Medical Imaging Processing

Chapter 2: Image Acquisition Systems

2.1a: Introduction

- A biomedical image acquisition system captures and records localized information about the physical and/or functional properties of tissues or components of tissues (e.g., cells)
- Accuracy – is the image a realistic representation of the targeted object?
- Efficiency – how long will it take to acquire the image?
- Most imaging systems are computerized and need computers to do some postprocess work, especially to produce 3D images

2.1b: Image Formation

- Some form of energy is measured after its passage through an interaction with a region of the body
- Mathematical estimates are computed and images produced of the 2D and 3D distribution of sensor readings on interactions of the energy with body tissue
- The interactions include absorption, attenuation, nuclear magnetic disturbances, etc.
- Many structures can be imaged simultaneously
- Many types of instrumentation may be used to measure the interactions between energy and tissues

2.1c: Image Characteristics

- Image comparisons can be made based on some characteristics:
  - Inherent spatial resolution
  - Contrast resolution
  - Temporal resolution
- Other imaging system characteristics:
  - Images of structure
  - Images of function

2.1d: Spatial Resolution

- In discrete digital images, each pixel (2D) or voxel (3D) has specific dimensions in the measurement space of the object
- The limits to spatial resolution in the final image are the smallest dimensions of the object differentiable by the total imaging system, including image reconstruction
- The resolution and dimensions may differ for each orthogonal direction represented in a volume image (anisotropic) or they may be equal (isotropic)

2.1e: Contrast Resolution

- In an image, individual structures are recognized by localized differences in signal strength (e.g., the amount of absorption, reflection, etc.) among immediately adjacent structures
- **Contrast resolution** is the ability of an imaging system to detect differences in signal intensity between two structures
- Contrast resolution is dependent on image acquisition, the energy form used, and the physical properties of the structures being imaged
- It usually specified as a percentage of the largest signal difference that can be detected and quantified

2.1f: Temporal Resolution

- Two definitions – the “aperture time” and the frame (or repetition) rate”
- The **aperture time** is the amount of time the system takes to capture the signal information to form a single image

  key component in eliminating motion artifact
- The **frame rate** is the image repetition rate, defined by the smallest interval of time required to produce successive images
- Both definitions do not include image reconstruction time or final image formation time

2.1g: More about Frame Rate

- The frame rate limits the ability of the system to acquire 4D data sets (with the time line)
- In most cases, the frame rate of the imaging system is mechanically/electronically limited
- It may be triggered by physiological events to acquire “gated” images
- “Gated” images are taken in accordance to the time intervals of certain repeated physiological events, e.g., heart beat, breath

2.2a: Biomedical Acquisition Systems

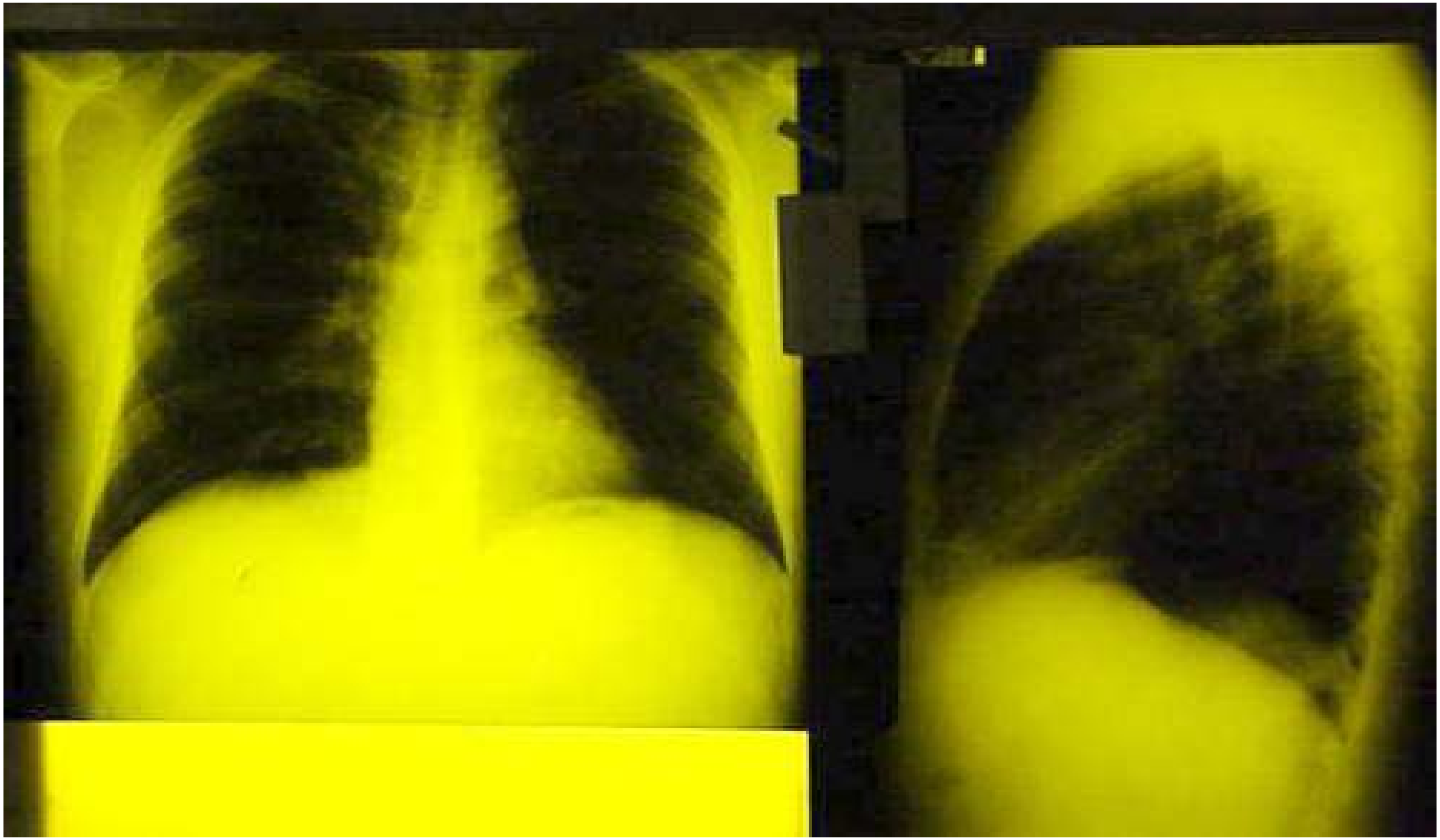
- Conventional radiography
- Conventional axial tomography
- X-ray computed tomography (CT)
- Magnetic resonance imaging (MRI)
- Nuclear medicine imaging
- Ultrasound
- Biomagnetic imaging
- Microscopy imaging

2.2b: Conventional Radiography

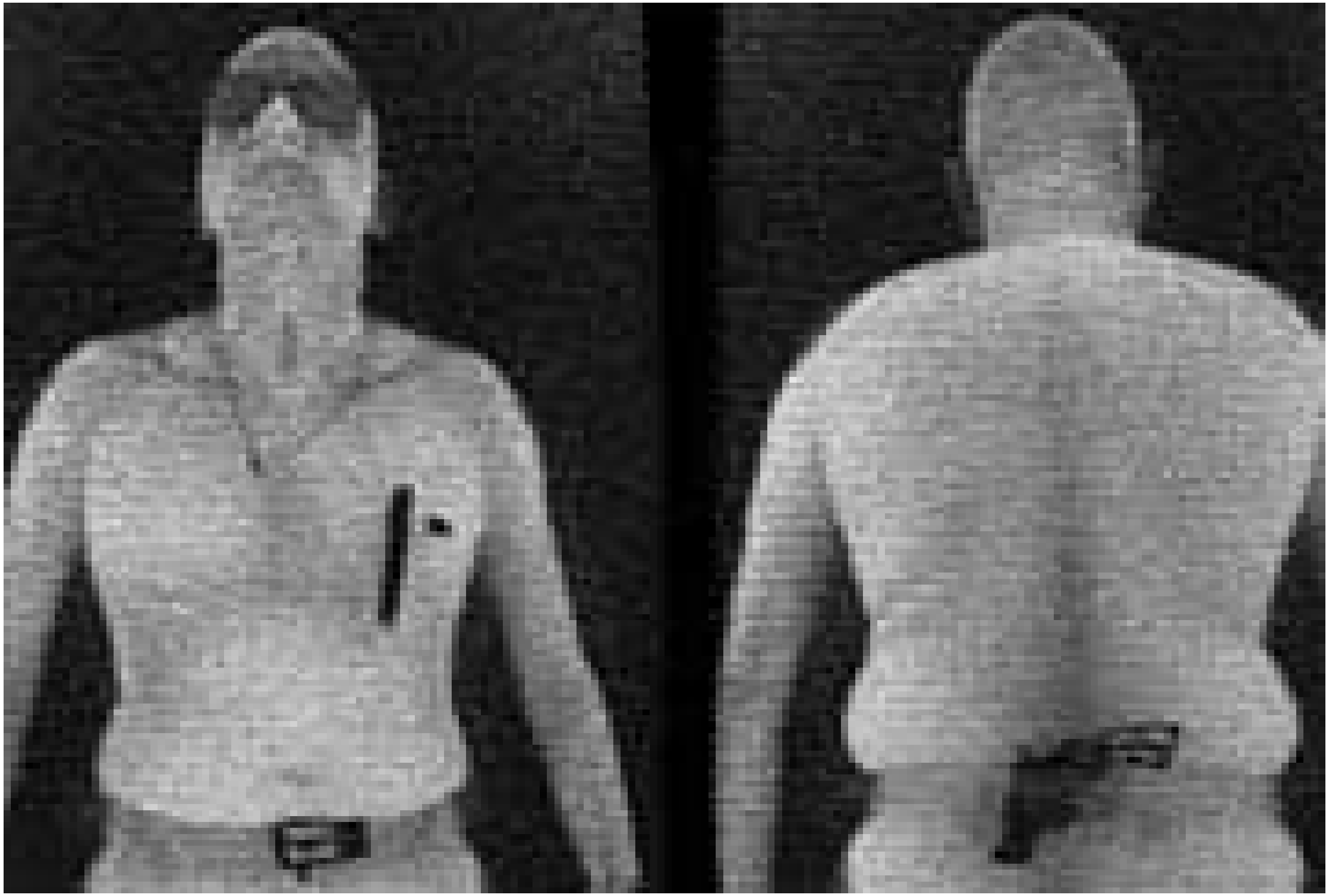
- Signal acquisition – a beam of X-rays passing through the body is differentially absorbed and scattered by structures in the beam path
    - physical density
    - atomic composition of the structures
    - energy of the X-ray beam
- The differential absorption pattern is recorded by an X-ray recorder
    - radiographic film
    - digital radiographs (store, process, transport)

2.2c: Siemens X-ray Machines
Film-based analogy multix top machines

2.2d: A Chest X-ray Picture



2.2e: Other Use of X-ray Machines



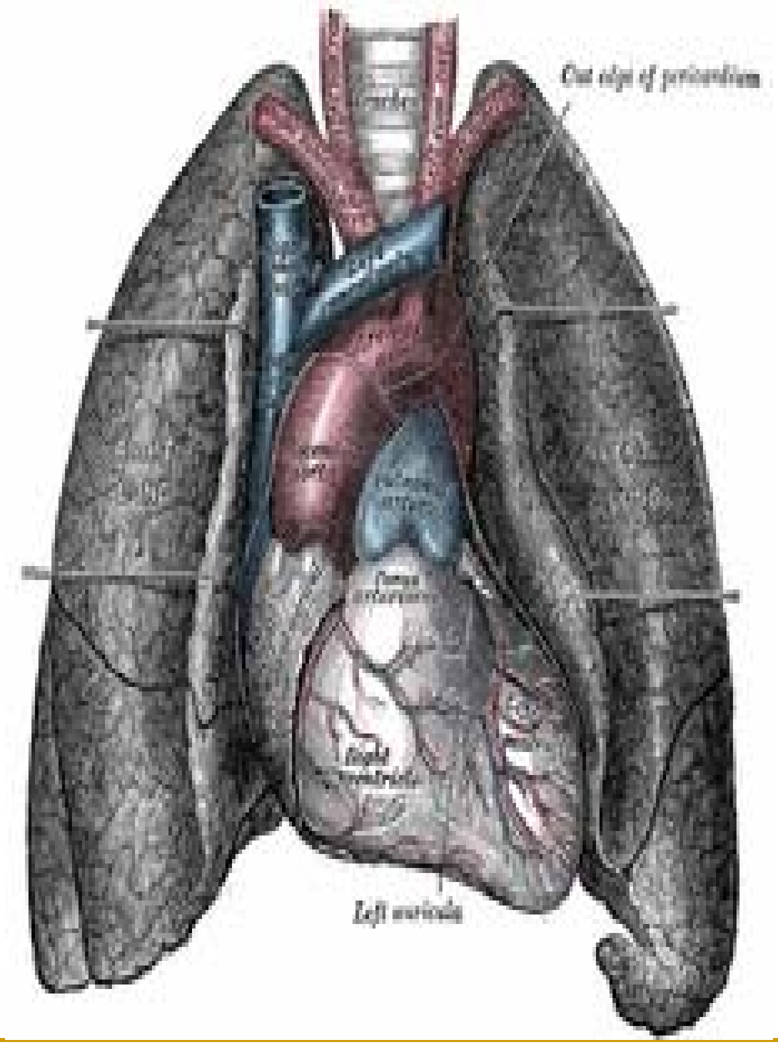
2.2f: X-ray Image Characteristics

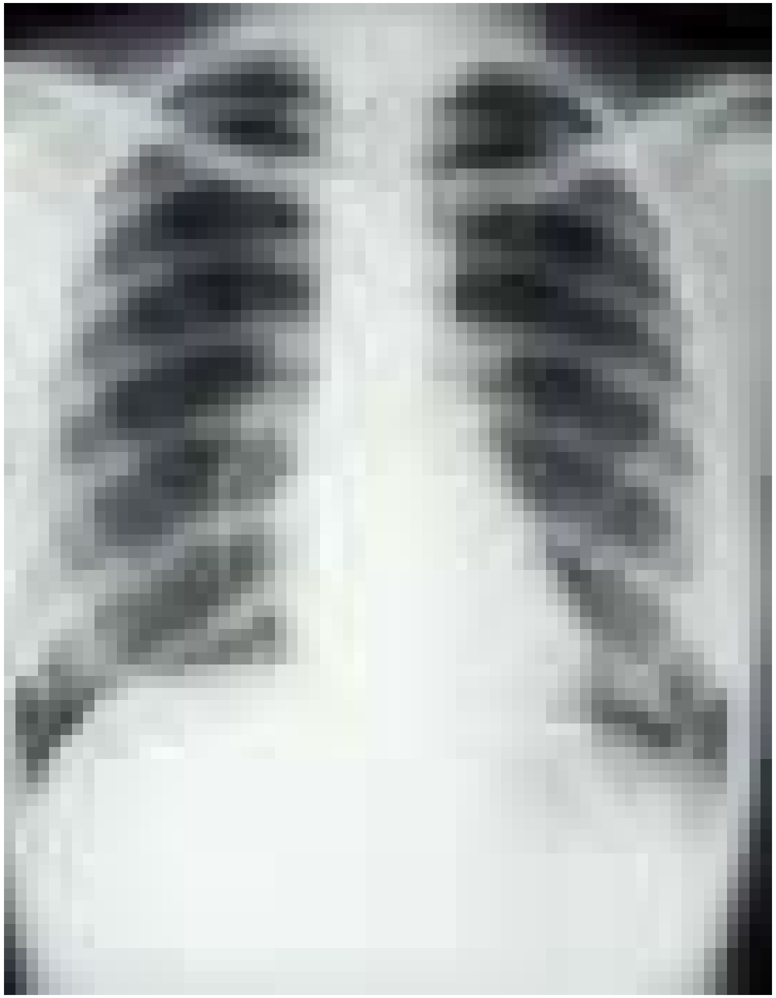
- X-ray is mostly used for structural imaging, the parameter recorded is the energy absorption
- Dimensionality is strictly 2D (a projection of a 3D structure onto a 2D plane)
- Spatial resolution is high, from 1.0 to 0.5 mm^2
- Contrast resolution is on the order of 1% of full range
- Temporal resolution is about 10 milliseconds
- Digital radiographic images are usually represented over a 12-bit dynamic range from 0 to 4,096

