BME 50500: Image and Signal Processing in Biomedicine

Lecture 7: Medical Imaging Modalities X-Ray, CT, PET

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Content

Linear systems in discrete time/space
Impulse response, shift invariance
Convolution
Discrete Fourier Transform
Sampling Theorem
Power spectrum

Introduction to medial imaging modalities
MRI
➔ Tomography, CT, PET
Ultrasound

Engineering tradeoffs
Sampling, aliasing
Time and frequency resolution
Wavelength and spatial resolution
Aperture and resolution

Filtering
Magnitude and phase response
Filtering
Correlation
Template Matching

Intensity manipulations
A/D conversion, linearity
Thresholding
Gamma correction
Histogram equalization

Matlab

Medical Imaging

Imaging Modality	Year	Inventor	Wavelength Energy	Physical principle
X-Ray	1895	Röntgen (Nobel 1901)	3-100 keV	Measures variable tissue absorption of X-Rays
Single Photon Emission Comp. Tomography (SPECT)	1963	Kuhl, Edwards	150 keV	Radioactive decay. Measures variable concentration of radioactive agent.
Positron Emission Tomography (PET)	1953	Brownell, Sweet	150 keV	SPECT with improved SNR due to increased number of useful events.
Computed Axial Tomography (CAT or CT)	1972	Hounsfield, Cormack (Nobel 1979)	keV	Multiple axial X-Ray views to obtain 3D volume of absorption.
Magnetic Resonance Imaging (MRI)	1973	Lauterbur, Mansfield (Nobel 2003)	GHz	Space and tissue dependent resonance frequency of kern spin in variable magnetic field.
Ultrasound	1940-1955	many	MHz	Measures echo of sound at tissue boundaries.

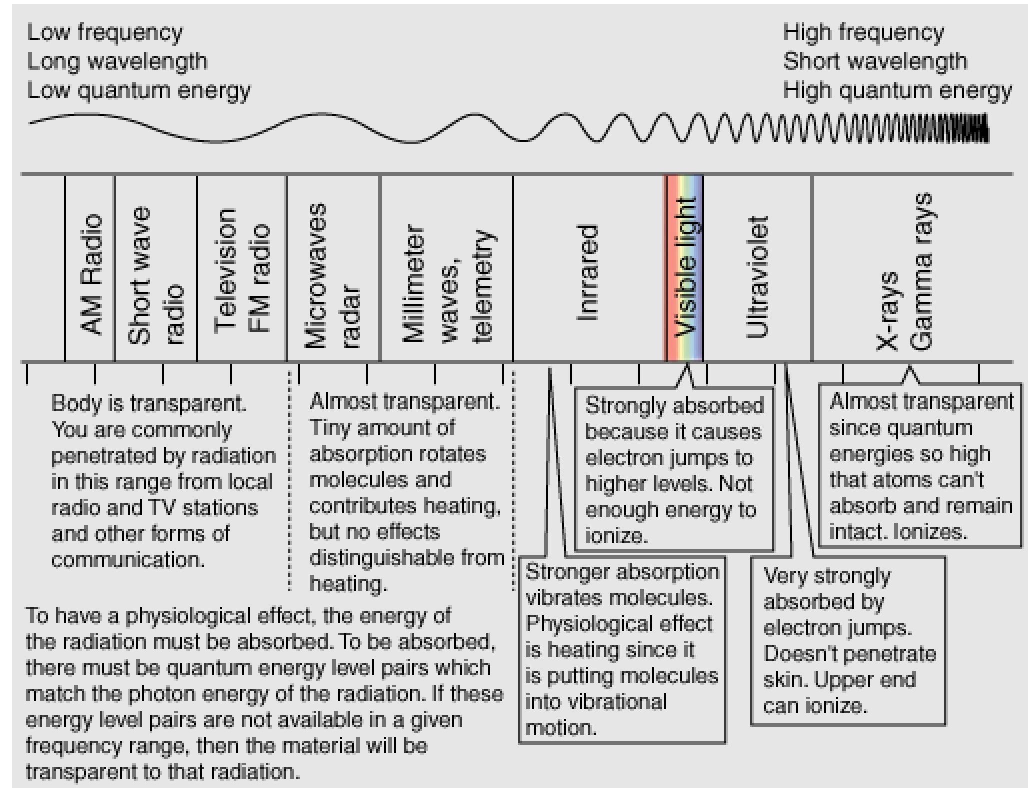
Resolution

Resolutions in a difraction limited imaging system depend on the wavelength and numerical aperture:

$$\Delta x_0 \geq \frac{2z}{\Delta x_1} \lambda$$

Wavelength is inverse with frequency, thus shorter wavelength and higher frequencies give better resolution:

$$\lambda = v / f$$

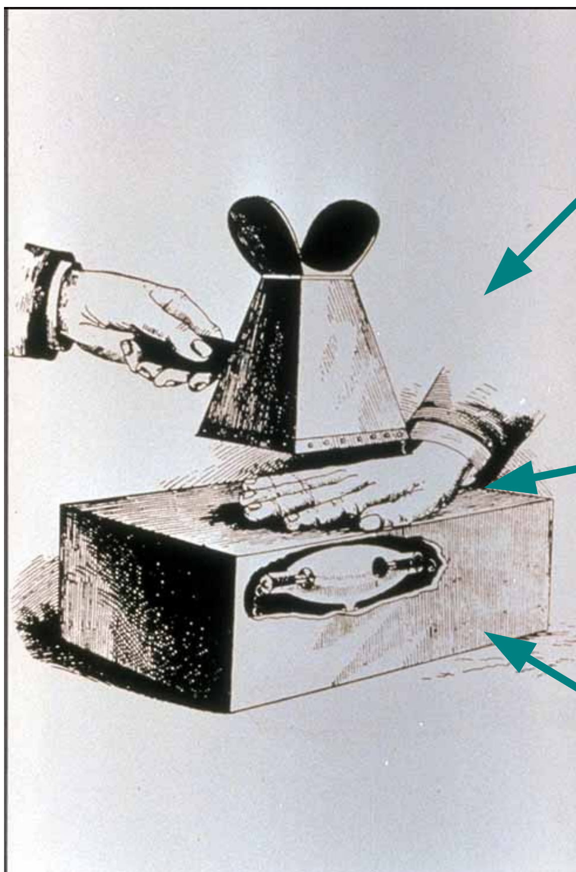


X-Ray Discovery

Wilhelm Conrad Roentgen (1845-1923) in 1896 and the first radiogram (of his hand) 1895:

Early X-Ray

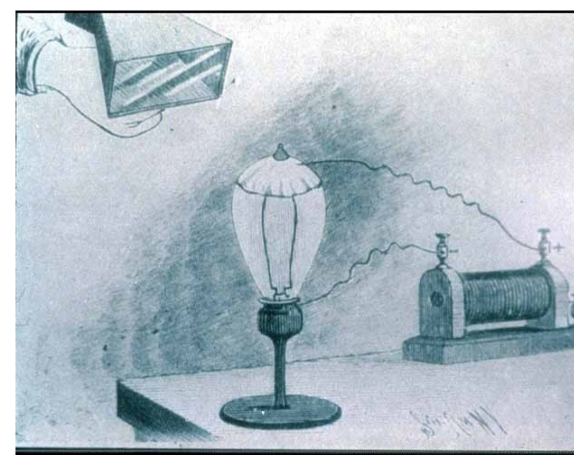
Schematic presentation of how it works:



Detection:
Fluorescent screen

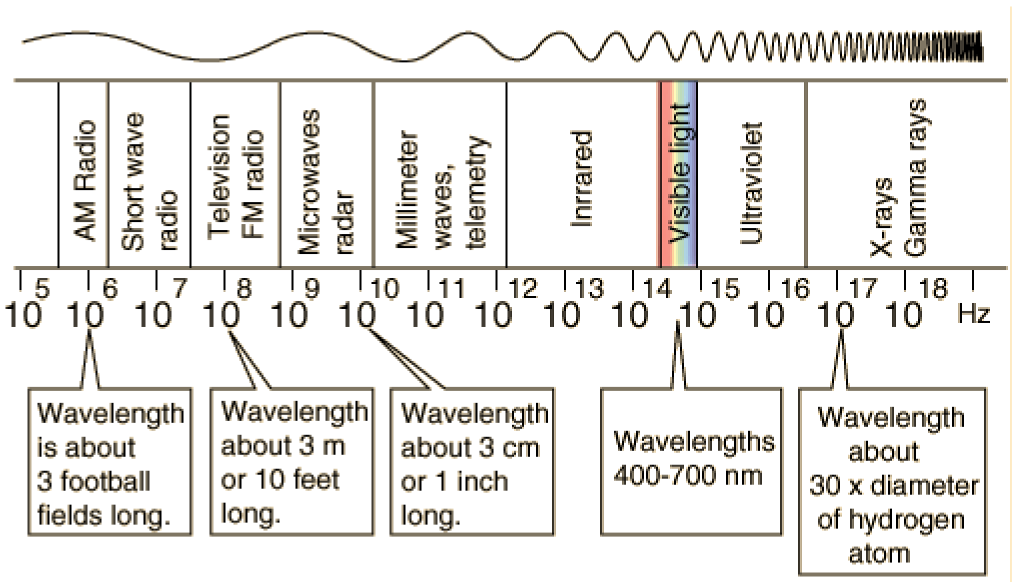
Interaction with tissue:
Absorption & Scatter

Generation:
X-Ray tube



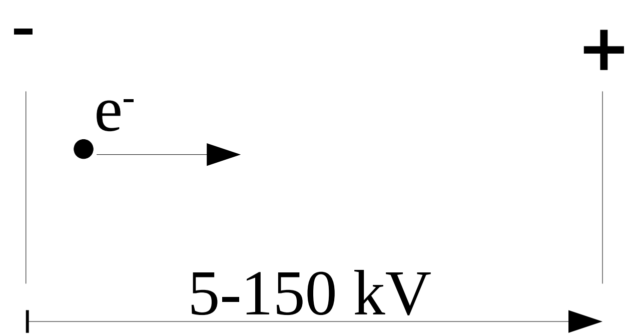
X-Ray Generation – Energy

X-ray are high energy electromagnetic radiation above $3x10^{16}$ Hz and below 10 nm.



