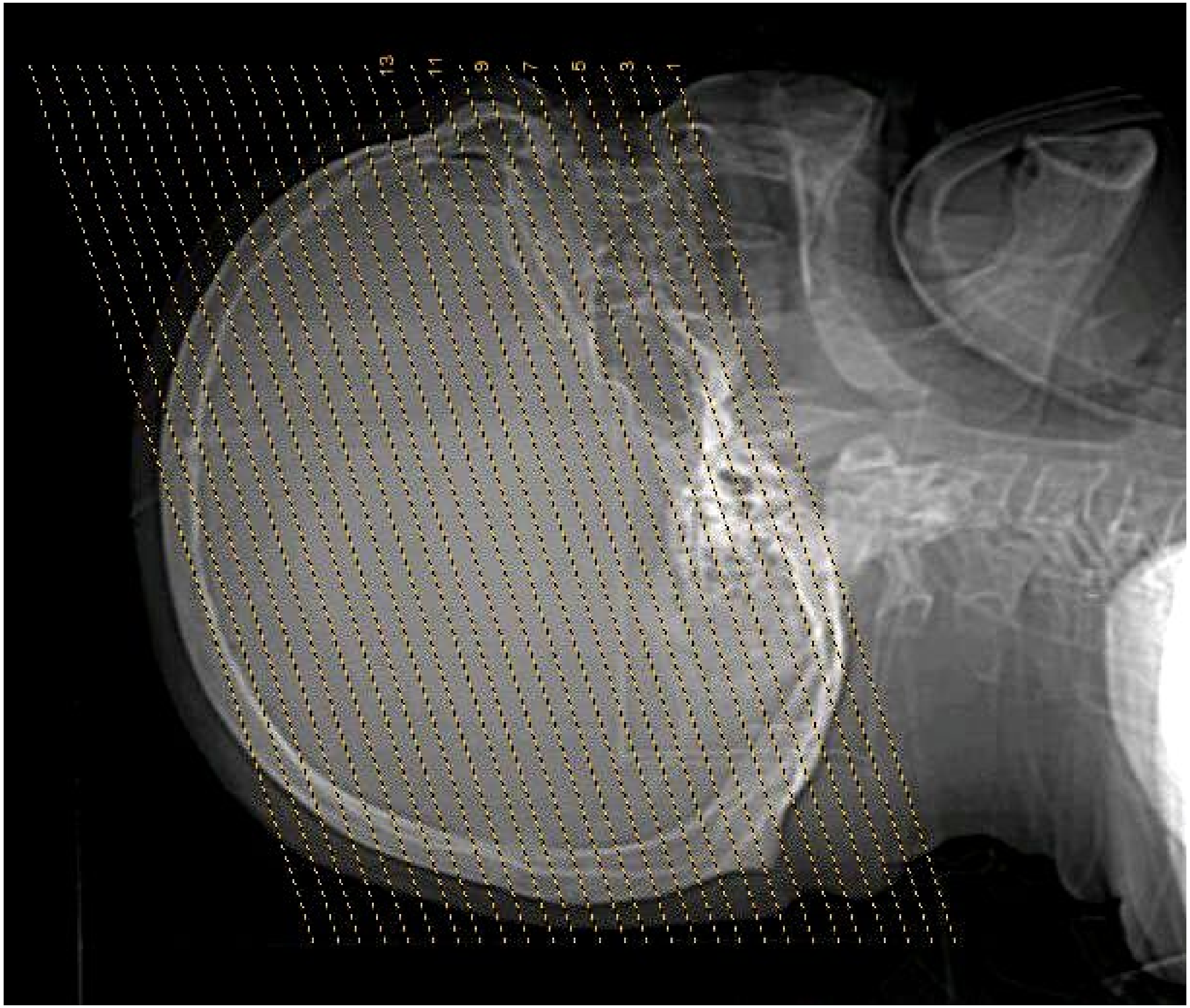


1 = Gantry; 2 = Hole; 3 = Table

“They’re Waiting For You Gordon ….”

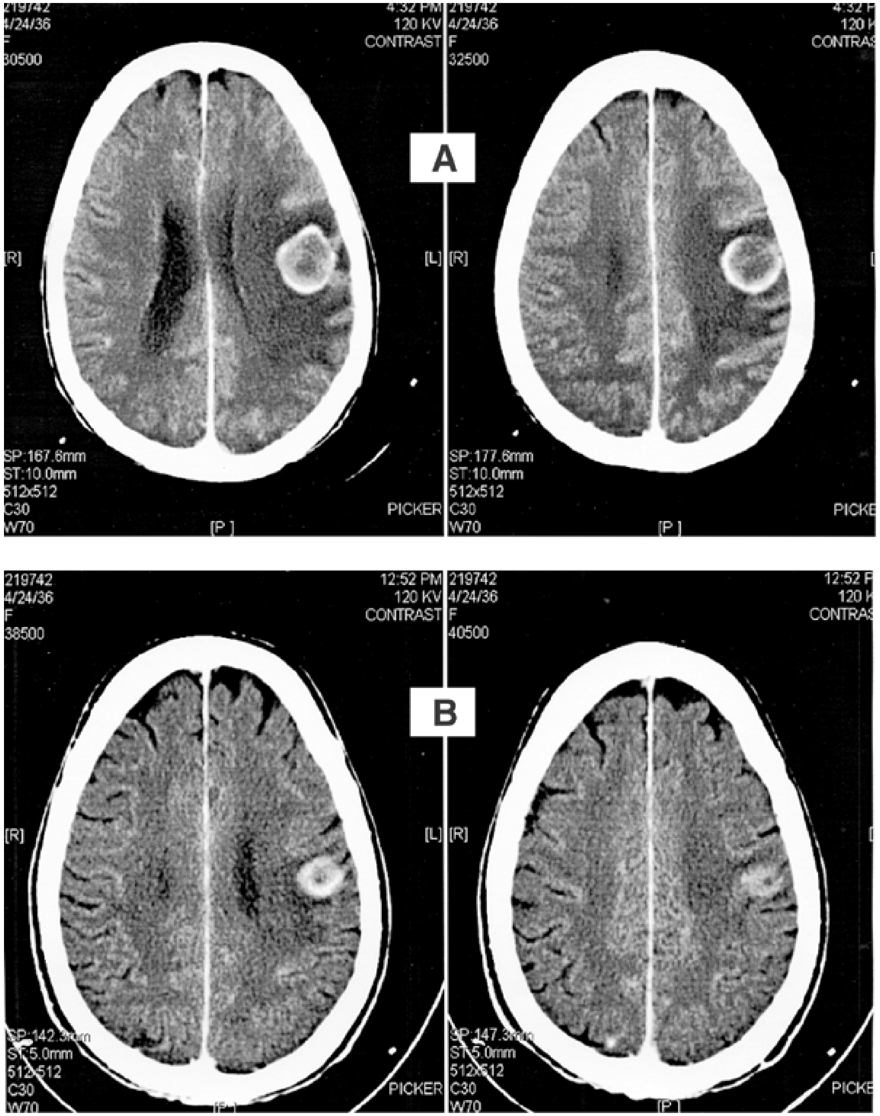
Source: YouTube

A Slice of Brain …

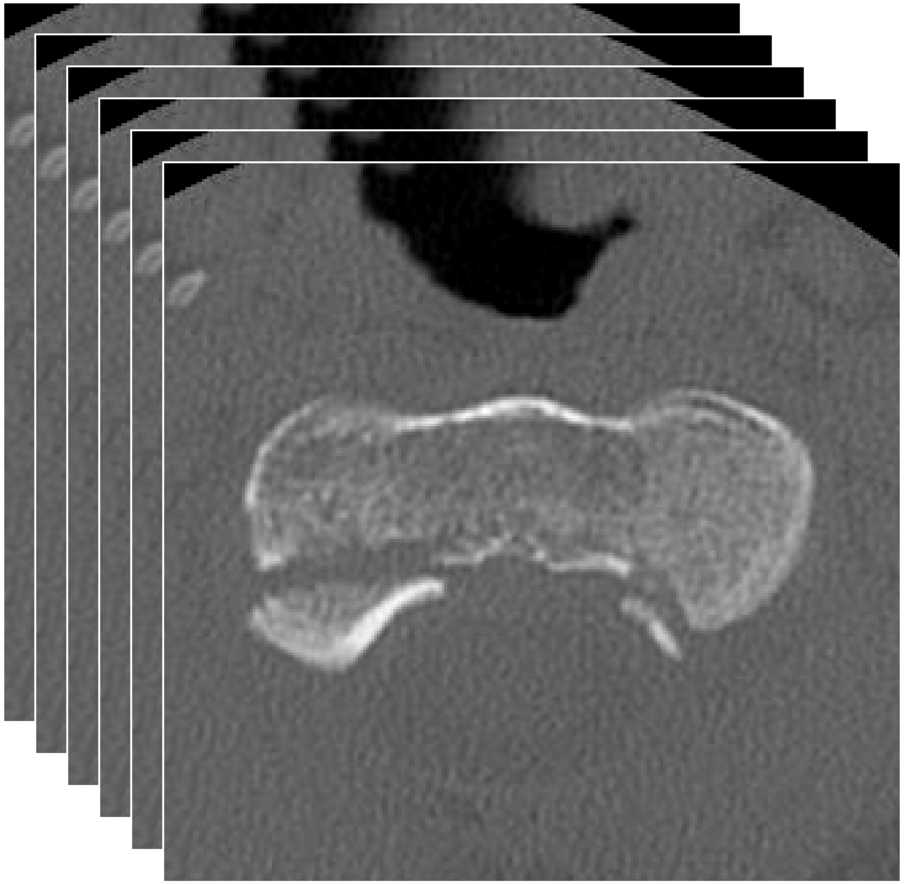


A Slice of Brain …

- Taking Many Many X-Rays Very Fast and “Stitch Together”
- Can Be With or Without Contrast
- Contrast and Resolution Superior To Conventional X-Ray



