ENG4BF3
Medical Image Processing

Medical Imaging Modalities

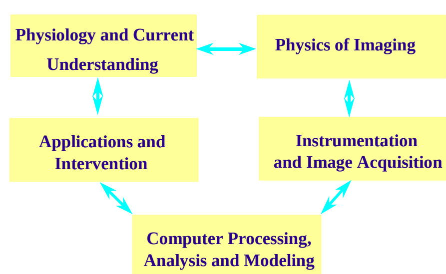
Imaging in Medical Sciences

- Imaging is an essential aspect of medical sciences for visualization of anatomical structures and functional or metabolic information of the human body.
- Structural and functional imaging of human body for understanding
  - body anatomy
  - physiological processes
  - function of organs
  - behavior of whole or a part of organ in abnormal physiological conditions or a disease.

A Multidisciplinary Field

- Medical imaging in diagnostic radiology has evolved as a result of the significant contributions of a number of different disciplines from basic sciences, engineering, and medicine.
- Computerized image reconstruction, processing and analysis methods have been developed for medical imaging applications
- The application-domain knowledge has been used in developing models for accurate analysis and interpretation.

A Multidisciplinary Field



A collaborative multidisciplinary paradigm of medical imaging research and applications.

Medical Imaging

- Radiological sciences in the last two decades have witnessed a revolutionary progress in medical imaging and computerized medical image processing.
- Advances in multi-dimensional medical imaging modalities
  - **X-ray Mammography**
  - **X-ray Computed Tomography (CT)**
  - **Positron Emission Tomography (PET)**
  - **Ultrasound**
  - **Magnetic Resonance Imaging (MRI)**
  - **functional Magnetic Resonance Imaging (fMRI)**
- Important radiological tools in diagnosis and treatment evaluation and intervention of critical diseases for significant improvement in health care.

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Medical Imaging and Image Analysis

- The development of imaging instrumentation has inspired the evolution of new computerized image reconstruction, processing and analysis methods for better understanding and interpretation of medical images.
- The image processing and analysis methods have been used to help physicians to make important medical decision through physician-computer interaction.
- Recently, intelligent or model-based quantitative image analysis approaches have been explored for computer-aided diagnosis to improve the sensitivity and specificity of radiological tests involving medical images.

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Medical Imaging Modalities

- **Radiation/Imaging Source**
- **External**
  - **X-ray Radiography**
  - **X-ray CT**
  - **Ultrasound**
  - **Optical: Reflection, Transillumination**
- **Internal**
  - **SPECT**
  - **PET**
- **Mixed**
  - **MRI, fMRI**
  - **Optical Fluorescence**
  - **Electrical Impedance**

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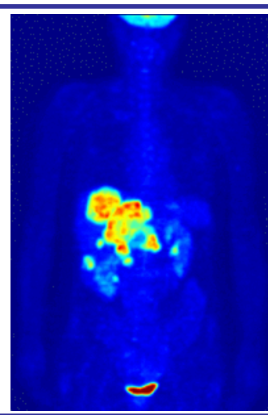

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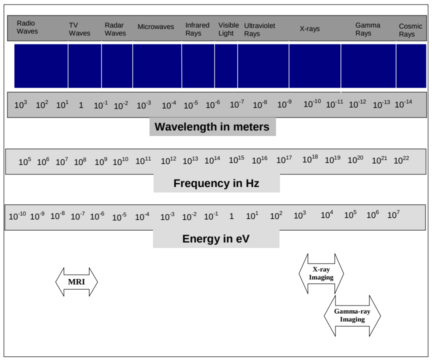
Electromagnetic Radiation Spectrum



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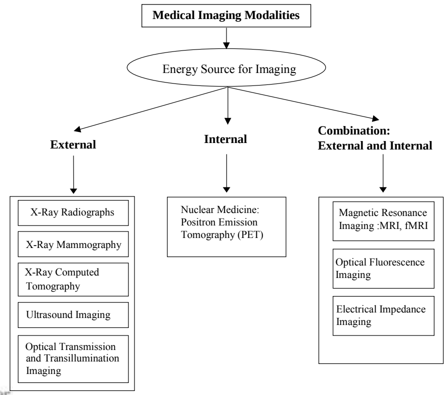