2.2g: 3D Superposition in Radiographs

- The attenuation is dependent on path length through an object as well as on the physical density and atomic composition of the object
- We cannot see from the film the different materials through which the beam passed
- The attenuation at different points along the beam path “add up” and are superimposed onto the same points on the detector
- Regions where high density differences exist between structures can be seen clearly

2.2h: More X-ray Picture (Lung and Heart)

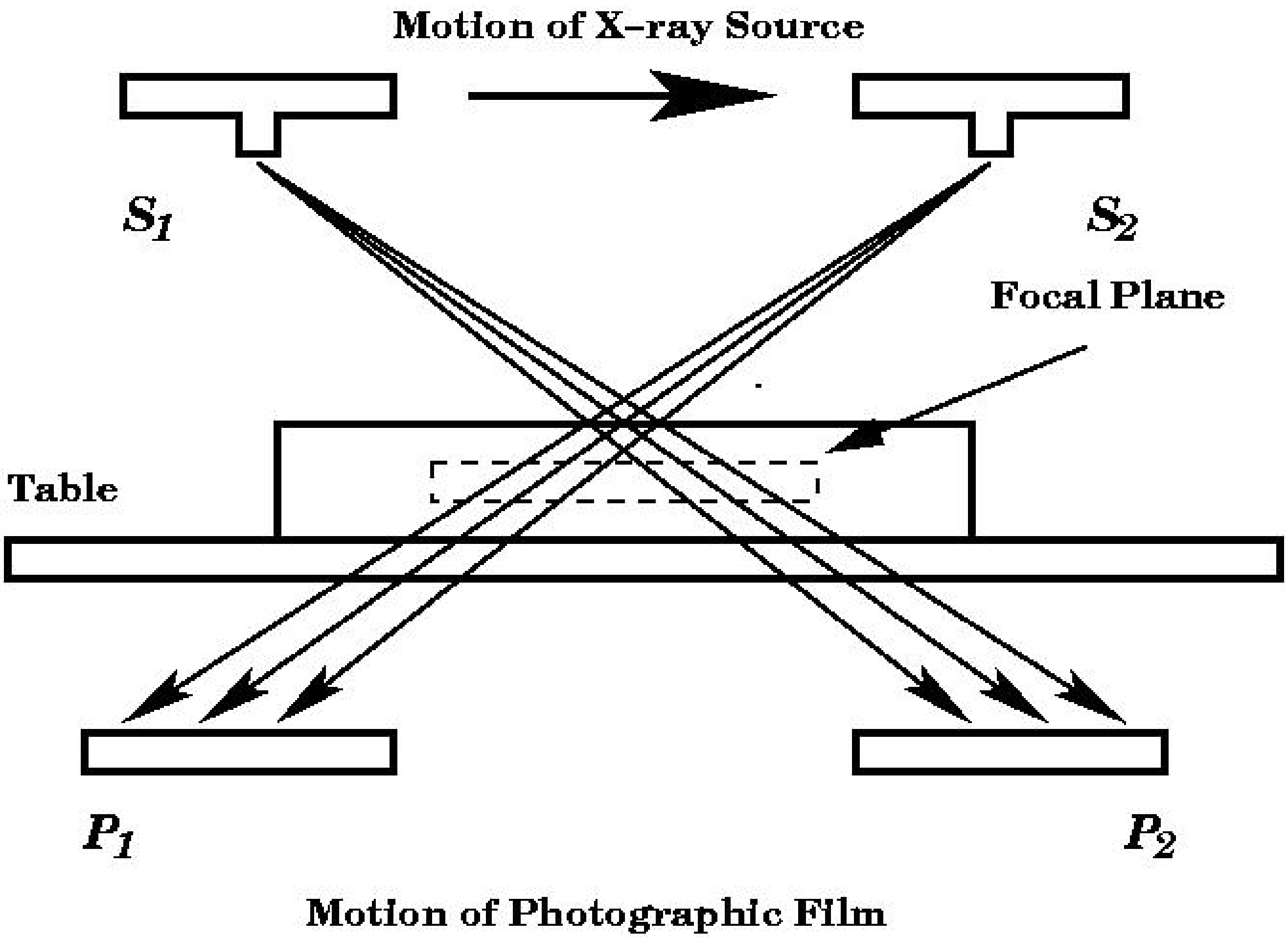




2.3a: Conventional Axial Tomography

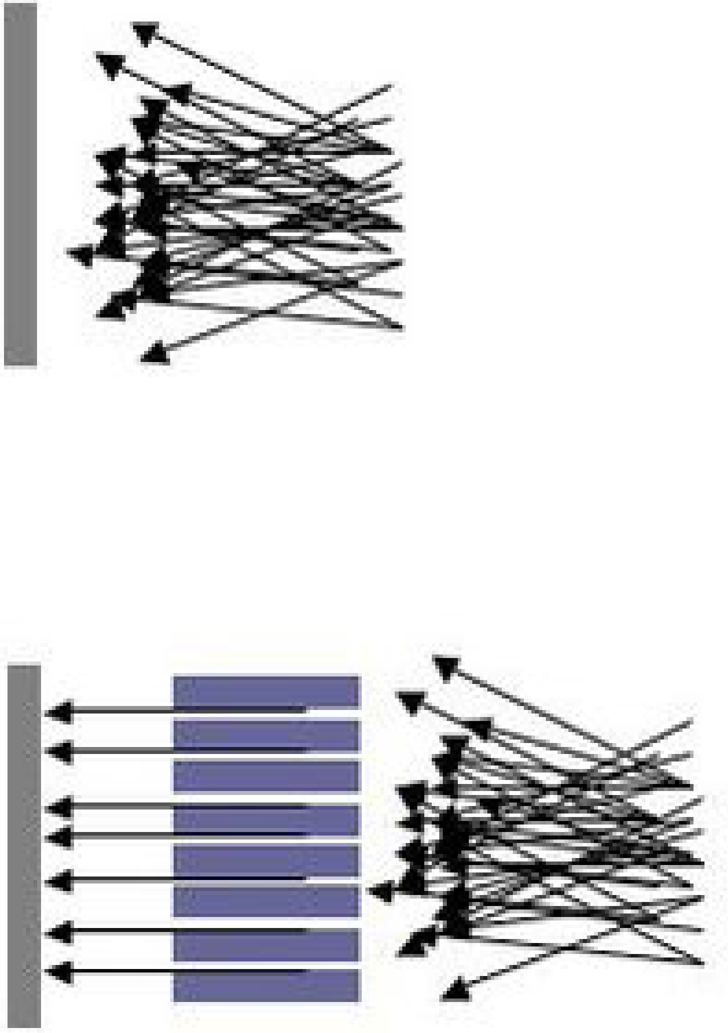
- Conventional axial tomography was developed in an attempt to overcome the superposition problem
- The X-ray source and photographic detector are moved in opposite directions parallel to the plane of the body to be imaged
- Distribution of densities of the focal plane will be sharply recorded, outside of the focal plane will be blurred
- It cannot overcome the superposition problem entirely, may blur the structure boundary

2.3b: Illustration of Conventional Axial Tomography



2.4a: X-ray Computed Tomography (CT)

- CT collimates the beam to minimize scatter, and eliminates superposition by scanning around a transaxial plane
- Recorded intensity differences can be less than 0.1%, individual attenuation coefficients of structures in the beam path can be determined to within 0.5% accuracy
- A full 3D representation can be obtained by reconstructing several cross sections of 2D slices, “stacking” the cross section like a roll of coins



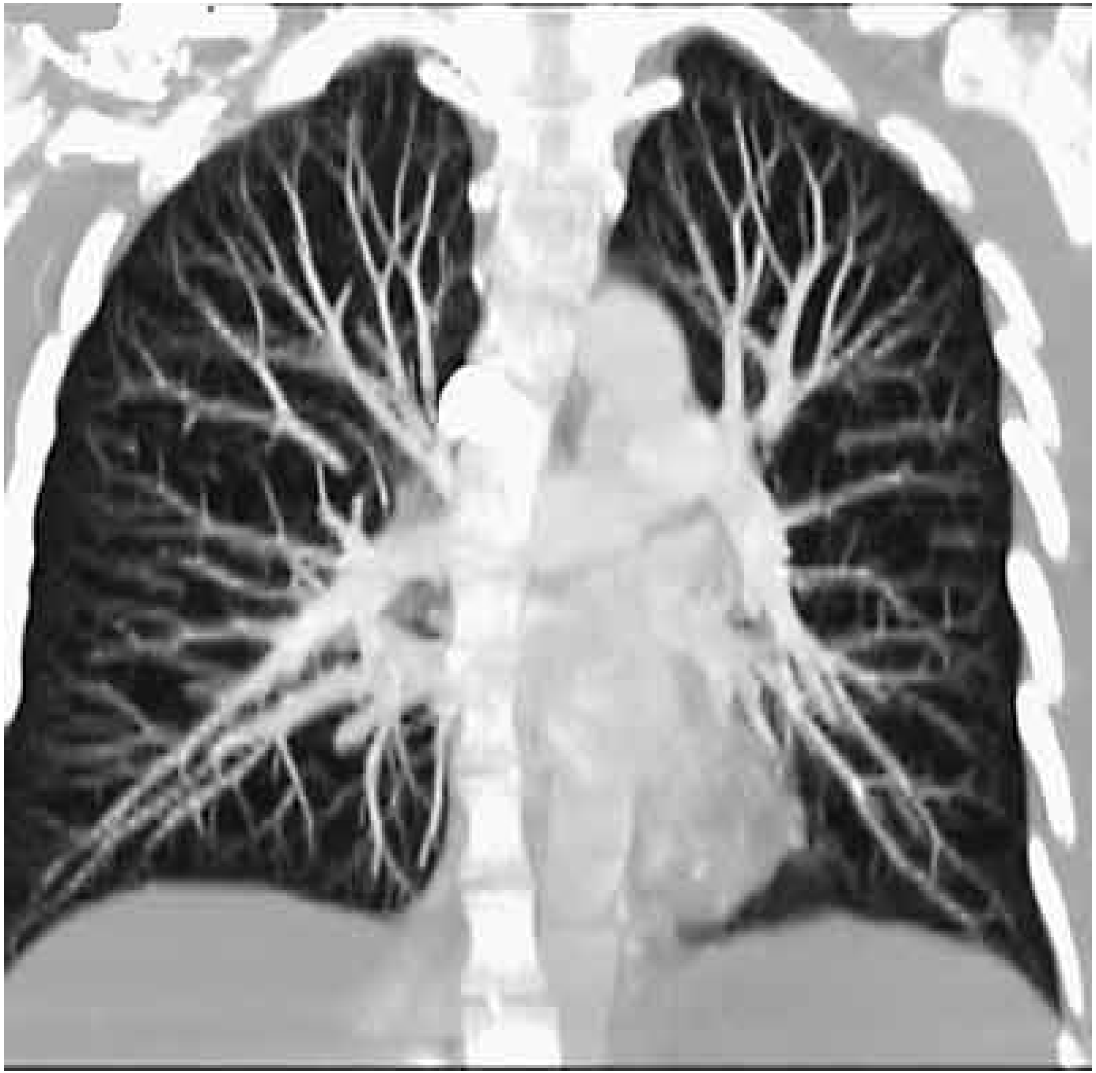
A **collimator** is a device used to filter a stream of rays (such as X-rays) so that only those travelling parallel to each other in a certain direction are allowed through.

2.4b: CT Machine for Body

2.4c: CT-Machine (Scanning)

2.4c: A 3D Reconstructed CT View of Kidneys and Ureters

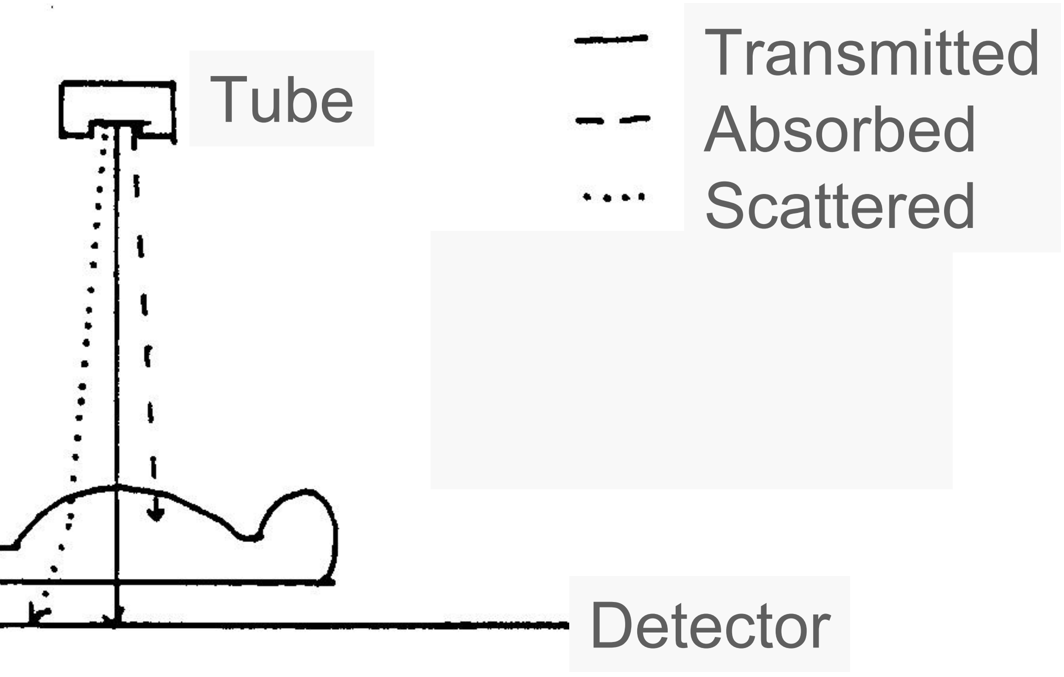
2.4d: 3D CT View of Chest (Pulmonary Vessels)



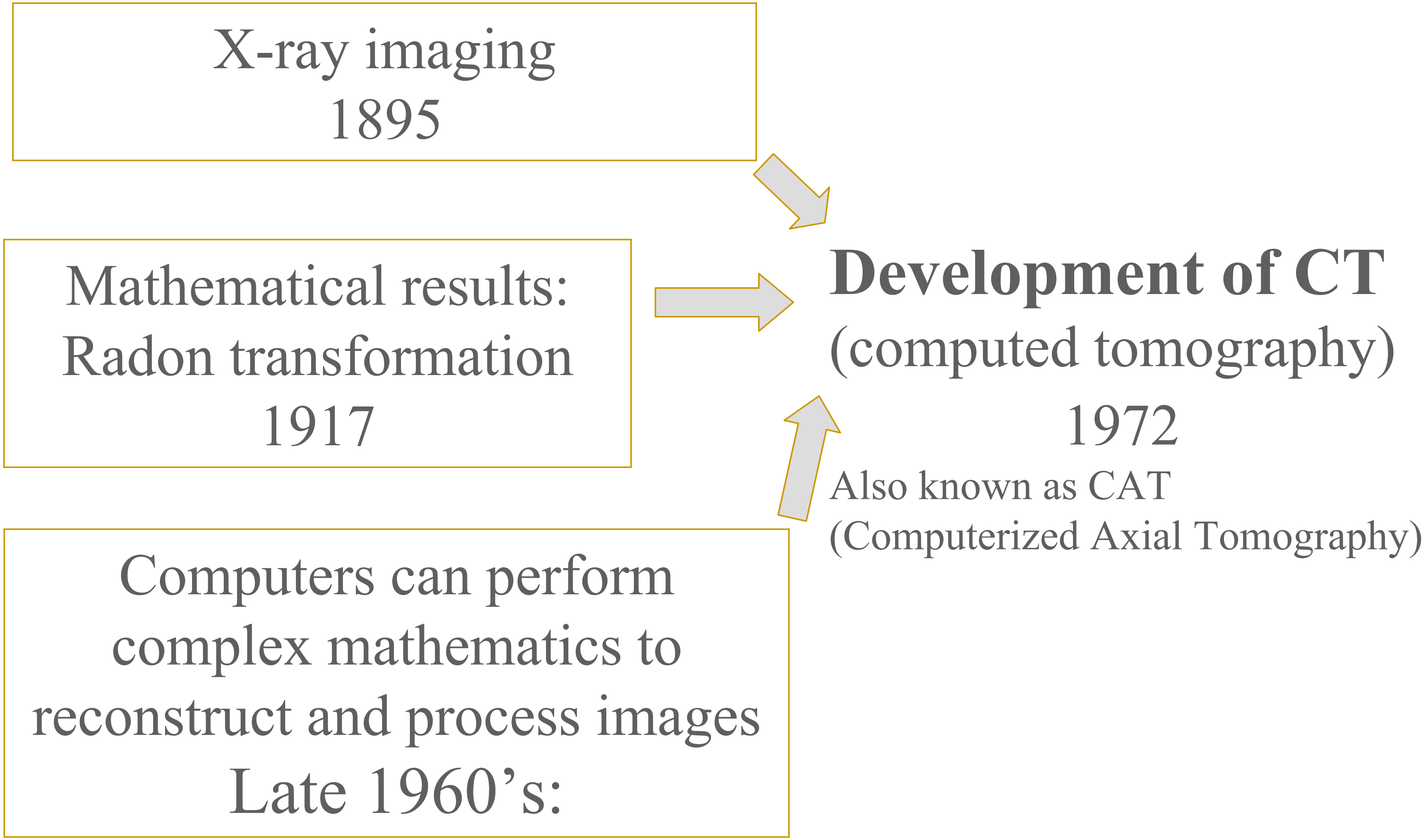
2.4e: Signal Acquisition

- Conventional X-ray CT scanners use a single X-ray tube that rotates through a full 360° rotations while recording projections at fine angular increments during the rotation (every 0.5° to 1°)
- The projection images are processed in a computer and an image is formed through mathematical reconstruction techniques
- X-ray beam forms a flat fan-beam geometry and the projects are coplanar, the detector is a curvilinear array of solid state elements