$$c = \lambda \nu$$
$$c = 3 \times 10^8 \, m/s$$

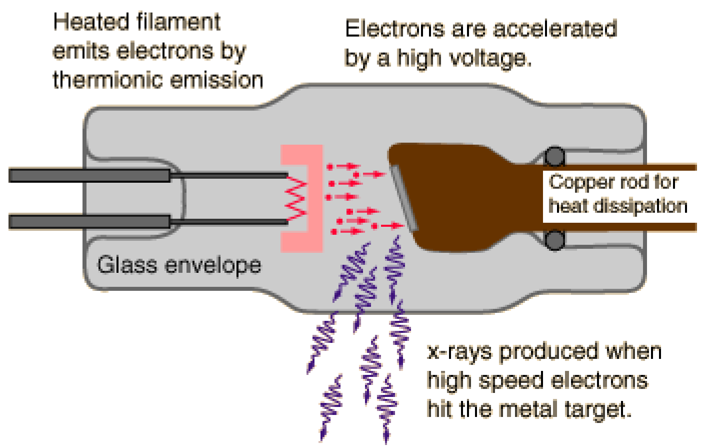
Energy in the keV range:



$$E = \nu \, h$$
$$h = 4.136 \times 10^{-15} \, eV \, s$$

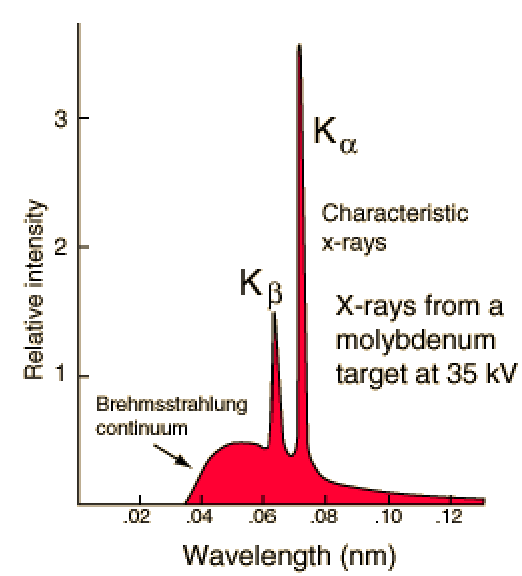
X-Ray Generation - Tube

X-ray vacuum tube accelerates electrons emitting form a heated cathode towards anode. When electrons impact on anode x-rays are emitted



This leads to two forms of radiation:

1. Bremsstrahlung or “breaking radiation”
2. Characteristic radiation



X-Ray Generation – Tube Design

Rotating anode (typically Tungsten) is used to increase surface area and reduce heating.

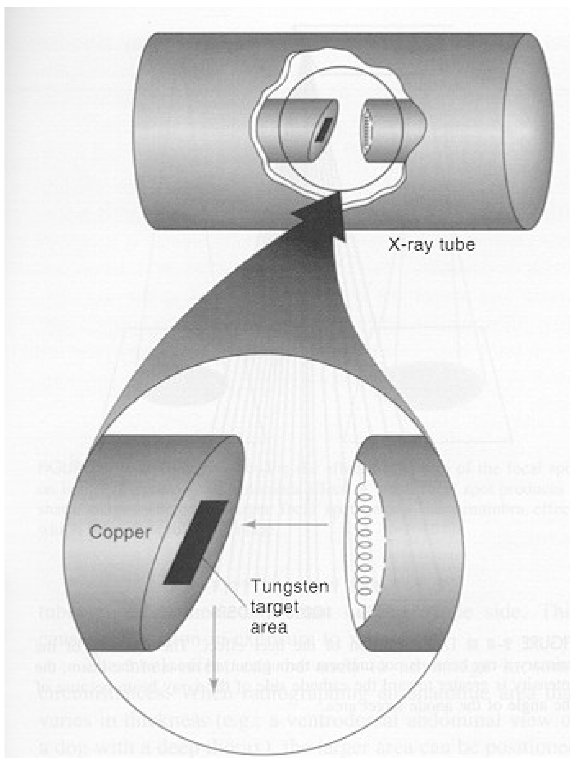


FIGURE 2–5 ■ Stationary anode construction.

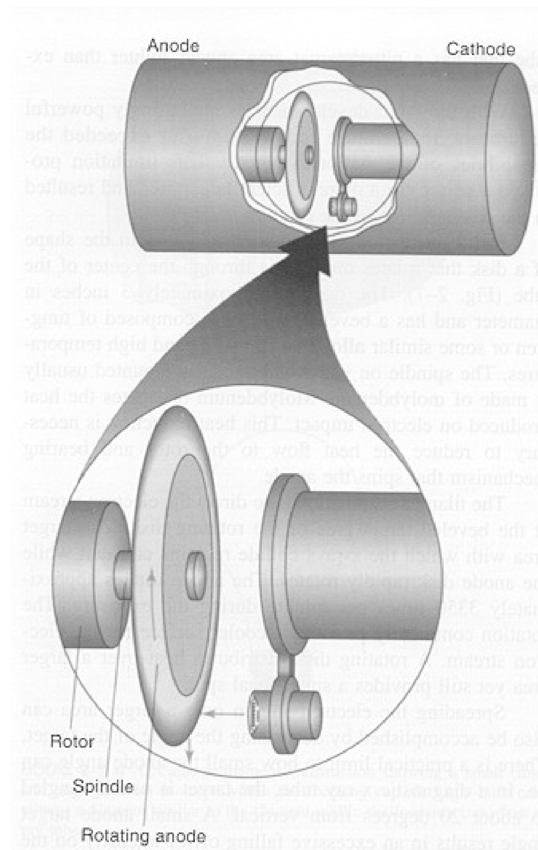


FIGURE 2–7 ■ Example of a rotating anode.

X-Ray Generation – Tube Design

Due to finite size of focal spot on the anode the image of a disk has a penumbra. This leads to blur in the final image, i.e. reduced spatial resolution. The goal is to reduce effective focal spot.

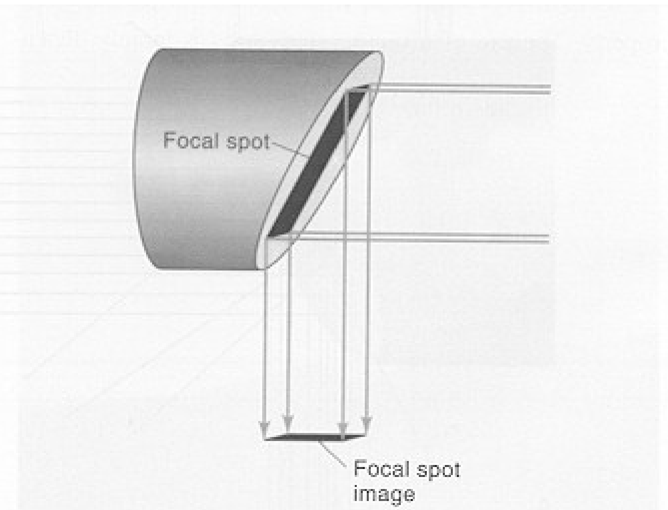


FIGURE 2–9 ■ The focal spot is the area in which the electrons collide with the target.

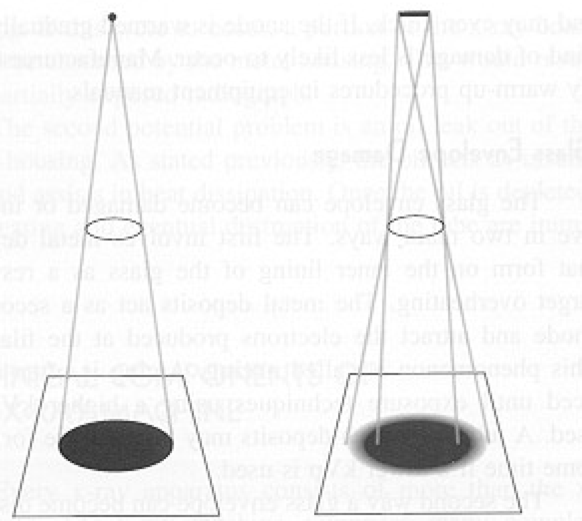
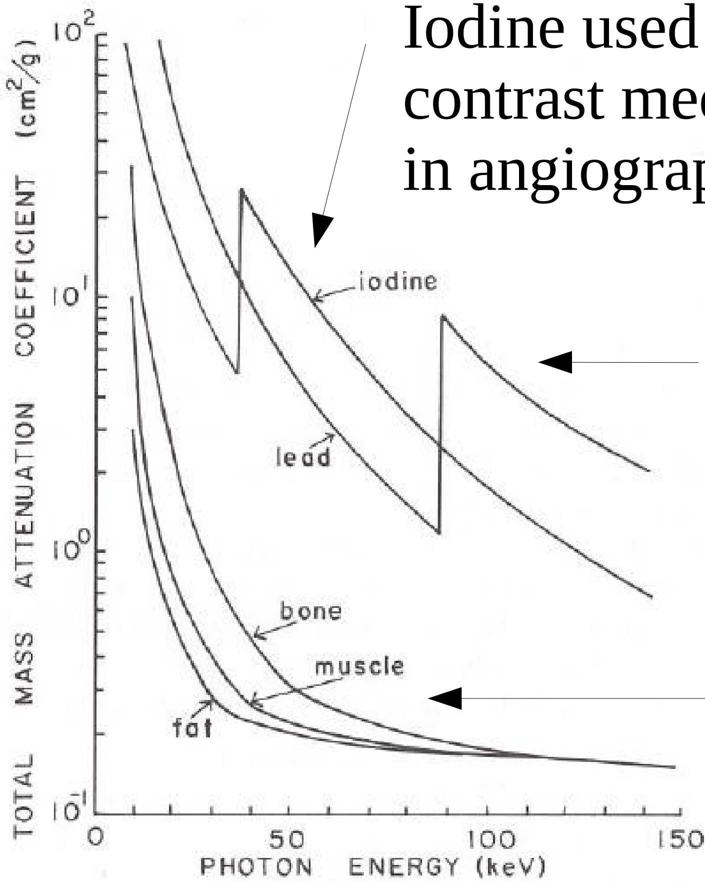


FIGURE 2–10 ■ Diagram showing the effect of the size of the focal spot on image sharpness—the penumbra effect. A small focal spot produces a sharp image, whereas a larger focal spot causes the penumbra effect which blurs the projected image.