Scan in One Plane But "Stitch" in Any Plane



Scan Always Axially…

…Stack and *re-slice* in any Plane

The “Smarts” is in The Image Processsing

Source: YouTube

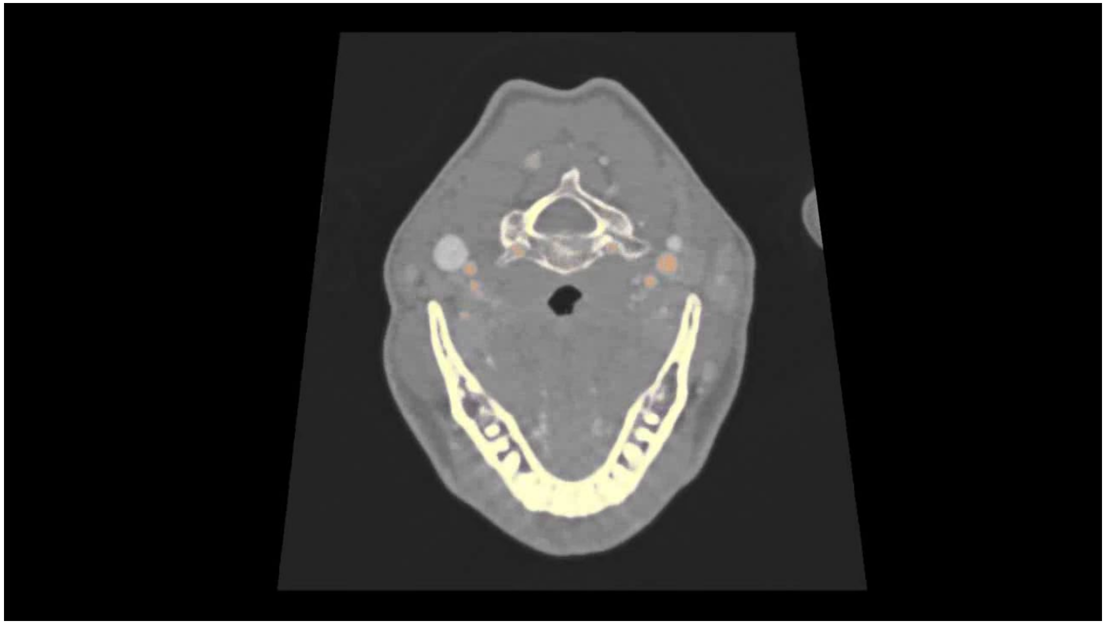
Another Nobel Worthy …. 1979

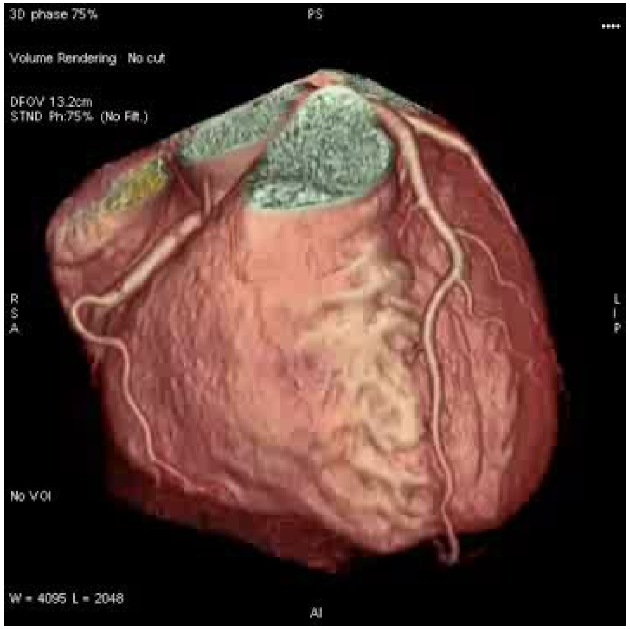

Allan M. Cormack and Godfrey N. Hounsfield

- A CT image is a pixel-by-pixel map of X-ray beam attenuation (density) in Hounsfield units (HU)
- Bright is dense
- Typical values (HU)
  - Air -1000
  - Fat -100
  - Water 0
  - Brain 20-40
  - Blood clot 60
  - Calcification >150
  - Bone 1000
  - Metal >1000

CT Angiography

- Unsurpassed Detailed Imaging of Blood Vessels in 3D
- Diagnose and Evaluate Blockages and Aneurysms
- Boluses of Iodine-Rich Contrast Agent Injected Into Small Vein in Arm or Leg, Then Flow Through Heart Can be Visualised – Full Scan Takes Only 20-30 secs
- Much Better Than Conventional Angiograms
- Informs Further Course of Therapy – Stents, Bypass or Angioplasty

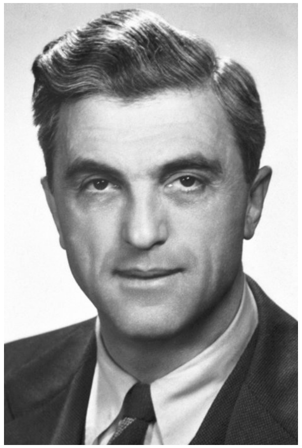


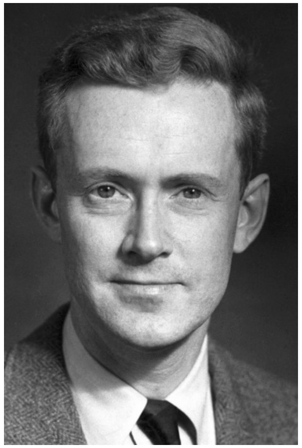


Source: YouTube

IMPORTANT: X-RAYS AND CT IMAGING BOTH INVOLVE RADIATION EXPOSURE TO THE BODY AND CANNOT IMAGE SOFT TISSUES IN HIGH ENOUGH RESOLUTION FOR BETTER DIAGNOSIS

Second Biggest Leap in Medical Imaging





1952 Nobel in Physics

Independent Discovery of Nuclear Magnetic Resonance in Liquids and Solids

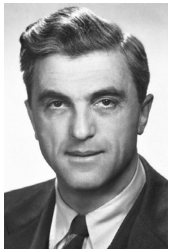
Felix Bloch and Edward Mills Purcell

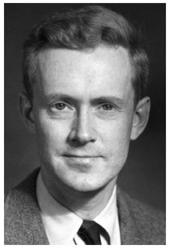
2003 Nobel in Medicine

Application of NMR to Image the Human Body – Magnetic Resonance Imaging (MRI) As We Know Today

Paul C. Lauterbur and Sir Peter Mansfield

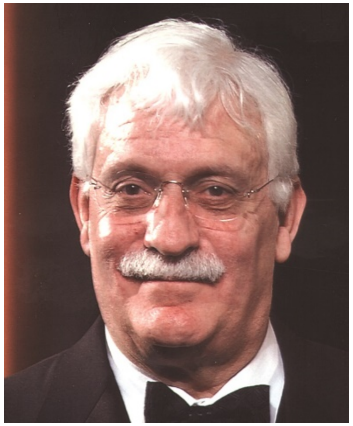
Sometimes …. Due Credit Can be Missed





Felix Bloch and Edward Mills Purcell

Paul C. Lauterbur and Sir Peter Mansfield



Raymond Damadian Invented First MRI Scanner in the 70s and Imaged First Patient in 1977!

Tumor Detection by Nuclear Magnetic Resonance

Abstract. *Spin echo nuclear magnetic resonance measurements may be used as a method for discriminating between malignant tumors and normal tissue. Measurements of spin-lattice (T_1) and spin-spin (T_2) magnetic relaxation times were made in six normal tissues in the rat (muscle, kidney, stomach, intestine, brain, and liver) and in two malignant solid tumors, Walker sarcoma and Novikoff hepatoma. Relaxation times for the two malignant tumors were distinctly outside the range of values for the normal tissues studied, an indication that the malignant tissues were characterized by an increase in the motional freedom of tissue water molecules. The possibility of using magnetic relaxation methods for rapid discrimination between benign and malignant surgical specimens has also been considered. Spin-lattice relaxation times for two benign fibroadenomas were distinct from those for both malignant tissues and were the same as those of muscle.*

RAYMOND DAMADIAN*
Biophysical Laboratory, Department of Medicine, State University of New York, Brooklyn 11203

United States Patent [19]

Damadian

[54] **APPARATUS AND METHOD FOR DETECTING CANCER IN TISSUE**

[76] Inventor: **Raymond V. Damadian,** 64 Short Hill Rd., Forest Hill, N.Y. 11375

[22] Filed: **Mar. 17, 1972**

So What is an MRI Machine?

Basically a BIG A _ _ MAGNET that reveals secrets of the body!

- Strength of Magnet Typically Varied from 0.5 – 4 tesla Although 7-10 tesla Systems Are Common Now (cost $1-3M++++)
- Earth's Magnetic Field on Surface: 25-65 x 10^{-6} tesla
- Strong Fridge Magnet: 0.01 tesla
- Field Strength $\propto$ Energy^2

pet versus spect | Nuclear Medicin | The science of m | SPECT vs PET | R

www.bbc.com/future/story/20180420-the-worlds-most-powerful-mri-machine

Mega Builds | Future Video

The world's most powerful MRI machine

A collaboration between German and French researchers is creating a human MRI machine with unparalleled potential to illuminate the brain.

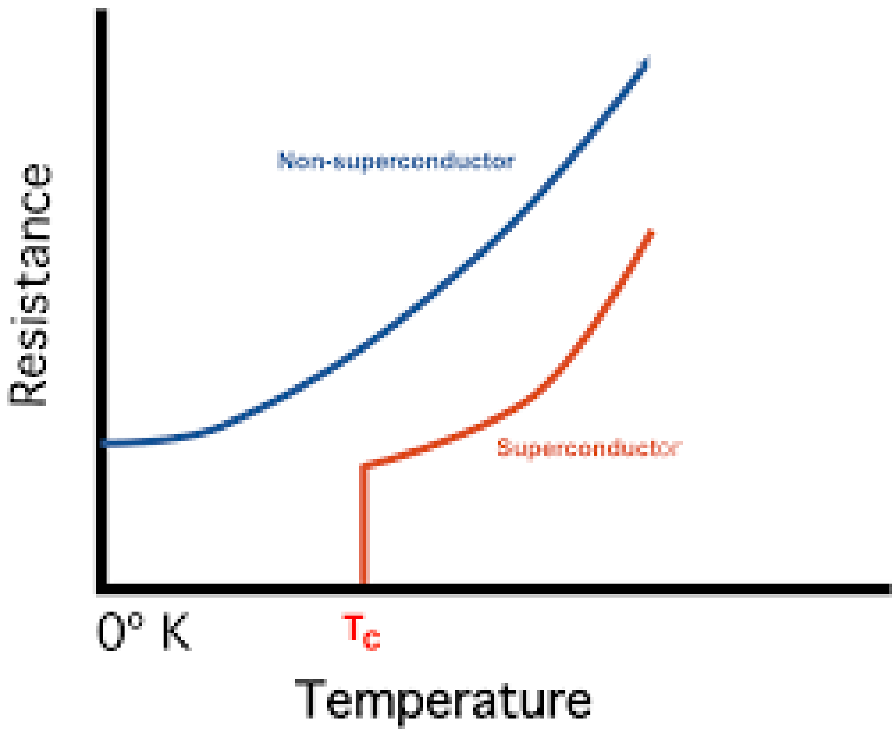
20 April 2018

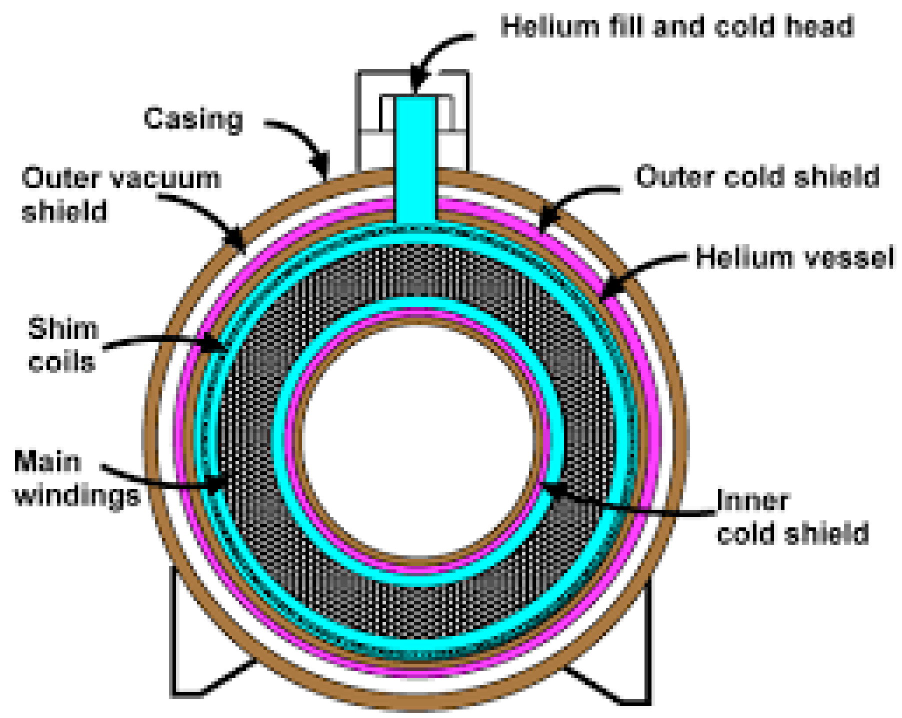
Nikola Tesla's last name isn't just a car brand. Tesla is also the metric for the magnetic strength of MRI machines.

Whereas historically powerful MRI machines have registered around 7-10 tesla, a new generation of machines are breaking the mold and registering up to 11.7 Tesla.

