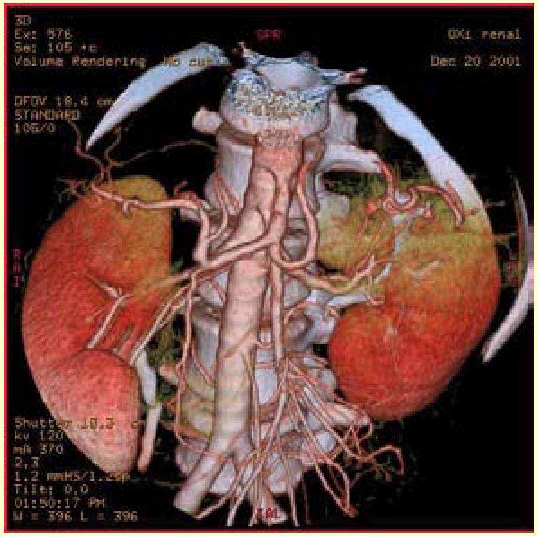
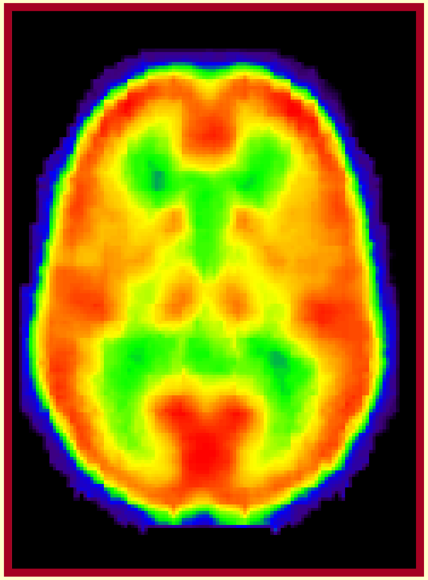




Medical Imaging

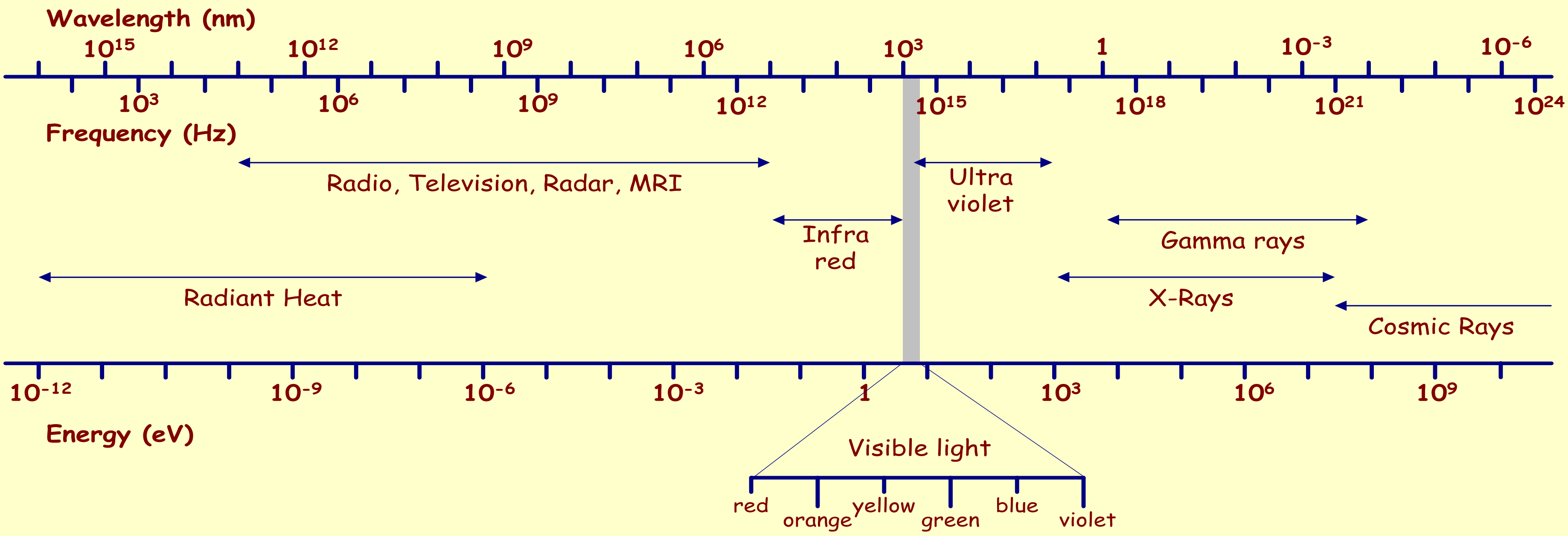
Gary Arbique, Ph.D.
UTSW Medical Physics Division

Medical Imaging Time Line

- 1895 - First x-ray image of human hand
- 1914 - First practical fluoroscope
- 1924 - Blumgart & de Hevesy perform first clinical tracer studies
- 1948 – Fluoroscopic intensifier tube
- 1952 - Wild & Reed: echo ultrasound image
- 1957 - Anger invents gamma camera
- 1972 - Hounsfield: x-ray computed tomography
- 1973 - Lauterbur: magnetic resonance imaging

Electromagnetic Spectrum

- aside from ultrasound, medical imaging relies on electromagnetic radiations
- high and low energy portions of the spectrum used in medical imaging
- mechanism of interaction depends on energy of the radiation



Contrast

- imaging relies on contrast differences
- in diagnostic imaging, contrast must distinguish anatomy, and/or physiological processes
- different imaging modalities produce contrast through differing physical processes
- various modalities offer advantages and disadvantages

X-Ray Modalities

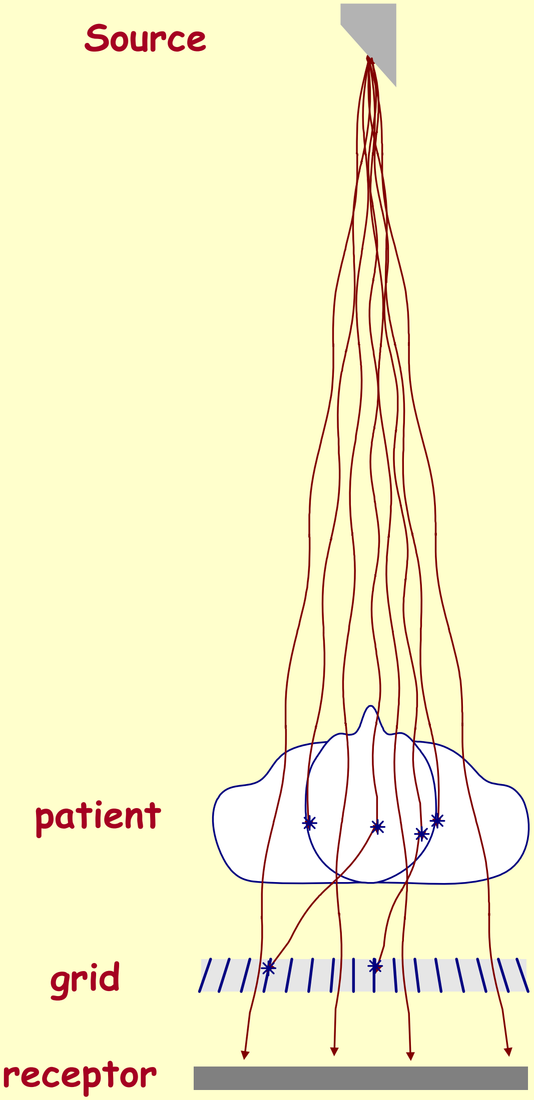
- x-ray modalities are the most common imaging modalities in medical diagnostic imaging
- modalities include:
  - Radiography
  - Fluoroscopy
  - Computed Tomography