Plane X-ray imaging



Towards 3D imaging



X-ray imaging
1895

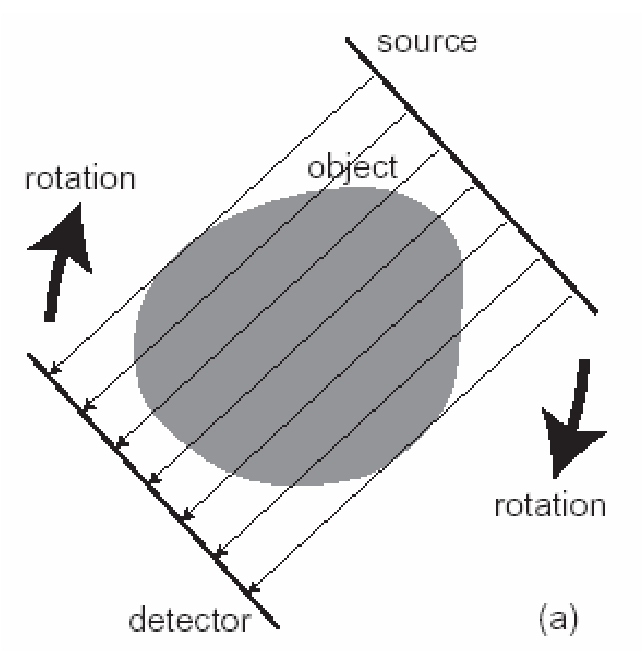
Mathematical results:
Radon transformation
1917

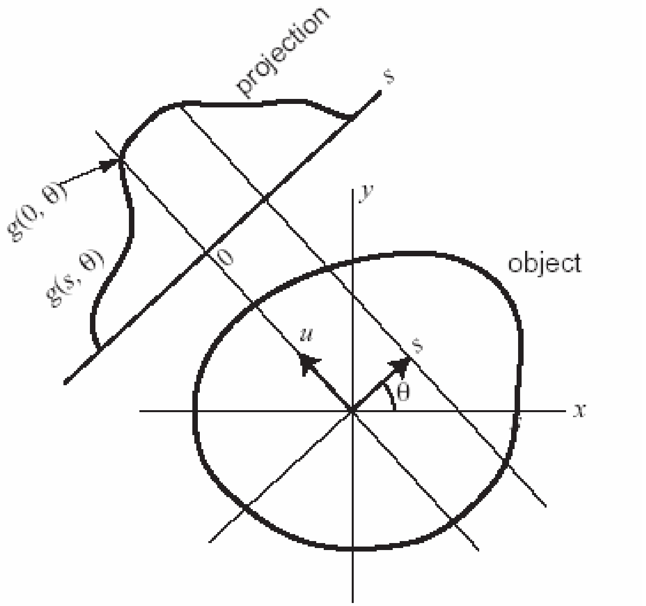
Computers can perform complex mathematics to reconstruct and process images
Late 1960’s:

Development of CT
(computed tomography)
1972

Also known as CAT
(Computerized Axial Tomography)

Radon Transformation

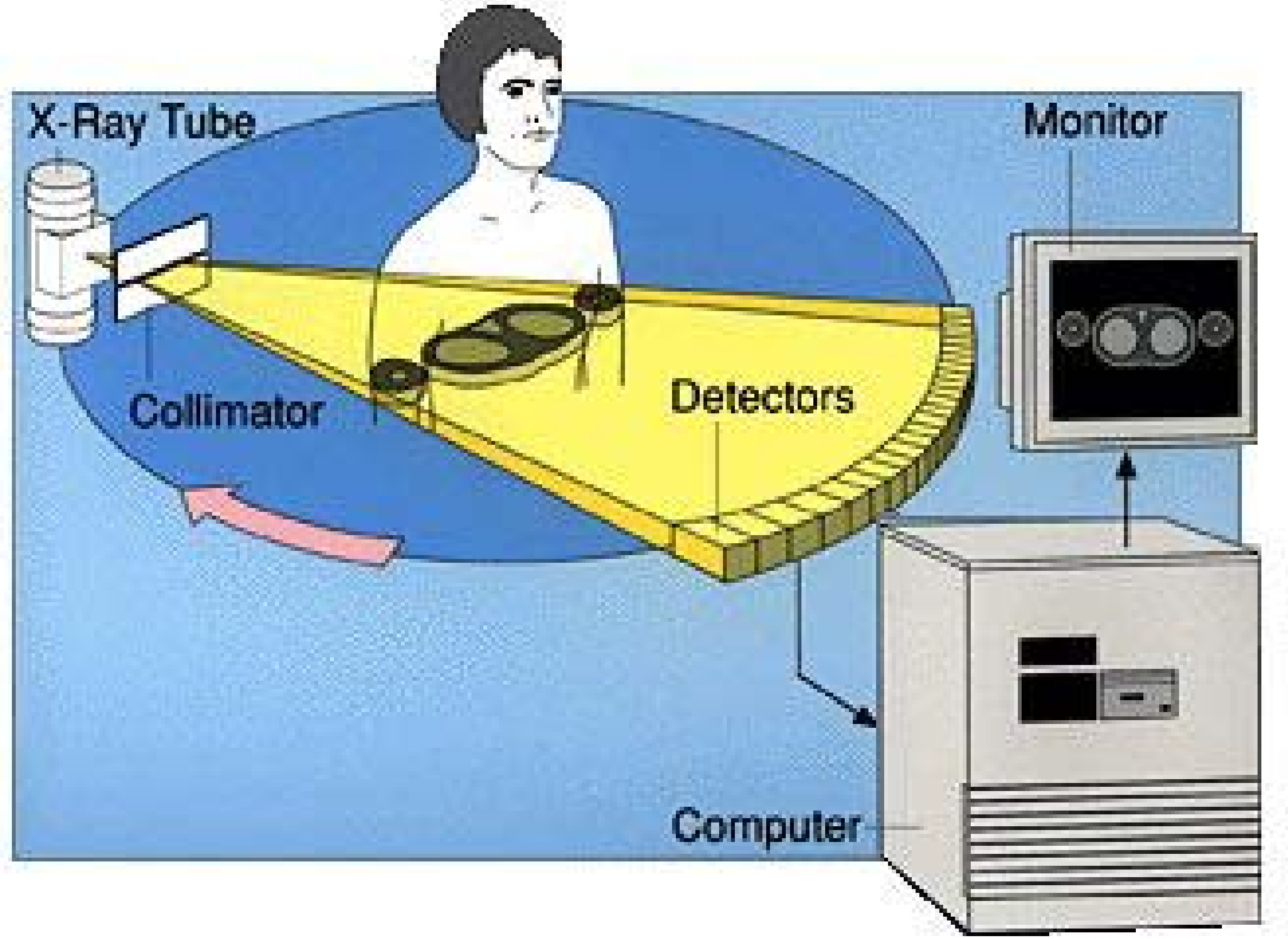




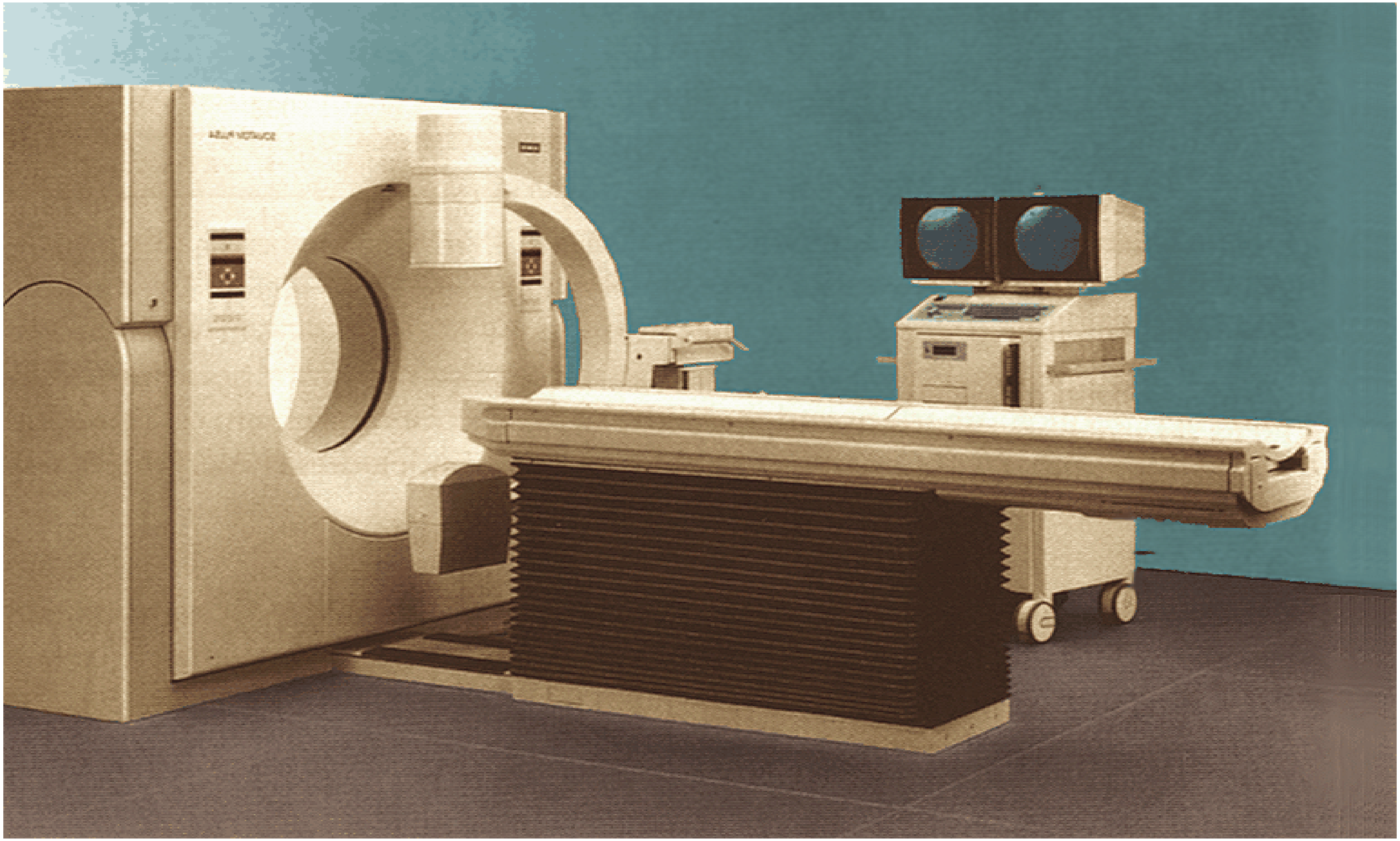
$$g(s,\theta)=\iint_{-\infty}^{\infty} f(x,y)\,\delta(x\cos\theta+y\sin\theta-s)\,dx\,dy$$

- Mathematical transformation (related to Fourier)
- Reconstruction of the shape of object (distribution *f(x,y)*) from the multitude of 2D projections $g(s,\theta)$