Europe At The Forefront

Making a MRI Magnet



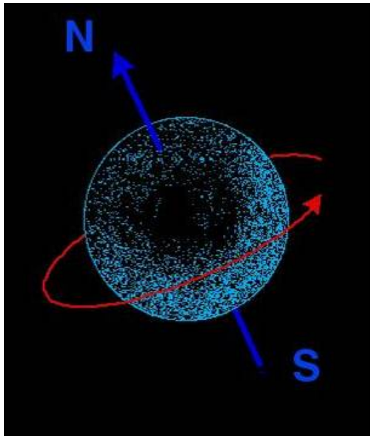


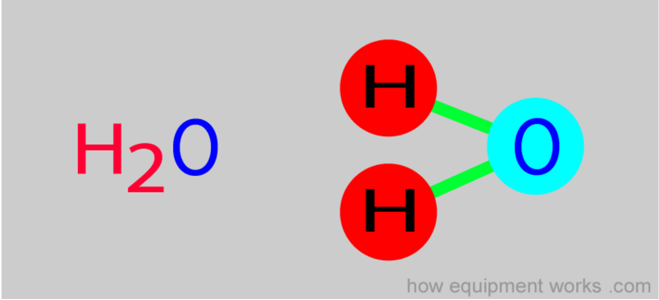
An Electromagnet at -273 °C Will Exhibit Zero Resistance

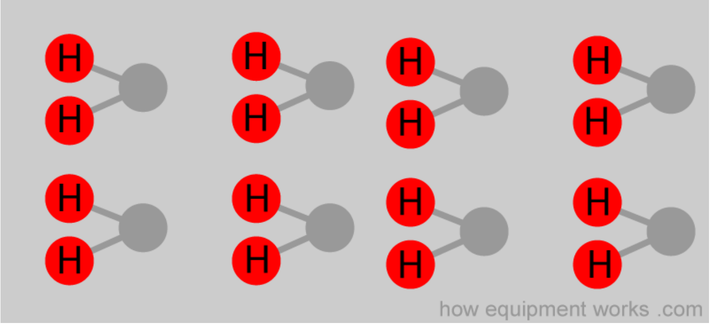
Temperature is Maintained By Keeping Coil in Liquid Helium

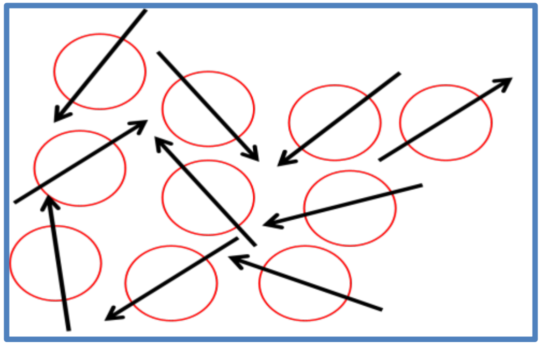
Understanding Nuclear Magnetic Resonance

- Understanding How Water Behaves in a Magnetic Field
- Humans are 60% Water
- Hydrogen Nuclei Exhibit Quantum Spin
- Spin is Random in All Orientations





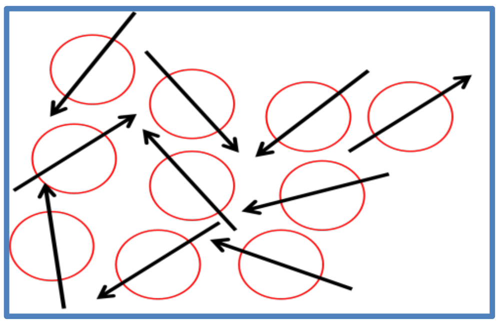


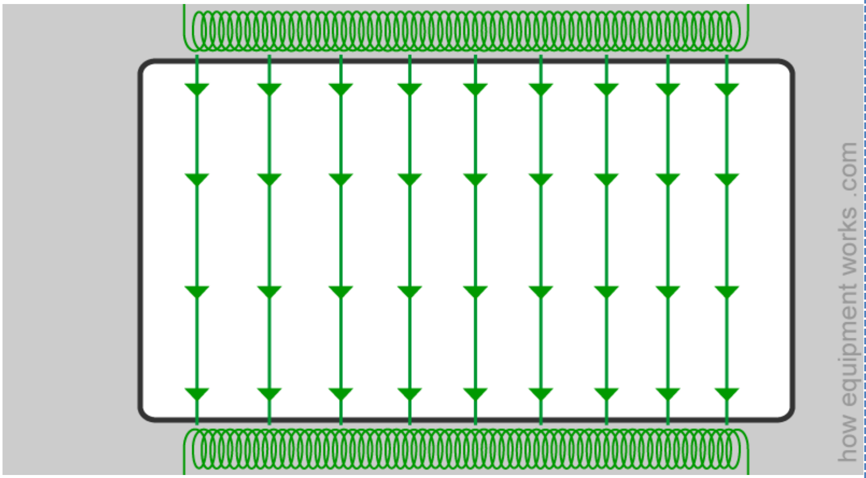


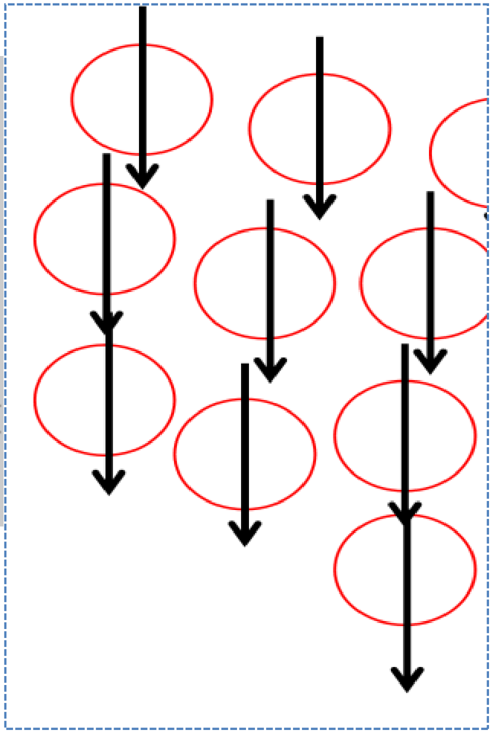
Source: https://www.howequipmentworks.com/mri_basics/

Understanding Nuclear Magnetic Resonance

- When Placed in A Strong Magnetic Field, Nuclei Align in the Direction of the Field
- Some Will Align Parallel (Low Energy State) and Some Opposite (High Energy State)



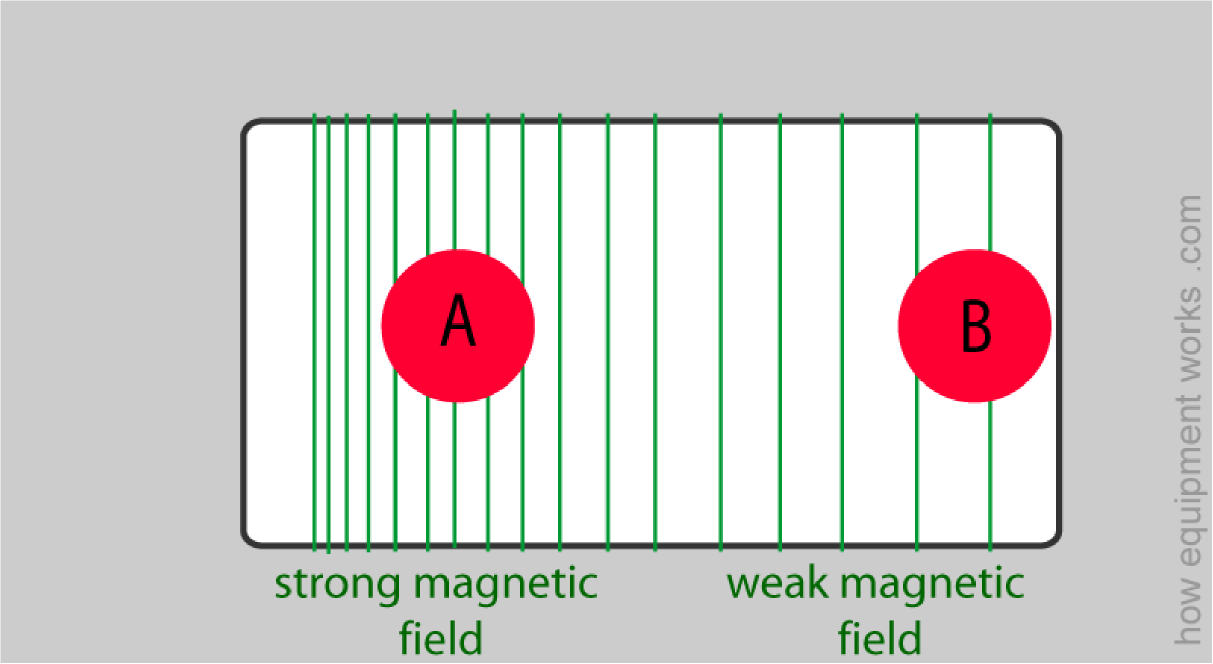




Source: https://www.howequipmentworks.com/mri_basics/

Understanding Nuclear Magnetic Resonance

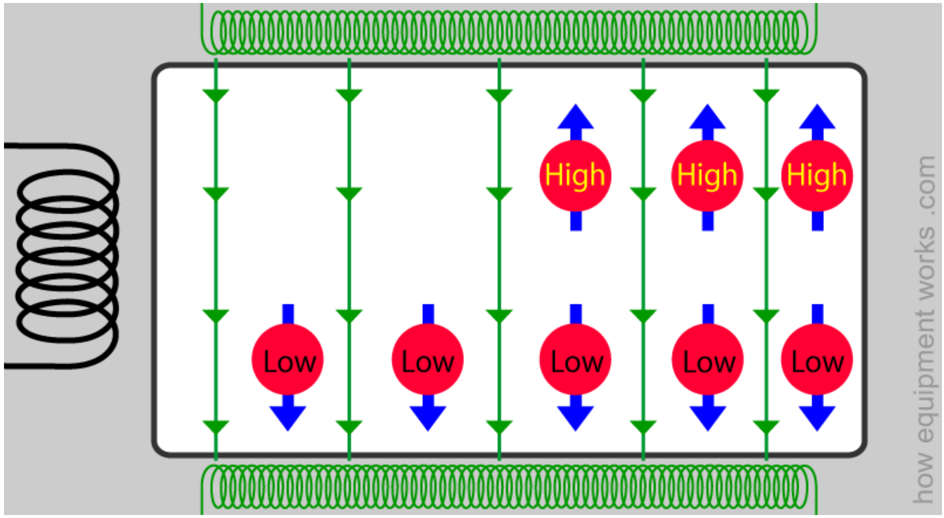
Separate Gradient Coils Vary The Field Strength Across the Length of the Scanner

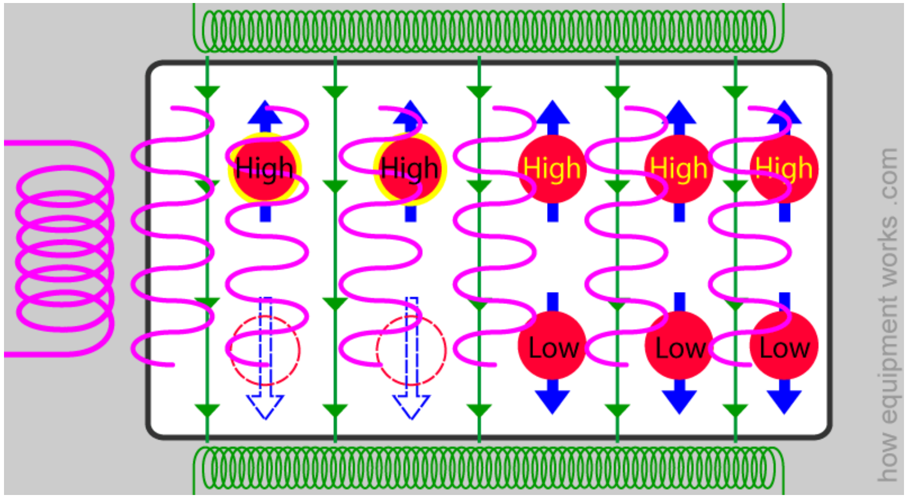


Source: https://www.howequipmentworks.com/mri_basics/

Understanding Nuclear Magnetic Resonance

Third Set of Coils (RF Coils) Emit an RF Signal At Different Frequencies and Also Have Detector Coil Components