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Medical Imaging Information

- **Anatomical**
  - **X-Ray Radiography**
  - **X-Ray CT**
  - **MRI**
  - **Ultrasound**
  - **Optical**
- **Functional/Metabolic**
  - **SPECT**
  - **PET**
  - **fMRI**
  - **Ultrasound**
  - **Optical Fluorescence**
  - **Electrical Impedance**

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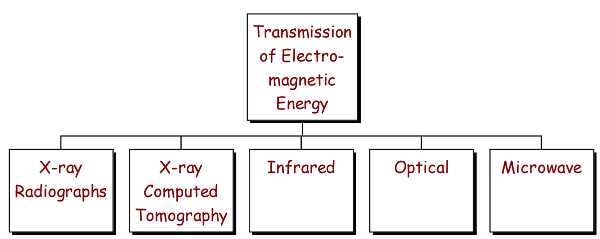
Medical Imaging Thru Transmission

Basic Principle: Radiation is attenuated when passed through the body.



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Transmission Imaging

- Not all wavelengths in electromagnetic radiation spectrum are suitable for transmission imaging for human body.
- Resolution of the desired image of human body imposes the restrictions on the use of electromagnetic radiation.
- There are two important considerations when selecting an electromagnetic radiation for imaging human body:
  - Resolution: For a useful image, the wavelength must be under 1.0 cm. Higher wavelengths will not provide useful resolution in the image. Wavelength should be shorter than the resolution of interest.
  - Attenuation: The radiation should be reasonably attenuated when passed through human body. Too much attenuation will result in poor signal-to-noise ratio. If it is completely transmitted, it will not provide any meaningful structural details in the image.

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Electromagnetic (EM) Radiation and Imaging

- Wave concept of EM radiation explains why it may be reflected, refracted, diffracted, and polarized.
- Short EM waves, such as x-rays may react with matter as if they were particles rather than waves.
- These particles are actually discrete bundles of energy.
- Each bundle of energy is called a quantum or a photon.
- Photons travel at the speed of light.
- The amount of energy carried by a photon depends on the frequency of the radiation (I.e. number of vibrations per second).
  - $E = h\nu$
- E is the photon energy; h is the Planck's constant = $4.13X10^{-18}$ keV sec and ν is frequency.
- The particle behavior of photon leads to photoelectric effect and Compton scatter.

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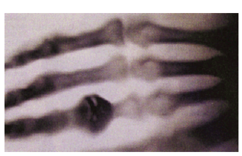
X-rays

- Wilhelm Conrad Röntgen (1845-1923)

Nobel Prise in Physics, 1901



- "X" stands for "unknown"
- *X-ray imaging* is also known as
  - radiograph
  - Röntgen imaging

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X-rays

- X-rays were invented by in Conrad Rontgen in 1895 describing it as new kind of rays which can penetrate almost anything. He described the diagnostic capabilities of X-rays for imaging human body and received the Noble Prize in 1901.
- X-ray radiographs are the simplest form of medical imaging through the transmission of X-rays through the body which are then collected on a film. The attenuation or absorption of X-rays is described by the photoelectric and Compton effects providing more attenuation through bones than soft tissues or air.

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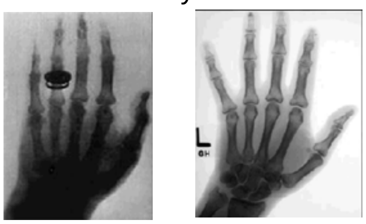
X-rays

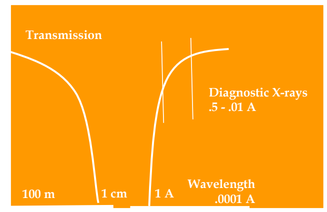


Bertha Röntgen's Hand 8 Nov, 1895

- Calcium in bones absorbs X-rays the most
- Fat and other soft tissues absorb less, and look gray
- Air absorbs the least, so lungs look black on a radiograph