CT imaging

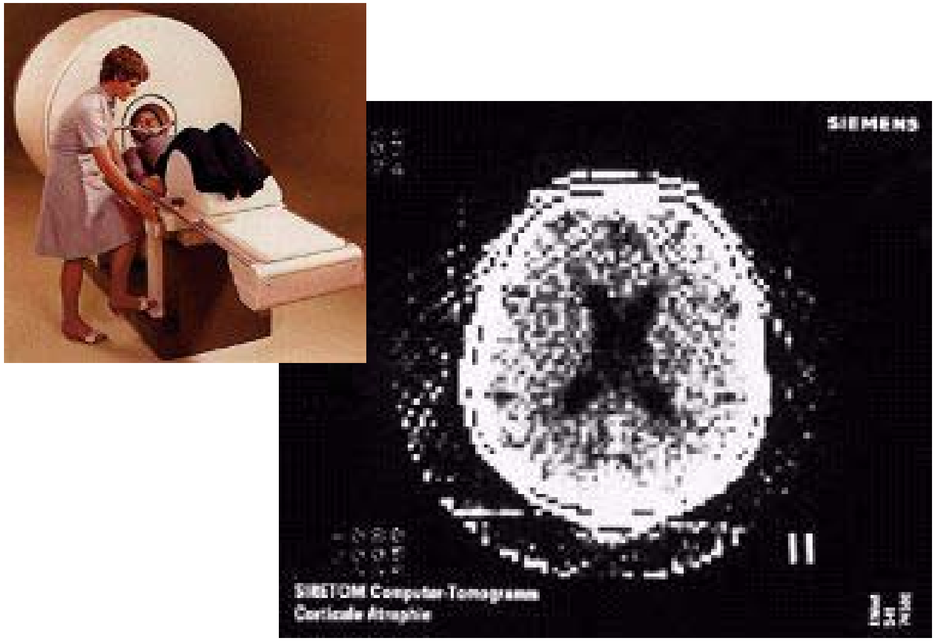


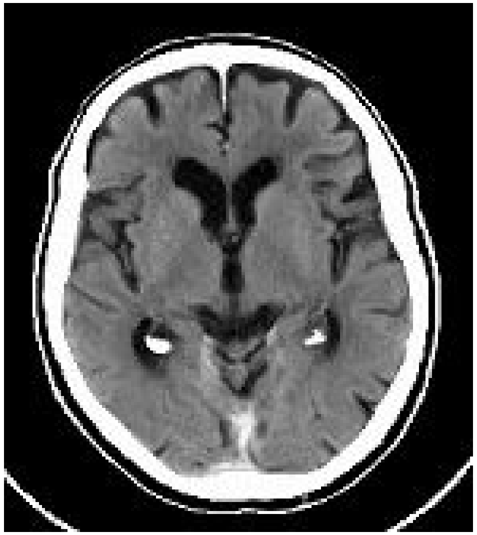
CT Scanner



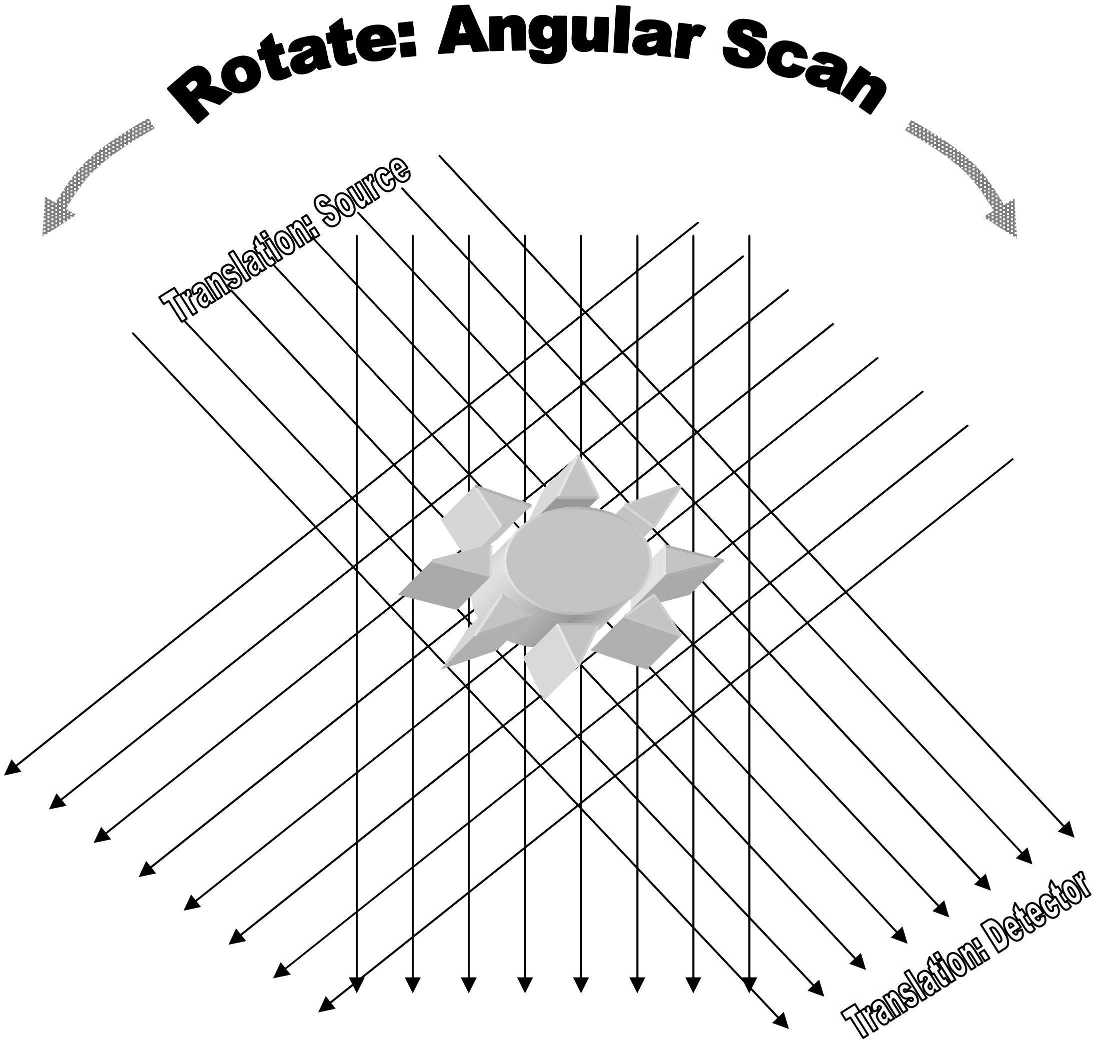
CT imaging, inventing (1972)

- Sir Godfrey Hounsfield Engineer for EMI PLC 1972
- Nobel Prize 1979 (with Alan Cormack)

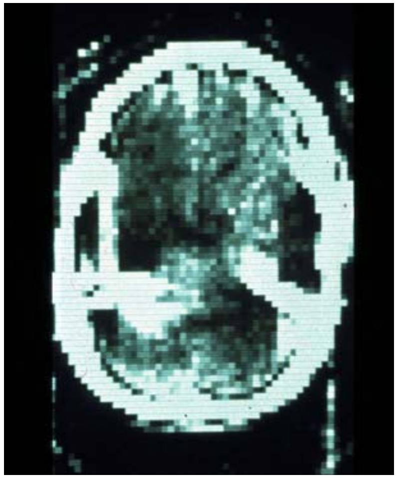

SIEMENS
SIRETOM Computer-Tomogramm
Corticale Atrophie

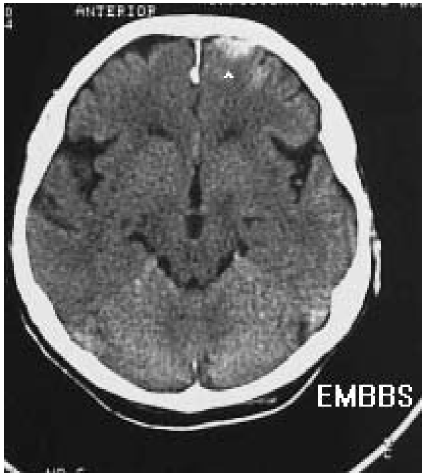


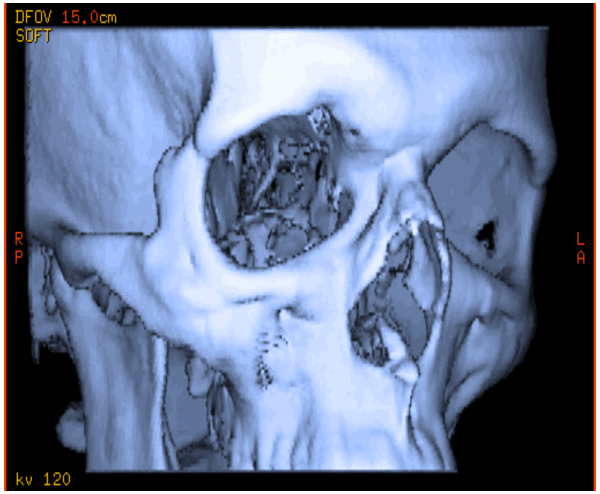
Principle of a CT Scanner



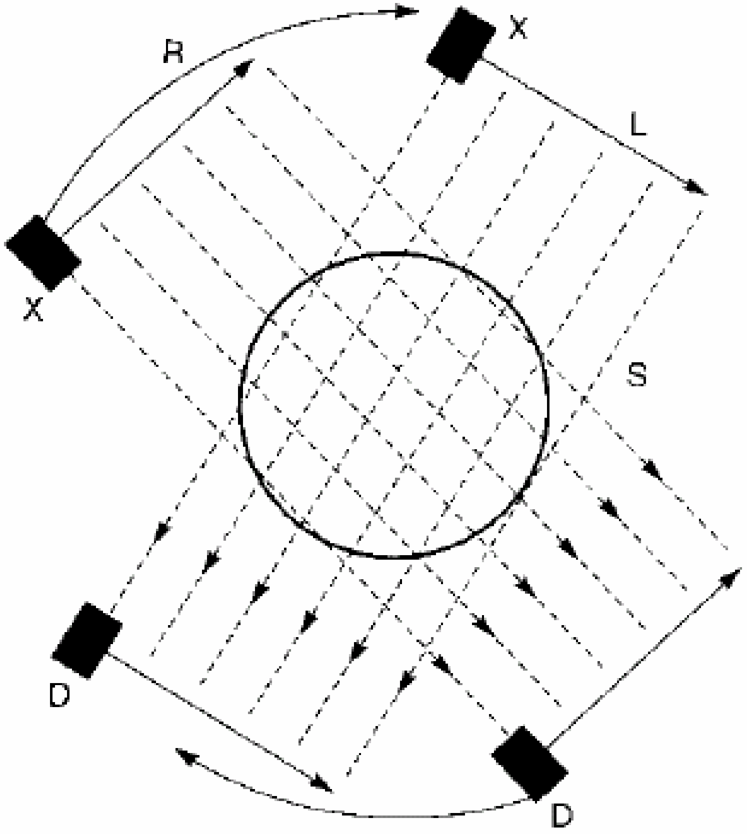
30 Years of CT







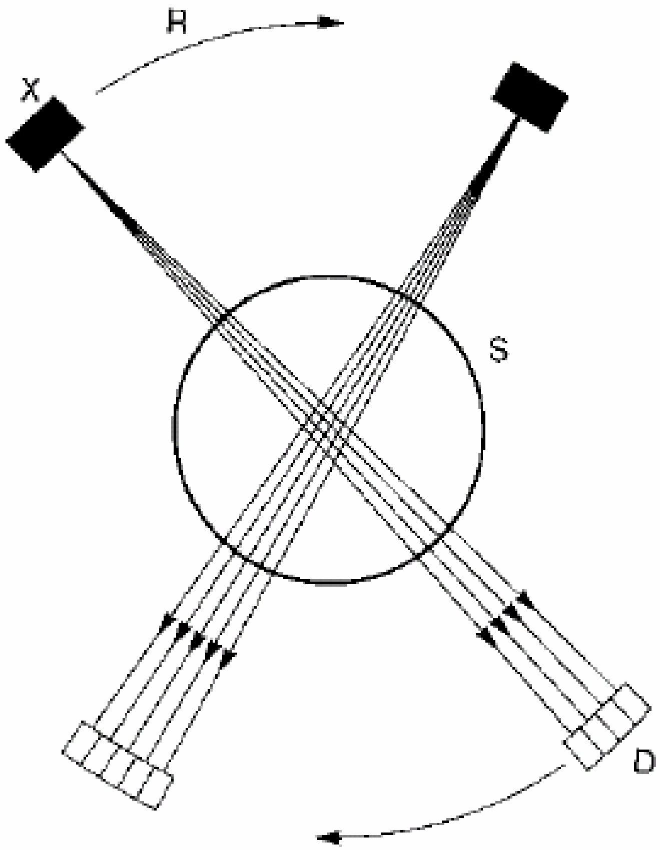
First Generation Scanners



X: X-ray source
S: subject
D: detector

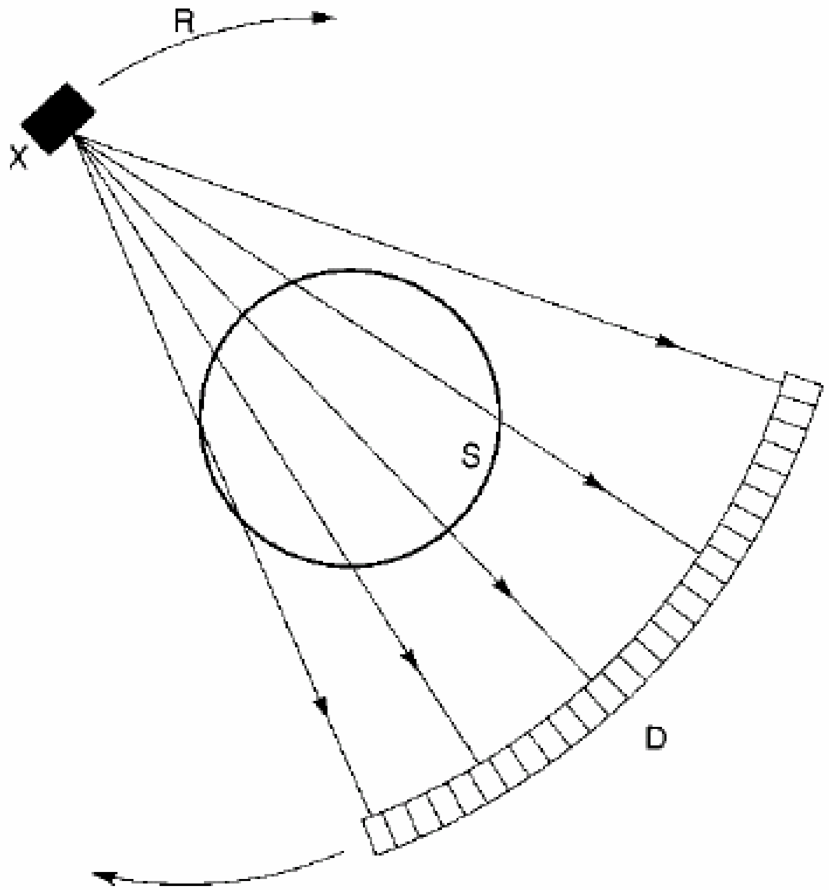
- Rotation in X intervals
- Time ~ 4 min!!!!

Second Generation Scanners



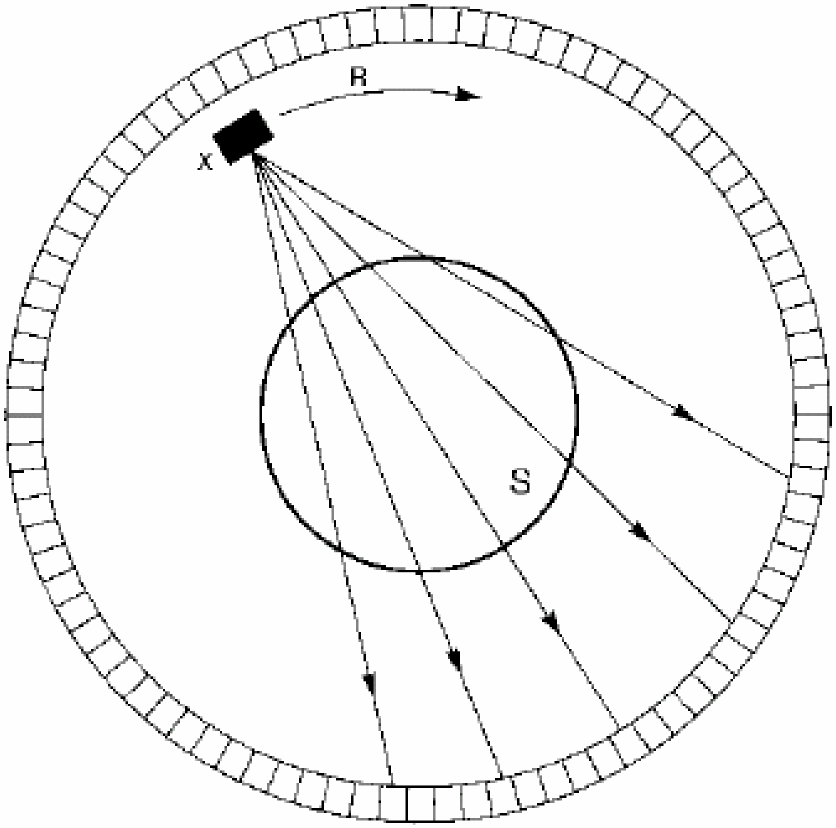
- Single source with narrow fan of detectors which traversed and rotated.
- Time ~ 20 sec.

Third Generation Scanners



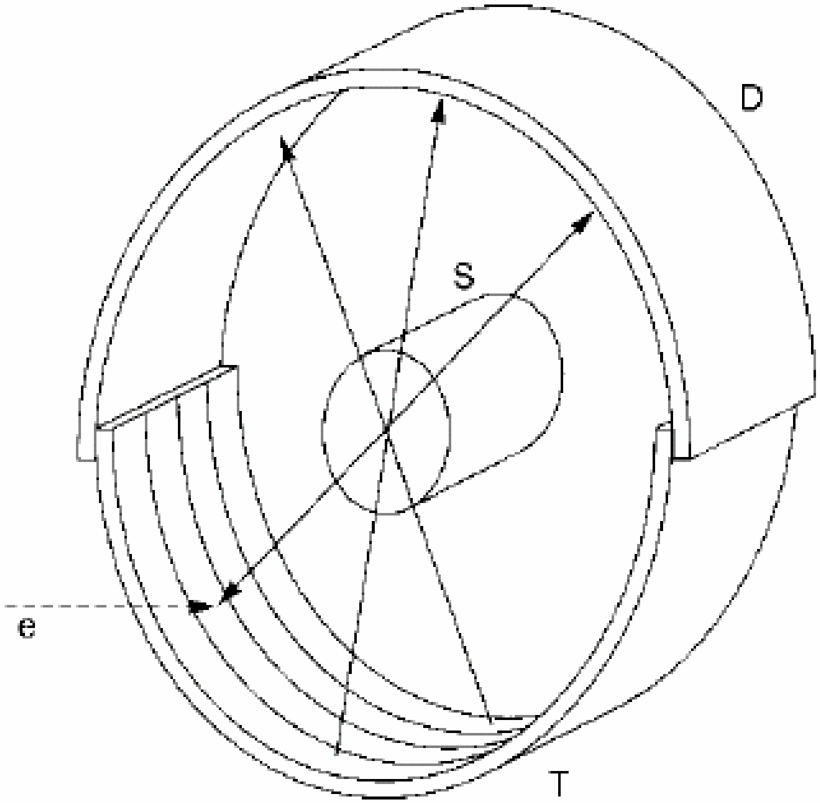
- Moving source with more detectors.
- Time ~ 4-5 sec.