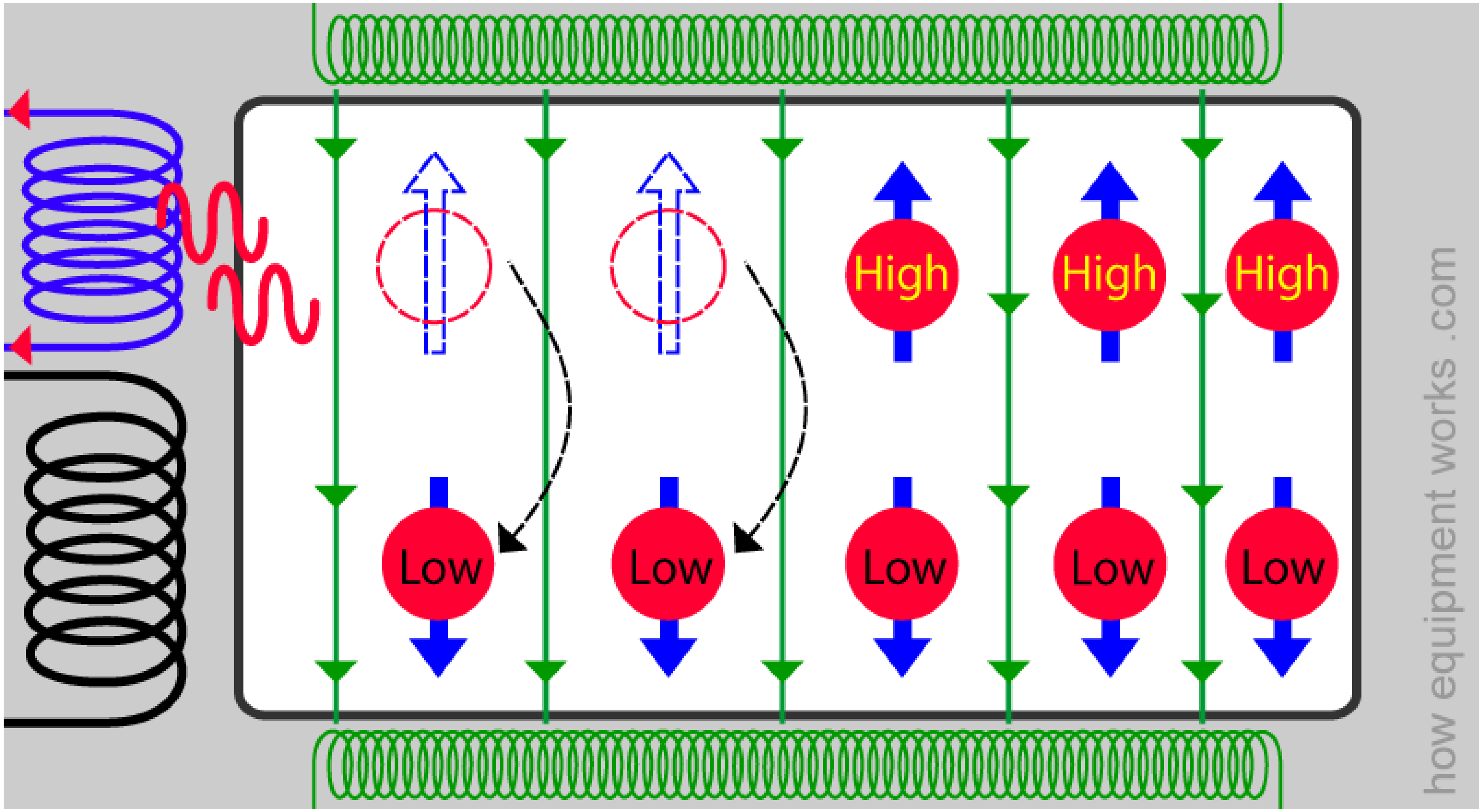




Source: https://www.howequipmentworks.com/mri_basics/

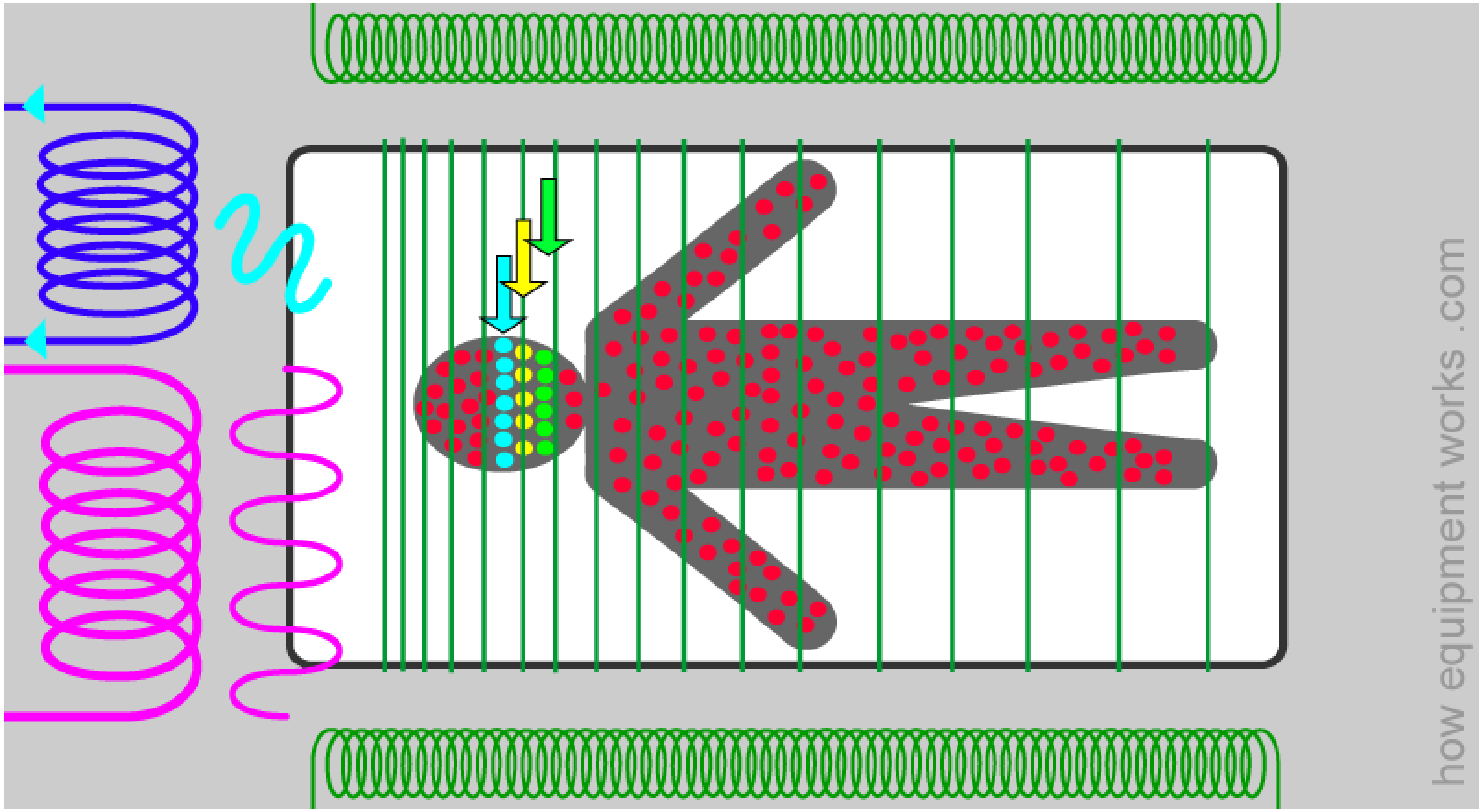
Understanding Nuclear Magnetic Resonance

When Nuclei Return to Their Original State, They Produce a Small Electrical Current Which Can be Detected in a Receiver Coil



Understanding Nuclear Magnetic Resonance

Scanning is Done One Slice at a Time Using Different Frequencies of the RF Signal – The Gradient Coils Make Hydrogen Nuclei Resonate At Different Frequencies