X-Ray Interaction – Attenuation Coefficient

Likelihood of scatter and absorption events depend on photon energy:



Iodine used as contrast medium in angiography

Material	μ(cm⁻¹) at 60keV
Air	0
Water	0.21
Muscle	0.2
Fat	0.18
Bone	**0.38**

Lead used for x-ray shielding

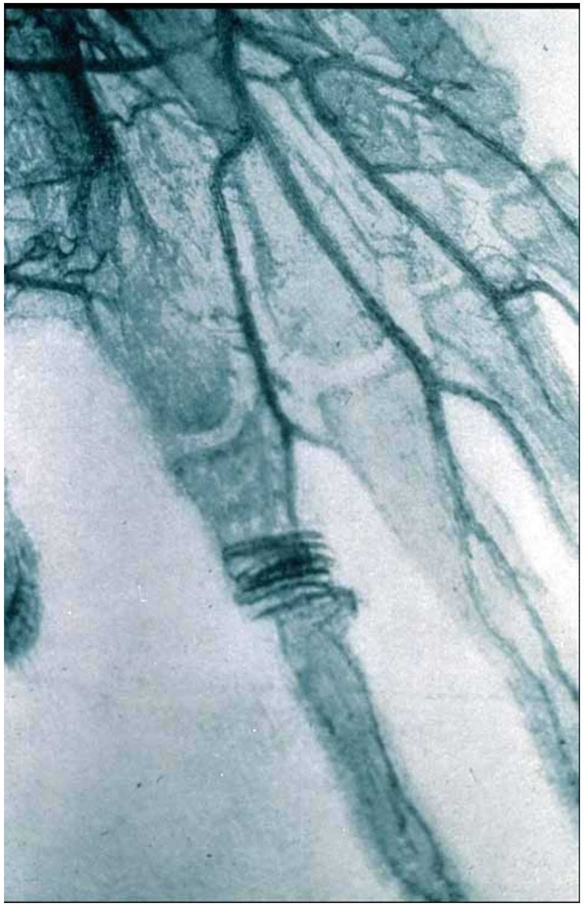
Notice contrast between bone and soft tissue.

Lower energies give better soft tissue contrast.

(Attenuation coefficient is sometimes given as a density to factor out the effect of mass density ρ)

X-Ray Interaction with tissue

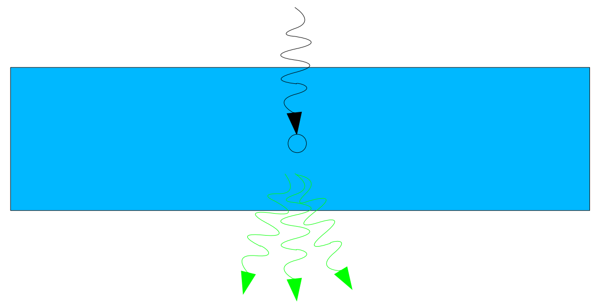
This first Angiography image of 1896 demonstrates well the contrast of due to high and low Z:



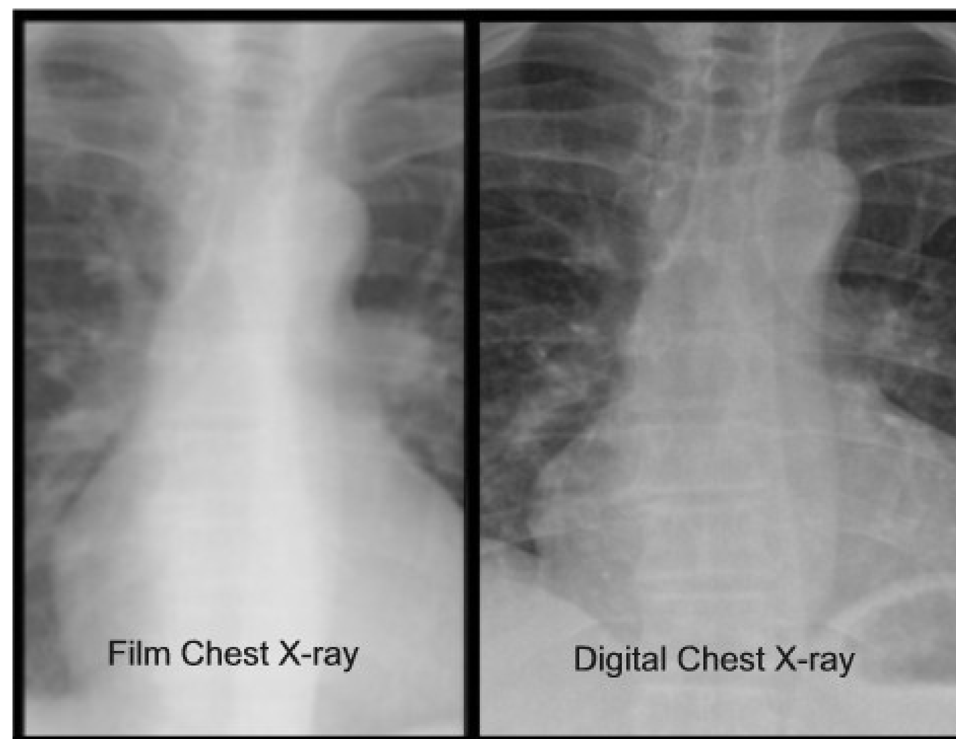
Post-mortem injection of mercury compounds (Haschek and Lindenthal of Vienna 1896).

X-Ray Detection – Phosphor screen

- Phosphor screen converts X-ray to visible light.

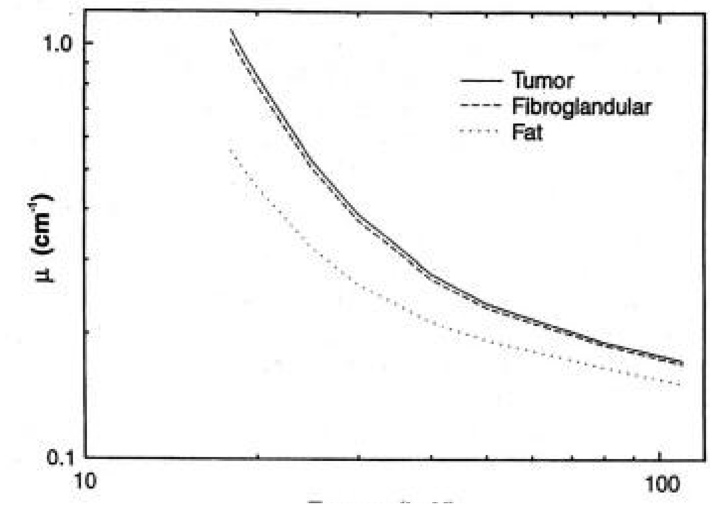


- Rare earth elements (phosphors) absorb x-ray and emit visible light. Single high energy x-ray photon is converted into many visible photons at lower energy.
- Light is then captured by a photographic film and developed the same as in photography.
- Digital X-ray uses a CCD camera to capture X-ray directly to improve image quality by sidestepping sources of blur and noise.

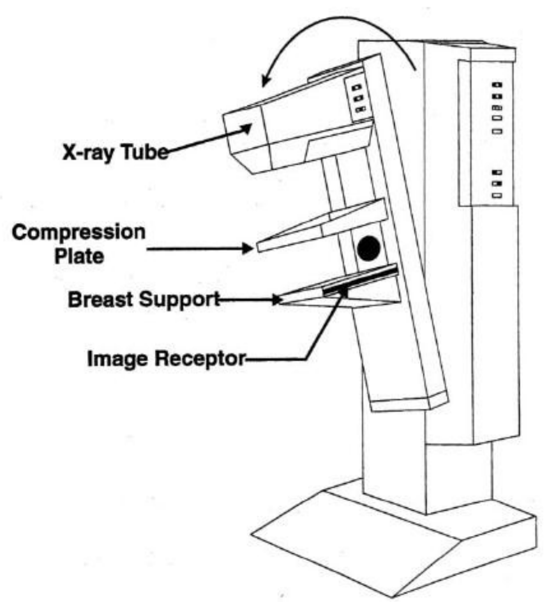


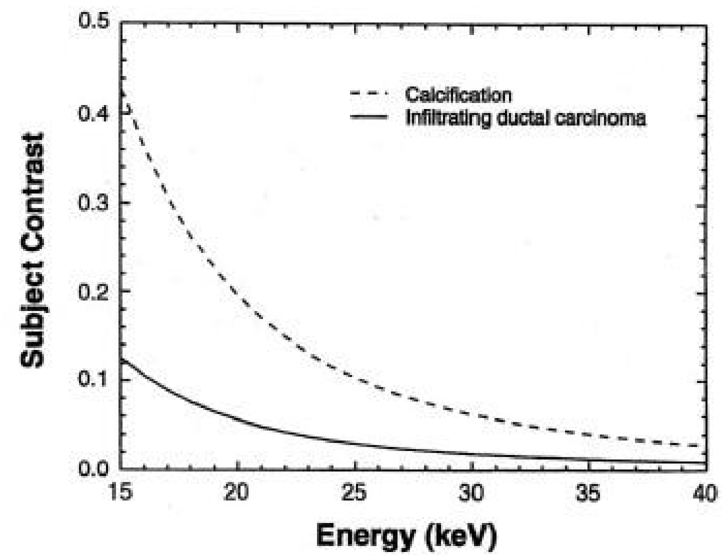
X-Ray Mammography

Low dose imaging at low energies to detect breast tumors at approx. 40 μm resolution.



- Soft tissue contrast best at low energies (18-23 keV)
- Collimator used to improve PSF and reduce background noise.
- Low dose to minimize seeding.