X-Ray Contrast

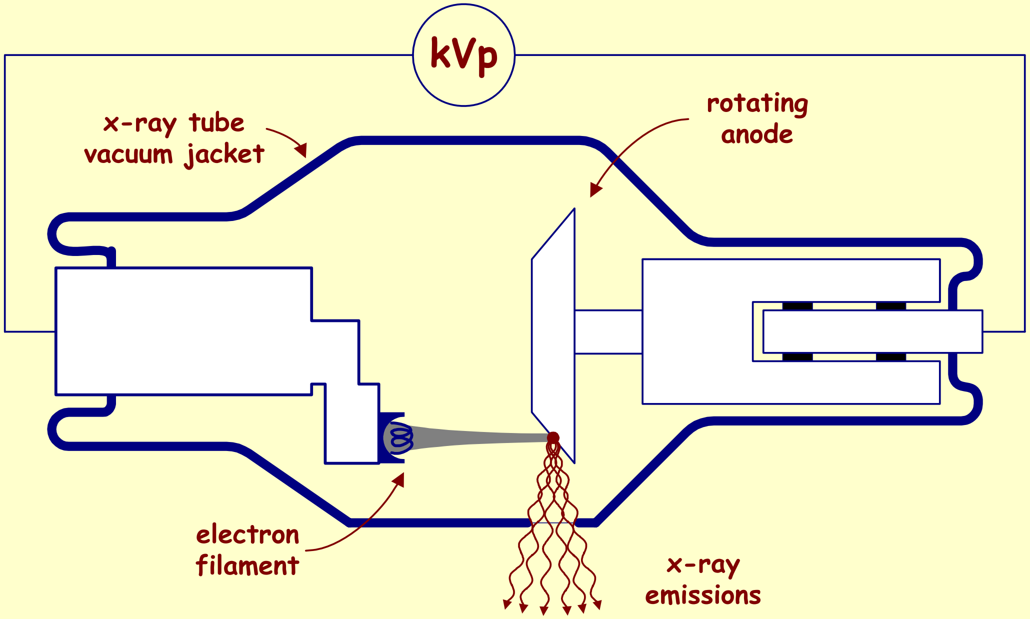
- low energy x-rays produce contrast through absorption in tissue
- relative absorption depends on tissue density and atomic composition
- down-side: absorption and scattering results in ionization (radiation dose) and potential biological damage, however, **benefit outweighs risk**

X-Ray Imaging Basics

- source produces collimated beam of x-rays
- x-rays absorbed, scattered or transmitted through patient
- if imaged, scattered x-rays reduce contrast, typically removed by a grid
- receptor captures an image of the transmitted x-rays



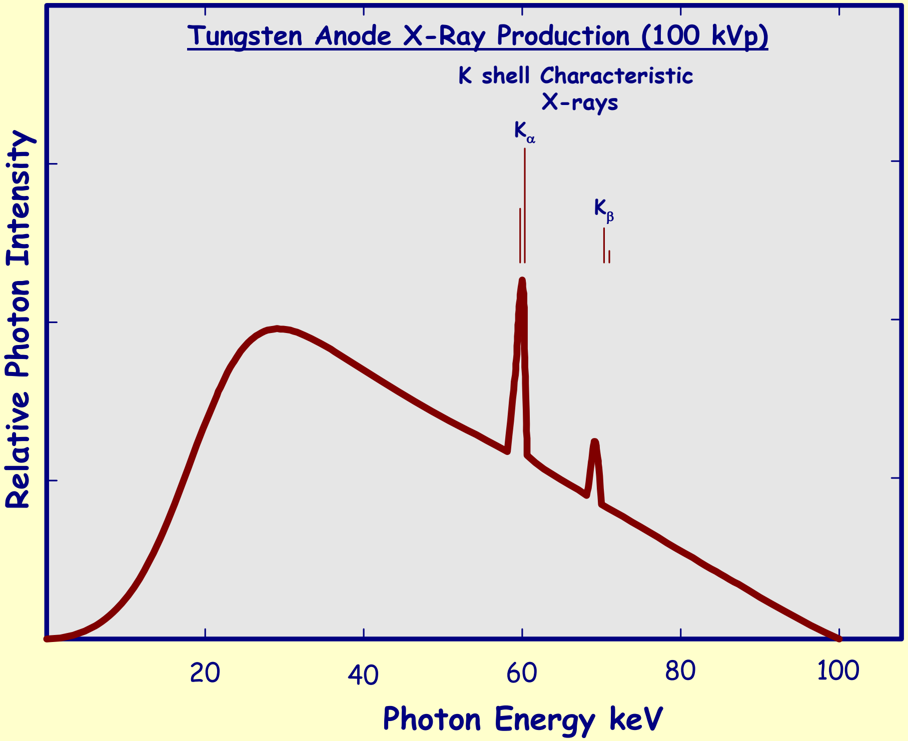
X-ray Production



- X-ray vacuum tube: apply an DC voltage (kVp) between a cathode (electrode filament) and anode
- high energy electrons striking the anode produce
  - heat (typically > 99% of electron energy),
  - bremstrahlung radiations, and
  - characteristic x-ray radiations

Anode Target X-Ray Spectrum

- polyenergetic bremstrahlung (i.e., braking radiation) spectrum, and
- monoenergetic characteristic (fluorescent) spectral lines
- upper energy limit set by generator kVp (typical diagnostic energies 50 – 120 kVp)
- in practice, lower energy x-ray spectrum preferentially attenuated (filtered, hardened) by inherent and added filtration
- attenuation desirable since low energy x-rays otherwise totally absorbed in patient, and contribute disproportionately to patient dose



Radiography

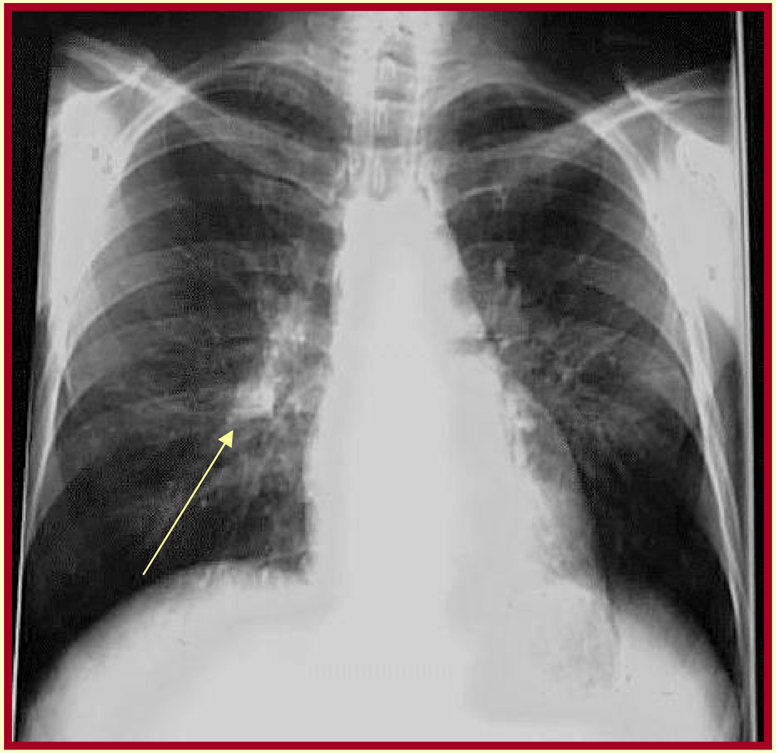
Wall Stand

Table

- radiography or plain x-rays, the most common x-ray imaging modality
- in radiography, static anatomy images produced, typically on film
- film not very sensitive to x-rays, fluorescent "screen" used to convert x-rays to visible light and expose film
- typical radiography suite comprises a gantry mounted tube, a table, and a wall stand

Radiograph Example

- plain x-rays used to image most aspects of anatomy
- chest x-ray a common radiographic procedure
- negative image produced for reading by radiologist
- dark image regions correspond to high x-ray transmission
- image visualizes lung field and silhouette of mediastinum
- used to diagnose lung and mediastinal pathologies (e.g., pneumonia, and cardiomegaly)