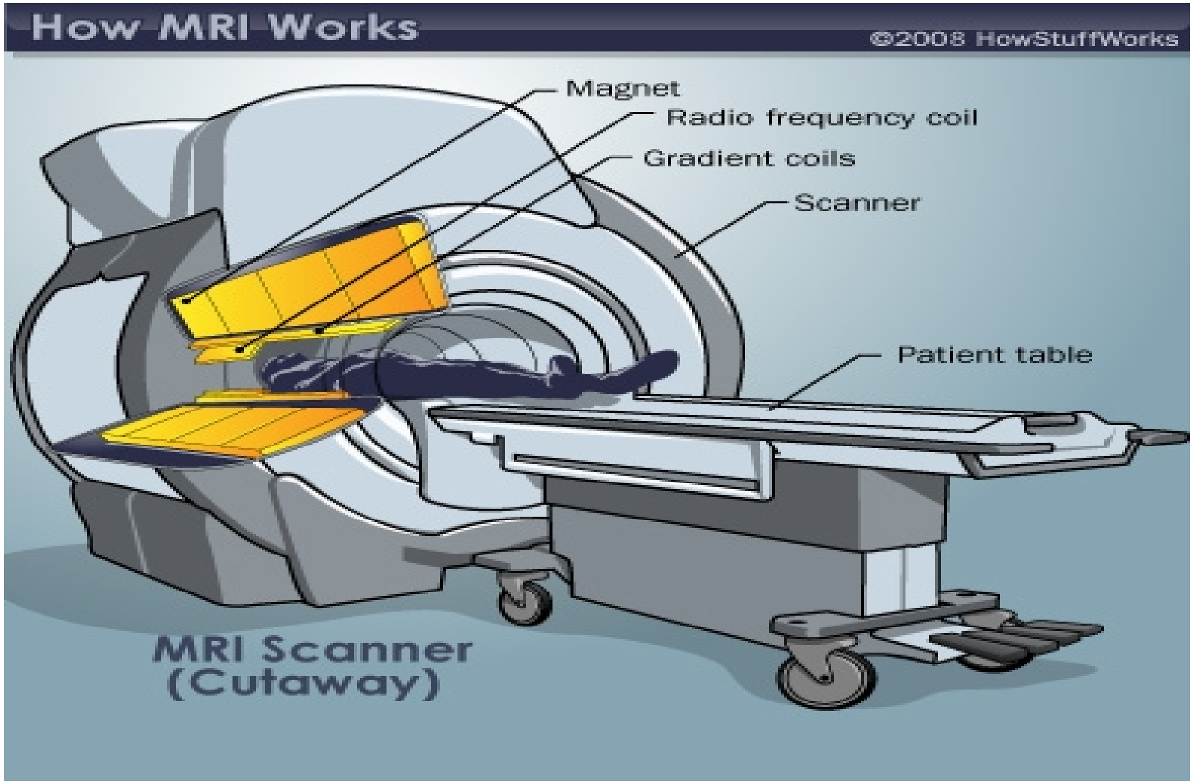


Source: https://www.howequipmentworks.com/mri_basics/

Understanding Nuclear Magnetic Resonance

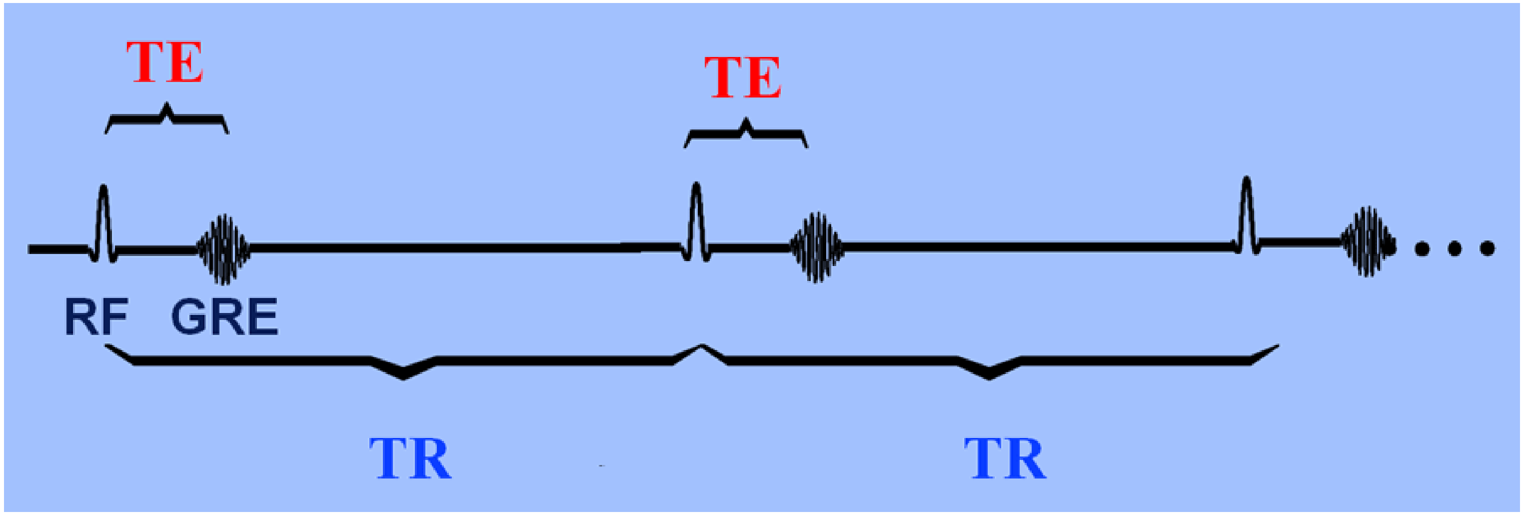
Signals Are Processed (Fourier Transformed) by a Powerful Computer That Also Performs Reconstruction of Images

Within the Same Resonant Frequency, Different Tissues Will Absorb Different RF Amounts and Therefore Appear Different!



T1 and T2 Weighted MRI

- Two Common Pulse Sequences – T1 and T2 Based on Two Timing Parameters (Time to Repeat – TR and Time to Echo – TE)

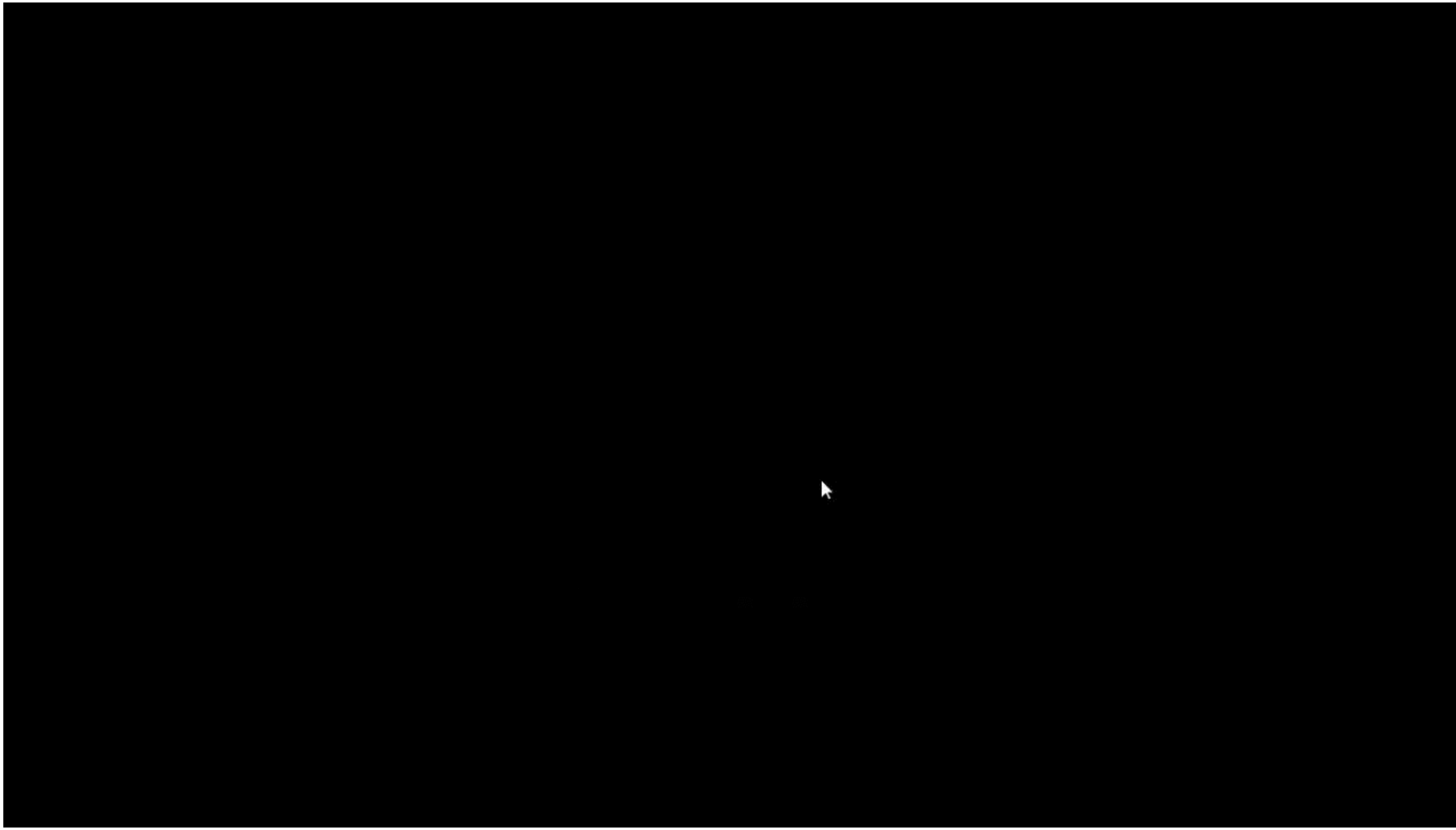


- **Short TR and TE Times Result in a T1-Weighted Image**
- **Longer TR and TE Times Result in a T2-Weighted Image**

T1 and T2 Weighted MRI

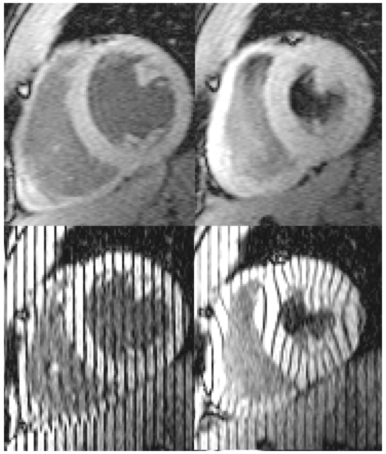
Tissue	T1	T2
• Fat	high (whitish)	intermediate
• Muscle	intermediate (grey)	intermediate
• Cartilage	intermediate	intermediate/low
• Ligaments and tendons	low (dark grey)	low
• Bone	low	low
• Fibrous tissue	low	low
• Haemorrhage	high/intermediate	high
• Scar	intermediate/low	low
• Water/CSF	low (dark)	high

T1 and T2 Weighted MRI

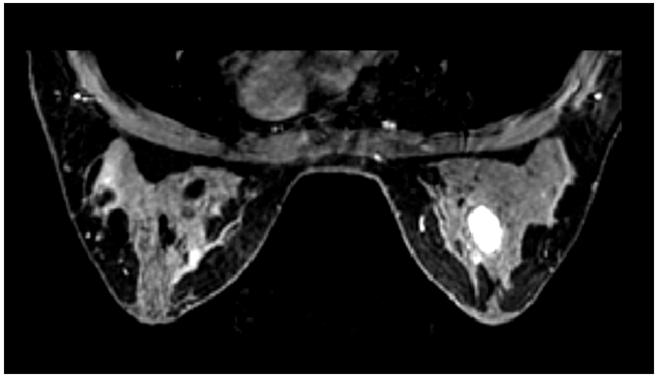


Source: YouTube

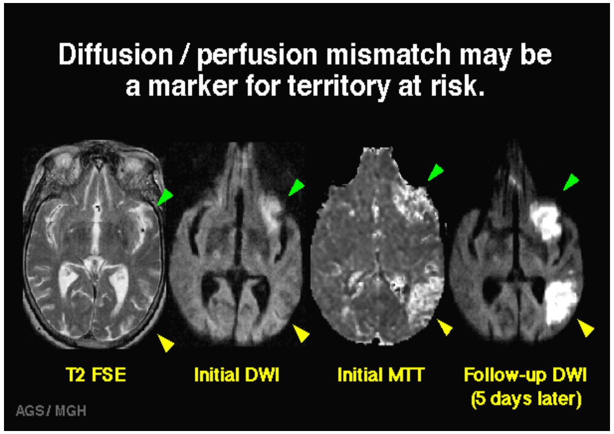
MRI



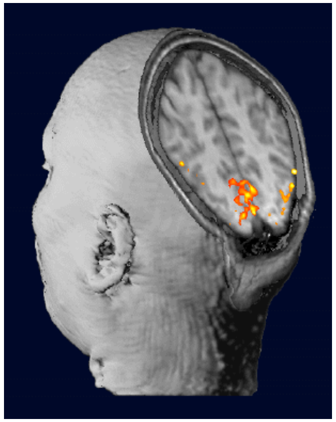
Cardiac



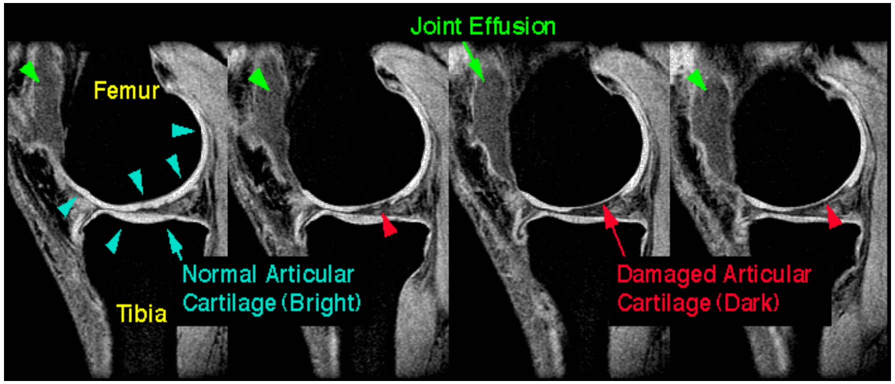
Cancer



Stroke



Neural Function



Joints

Lungs

Unsurpassable For Soft Tissue Detailed Imaging!!