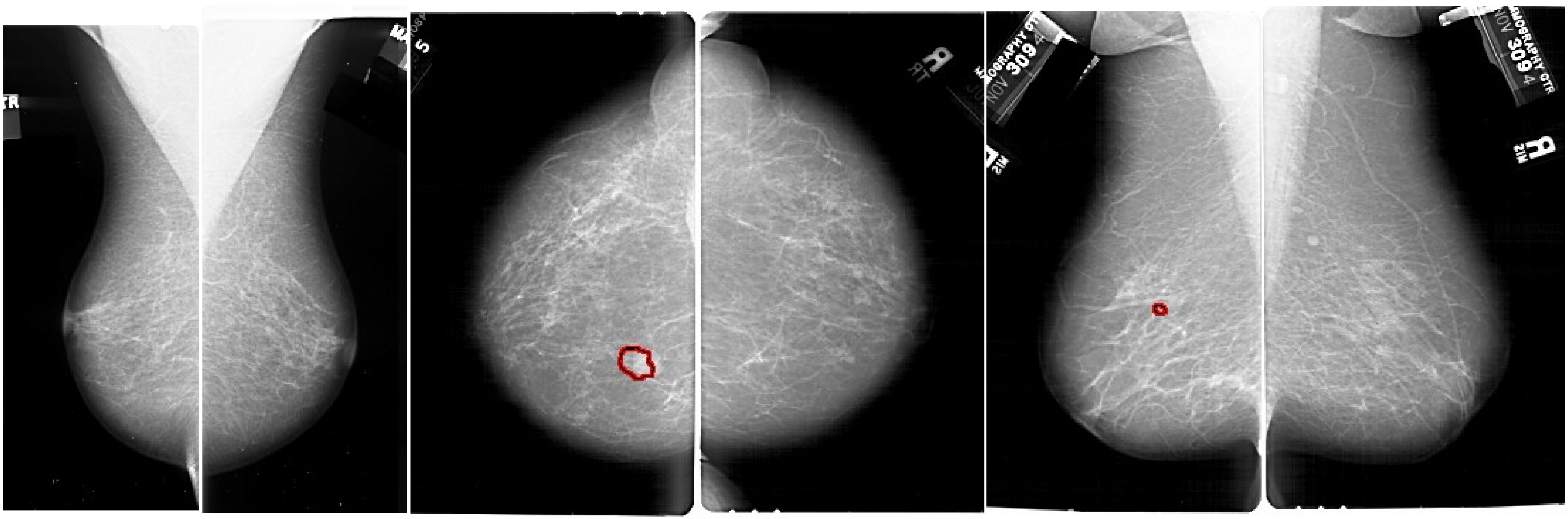




X-Ray Mammography

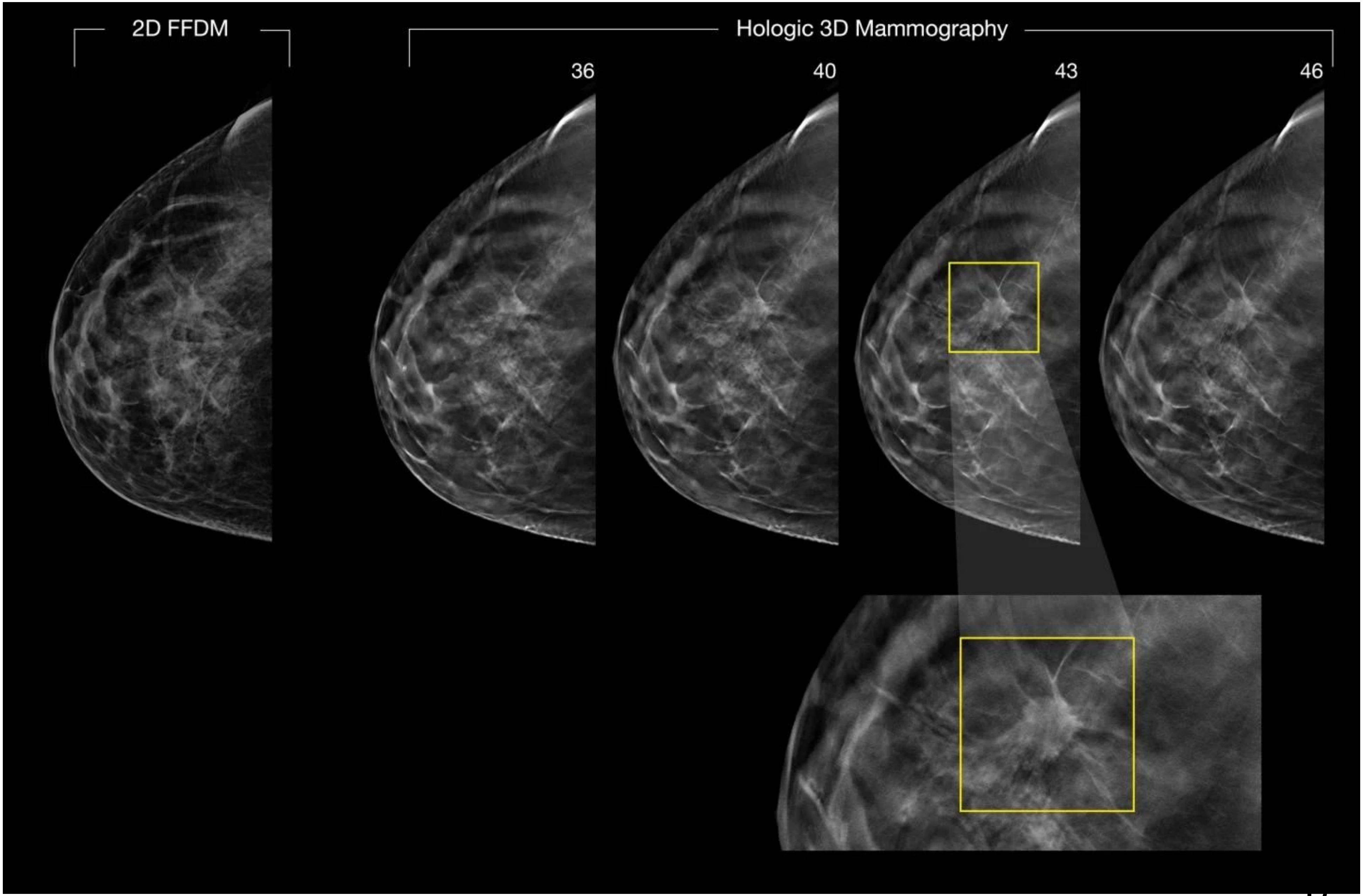
Tumor detection and diagnosis is difficult! It is based on:
- characteristic morphology of normal tissue and tumor mass
- micro-calcifications
- asymmetry between left/right breast.

Normal Benign Tumor



http://marathon.csee.usf.edu/Mammography/Database.html

2D Mammography vs Tomosynthesis



X-Ray Angiography

- Iodine compound injected as contrast agent to visualize blood vessels.
- Images at approx. 100 μm
- Short pulse to minimize motion blurring (10-100 ms depending on application)
- Most important application is the detection arterial obstructions.
- Also used in combination with fluoroscopy for real time monitoring of interventions such as angioplasty, catheter placement, etc.
- *Digital Subtraction Angiography* requires accurate (and flexible) registration of pre/post injection images.
- Composite images (on the left) also require accurate registration.

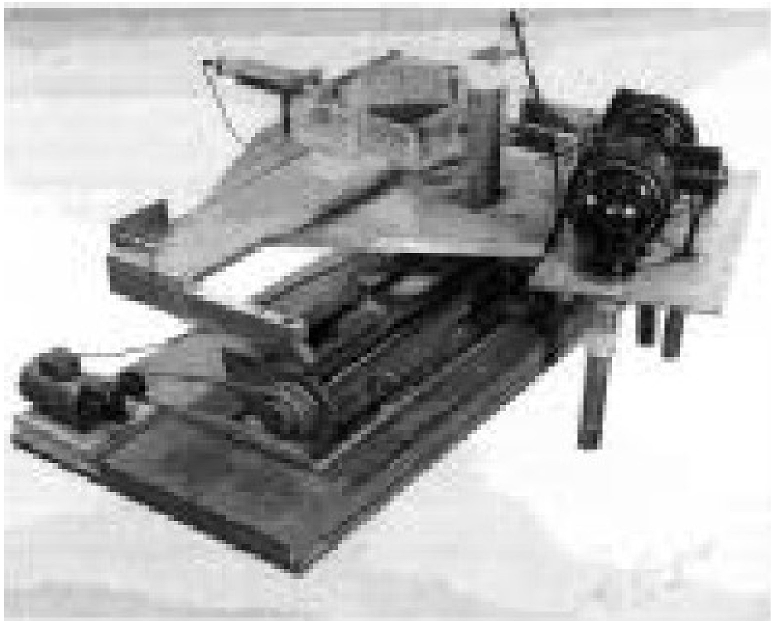
X-Ray Fluoroscopy

- Real-time x-ray imaging.
- Used in instruments during surgical interventions.
- Reduced x-ray intensity to minimize dose during continuous exposure.
- Therefore often contrast enhanced, e.g. blood vessels, and colon.

Example left: Air contrast Barium enema.

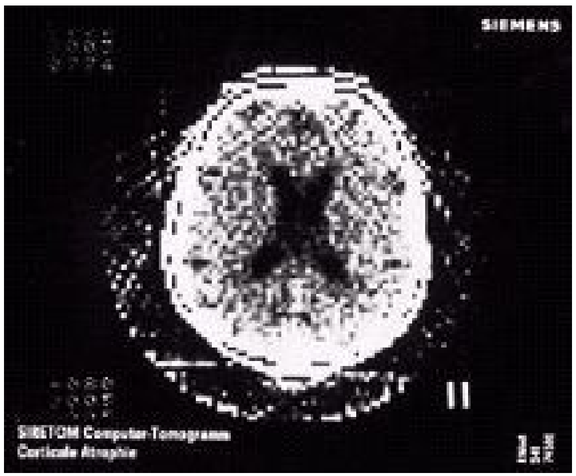
CT - Origins

- Mathematical basis developed by Radon (1917)
- Idea popularized by Cormack (1963)
- First practical x-ray CT scanner by Hounsfield (1971)



CT – then and now

1971



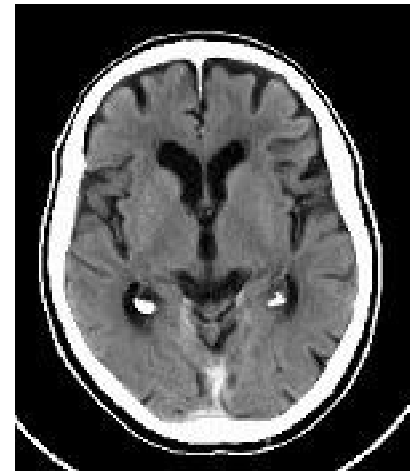
Original axial CT image from the dedicated Siretom CT scanner. Ability to see the soft tissue structures of the brain, including the black ventricles for the first time.