Fourth Generation Scanners



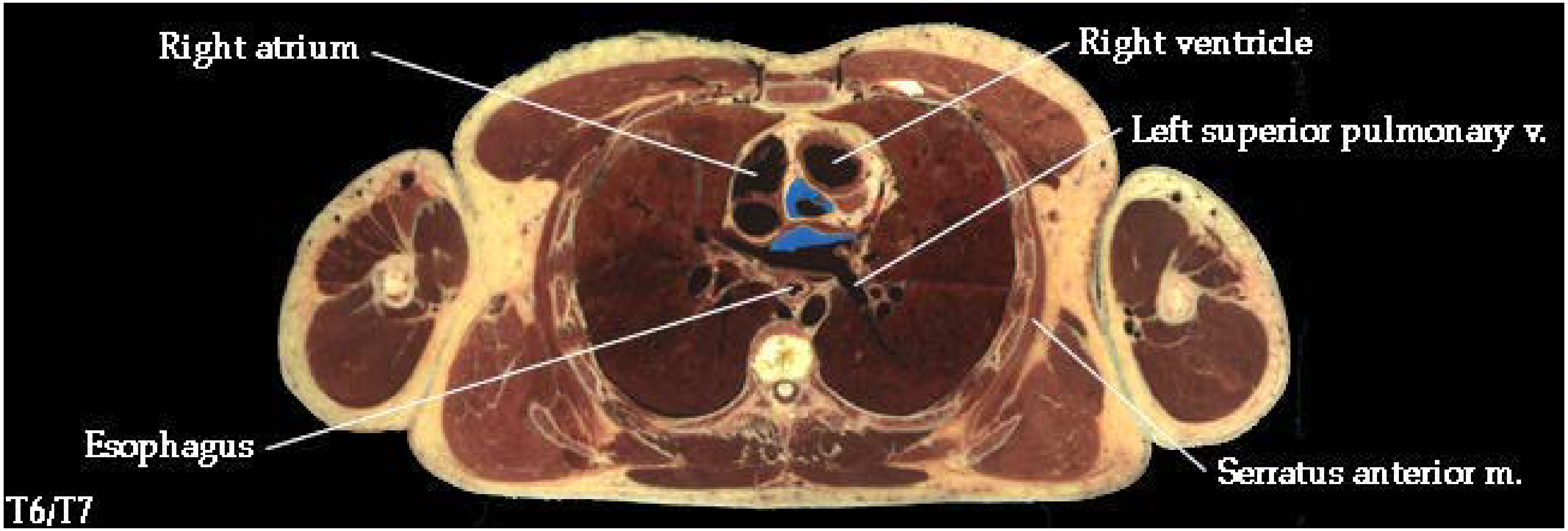
- Stationary 360 degree ring of detectors and a moving source.
- Time ~ 1 sec.

Fifth Generation Scanners

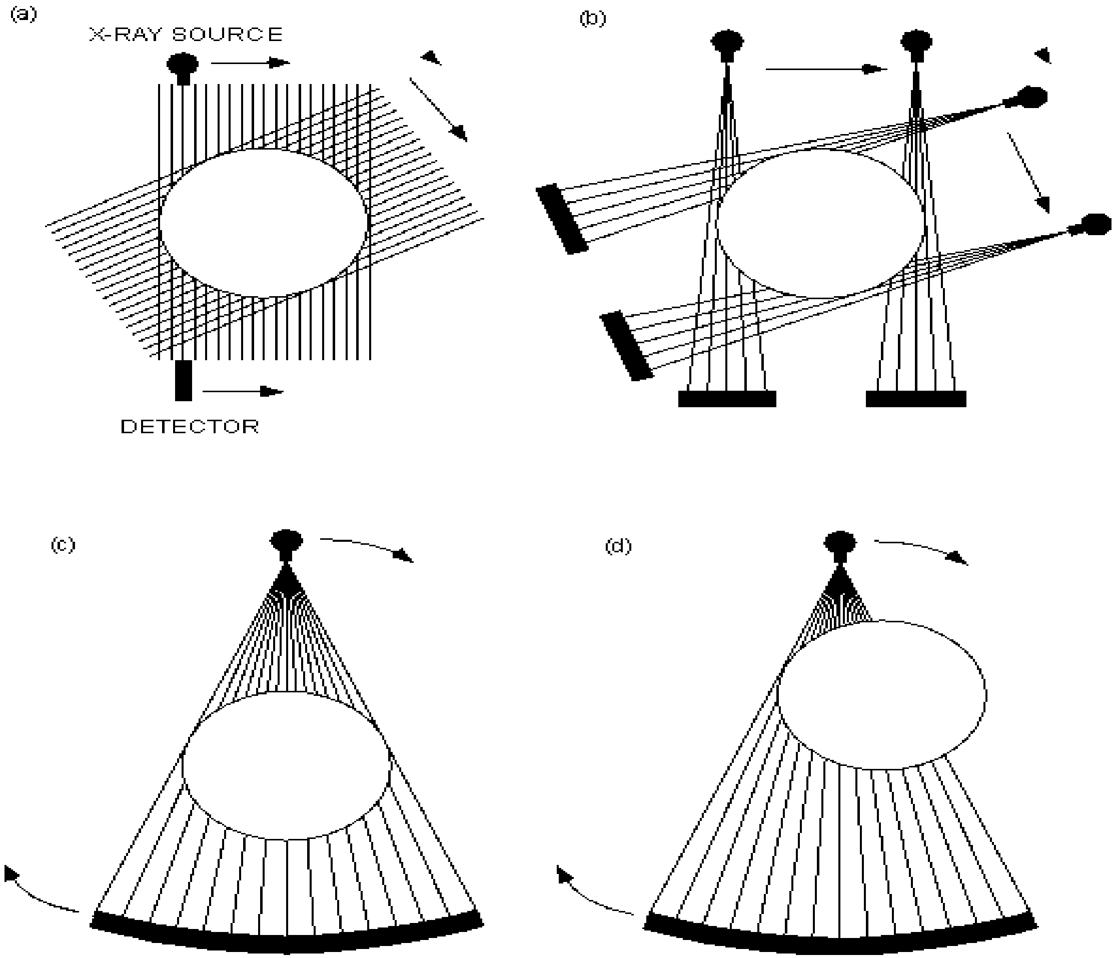


- Uses no moving parts.
- Tube with the patient inside 210 deg.
- The detector ring is similar.
- An e- beam scans around the body in multiple adjacent tracks to generate x-rays.
- Time ~ 0.1s to a few ms or real time

CT Chest Images



2.4f: Illustration of CT Systems



a: 1st generation: translate rotate pencil beam geometry

b: 2nd generation: translate rotate fan beam geometry

c: 3rd generation: rotate only geometry

d: 3rd generation: off-set mode geometry

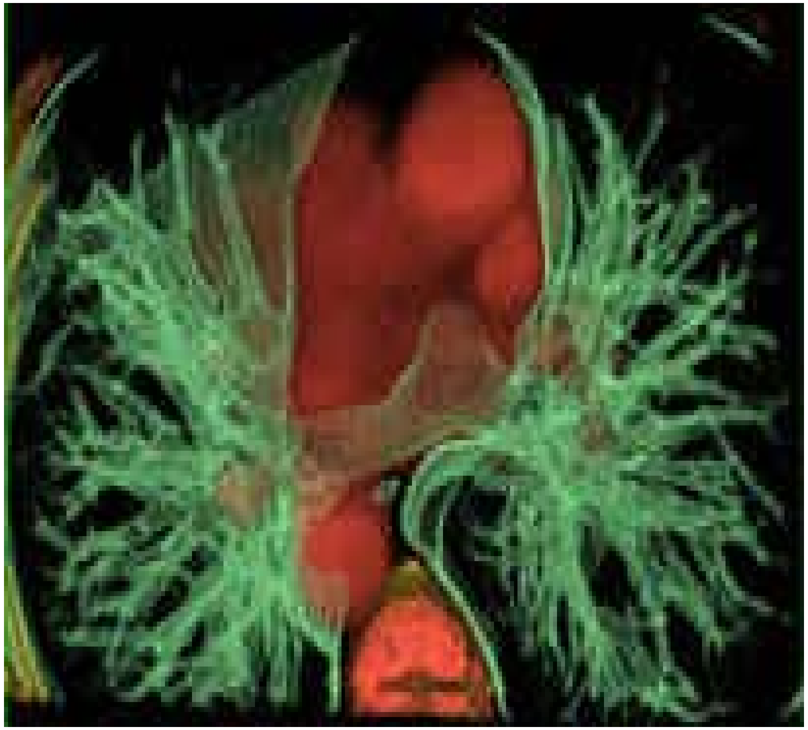
2.4g: Spiral (Helical) CT

- The projection acquisition process traces out a spiral trajectory rather than a sequence of parallel, flat projection fans
- This is achieved by a combination of continuous beam-detector rotation and continuous table movement causes the projection data to be acquired along a spiral path. It is fast
- It is the X-ray CT imaging system of choice for acquiring 3D volume images of many structures
- Good for the application of 3D visualization and quantitative analysis techniques

2.4h: Spiral CT

Photo simulation of spiral CT on abdomen

Virtual reality 3D image of lungs



2.4i: Image Formation/Reconstruction

- **Tomography** is the graphic representation of a cut, or slice, and implies the formation of 2D cross-sectional images free of blurring from structures not in the planes of interest, the tomograms
- **Computed tomography (CT)** is the formation of tomograms of X-ray absorption coefficients by the method of reconstruction from recorded projections
- The term CT may be applicable to any techniques that requires computation in order to reconstruct an image with non-ambiguous resolution in 3D

2.4j: Computed Tomography

- All biomedical imaging systems that produce 3D volume images use computed tomography
- It is a computer implementation of an appropriate inversion formula to mathematically reconstruct adjacent cross sections of an object from measured fluctuations of some energy traversing the object from several different directions
- It reconstructs 3D images from a series of 2D projects, or reconstructs 2D distribution of X-ray attenuation coefficients in a plane (slice) from a number of 1D projections

2.4k: CT Numbers

- The CT number produced by X-ray scanner systems is an expression of the relationship of the linear attenuation of X-rays by a given material (tissue) to that by water for the same X-ray energy, it is

$$\text{CT Number} = k \cdot (\mu - \mu_w) / \mu_w$$

where μ is the attenuation coefficient of the material and μ_w is the attenuation coefficient of water

The CT number is often called the Hounsfield unit (*H*), in honor of the inventor of the first X-ray CT scanner

2.4l: Hounsfield Unit

- A Hounsfield unit (*H*) is given by

$$H = 1000 \cdot \left(\frac{\mu}{\mu_w} - 1\right)$$

- To obtain the value of the attenuation coefficient relative to water

$$\frac{\mu}{\mu_w} = 1 + H / 1000$$

2.4m: Image Characteristics

- The spatial resolution of voxels of CT data ranges from 0.1 to 1 mm^2 in the plane of acquisition, with the slice thickness ranging approximately from 1 to 10 mm. With spiral CT, the thickness can be reduced to 0.5mm
- The CT data is represented in a calibrated set of numbers (the Hounsfield scale), ranging in discrete value from -1,000 to 1,000. They are often shifted in positive range (0 t0 2,048), stored as a 16-bit computer value

2.5a: Magnetic Resonance Imaging (MRI)

- MRI provides mechanism for intricate control of the signal being measured through modulation of the magnetic field and radiofrequency pulse sequences used to alter the spins of protons in the structure being imaged
- It is noninvasive, does not use ionizing radiation, as in the X-ray
- MRI images the distribution of protons, and is an excellent soft tissue imaging modality, providing highly detailed structural images. (CT is better for higher density structures, such as bones)

2.5b: MRI Machines

2.5c: Signal Acquisition

- Hydrogen nuclei (protons) are imaged due to their strong magnetic moment and prevalence in the soft tissues of the body (water molecules)
- The externally applied magnetic field is called the B_0 field in MRI, which makes the spin line up with the field
- The full collection of spinning results in a net magnetic moment for all spins in the direction of the externally applied magnetic field

2.5d: Radiofrequency Pulses & MRI Signal

- The precessional frequency of a given atomic nucleus about the B_0 field axis is given by (Larmor)

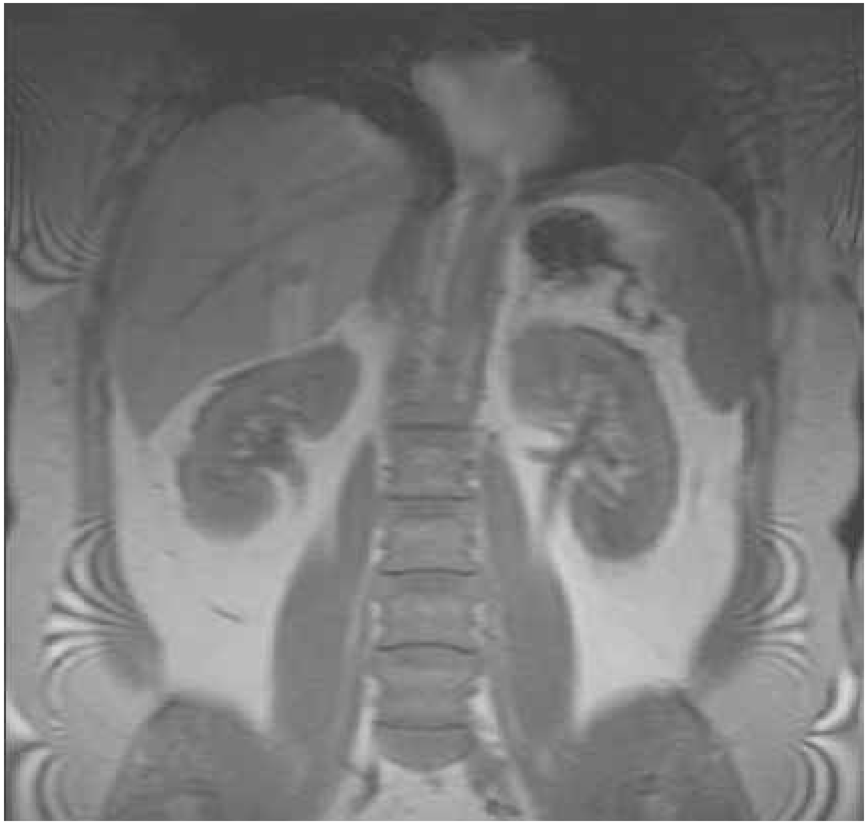
$$\gamma B_0 = F$$

- where F is the precessional frequency, B_0 is the strength of the externally applied magnetic field, and γ is a property of the magnetic moment for the specific type of nucleus under consideration
- For hydrogen γ = 4,257 Hz/G, and the common field of strength B_0 = 1.5Tesla, and F = 63.855 MHz