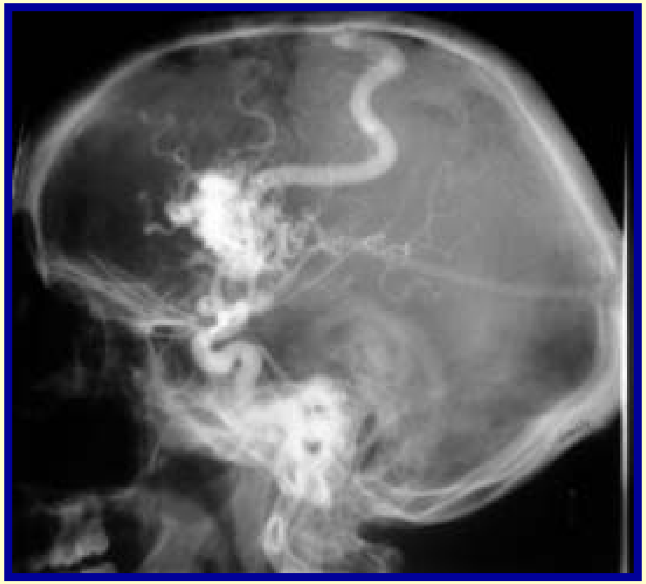


Pnuemocystis

Contrast Enhancement

- contrast agents (dyes) can be injected into the blood vessels (angiograms) and cavities to improve visibility
- for example: iodine and barium absorbs more x-rays than tissue

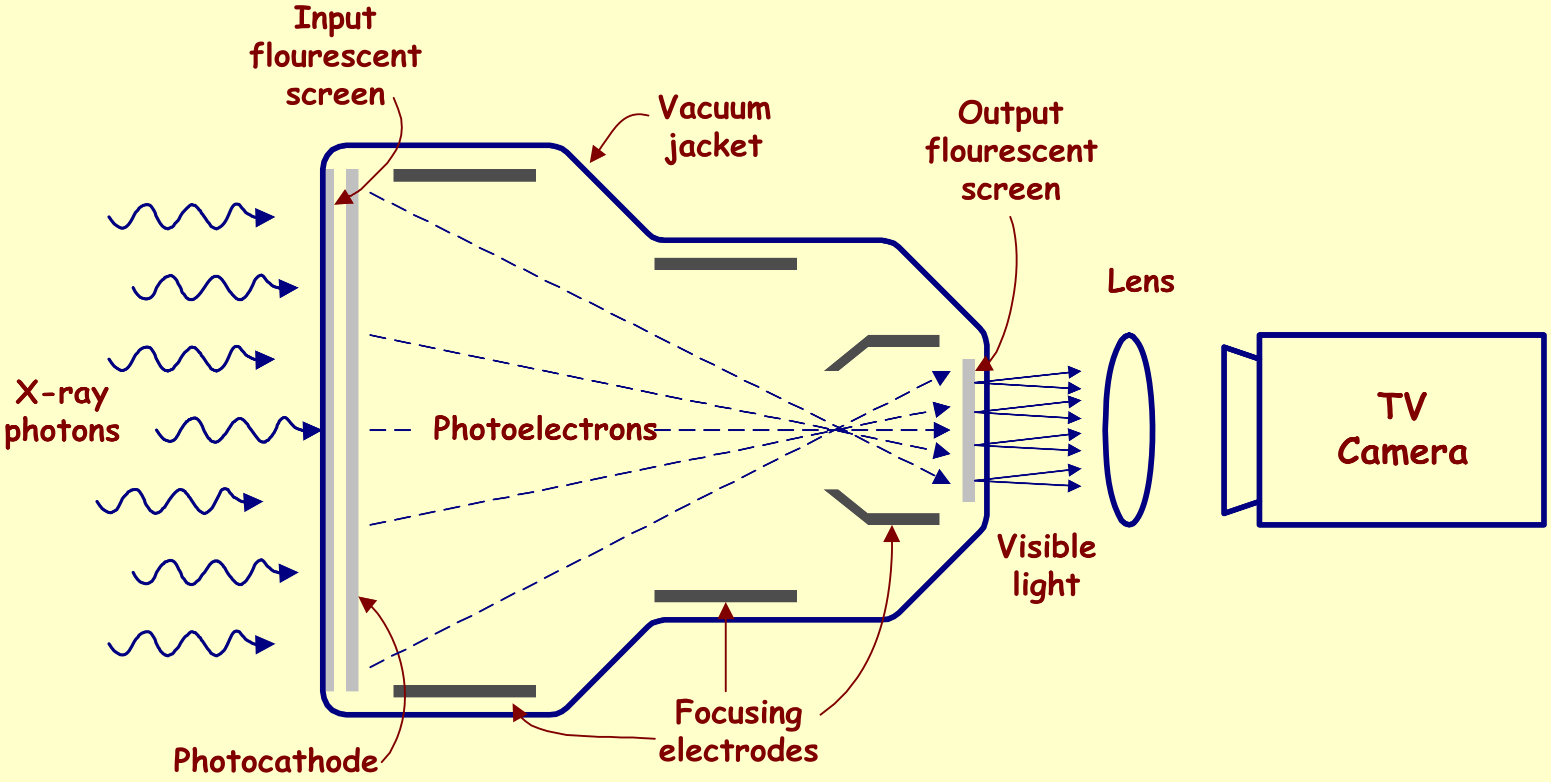
Air-Contrast Barium Enema



Cerebral Arteries

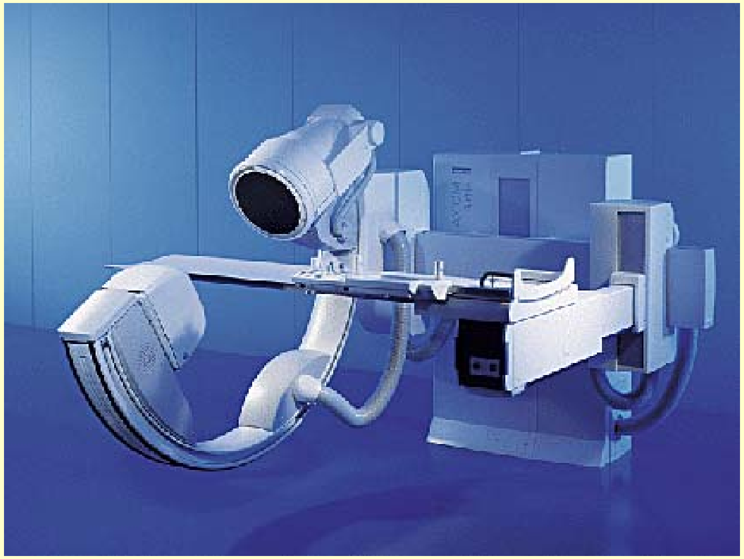
Fluoroscopy

- fluoroscopy used to obtain real time x-ray images
- image receptor converts x-ray image into a TV signal
- video images can also be recorded (film, video-tape)

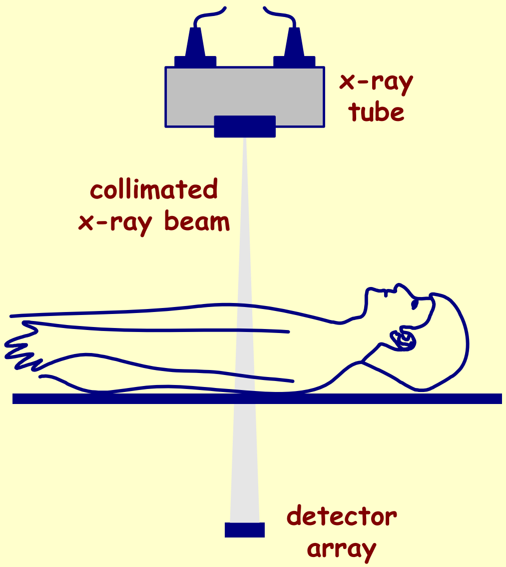


Fluoroscopy Suites

- table and c-arm arrangements available
- fluoroscopy typically used for observing the digestive tract, catheter guiding, and cardiac angiography