128x128 pixel

1-4 hours acquisition time

1-5 days computation

2000



Axial CT image of a normal brain using a state-of-the-art CT system.

512 x 512 pixel

0.35 sec acquisition time

1 sec computation

CT – CT number

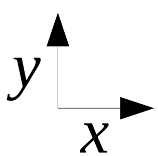
Hounsfield Units or "CT number" are units for attenuation coefficient relative to watter attenuation at μ_{water} at 70keV.

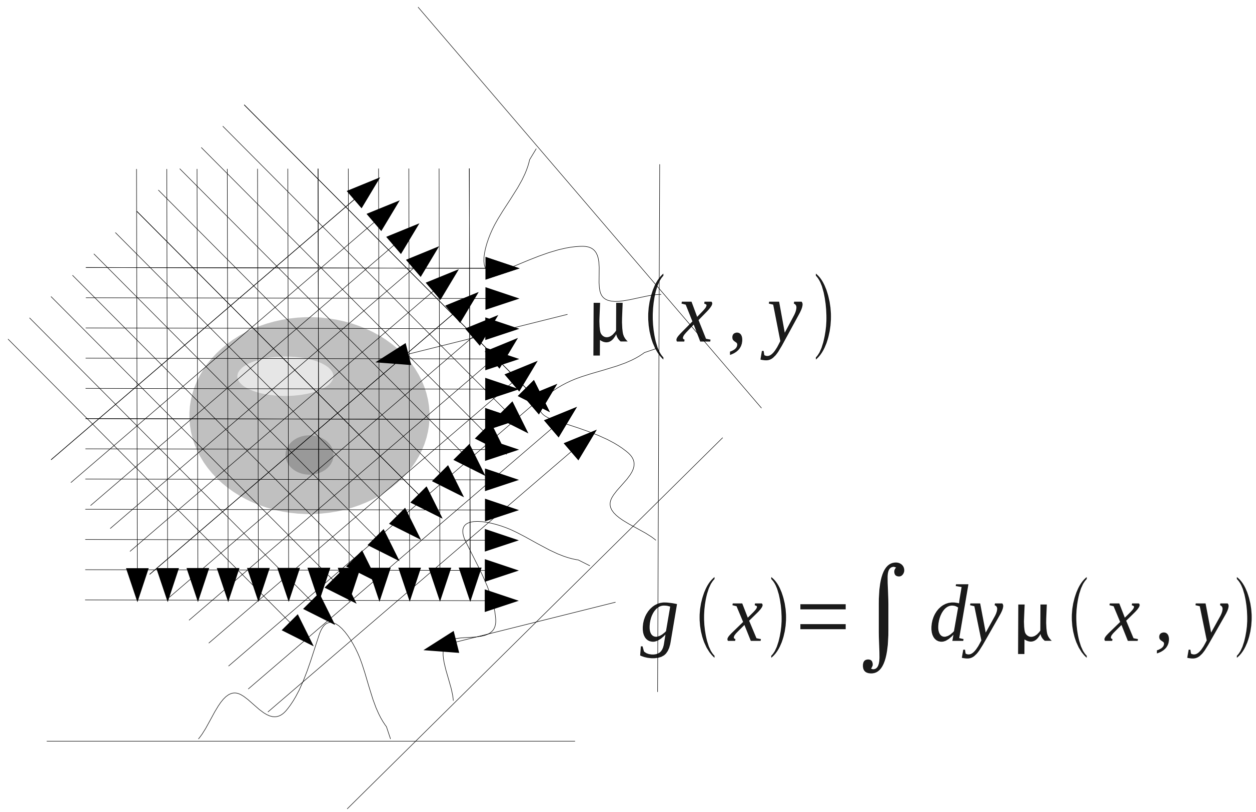
$$HU = 1000 \frac{\mu - \mu_{water}}{\mu_{water}}$$

Tissue	**CT number (HU)**
Bone	1000
Liver	40 ... 60
White matter (brain)	46
Grey matter (brain)	43
Blood	40
Muscle	10 – 40
Kidney	30
Cerebrospinal fluid	15
Water	0
Fat	–50 ... –100
Air	–1000

CT - Imaging Principle

Computed Axial Tomography: Multiple x-ray projections are acquired around the object and a 2D image is computed from those projections.

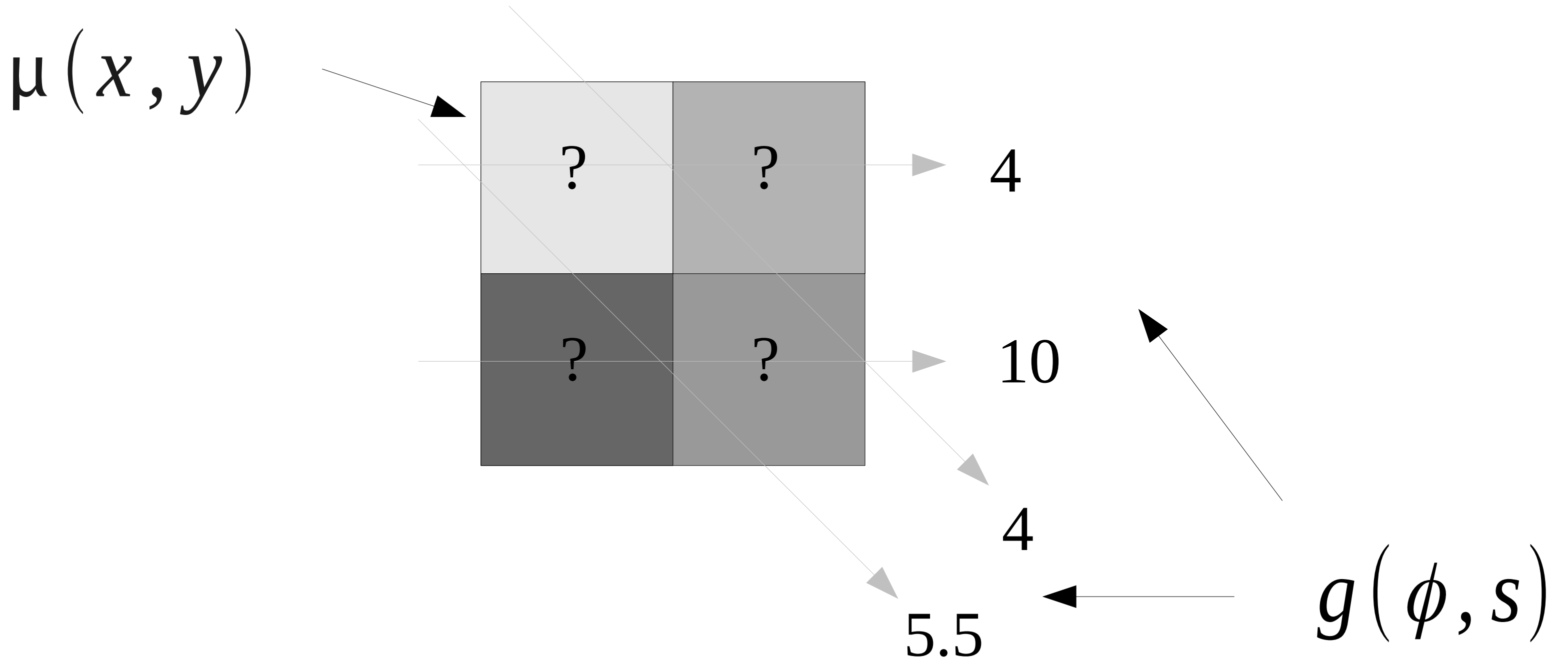




Idea: Reconstruct 2D attenuation distribution $\mu(x,y)$ from multiple 1D x-ray projections $g(\,)$ taken at different angles ϕ .

CT – Simple Inversion Example

Given the observed detector values how can one compute the unknown attenuation coefficients?



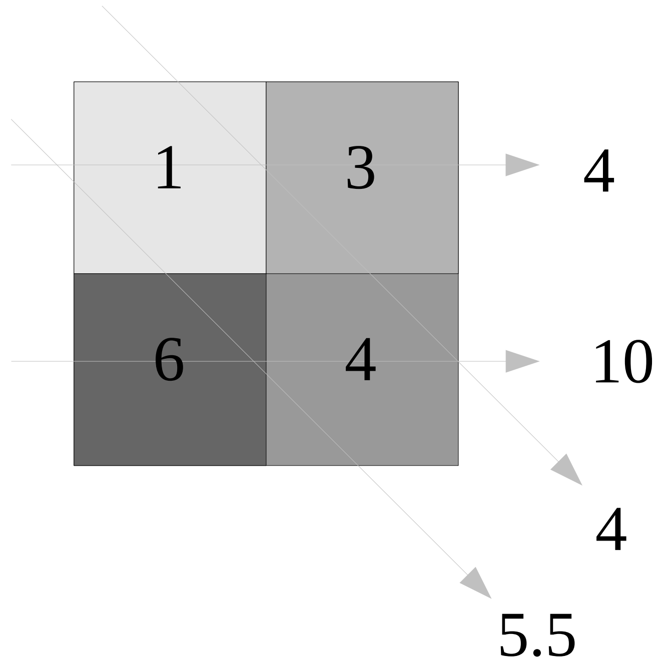
$g(1,1) = \mu(1,1) + \mu(1,2)$
$g(1,2) = \mu(2,1) + \mu(2,2)$
$g(2,1) = (\mu(1,1) + \mu(1,2) + \mu(2,2))/2$
$g(2,2) = (\mu(1,1) + \mu(2,1) + \mu(2,2))/2$

$$\boldsymbol{g} = M\,\boldsymbol{\mu}$$

$$M = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0.5 & 0.5 & 0 & 0.5 \\ 0.5 & 0 & 0.5 & 0.5 \end{bmatrix}, \quad \mu = \begin{bmatrix} \mu(1,1) \\ \mu(1,2) \\ \mu(2,1) \\ \mu(2,2) \end{bmatrix}, \quad \boldsymbol{g} = \begin{bmatrix} g(1,1) \\ g(1,2) \\ g(2,1) \\ g(2,2) \end{bmatrix}$$

CT – Inversion Simple Example

Given the observed detector values how can one compute the unknown attenuation coefficients?