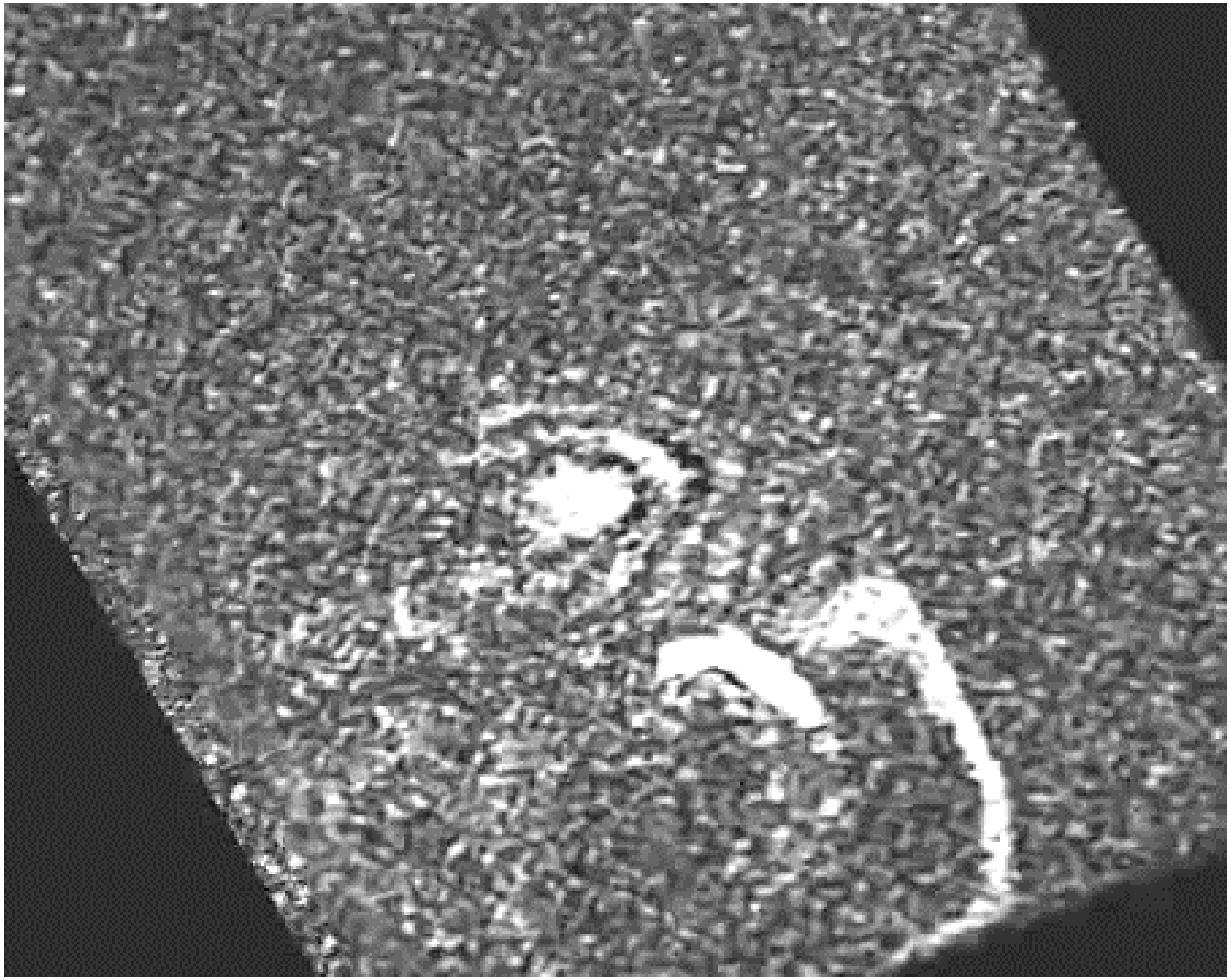
A Beautiful Beating Heart

https://www.youtube.com/watch?v=G4dFVeP9Vdo

And a Lot More …

- Can Image Many Tissues
- In Brain: Identify Bleeds, Blockages, Tumours or Swelling
- Locate Organs, Muscles, Joints
- Detect Inflammation – Change in Water Content
- Diagnose Problems With Eyes, Ears, Heart, Lungs, Pelvis, Spinal cord, etc.
- Can Even Image Patterns of Neural Activity – Functional (F) MRI

FMRI



OK WE GOT REALLY GREAT IMAGES OF PRETTY MUCH EVERYTHING – SOFT TISSUES AND BLOOD (MRI) AND REMAINING (X-RAY AND CT) …

WHAT IF YOU WERE PREGNANT?

WHAT IF YOU WERE AN ICU PATIENT?

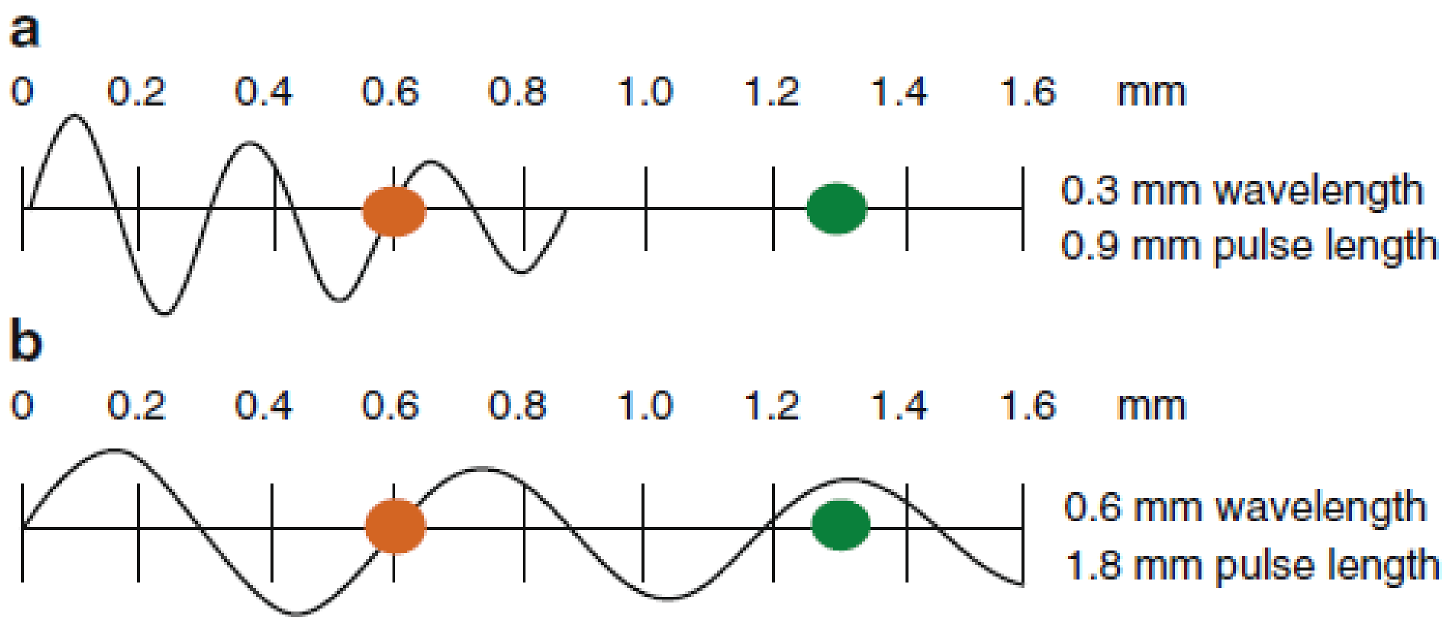
WHAT IF YOU HAD AN IMPLANT?

THE ANSWER LIES NOT IN LIGHT ….

Basics of Ultrasound Imaging

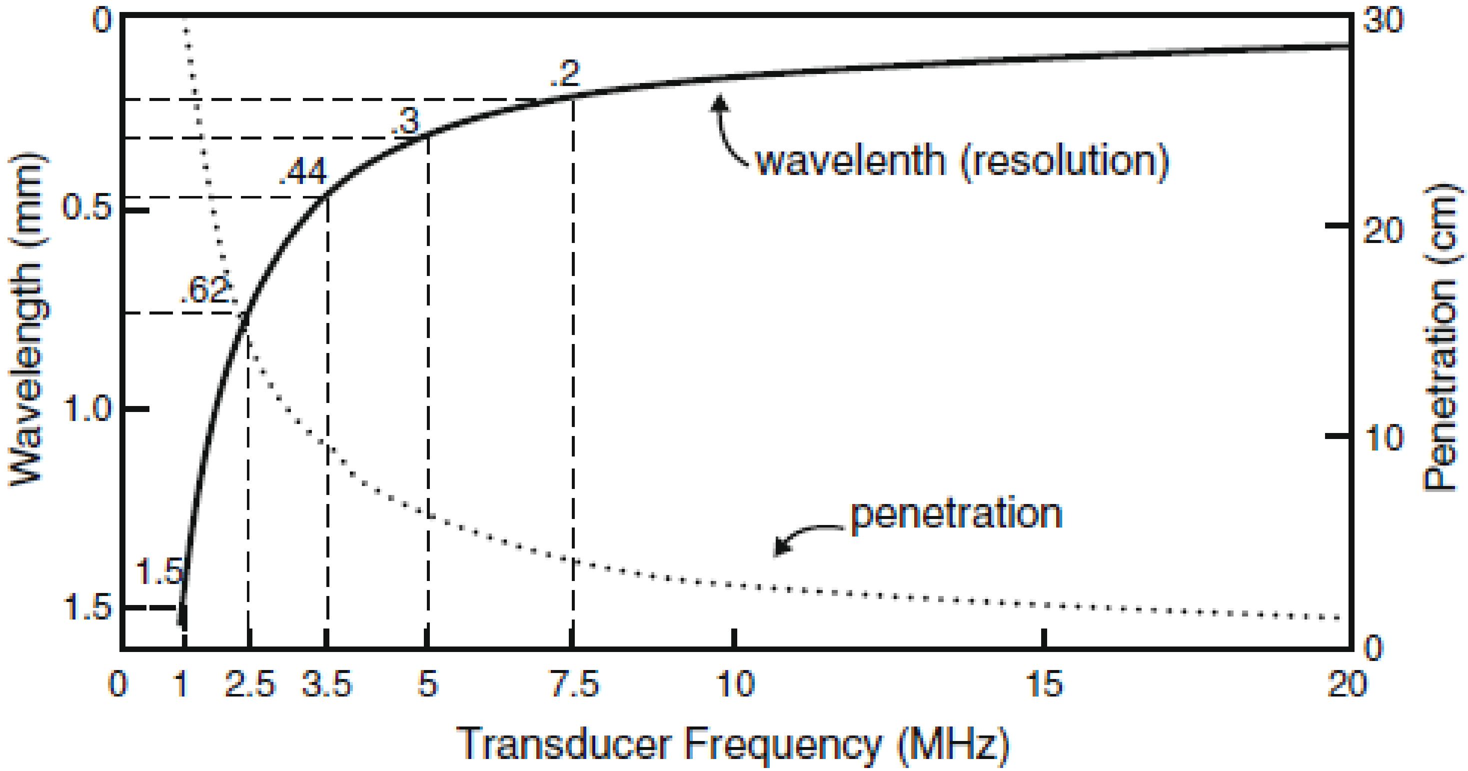
Source: Chan & Perlas, "Basics of Ultrasound Imaging" in Atlas of Ultrasound-Guided Procedures in Interventional Pain Management, Springer, 2011