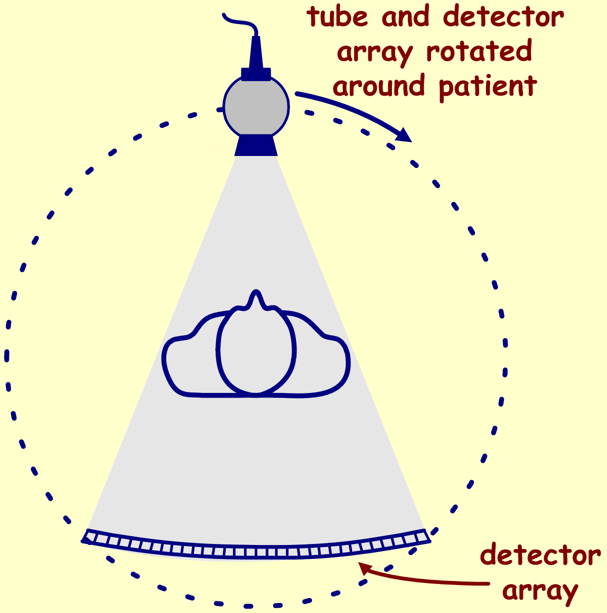


X-ray Computed Tomography (CT)



- conventional x-rays are projection images, and overlying structures can obscure anatomical details
- in CT slice projections (profiles) through patient measured by a detector array

- by rotating the tube and detector array, profiles are taken at multiple angles
- a computer then processes the profiles using a mathematical algorithm (convolution) to create a cross-sectional image on a video screen



CT Scanner

- cowling covers rotating tube and detector electronics
- central port and table for patient
- computer console for control and image viewing

CT Slice Images

abdominal scan at kidney level

abdominal scan spleen/liver level

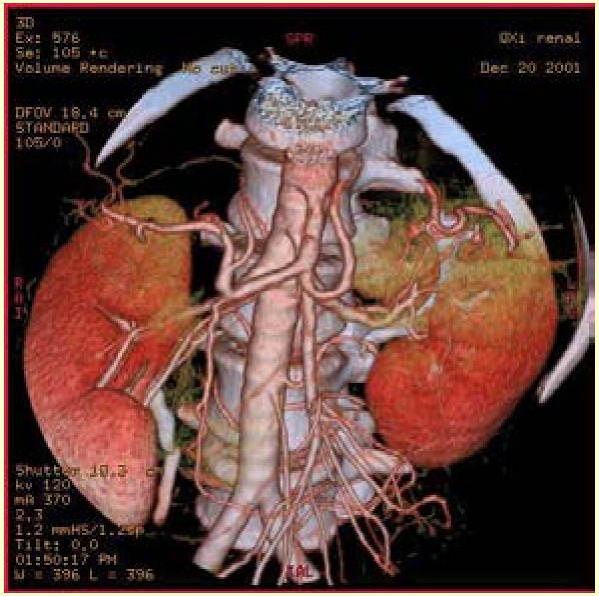
head scan showing ventricles

- CT eliminates the shadow overlap problem of conventional X-rays
- contrast agents commonly used in CT

Helical CT

- modern CT scanners use continuous tube rotations and table translation
- with respect to patient, the tube follows a helical path
- results in faster scans (e.g., a single breath hold lung scan)
- helical scan profiles are interpolated to form slice images
- modern computer reconstruction can reformat data to view slices at arbitrary angles
- three-dimensional rendered images of complex blood vessels like the renal arteries or aorta are also possible

Simulated helical x-ray beam path for a scan of the of the abdomen. The highlighted area is a man's stomach (man is lying on his back with his arms over his head).



3D rendering of kidneys

3D Rendered CT Images

Heart

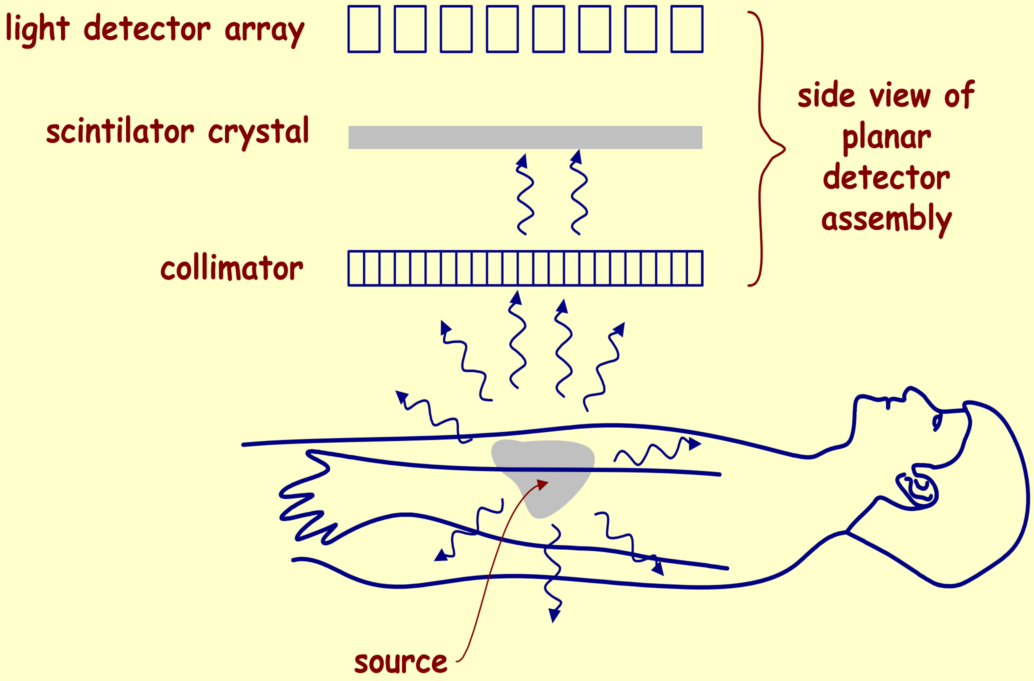
Colon Fly Through

Nuclear Medicine Imaging

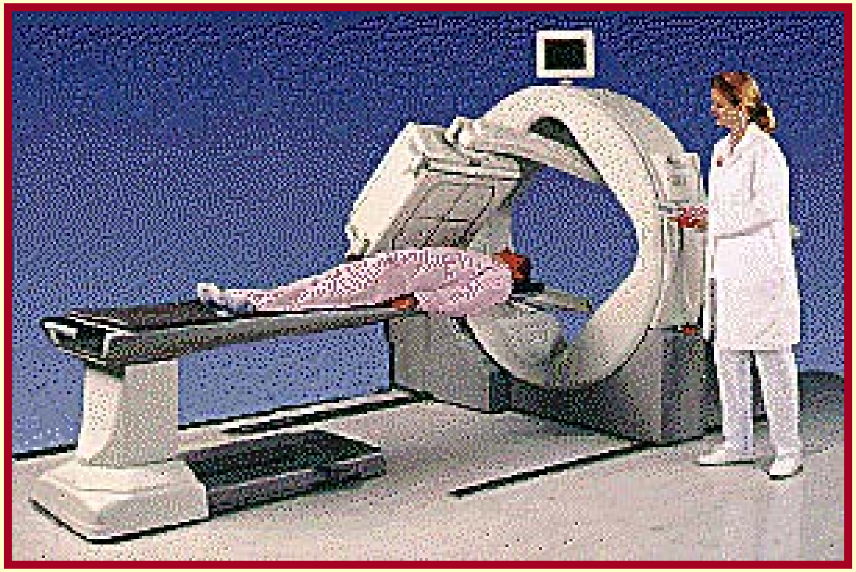
- radio-isotopes are natural and artificially produced unstable isotopes that decay through gamma-ray and/or particulate emissions (e.g., positrons)
- ideal imaging isotopes feature low dose to the patient (e.g., short physical and/or biological half lives)
- medical isotopes produced in nuclear reactors and by particle accelerators
- nuclear medicine images visualize radioisotope concentrations
- by “tagging” radio-isotopes to biological molecules, physiological processes can be measured
- **nuclear imaging is functional, not anatomic**

