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 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 bremsstrahlung (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

- 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.
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)

![Diagram of fluoroscopy](attachment:fluoroscopy_diagram.png)
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)**

- **x-ray Computed Tomography (CT)**

- **x-ray tube**

- **collimated x-ray beam**

- **detector array**

- **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**

- **tube and detector array rotated around patient**

- **detector array**
CT Scanner

- cowling covers rotating tube and detector electronics
- central port and table for patient
- computer console for control and image viewing
CT eliminates the shadow overlap problem of conventional X-rays

- contrast agents commonly used in CT

CT Slice Images

abdominal scan at kidney level

abdominal scan spleen/liver level

head scan showing ventricles
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 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 $\gamma$-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 annihilate 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).
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

- 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$_2$O 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 × earth’s magnetic field), here the hydrogen Larmor frequency is ~42 MHz (i.e., close to TV and FM frequencies)
MRI Image Acquisition

- 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 acquired
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.
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

"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 Pulse**

- **Diffuse Reflections** from small objects (~ λ).
- **Specular Reflections** from large objects (>> λ).
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

- 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
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
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
PACS Environment Example

TCP/IP
Wide Area Network

Reading Stations

Information Services

Web Access

Archive Server

Printing

Acquisition

CR Station  CT Station  Digitizer

Hospital  Radiology
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


• 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**