Ultrasound = Frequencies > 20,000 Hz



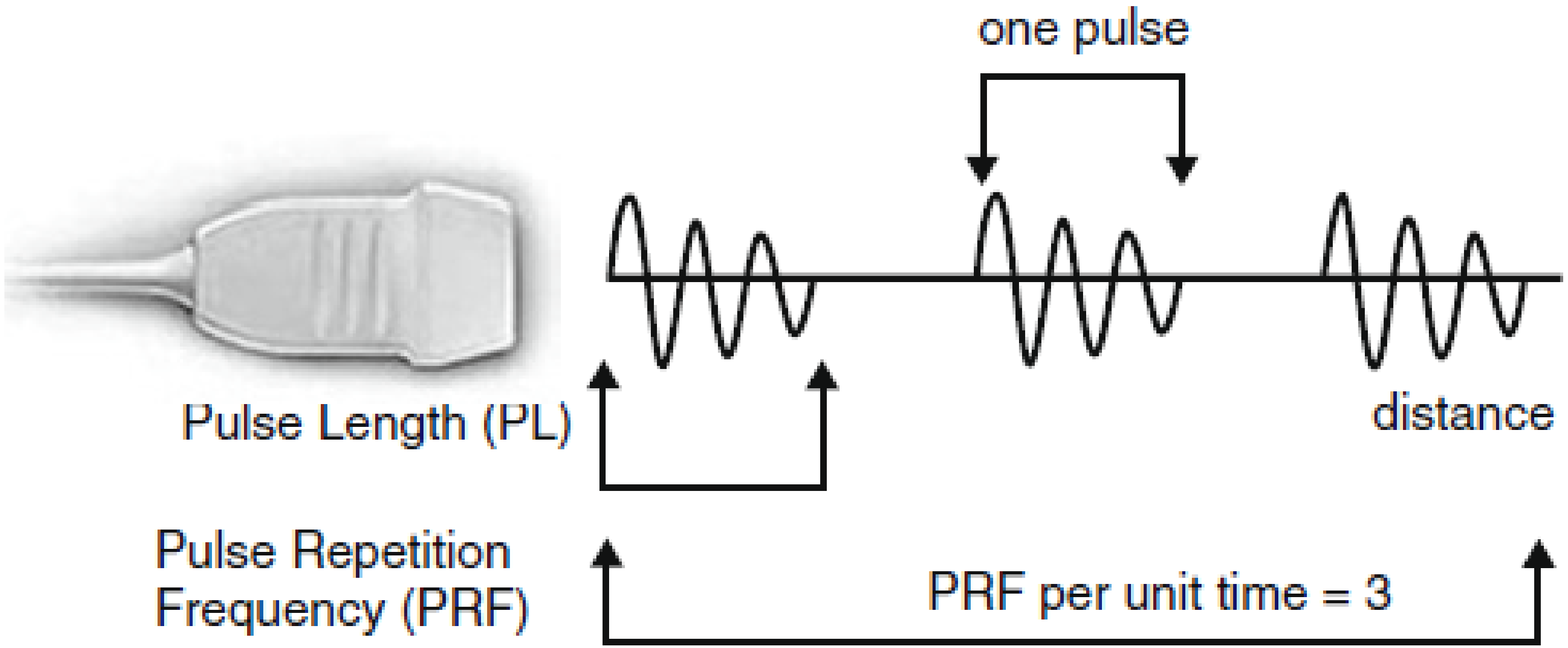
Source: Chan & Perlas, "Basics of Ultrasound Imaging" in Atlas of Ultrasound-Guided Procedures in Interventional Pain Management, Springer, 2011

Higher Frequencies/Shorter Wavelengths Penetrate Less But Give Better Resolution



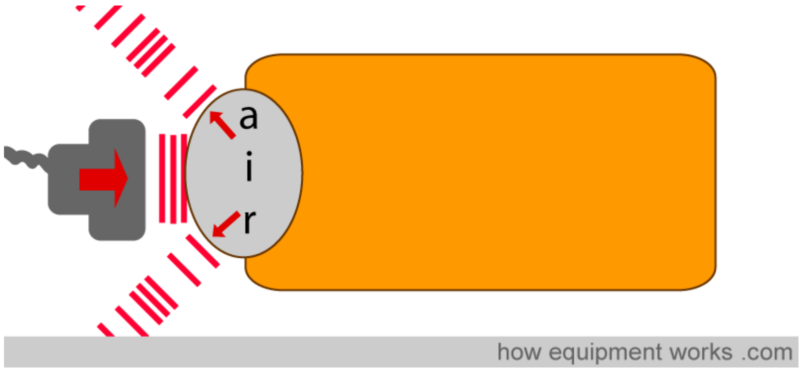
Source: Chan & Perlas, "Basics of Ultrasound Imaging" in Atlas of Ultrasound-Guided Procedures in Interventional Pain Management, Springer, 2011

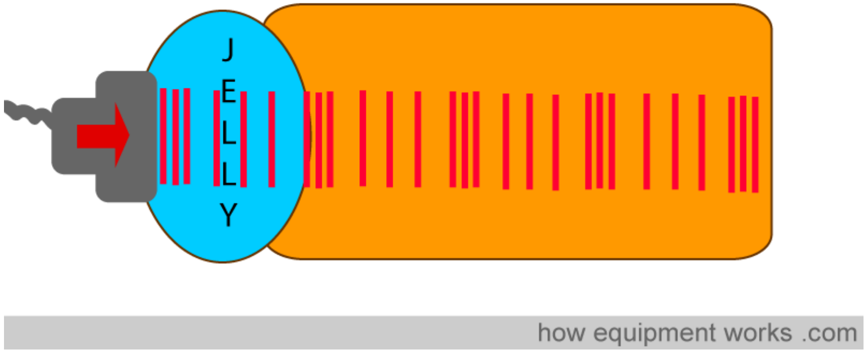
Ultrasound Transducers Generate US Pulses

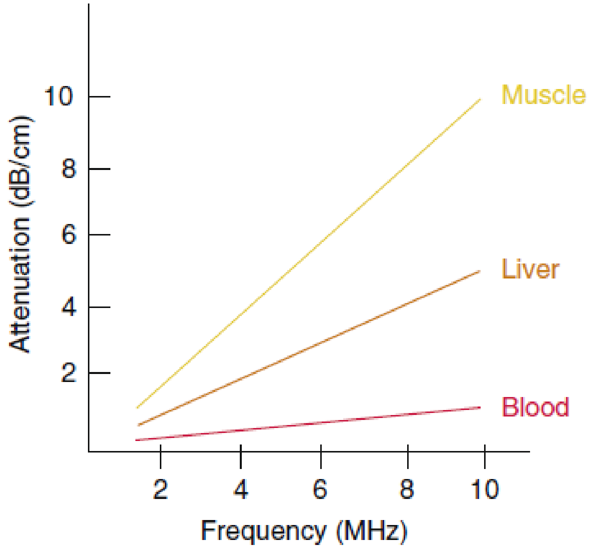


Source: Chan & Perlas, "Basics of Ultrasound Imaging" in Atlas of Ultrasound-Guided Procedures in Interventional Pain Management, Springer, 2011

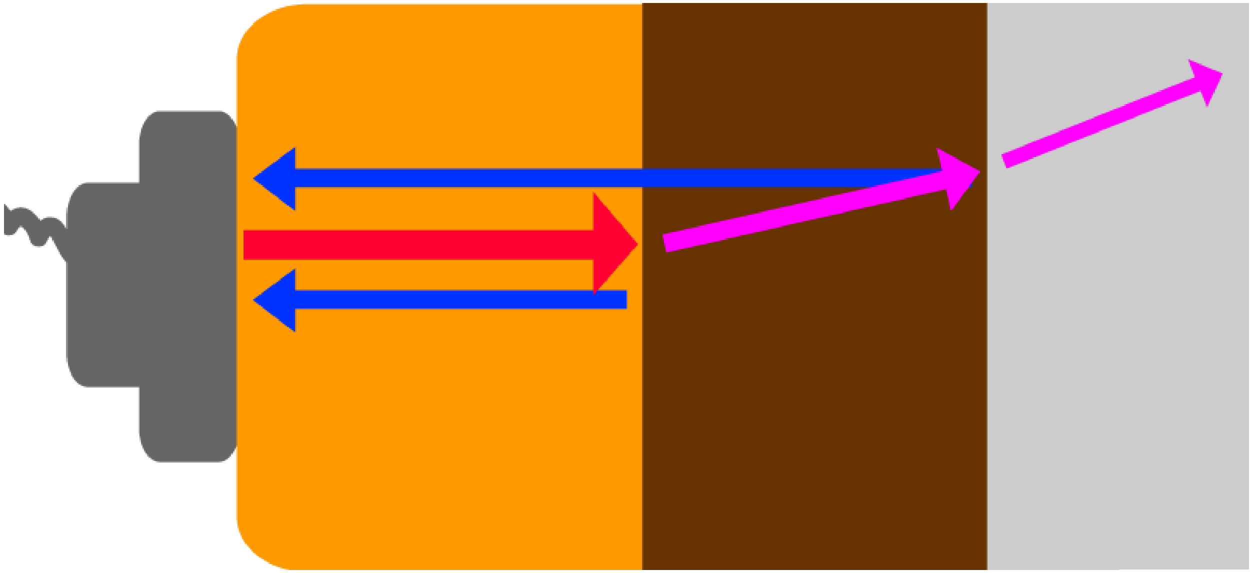
Air Blocks Ultrasound – Body Parts Allow US To Penetrate