Planar and SPECT Cameras

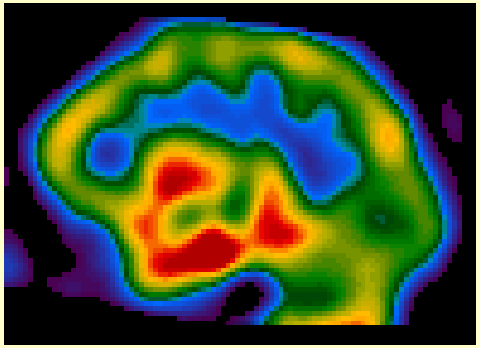
- relies on isotopes that emit γ-rays (e.g., ^{99m}Tc)
- planar camera comprises a collimator, scintillator crystal (e.g., NaI) and a light detector array
- by rotating a planar camera, data for tomographic images acquired
- SPECT an acronym for single photon emission computed tomography



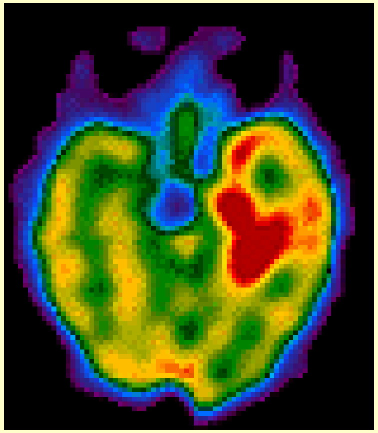
SPECT Camera & Images



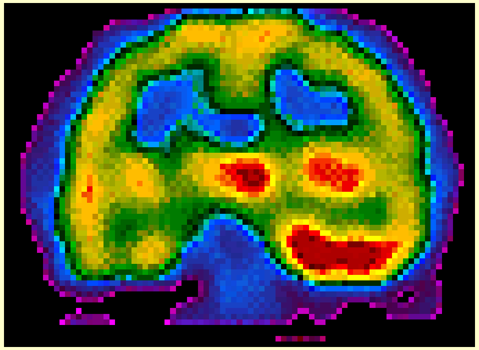
rotating planar SPECT camera



sagittal



transaxial

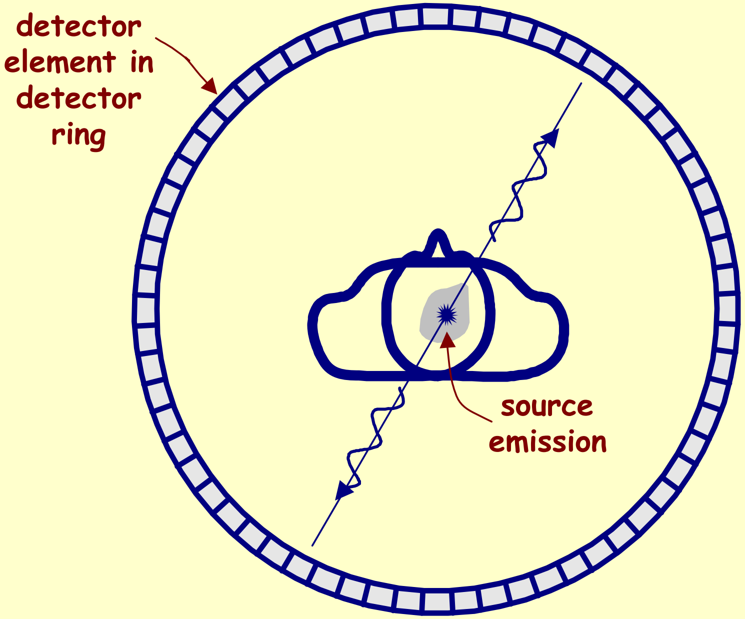


coronal

Tc-99m HMPAO SPECT perfusion images, showing decreased blood perfusion to posterior frontal and anterior temporal lobes

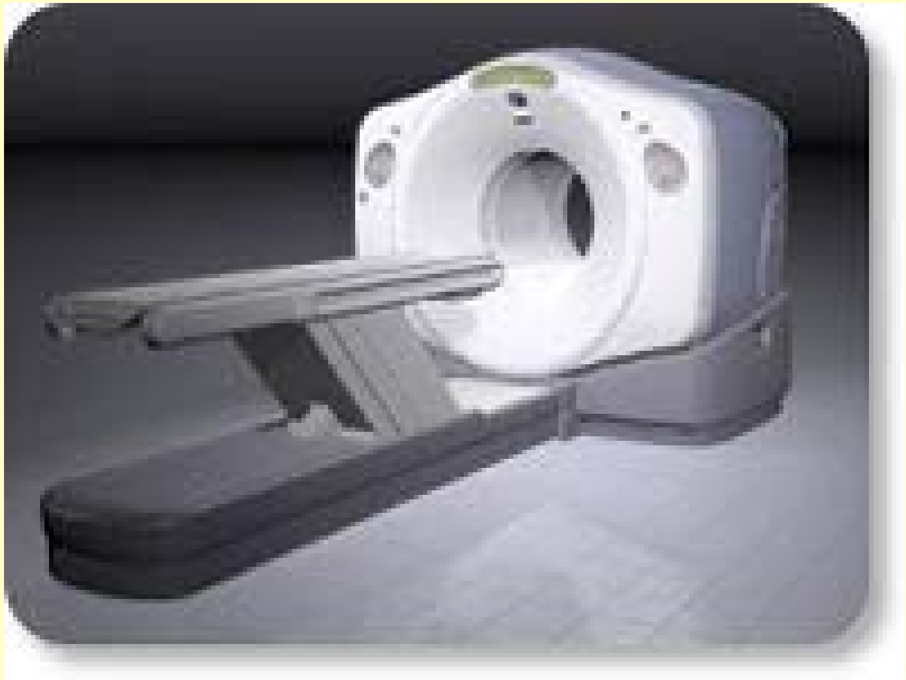
PET Imaging

- some radio isotopes decay with the emission of a positron (e.g., ^{18}F)
- positrons annhilate with electrons shortly after emission, resulting in emission of two coincident 511 keV photons traveling in opposite directions
- positron emission tomography (PET) camera detects coincident photon emissions to form tomographic data sets for computer image reconstruction
- PET has higher sensitivity and resolution than SPECT
- ^{18}FDG commonly used in PET to detect increased cellular metabolism (e.g., detecting and staging cancer)



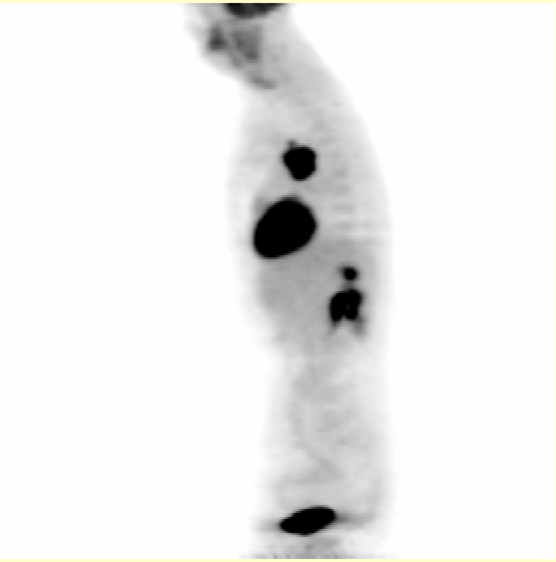
PET camera

State of the Art PET-CT Scanner



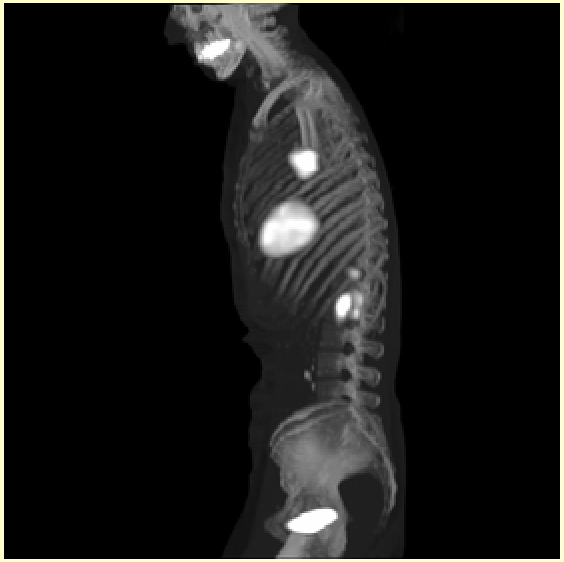
- PET-CT systems generate PET functional and CT anatomy images of a patient in a single study