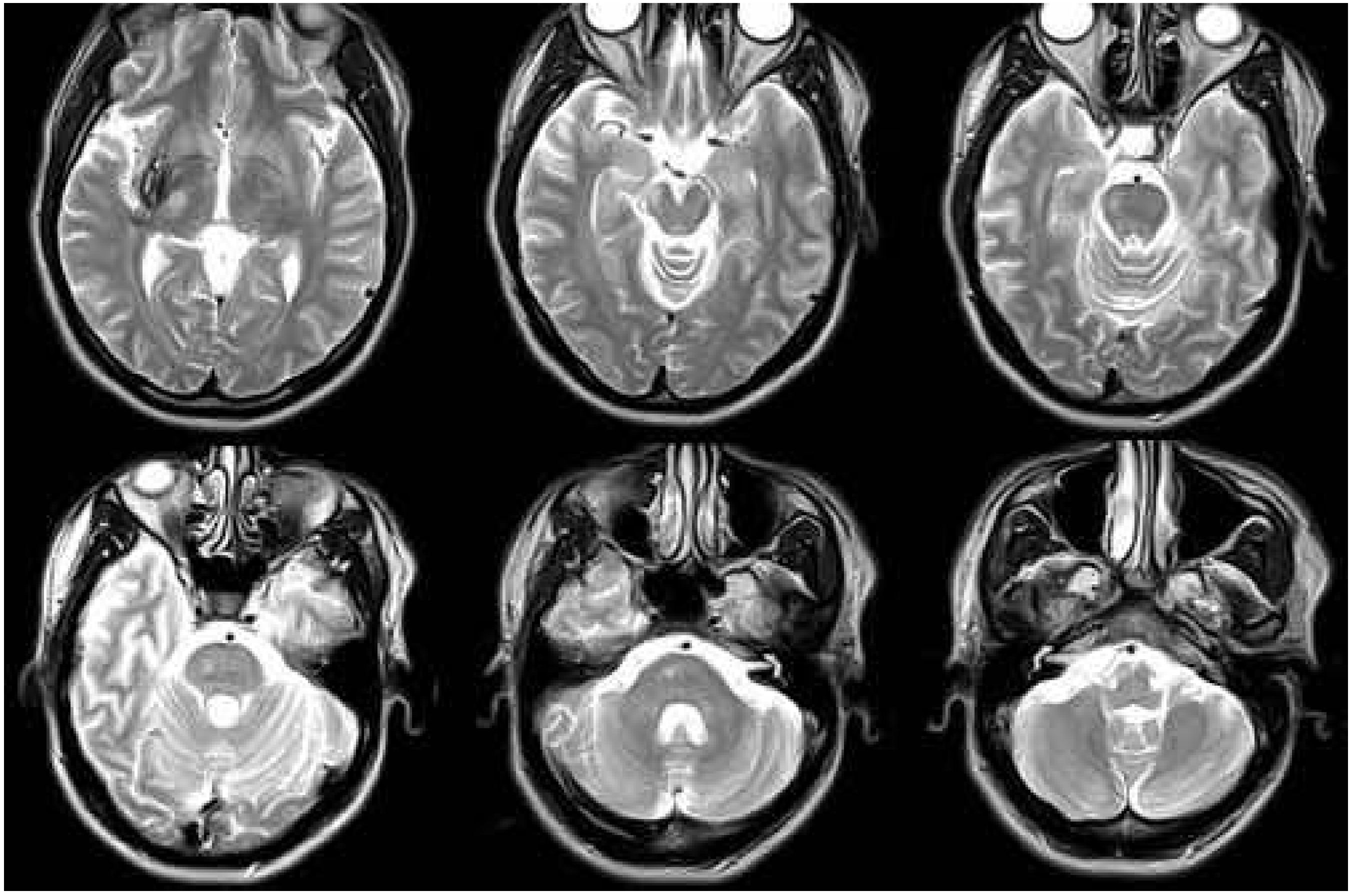
2.5e: MRI Signal

- The radio frequency (RF) pulses distribute energy to the protons, causing them to absorb energy when the RF pulses are on, and dissipate that energy when off. This is the “resonance”
- The RF frequency perpendicular to the B_0 external magnetic field is called the B_1 field.
- The net magnetic moment rotated about the B_0 field induces a current (AC) in a coil of wire located in the transverse plane. The signal from the induced current is the source of signal for MR imaging

2.5f: MRI Scan of Body (Liver and Kidneys)



2.5g: MRI Scans of Head



2.5h: Public Recognition

- The 2003 Nobel Prize in Physiology or Medicine was awarded to Paul C. Laterbur at the University of Illinois at Urbana, and Peter Mansfield at the University of Nottingham in England
- They are not doctors (chemist and physicist)
- Dr. Raymond Damadian, the MRI patent (1974) holder, was not one of the recipients. He published his first MRI paper in 1971

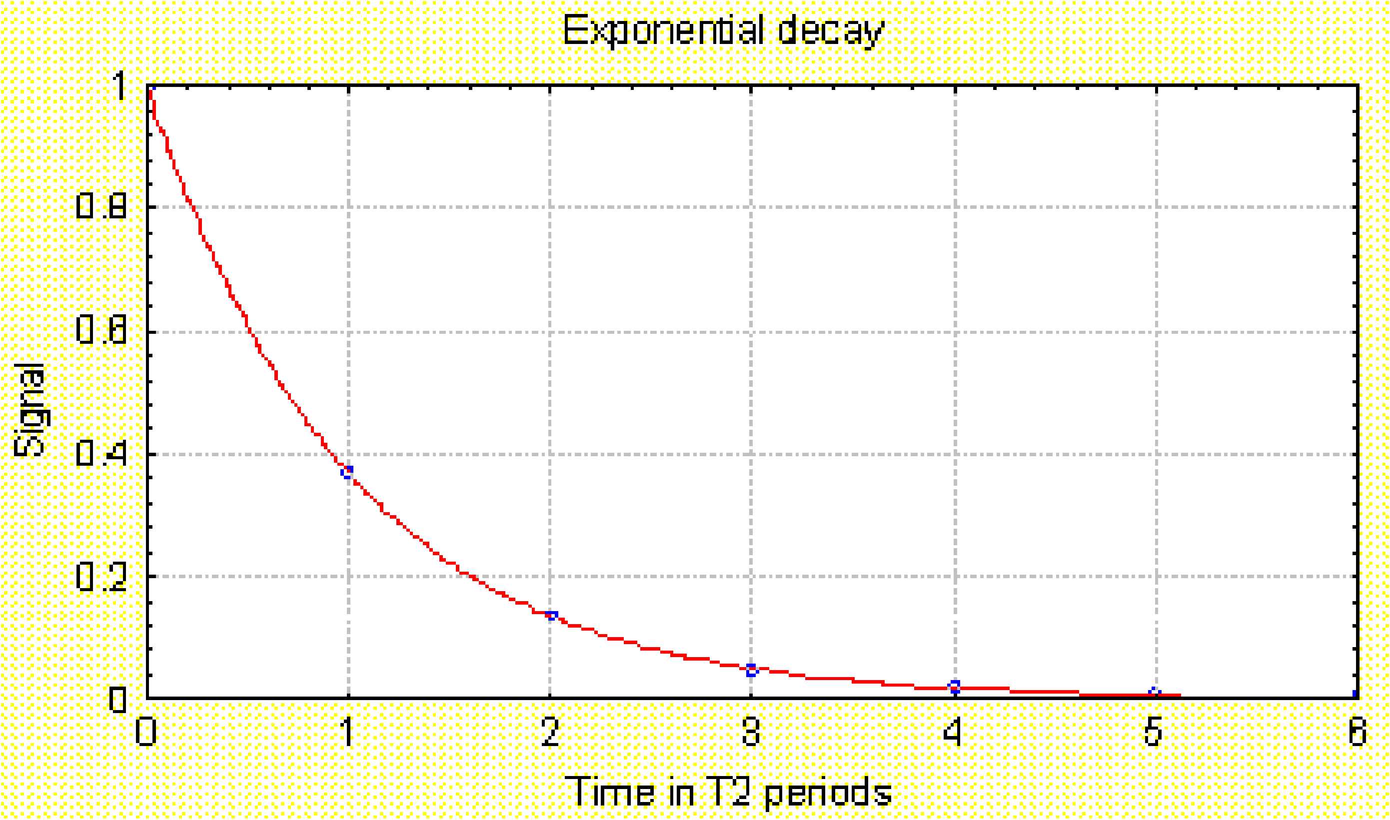
2.5i: Magnetic Moment Relaxation

- The RF energy can move the net magnetic moment away from the B_0 field axis by a flip angle. Once the RF energy is turned off, the spins will begin to realign themselves with the external B_0 field. This process is called “relaxation”
- If a 90° RF pulse is used to rotate the net magnetic moment into the transverse plane and then turned offer, the receiver coil oriented in the transverse plane will initially have a current proportional to the full magnetic moment, but will diminish gradually
- The signal in the transverse plane has a characteristic exponential decay rate time constant, called the T2* constant

2.5j: T2 Relaxation Time

- The variation in precession rates of spins causes dephasing of the contribution of each individual proton’s magnetic moment to the net magnetic moment, causing it to decay
- The dephasing is related to the physical properties of the tissues being imaged. The T2 constant, or spin-spin relaxation, is measured as these spin decay and come back into alignment

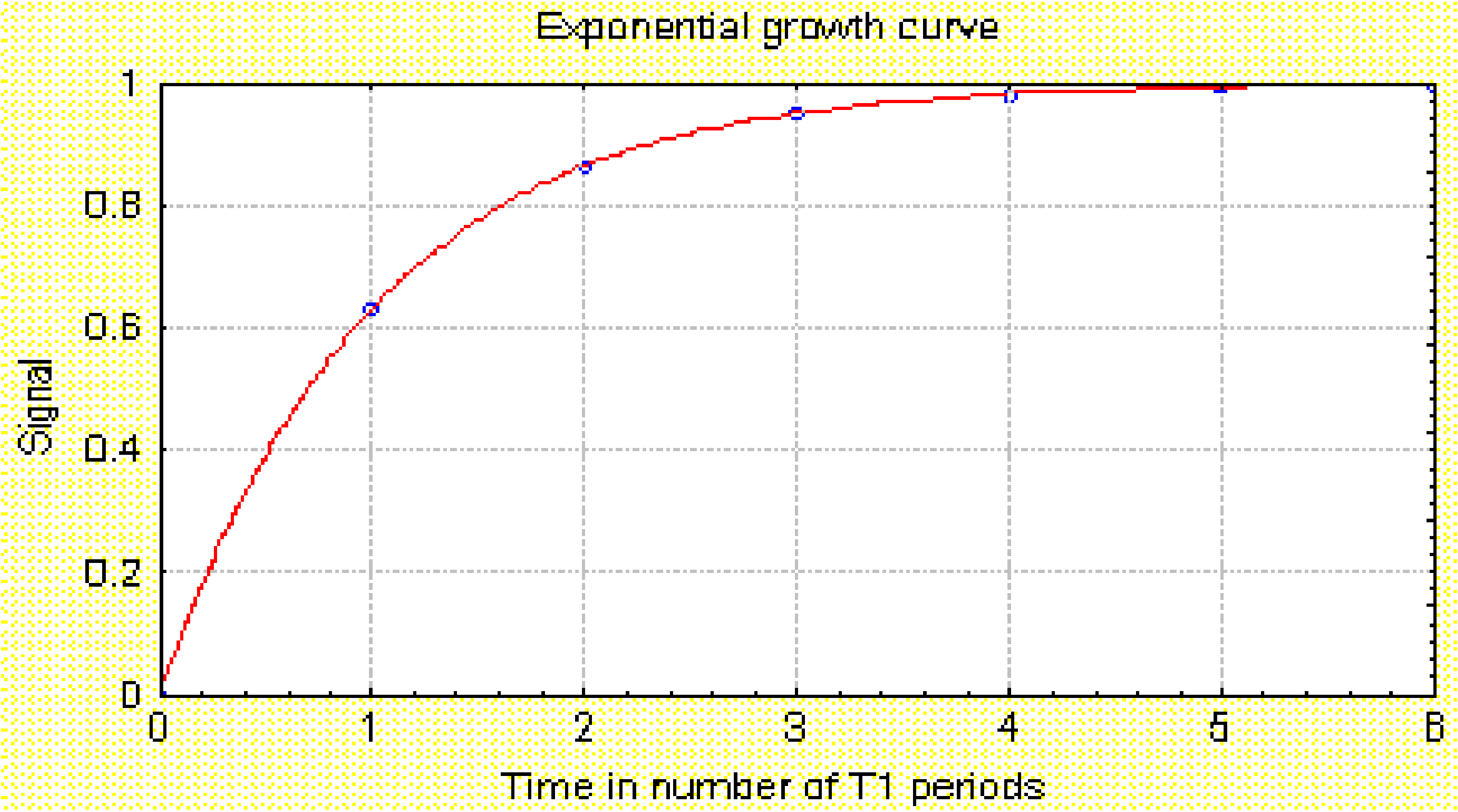
2.5k: Exponential Decay of Signal Strength (Brain White Matter T2=0.07S)



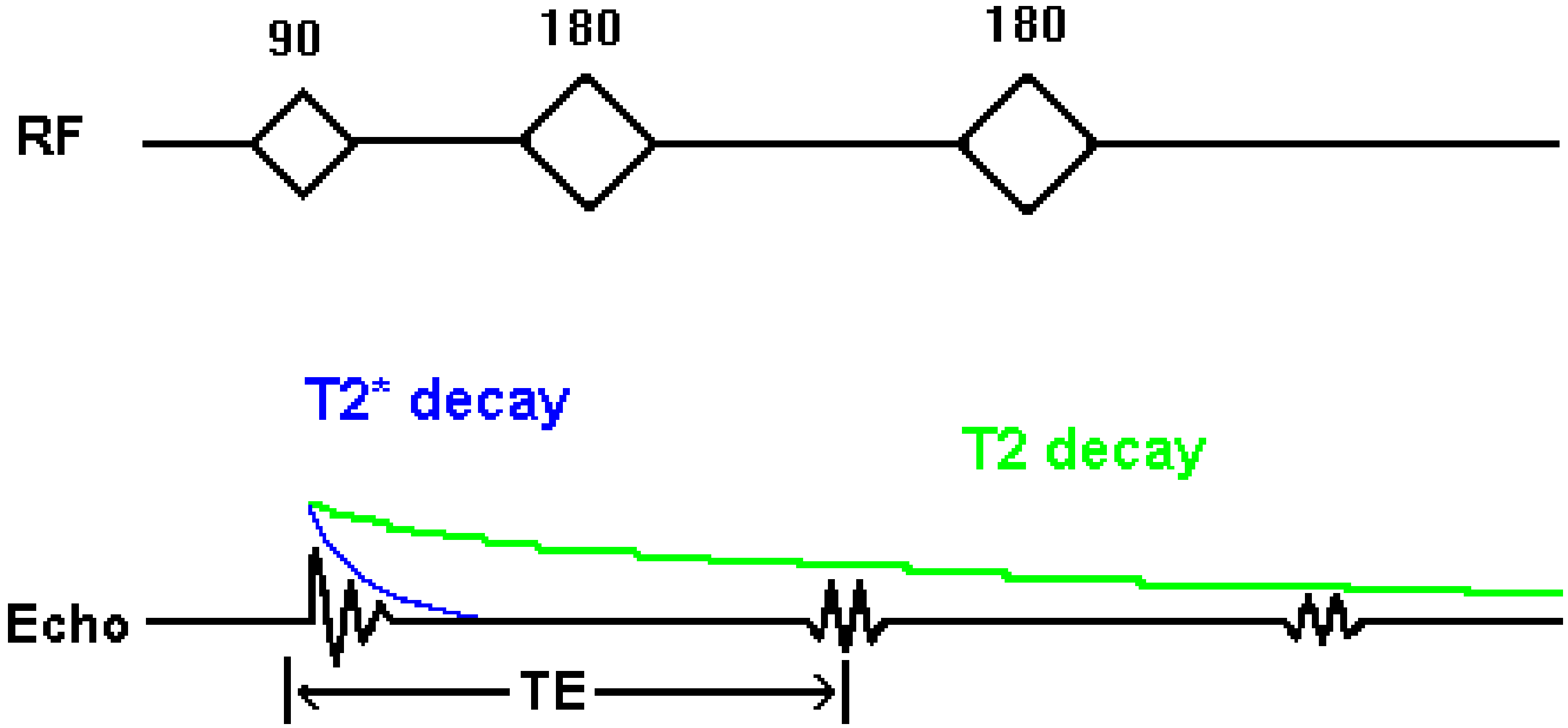
2.5l: T1 Relaxation Time

- Immediately after a 90° pulse, the net magnetic moment along the longitudinal plane is zero. It will increase as the spins return to their alignment in this plane with B_0
- This is the spin-lattice relaxation process and is characterized by an exponential time constant T1
- A coil in the longitudinal direction can measure the buildup of signal along the external field axis as spins return to equilibrium
- T1 relaxation time can be computed for different imaged tissues in the body