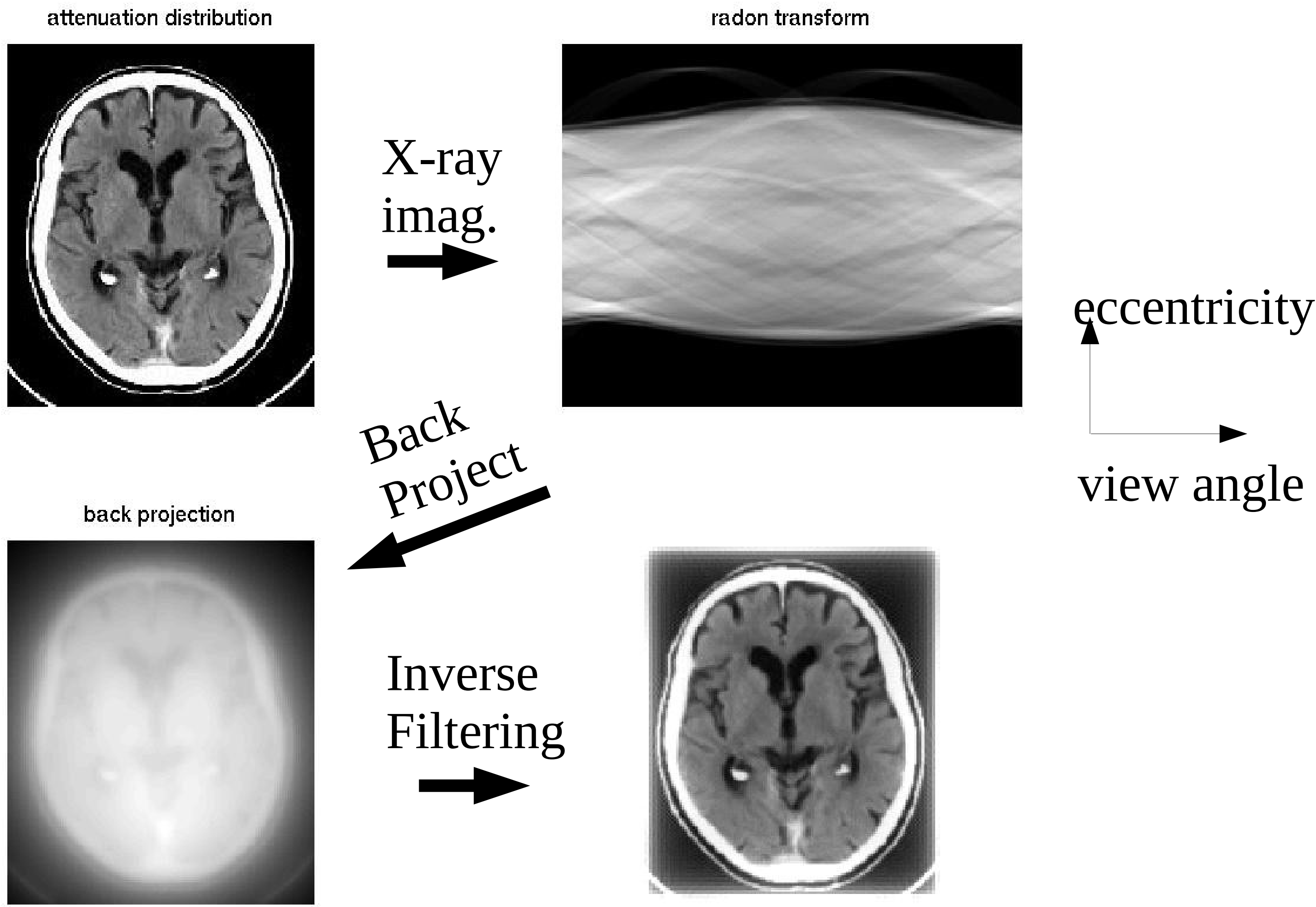
$$\boldsymbol{g} = M\,\boldsymbol{\mu}$$

Answer: linear inversion!

$$\mu = M^{-1}\boldsymbol{g}$$

$$M^{-1} = \begin{bmatrix} 0 & -1 & 0 & 2 \\ 1 & 1 & 0 & -2 \\ 1 & 1 & -2 & 0 \\ -1 & 0 & 2 & 0 \end{bmatrix}, \quad \mu = \begin{bmatrix} 1 \\ 3 \\ 6 \\ 4 \end{bmatrix}, \quad \boldsymbol{g} = \begin{bmatrix} 4 \\ 10 \\ 4 \\ 5.5 \end{bmatrix}$$

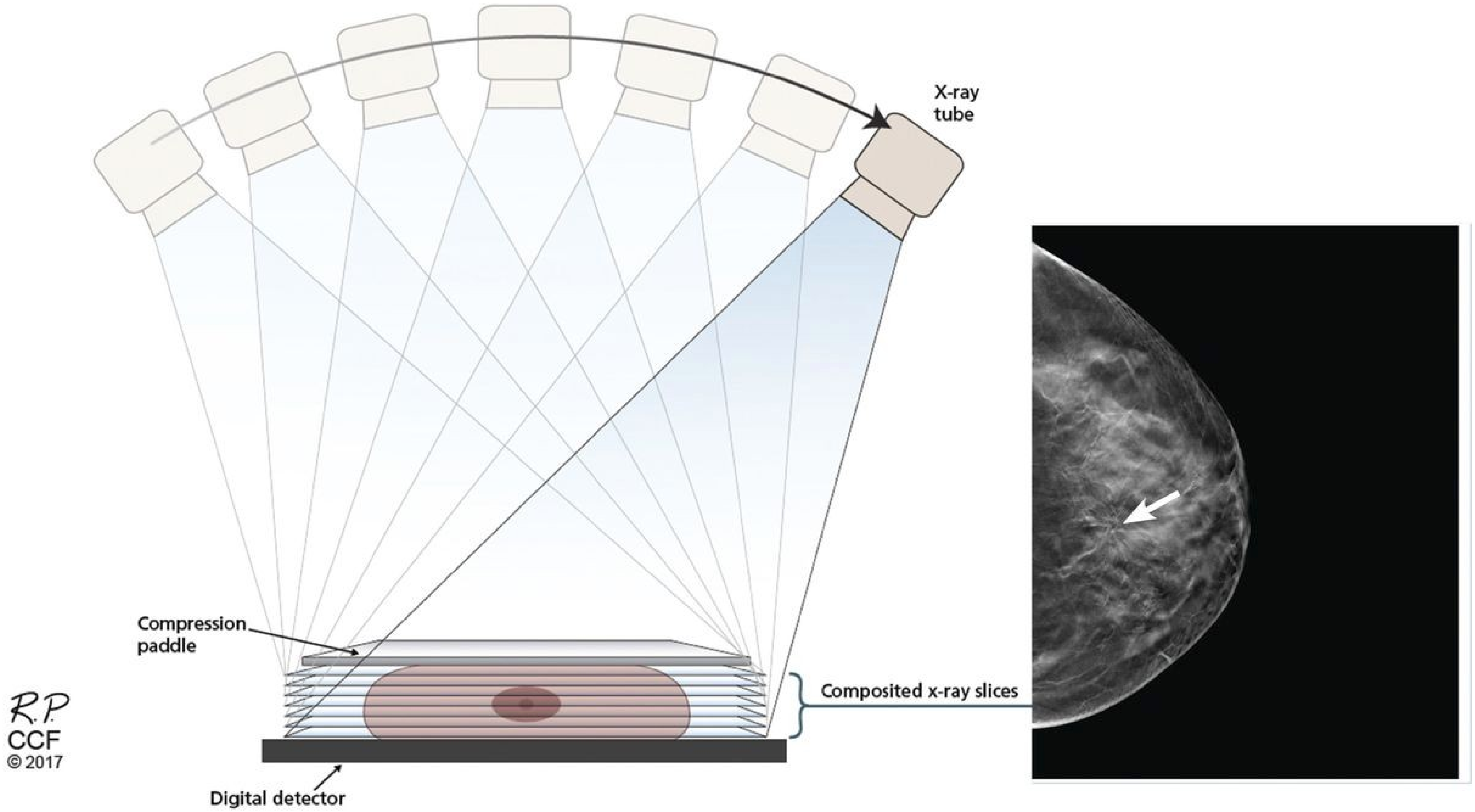
CT – Back Projection, Inverse Filtering



Note edge effects

Tomosynthesis

Similar to CT, but not a full 3D reconstruction.



Tomosynthesis

Tumors may be visible in different slices.