3D Image Co-registration



PET Uptake

CT Anatomy



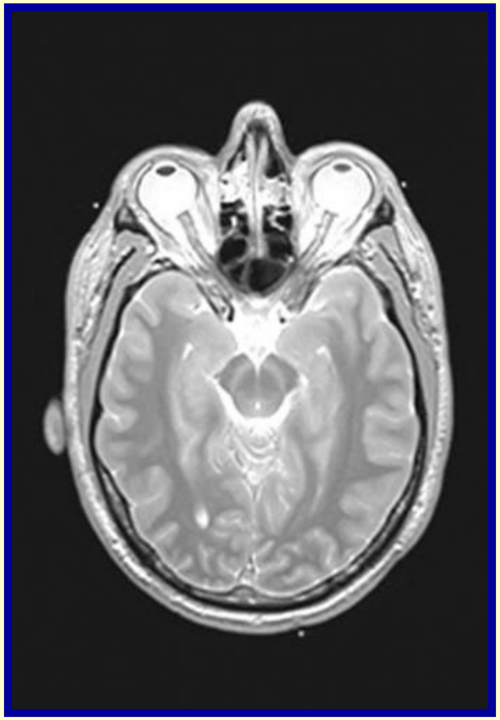
Co-Registered

- functional and anatomical images registered and fused to form a single image

Magnetic Resonance Imaging (MRI) Basic Physics

- protons and neutrons have a quantum property called spin
- in a classical description, the spin property is similar to a tiny magnet
- in a strong DC magnetic field, spin moments align with the magnetic field to form a net magnetization

- hydrogen atoms have a net spin moment and the high content of H_2O in tissue makes it ideal for anatomical imaging



Magnetic Resonance Imaging (MRI) Basic Physics

- if disturbed (tipped) from steady-state alignment, the magnetization vector will precess at a characteristic (Larmor) frequency about an applied magnetic field (much like a nutating spinning top)
- the Larmor frequency is proportional to the magnetic field
- relaxation mechanisms cause the tipped magnetization to relax back to the steady state
- the magnetization can be tipped by transmitting electromagnetic waves at the Larmor frequency
- signal from the precessing magnetization can be detected by a receiver antenna

- magnetic fields used in MRI are typically > 1 Tesla (i.e., ~20000 x earth's magnetic field), here the hydrogen Larmor frequency is ~ 42 MHz (i.e., close to TV and FM frequencies)

MRI Image Aquisition

- imaging details very complex, however, “pulse sequences” are used to excite and receive magnetization signals
- small magnetic field gradients are applied in addition to the strong DC magnetic field
- the resulting Larmor frequency shifts encode signal levels as a function of position

- pulse sequences are characterized by a repetition time (TR) and a receiver delay time (TE)
- TR and TE are used to control signal levels from different tissues

- receiver signals computer analyzed to form an image
- mathematical algorithms based on the Fourier Transform
- tomographic and volume images can be aquired

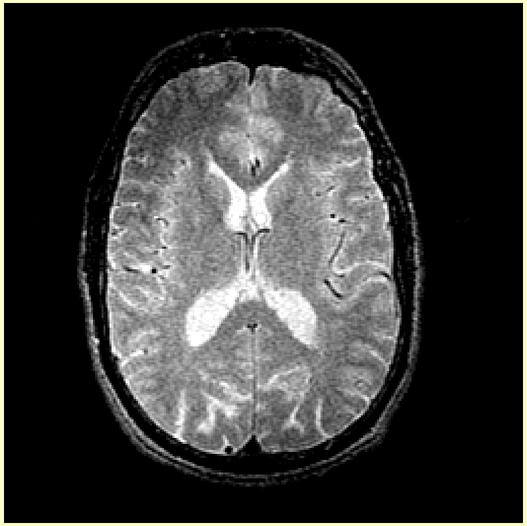
MRI Image Contrast

- contrast in MRI produced by variations in proton density and by variations in relaxation times in different tissues
- paramagnetic contrast agents can be employed to enhance contrast

- MRI offers anatomical diagnostic imaging features similar to CT, but, with "tuneable" contrast
- however, MRI does not image bone well because of low water content

- magnetic and rf fields levels used in MRI have no known biological risks

Spin-Echo Sequence
TR = 250 ms
TE = 20 ms



Spin-Echo Sequence
TR = 2000 ms
TE = 80 ms

MRI Scanner

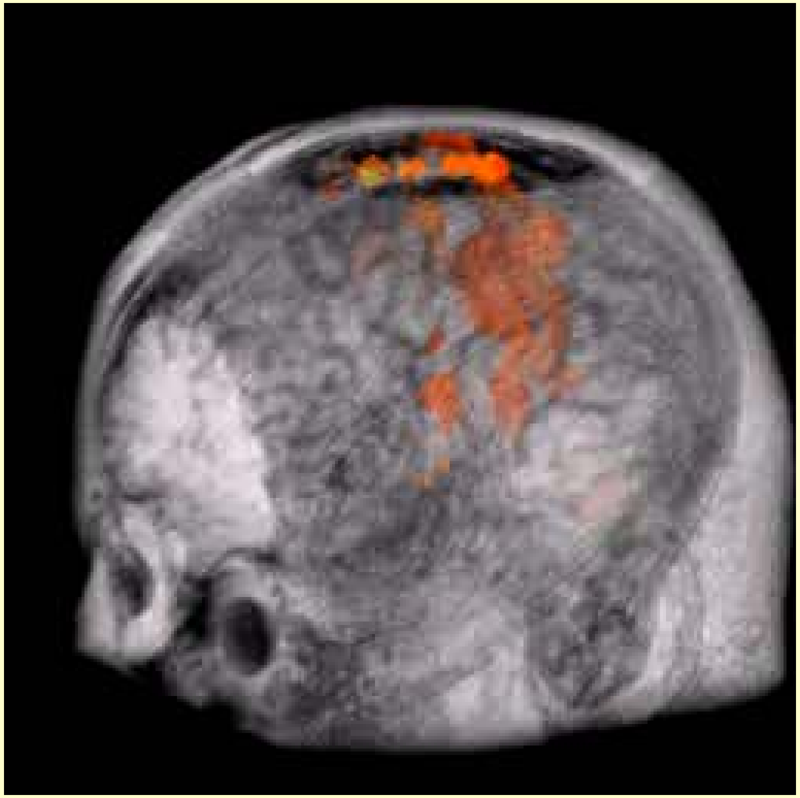
- solenoid magnet field scanner looks much like a CT scanner
- rf transmitter/reciever coil typical in scanner cowling, however, special coil assemblies for head and extremities imaging used
- scanner situated in a rf shielded room
- ferromagnetic metals, pacemakers are not compatible with MRI exams
- MRI is noisy (knocking noises) due rapid application of imaging field gradients

MRI Scanner

“bird cage” coil assembly
for head imaging

BOLD Imaging (fMRI)