2.5m: Exponential Nature of T1 Constant (63% spins return to its original position)



2.5n: T2* Relaxation Time and T2 Time



2.5o: Echo Time (TE) and Repetition Time (TE)

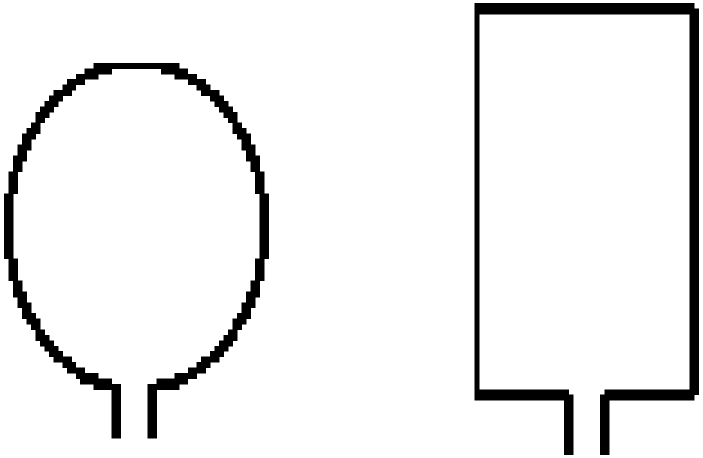
- The time between the original 90° pulse and the rephasing of the individual magnetic moments is called the "echo time" (TE) and is specified in the pulse sequence design
- The time needed for repeated excitation and echo formation is called "repetition time" (TR)
- The "flip angle" is the one that formed by the protons after the RF pulse moving the net magnetic moment away from the B_0 field
- These are the parameters used to design specific "pulse sequence" to image various structures in the body

2.5p: Magnetic Field Gradients and Spatial Localization

- Position information can be encoded into the signal by adding a magnetic field gradient
- The resonance frequency of the protons will vary along the gradient axis as each will have a slightly different magnetic field
- 3D spatial position can be encoded by adding gradients along three orthogonal spatial axes
- Special coils are used to produce these spatially varying field gradients for encoding the spatial position of any voxel in MRI

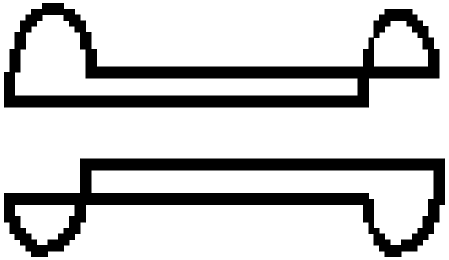
2.5q: Surface Coils and Paired Saddle Coils

Image spines, shoulders



Surface Coils

Image knees

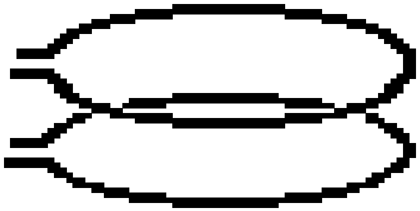


Paired Saddle Coil

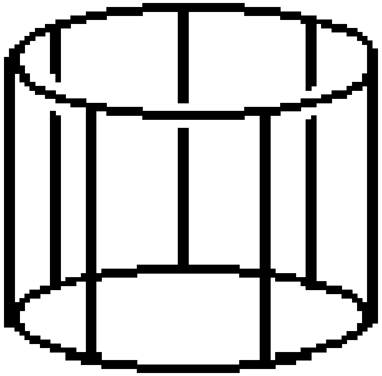
2.5r: Helmholtz Pair Coil and Bird Cage Coil

Image pelvis and cervical spines

Image head



Helmholtz Pair Coil



Bird Cage Coil

2.5s: Signal Acquisition & Reconstruction

- Signals are acquired as sums of all of the frequency components, each with distinct amplitudes and relative phases in the frequency domain
- They must be transformed into the spatial representation of the image using a Fourier transform
- The frequency space (k-space) data can be processed in many ways to reduce artifacts, noise, or correct for any inhomogeneities in signal or spatial encoding

2.5t: Image Characteristics

- The value at any given voxel in an MR image is a measure of the MR signal amplitude for the mobile protons contained within the discrete bounds of that 3D voxel
- A T2-weighted image is acquired with a long TR time and TE is prolonged to the range of tissue T2 values
- A T1-weighted image is obtained by a short TR time in the range of the T1 values for tissues and very short TE. This very short TE does not allow time for significant decay of the transverse relaxation, i.e., no T2 difference

2.5u: MRI Volume Images (2D to 5D)

- 2D images are single-slice reconstruction from a single section of structure (with a thickness)
- 3D images can be reconstructed from either 2D multiple adjacent slice techniques or true 3D volume acquisitions
- Most MR images are reconstructed into 256X256 matrix (interpolated from frequency and phase encodings ranging from 128 to 256) with 1 to 128 sections in a given volume image
- The in-plane spatial resolution ranges from 0.5 to 1 mm, with the slice thickness from 1 to 10 mm

2.5v: Some Definitions

- The matrix size is the number of frequency encoding steps, in one direction, and the number of phase encoding steps, in the other direction of the image plane
- The frequency encoding depends on how rapidly the signal is sampled by the scanner. Increasing the sampling rate has no time penalty
- The Field-of-View (FOV) is the total area that the matrix of phase and frequency encoding covers. Dividing the FOV by the matrix size gives the voxel size

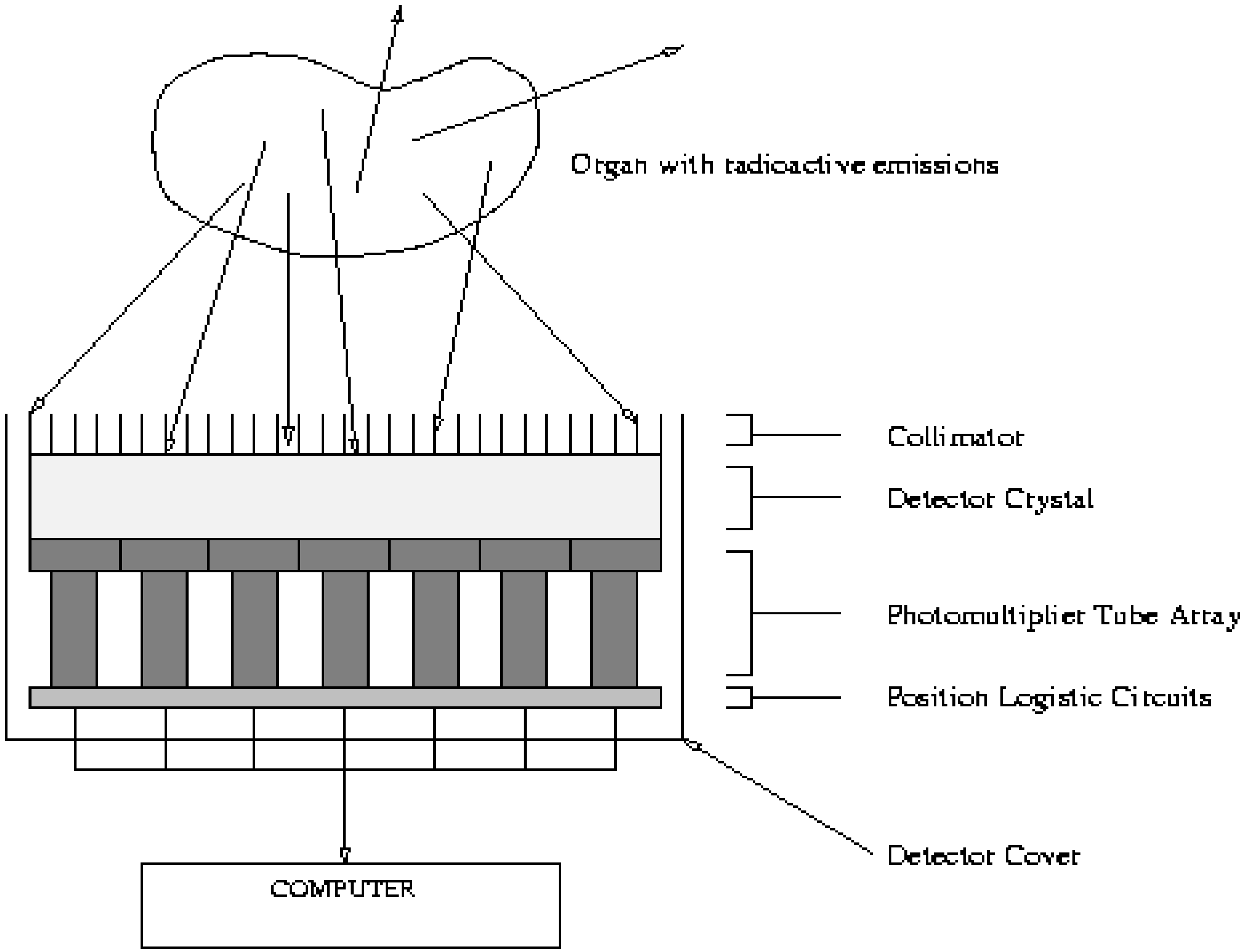
2.6a: Nuclear Medicine Imaging

- Nuclear medicine imaging systems image the distribution of radioisotopes distributed within the body, preferably to a specific organ or structure of interest
- It provides a direct representation of metabolism or function in the organ or structure being imaged
- Two main technologies: single photon emission computed tomography (SPECT) and positron emission tomography (PET)

2.6b: Single Photon Emission CT(SPECT)

- SPECT systems image the distribution of radiopharmaceuticals that emit photons upon decay – using a gamma camera
- Image reconstruction is similar to X-ray CT
- Patients will be injected or inhaled a small amount of physiologic radioisotopic tracers
- Its principal strength is its ability to provide functional information by the use of radiopharmaceuticals that are indicator of *in vivo* biochemical or hemodynamic functions

2.6c: SPECT Illustration

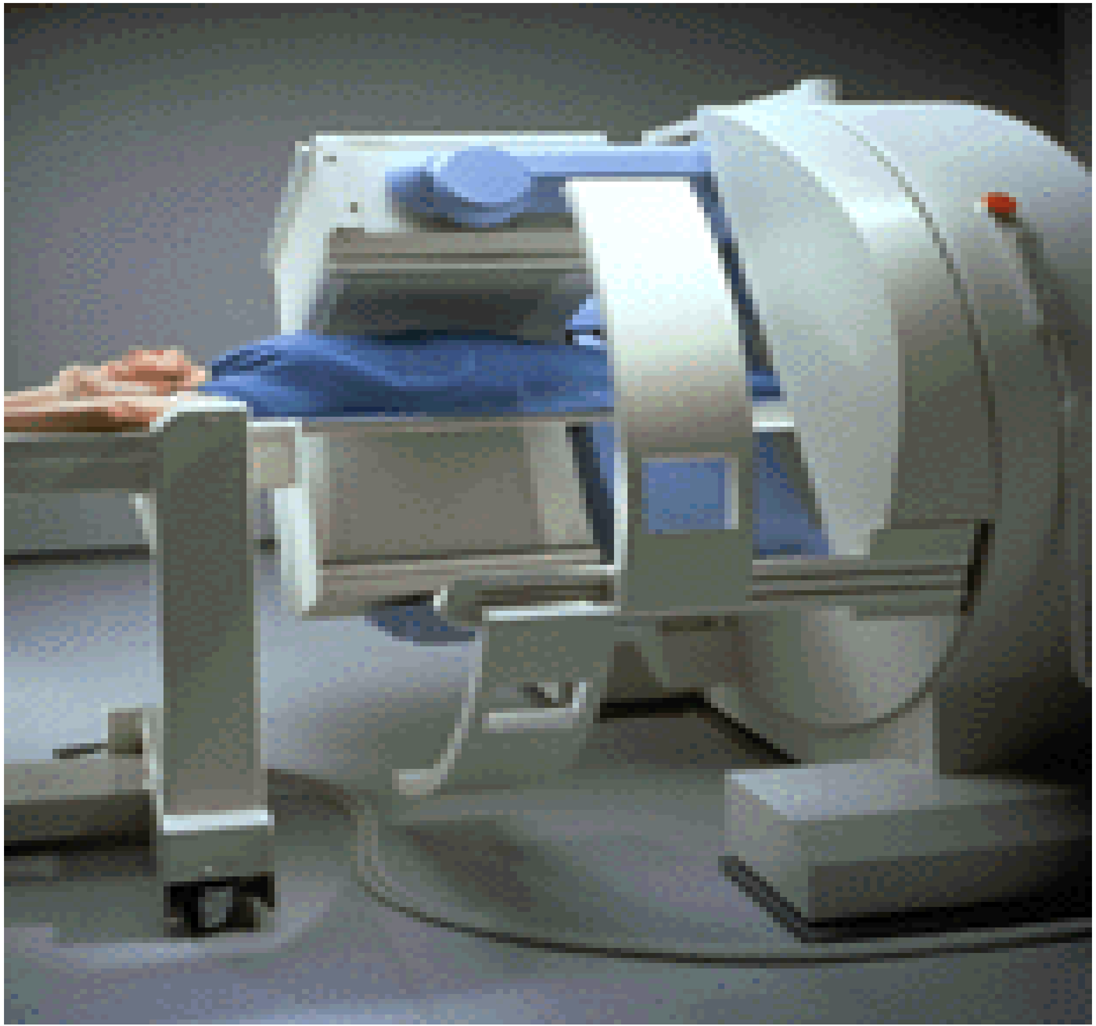


2.6d: Positron Emission Tomography (PET)

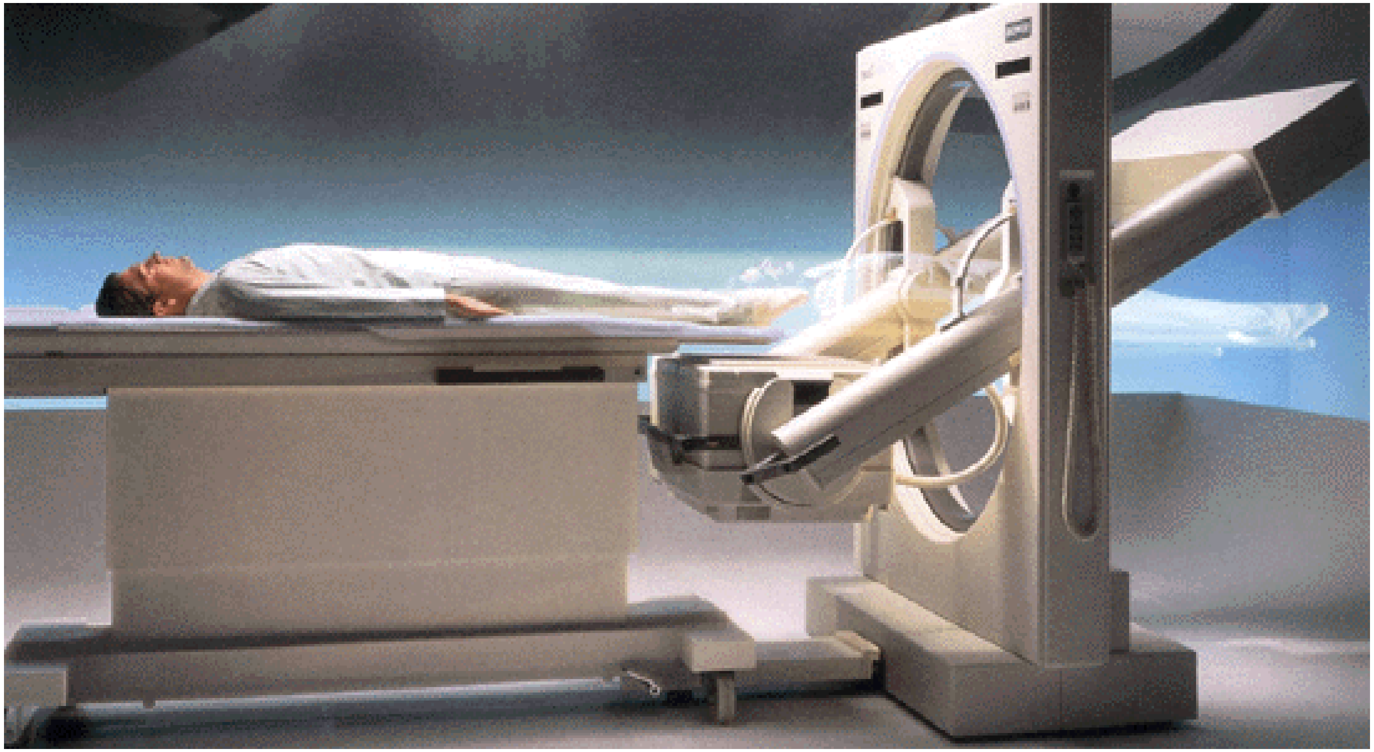
- PET produces transverse tomographic images of the distribution of positron-emitting radionuclides systematically administered to the subject under study
- The image data is supplied by the detection of the annihilation radiation emitted as a result of the annihilation of positrons in matter
- Radionuclides commonly used are carbon-11. nitrogen-13, oxygen-15, etc
- PET is very useful in the study of biochemical processes of fundamental importance in biology and medicine