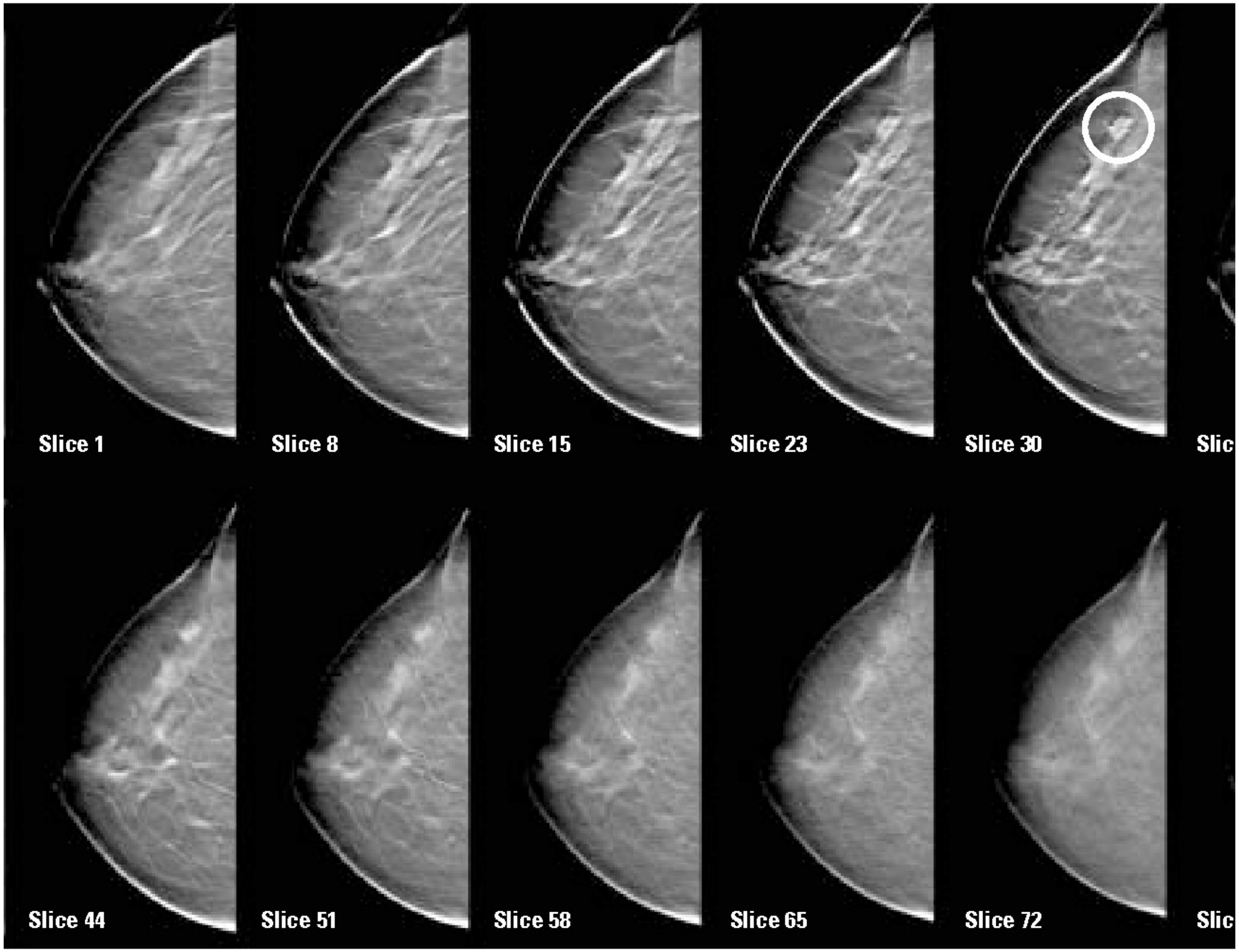
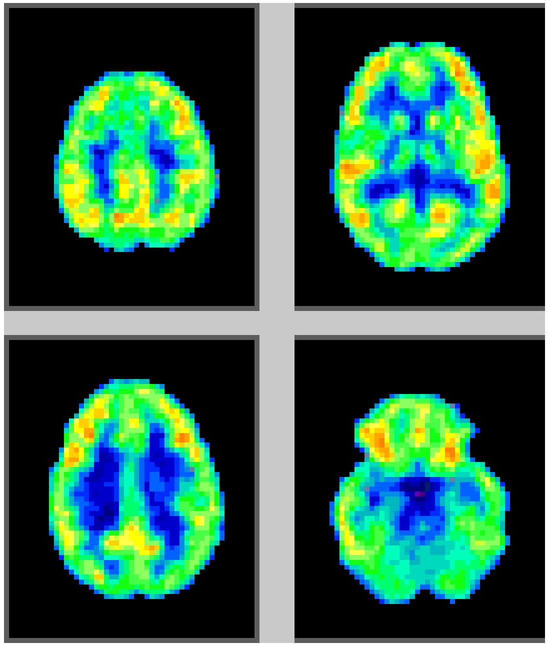


Figure 6b: Reconstructed tomosynthesis slices. An invasive lobular carcinoma can be clearly seen in slice 30.

Nuclear Imaging

- Molecules tagged with radioactive isotopes are injected.
- Disperse through the body according to biologic function.
- Meta-stable isotopes emit gamma rays in radioactive decay.
- Gamma rays are detected and converted into images as in x-ray CT.
- Images represent concentration of radiating isotopes in the body.
- Called emission tomography (as opposed to transmission tomography)
- Images represent anatomy and **function!**



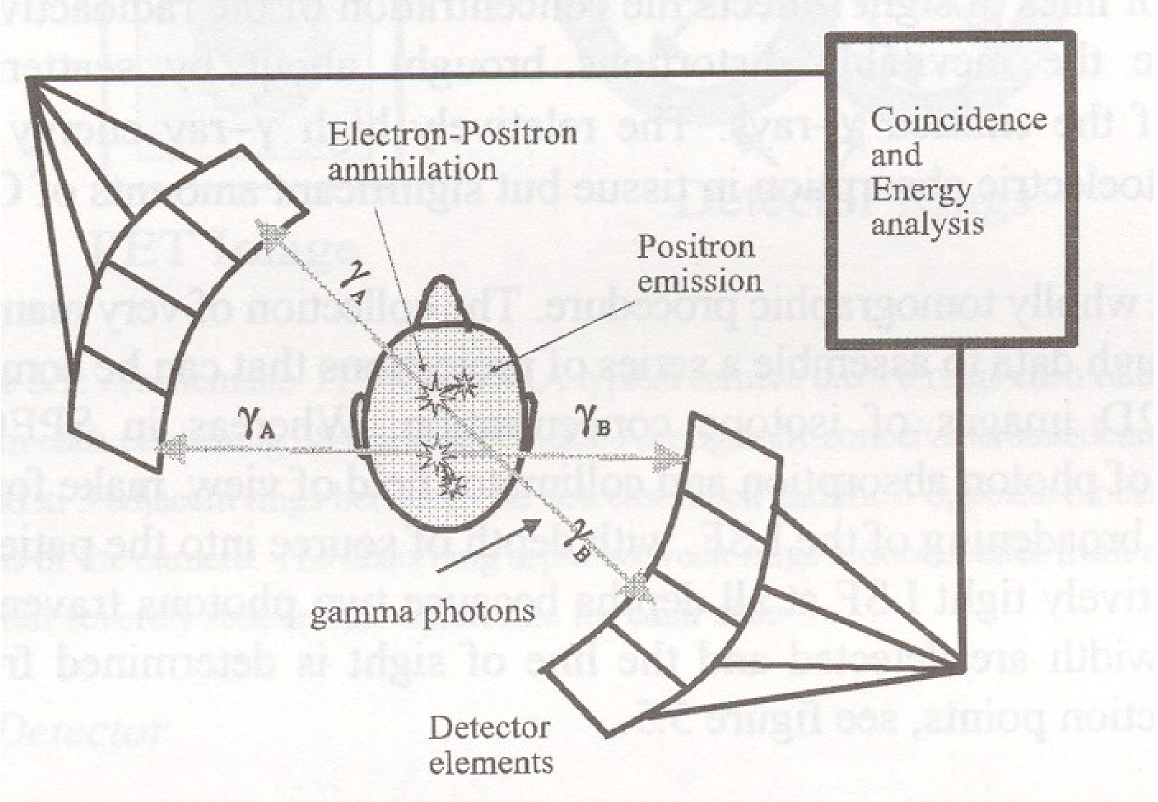
Example: PET of the brain

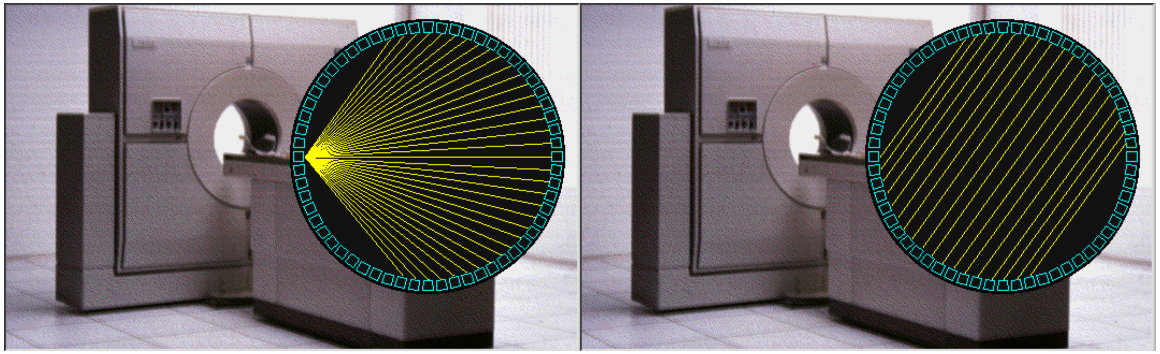
Nuclear Imaging - PET

- Coincidence detection (<12ns) ensures directional information.
- Due to poor SNR resolution only about 1cm.
- Typical isotopes in PET