At Different Tissue "Junctions" Refraction and Reflection of Sound Occurs

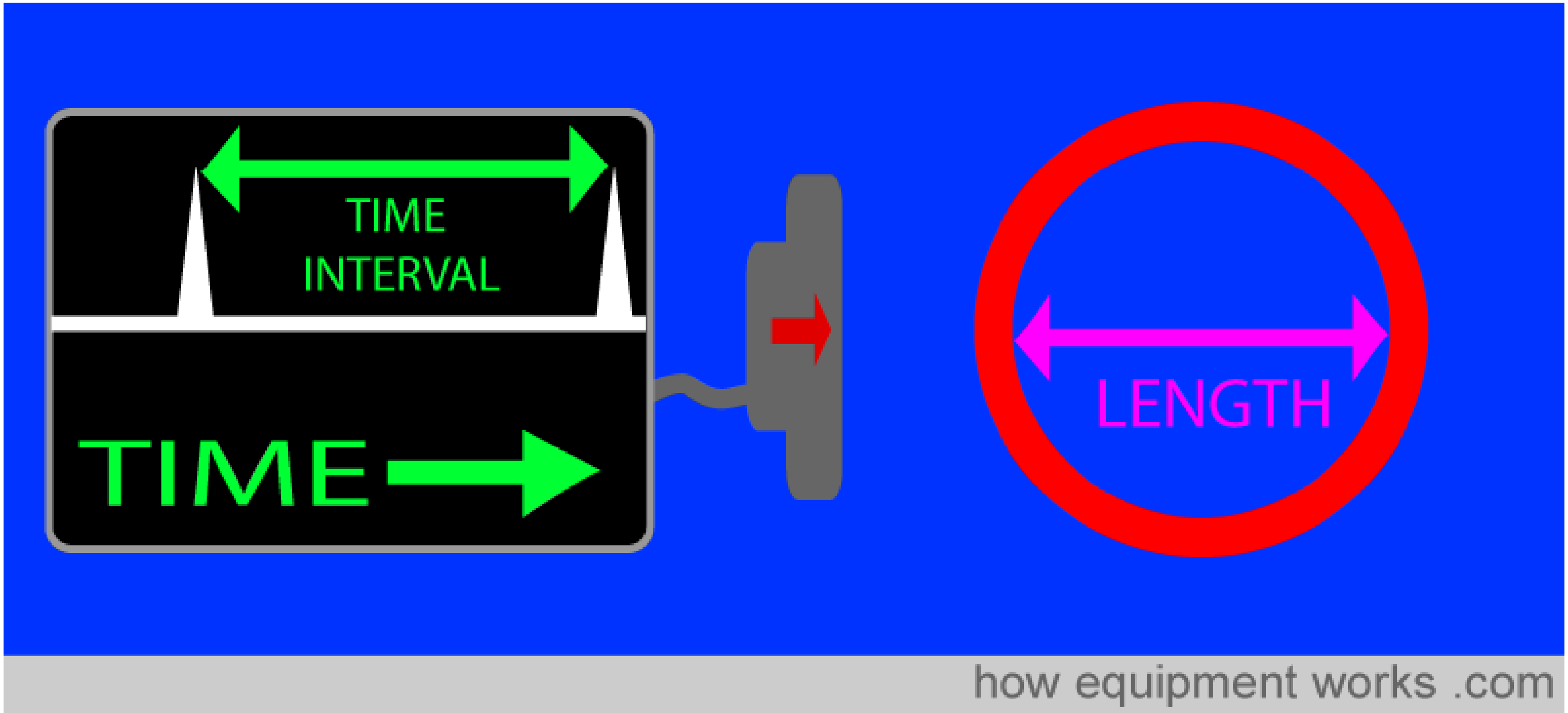


Amount of Echo ∝ Difference in Acoustic Impedance at Junctions

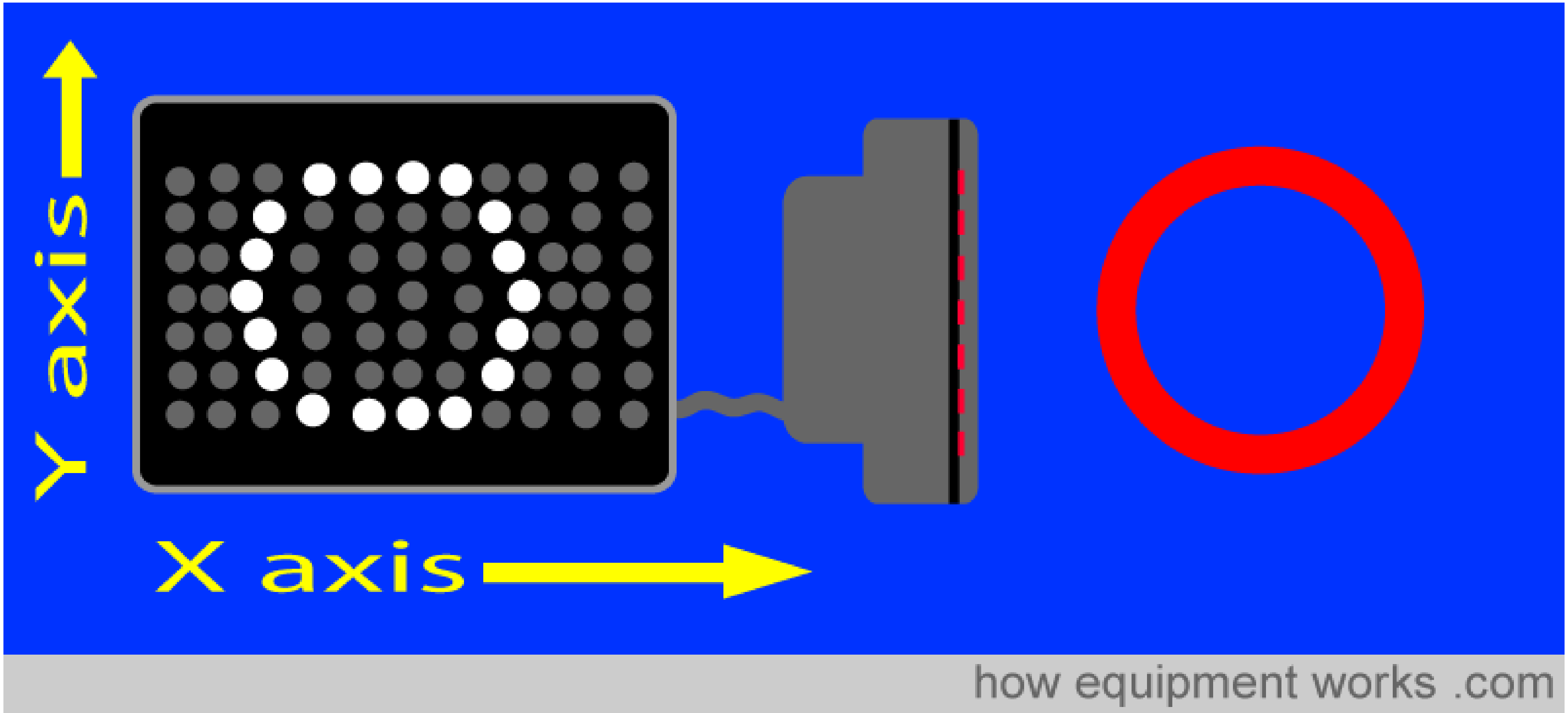
Table 2.1. Acoustic impedances of different body tissues and organs.

Body tissue	Acoustic impedance (10^6 Rayls)
Air	0.0004
Lung	0.18
Fat	1.34
Liver	1.65
Blood	1.65
Kidney	1.63
Muscle	1.71
Bone	7.8

A-Mode Scanning (Can't Really Get An Image)



B-Mode Scanning

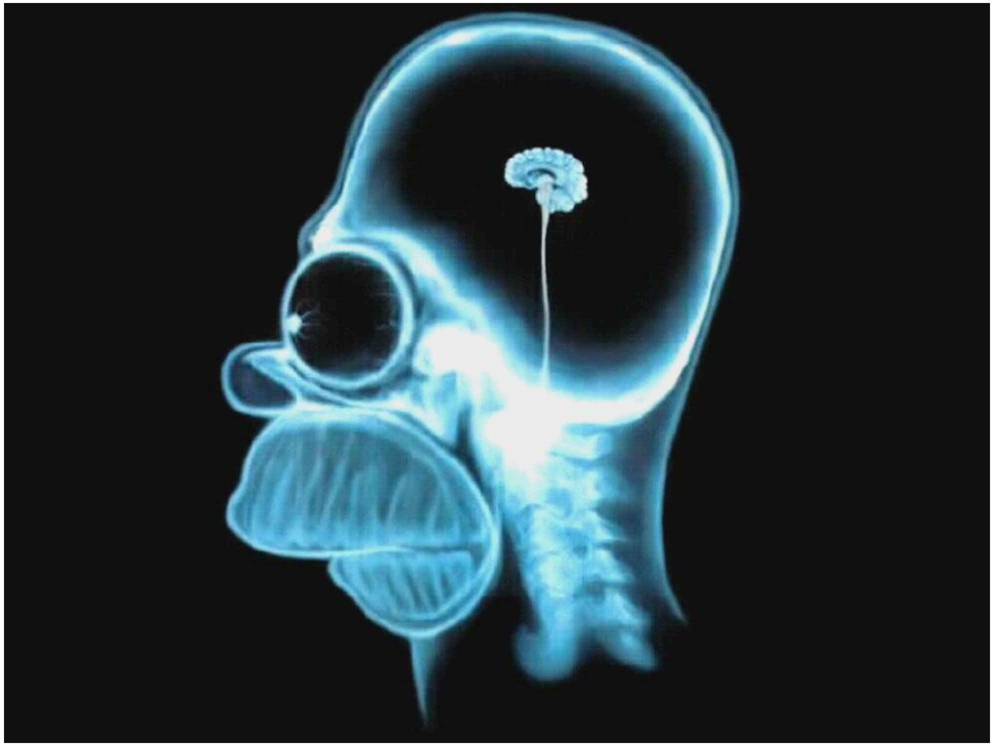


You're Going to Have a Boy!!

"He's a Healthy 2 cm at 9 weeks"

Fancy Smanshy ….

Ok So We Pretty Much Know Everything Right …



What If A Soft Tissue Tumour is Masked on an MRI??
All Modalities Discussed So Far Depend on Sending a "Signal" Then "Receiving" It

Can The Patient Become The "Source" of the Signal? YES!!

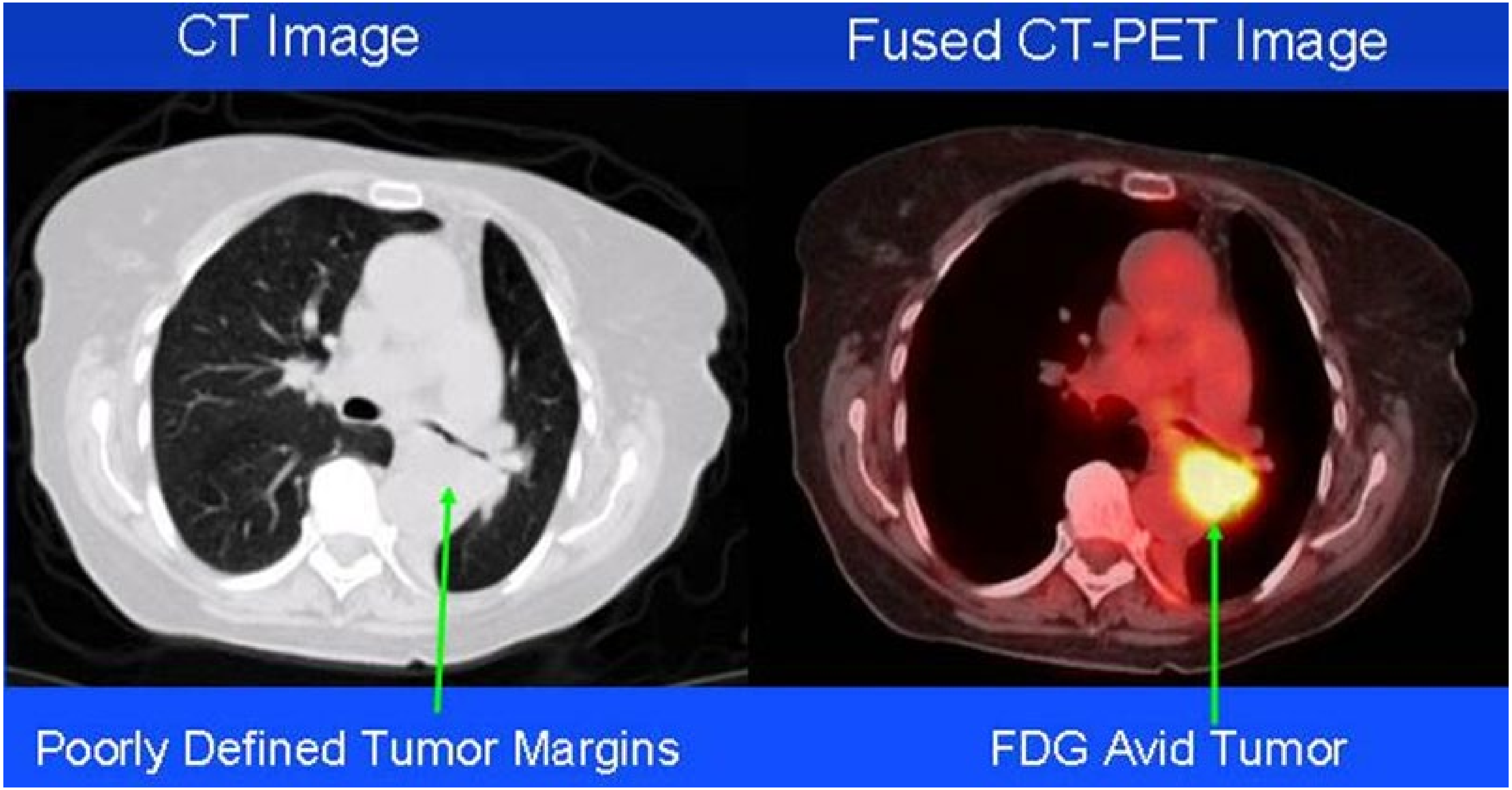
"Welcome to Nuclear Imaging"

1. Single Photon Emission Computerised Tomography (SPECT)
2. Positron Emission Tomography (PET)

Principles of SPECT and PET

- Radioactive Tracers are Injected Into Body Which Are Taken Up by Tissue and Start Decaying
- Decay Process Results in Emission of Gamma Rays – Single Direction (SPECT) or Positrons (PET)
- In PET, Positrons Collide With Electrons & Give Off Photons
- Gamma Rays (SPECT) or Photons (PET) Are Detected With an Array of Detectors
- Can Pin-point Exactly Where Tracer Has Been Taken Up By Organ – Very High Resolution Imaging
- Key Lies in the Different “Engineered” Tracers – Especially for Picking Up “Clever” Tumours
- Both Techniques Can Be Combined With CT To Get Anatomy

Tumours Can't Hide Anymore!



Principles of Both PET and SPECT

Ok So We're Definitely Covered Now!

1) Bones - ✓
2) Soft Tissues (Cartilage and Muscles) - ✓
3) Blood - ✓
4) Fat - ✓
5) Tumours - ✓
6) Brains - ✓
7) Heart - ✓
8) Babies - ✓
9) Air Pockets - ✓
10) Metallic & Foreign Objects - ✓

Thanks To X-Rays, CT, MRI, Ultrasound & PET/SPECT

Ok So We're Definitely Covered Now!