2.6e: Nuclear Medicine Machine

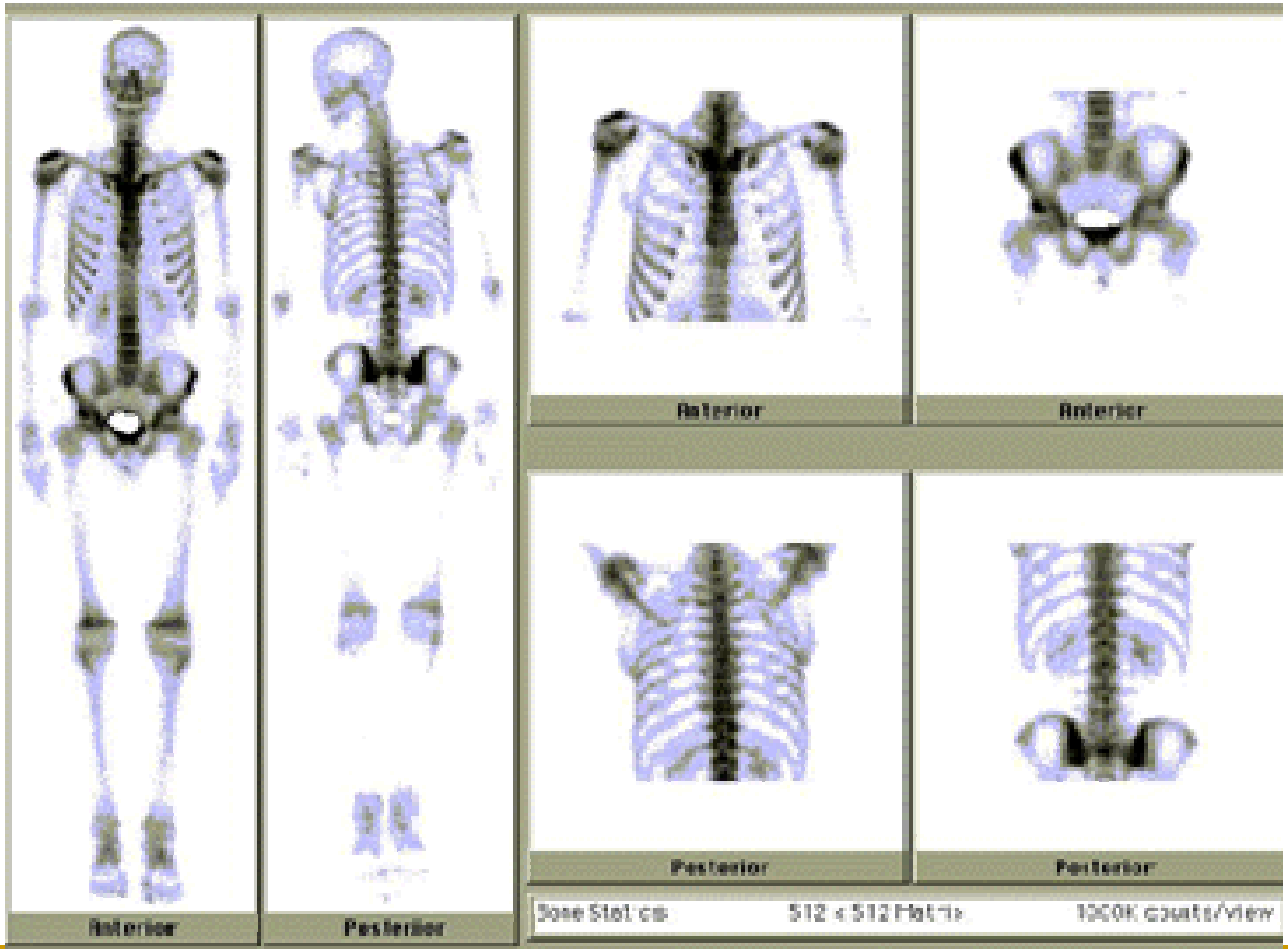
2.6f: Nuclear Medicine Imaging Machine



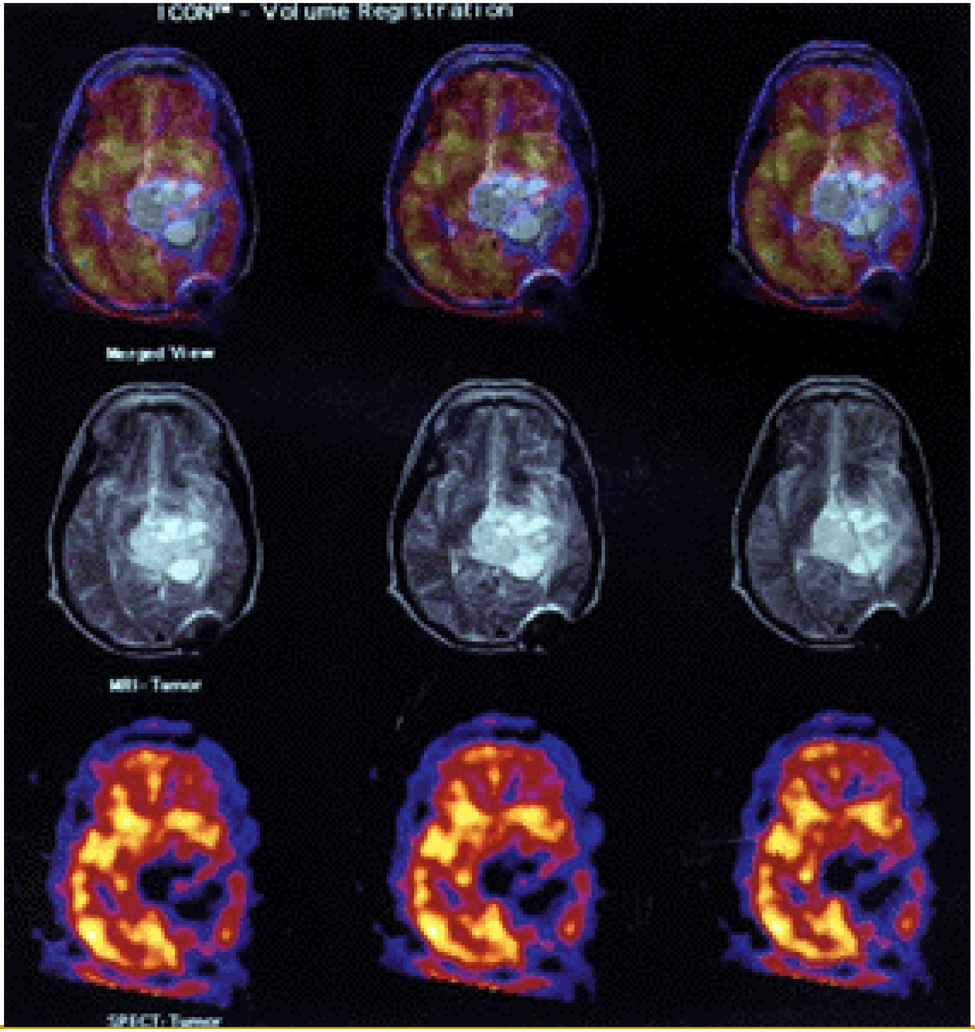
2.6g: Nuclear Medicine Machine



2.6h: Images of PET (Bones)



2.6i: PET and MRI Images

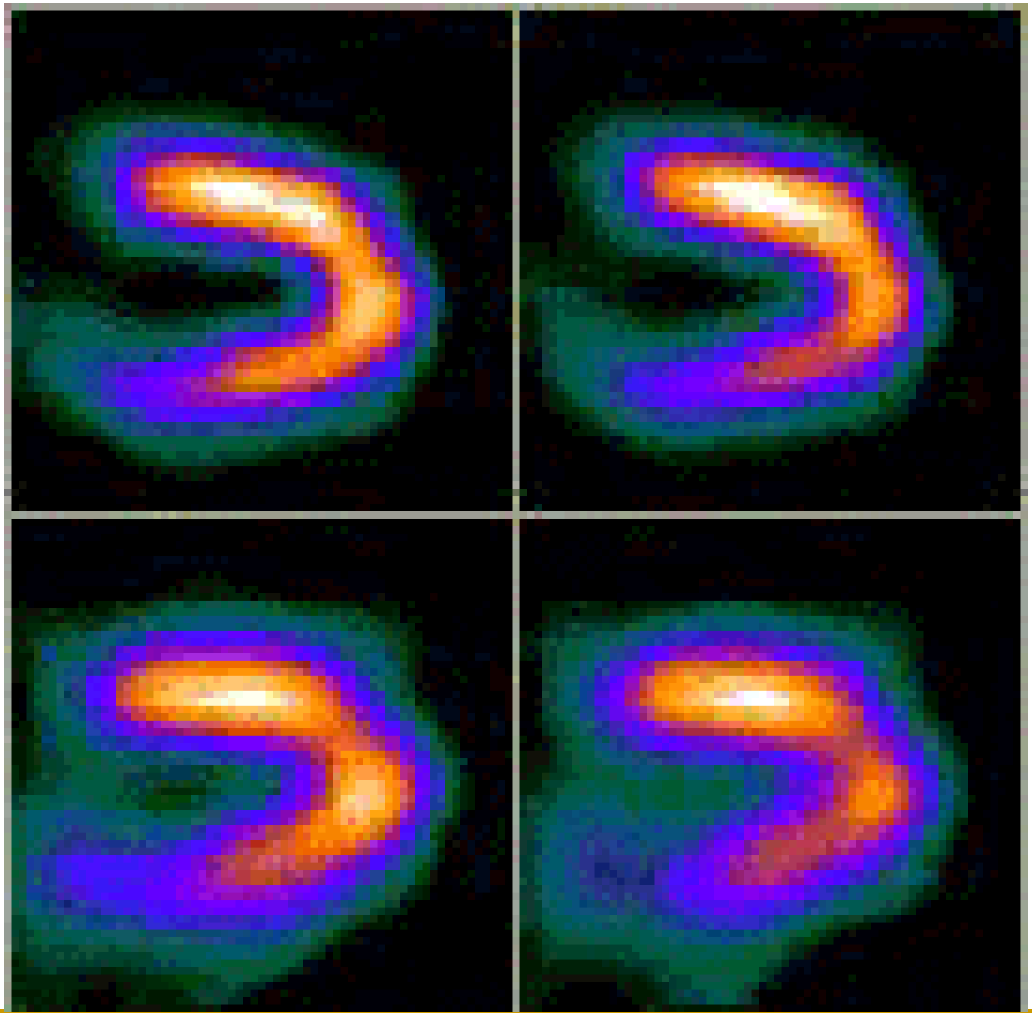


Combined

MRI

PET

2.6j: PET (Hearts)



Exercised

Rest

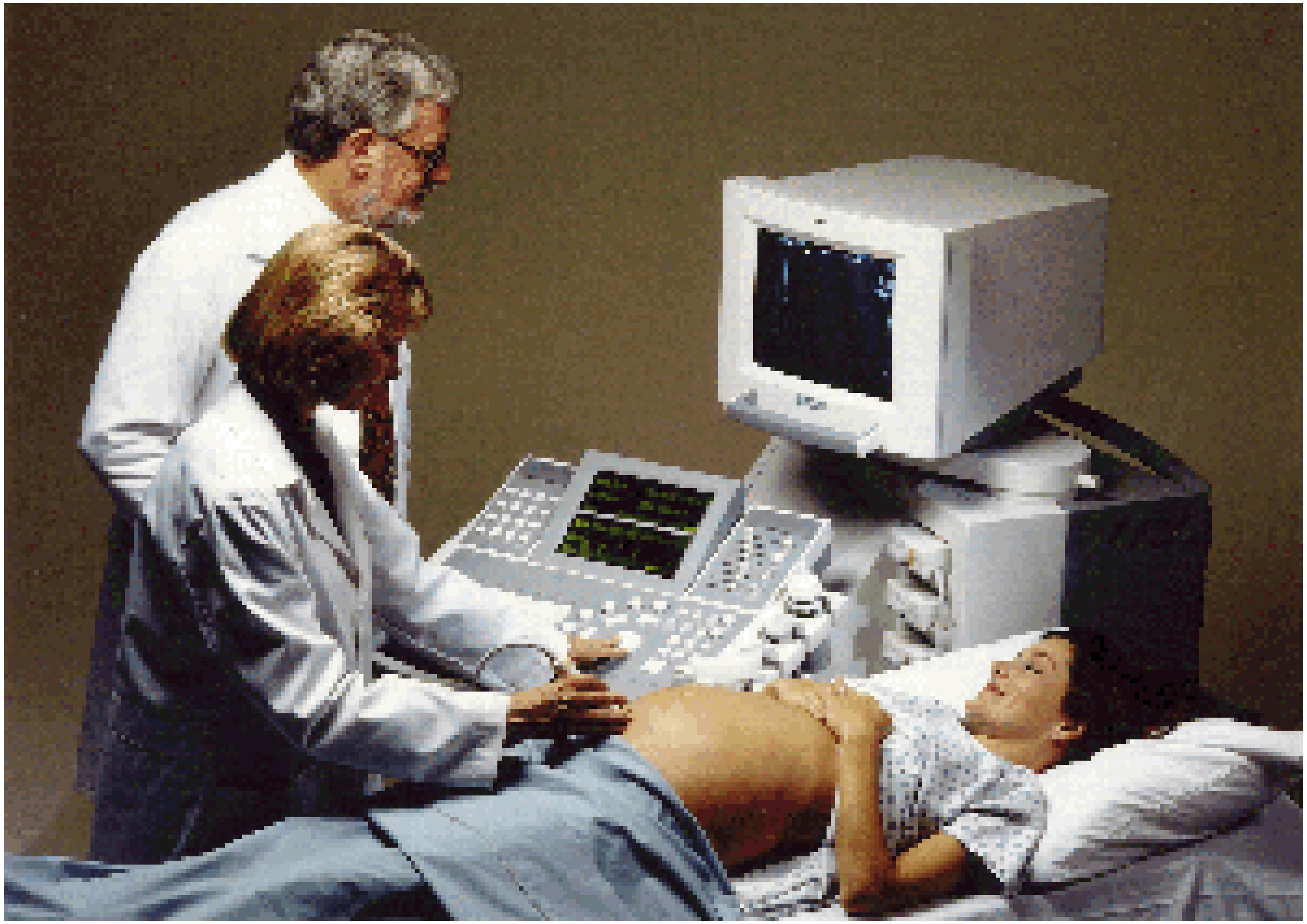
2.7a: Ultrasound

- Ultrasound is acoustical energy that contains frequencies higher than the upper audible limit
- In diagnostic imaging context, longitudinal waves usually have frequencies between 0.5 and 15MHz
- The basis of ultrasonic imaging is to determine information about intrinsic tissue properties from observations of the way in which probing waves are perturbed or “scattered” by the tissues
- B-scan imaging records pulse echoes from a single transducer over time and shape and is tomographic

2.6b: New Ultrasound Techniques

- New generation ultrasound techniques usually employ a computer to reconstruct images from raw or measured data
- Small ultrasound transducers can be made sufficiently small to be inserted into body for internal imaging
- The biggest advantages of ultrasound imaging is that the system is inexpensive and the procedure is safe

2.6c: Ultrasound Machine



2.6c: Ultrasound Image of Fetus

2.6e: Ultrasound Image of Kidney