- MRI can measure physiological processes (i.e., functional MRI)
- oxy- to deoxy-hemoglobin results in changes to local relaxation processes thus affecting signal level
- technique called blood oxygen level-dependant (BOLD) MRI
- hemodynamic changes can be imaged and correlated to neuronal activity
- subjects given specific challenges during imaging to isolate associated activity areas in the brain

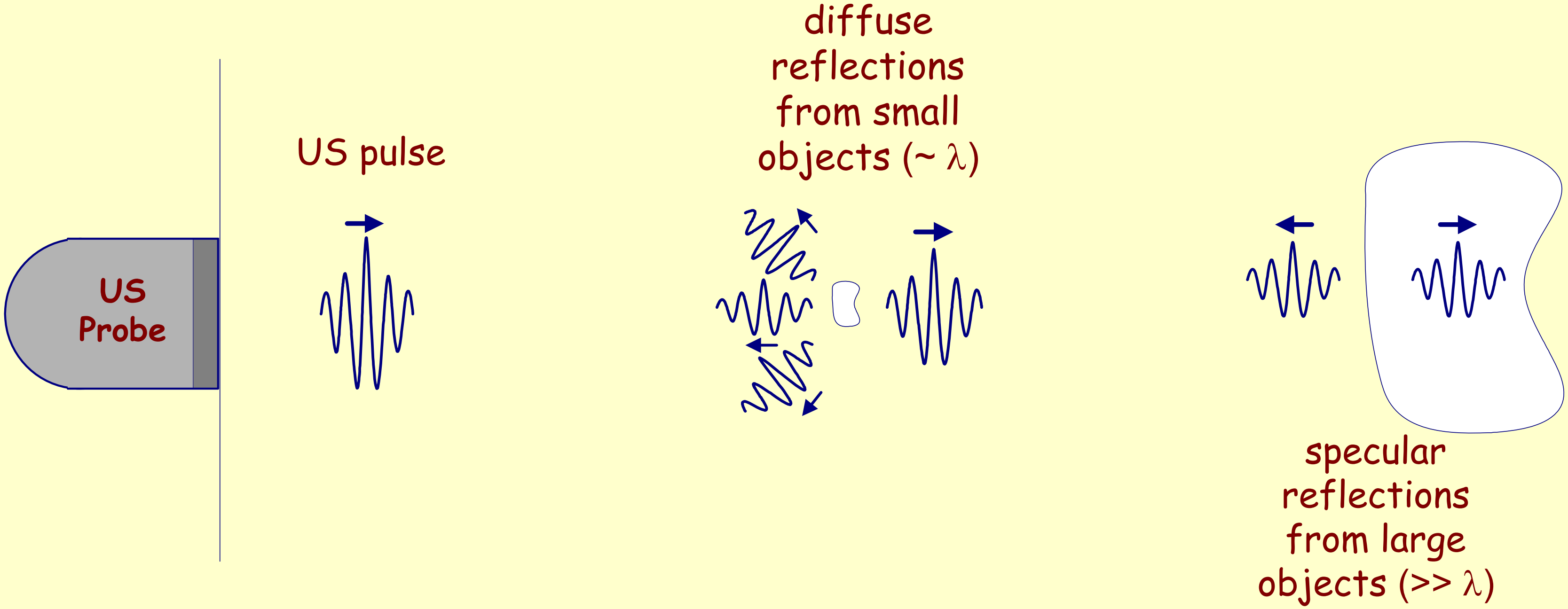


motor strip localization

(co-registered 3D image)

Ultrasound (US) Imaging

- US uses high frequency (> 1 MHz) ultra-sound waves (i.e., not electromagnetic) to create static and real time anatomical images
- contrast results from reflections due to sound wave impedance differences between tissues
- at diagnostic levels, no deleterious biological effects from US pulses
- technique similar to submarine ultrasound, a sound pulse is sent out, and the time delays of reflected "echoes" are used to create the image
- image texture results from smaller scatters (diffuse reflectors)
- boundaries result from specular reflections (large objects)



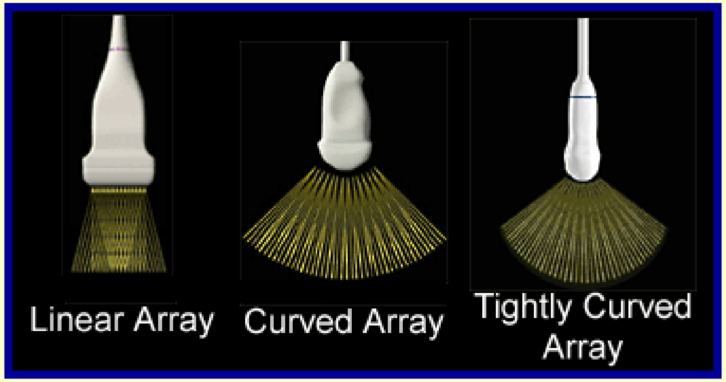
US Images

- by sending pulses out along different directions in a plane, slice images of anatomy are produced for viewing on monitor
- US does not work well through lung or bone, used mainly for imaging abdominal and reproductive organs
- one of the most well known US procedures is the examination of the living fetus within the mother's womb
- 3D imaging scanners now available (real time, so called 4D)

US Scanner

US Scanner

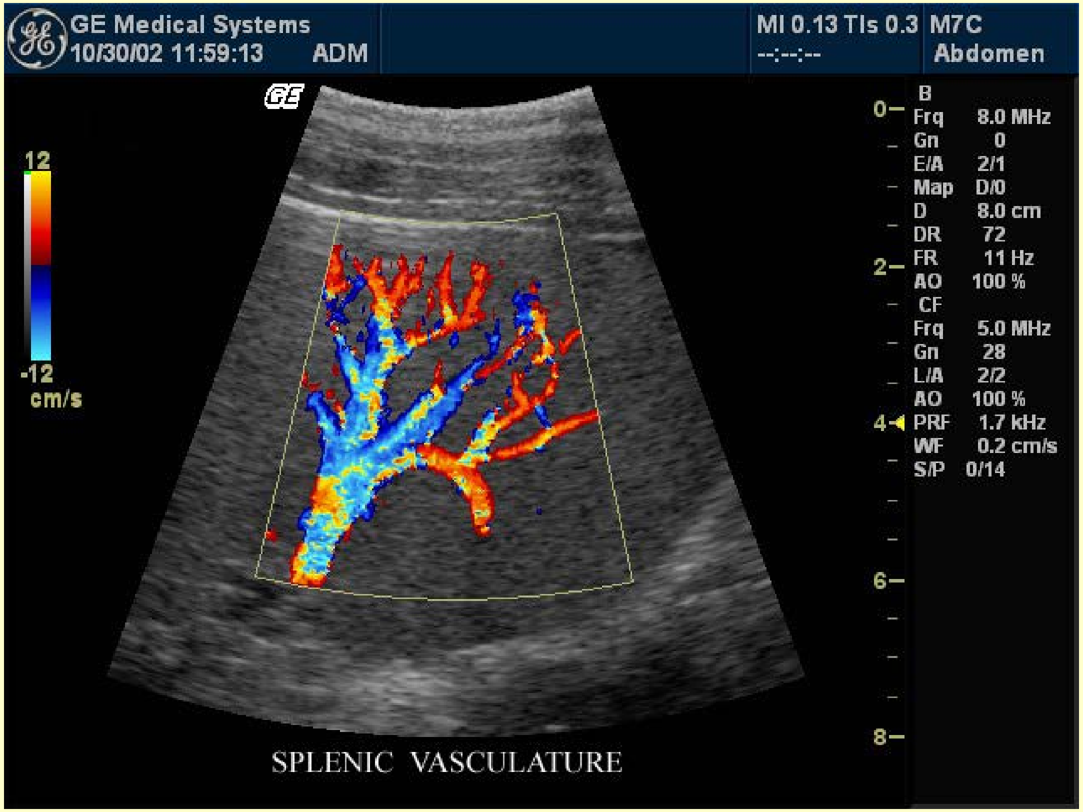
- scanner features probes, data processing computer, and image viewing monitor
- probes specialized for exam requirements
- modern probes feature phased transmit/receiver arrays to electronically steer and focus the US beam