Radionuclide	Half-live (min)
^{11}C	20.4
^{15}O	2.07
^{13}N	9.96
^{18}F	1009.7

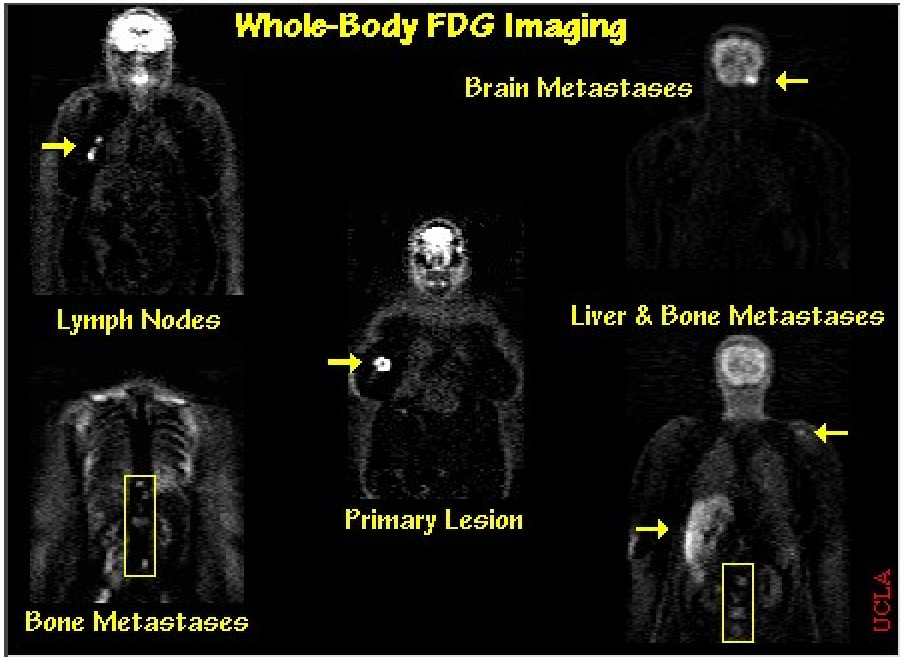
- Common tracer ^{18}F-labeled glucose, Fluorodeoxyglucose (FDG). Applications:
  - Neurology
  - Oncology
  - Cardiac function

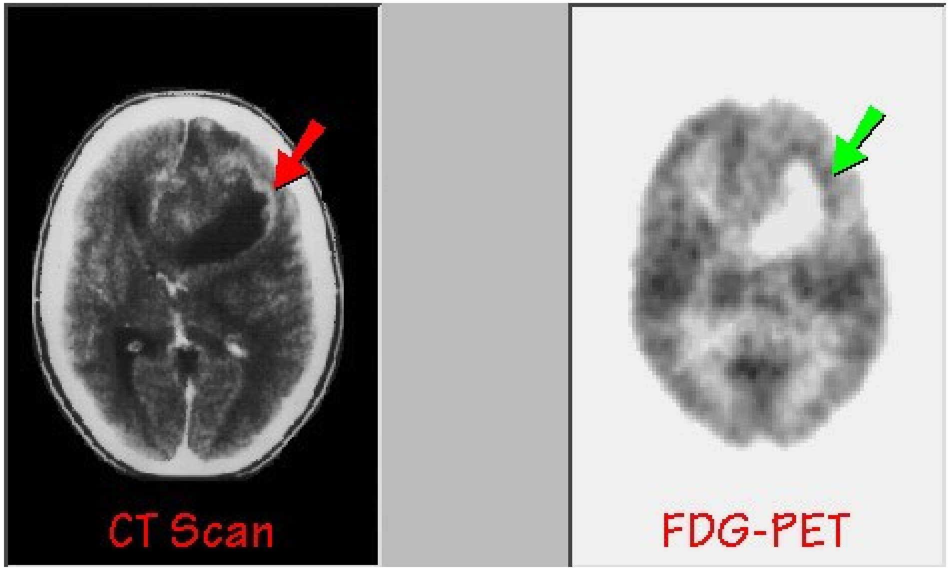




Nuclear Imaging – PET Applications

•Oncology: Tumour detection and diagnosis

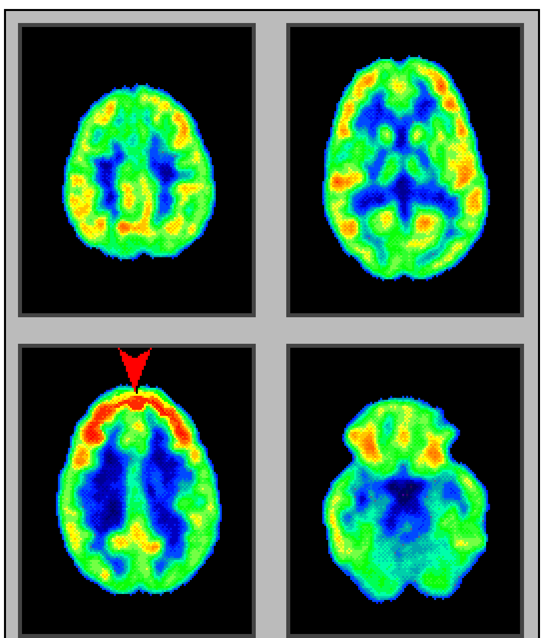




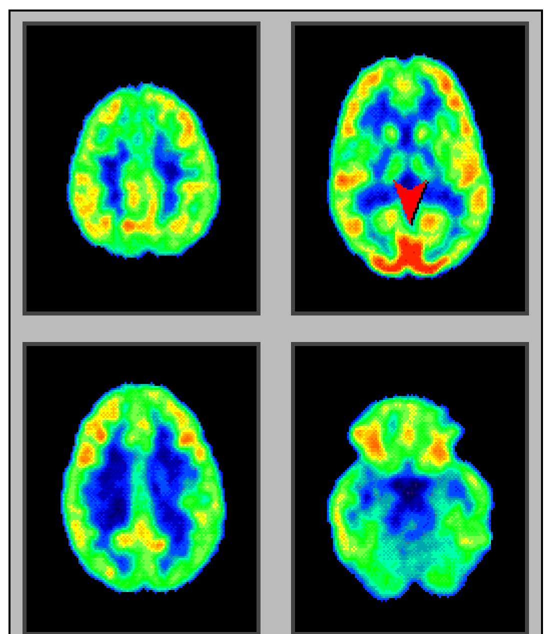
Nuclear Imaging – PET Applications

Neurology:
- normal brain function,
- Alzheimer's, Parkinson's,
- development,
- Trauma, ...

'thinking'



looking



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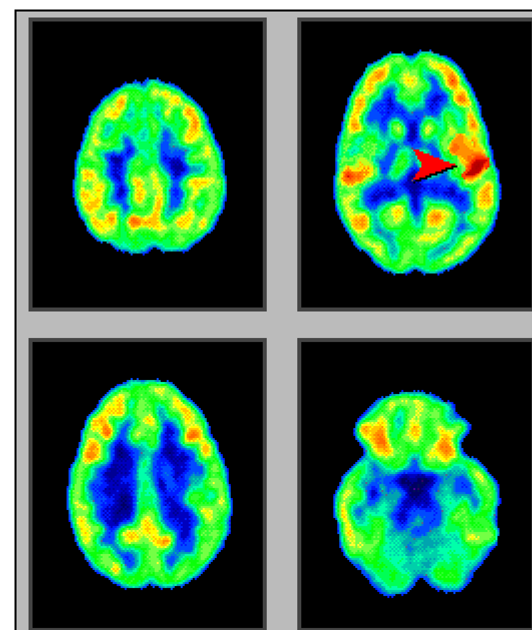
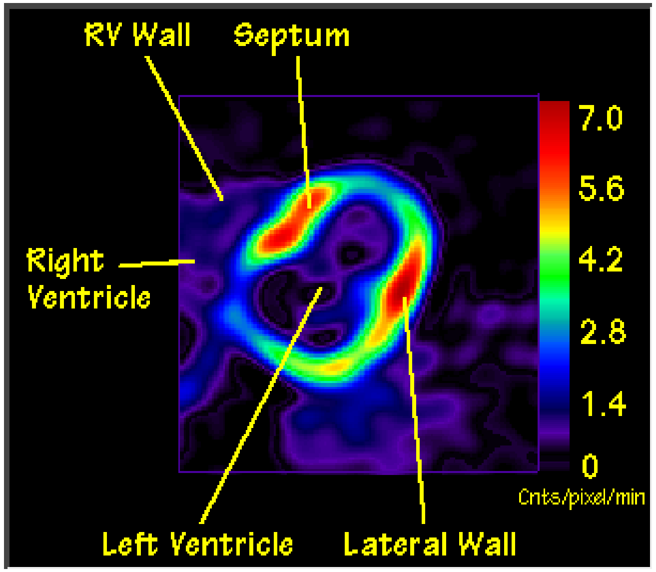
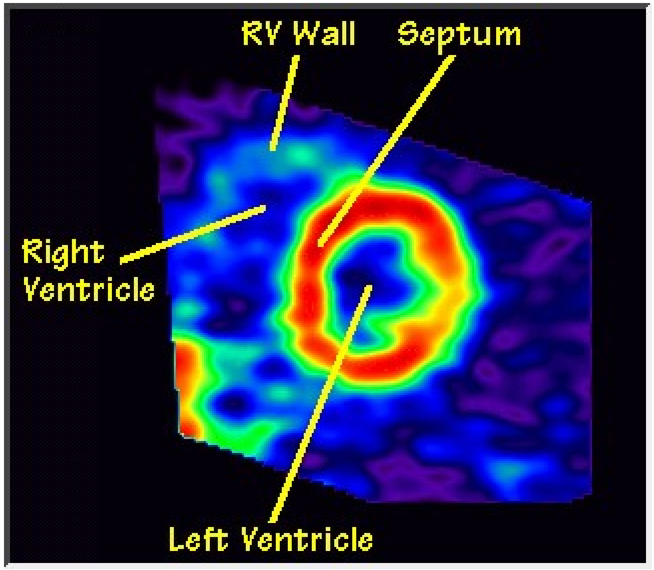
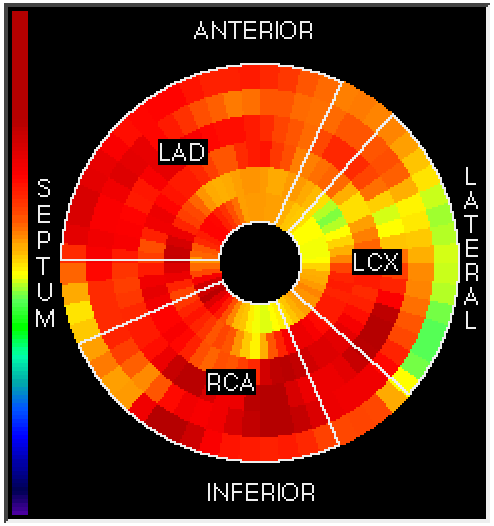


Nuclear Imaging – PET Applications

Cardiac function







Bone scan

Radioactive tracer is injected and imaged with conventional 2D xray screen to image bone metastases.