US Probes

Doppler Ultrasound Measures Blood Flow

- using a special form of US called Doppler (just like police speed RADAR) the speed and direction of flowing blood can be measured and illustrated in color images
- Doppler US allows Radiologists to image vasculature and detect blocked blood vessels in the neck, and elsewhere



B
Frq 8.0 MHz
Gn 0
E/A 2/1
Map D/0
D 8.0 cm
DR 72
FR 11 Hz
AO 100 %
CF
Frq 5.0 MHz
Gn 28
L/A 2/2
AO 100 %
PRF 1.7 kHz
WF 0.2 cm/s
S/P 0/14

SPLENIC VASCULATURE

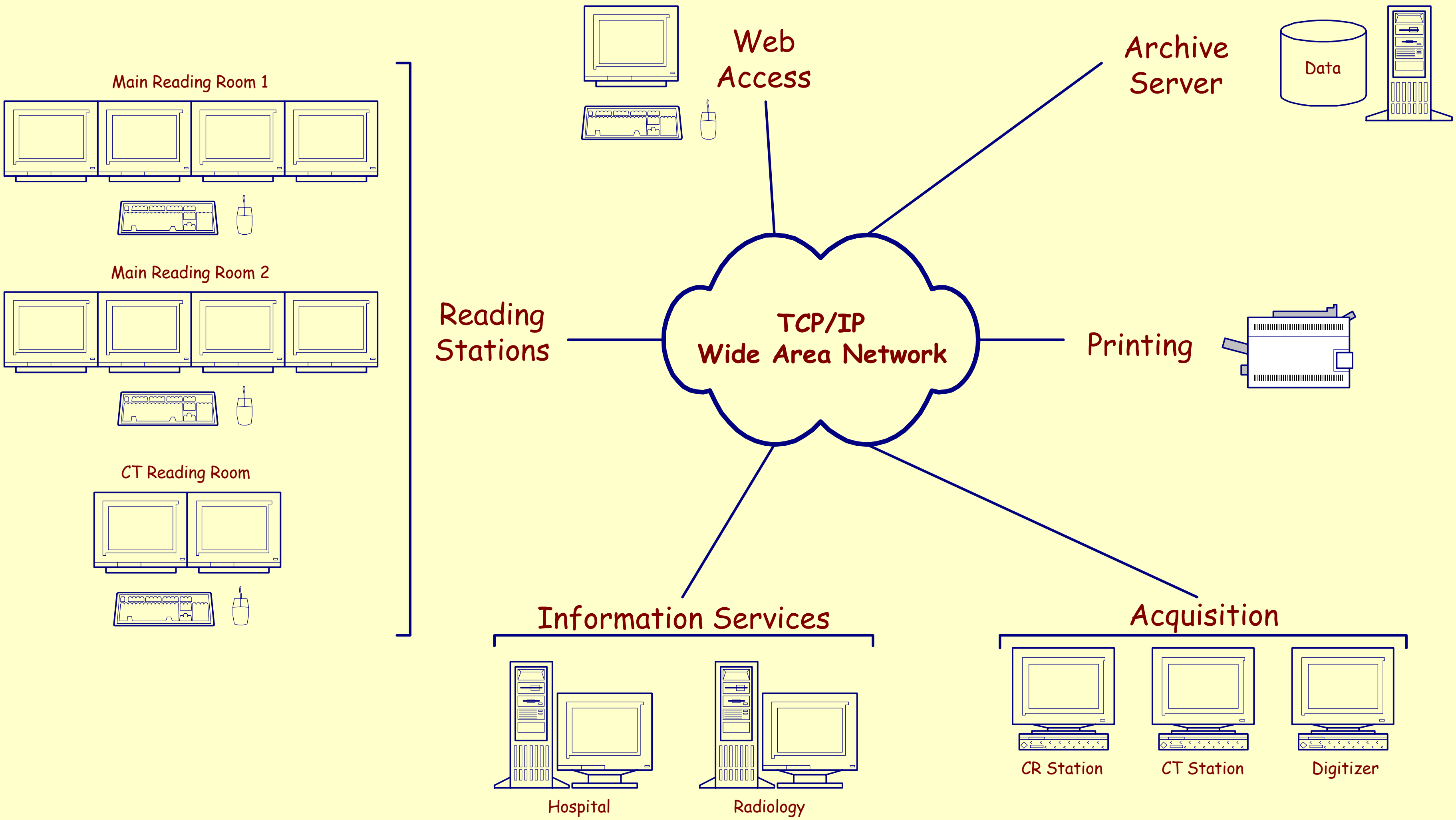
Transition to a Digital Imaging Environment

- modern radiology is making a transition to a digital imaging environment or **PACS** (picture archiving and communications system)
- advantages include efficient image distribution and reduced storage requirements
- integral to PACS, is digital image acquisition
- computer based modalities inherently digital
- film based modalities now being phased out by digital technologies

film (hard-copy) reading

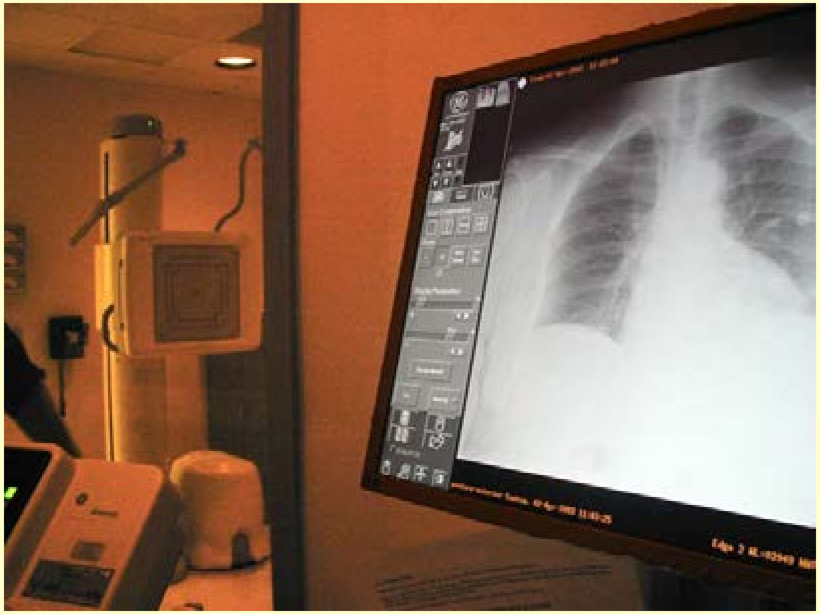
PACS soft-copy reading

PACS Environment Example



Digital Imaging Technologies Replacing Film in Radiology

DR: digital radiography uses an x-ray imaging detector **electronically** connected to a readout system (e.g., flat panel detectors).



CR: computed radiography uses a **storage phosphor** x-ray imaging detector which is read out by a separate digital reading device

Suggested Reference Material

- Physics of Radiology, A. B. Wolbarst, Medical Physics Publishing (ISBN 0-944838-95-2)
- Search the Internet

Role of the Physicist in Diagnostic Radiology (revenge of the nerds)

- Ensure equipment is producing high quality images
  - image quality control
  - periodic checks of equipment
  - supervise preventive maintenance

- Reduce dose to patients and personnel
  - monitor radiation dose records
  - evaluate typical doses for procedures
  - recommend equipment changes and/or dose reduction strategies

Medical Physics Skills

- **Measure Radiation Output**
- **Calculate Radiation Dose to Tissues**

- Supervise Radiation Safety Program
- Evaluate Equipment for Purchase
- Image Processing
- Computer Programming & Networking
- Teach Physics to Radiology Residents