X-ray Imaging

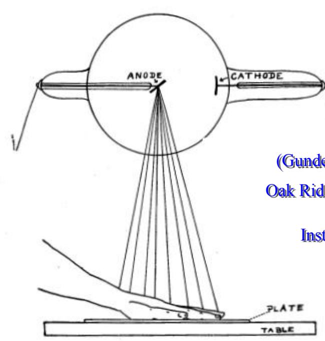
- c=λν, E= hc/λ
- c: velocity of light; λ: wavelength; ν: frequency
- h: plank's constant, E: energy (in eV)
- hc = 12.4; E = 12.4/λ keV
- Short wavelength < 1nm
- High energy > 1keV
- High frequency



X-ray Imaging

- The diagnostic range of X-rays is used between 0.5 and 10^{-2}. A wavelength which corresponds to the photon energy of approximately 25 kev to 1.0 Mev. In this range the attenuation is quite reasonable to discriminate bones, soft tissue and air. In addition, the wavelength is short enough for providing excellent resolution of images even with sub mm accuracy.
- The diagnostic X-rays wavelength range provides higher energy per photons and provides a refractive index of unity for almost all materials in the body. This guarantees that the diffraction will not distort the image and rays will travel in straight lines.
- Shorter wavelengths than diagnostic range of X-rays provides much higher photon energy and therefore less attenuation. Increasing photon energy makes the human body transparent for the loss of any contrast in the image.

X-rays Imaging

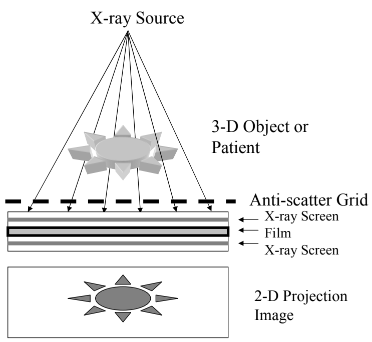


(Gundelach Tube, 1898 – 1905)

Oak Ridge Associated Universities

Health Physics
Instrumentation Museum

X-ray Radiography



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Chest Radiograph

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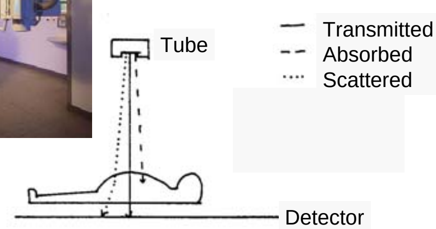
Plane X-ray imaging



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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)

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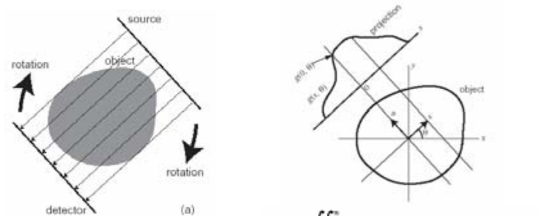
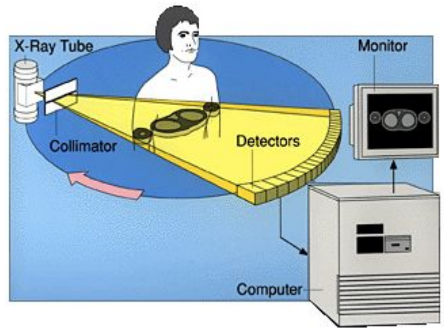
Radon Transformation



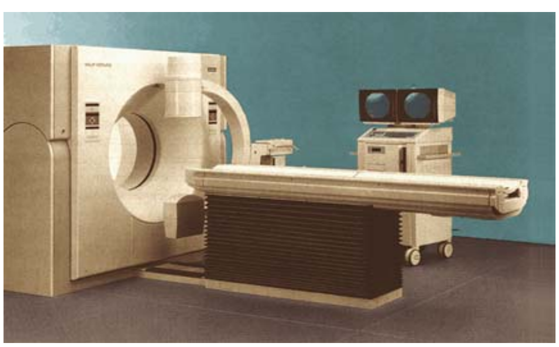
$$g(s,\theta)=\int\int_{-\infty}^{\infty} f(x,y)\,\delta(x\cos\theta+y\sin\theta-s)\,dx\,dy$$

- 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

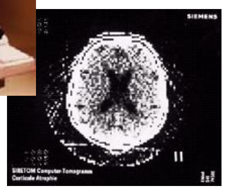


CT imaging, inventing (1972)

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

CT imaging, availability (since 1975)

1974

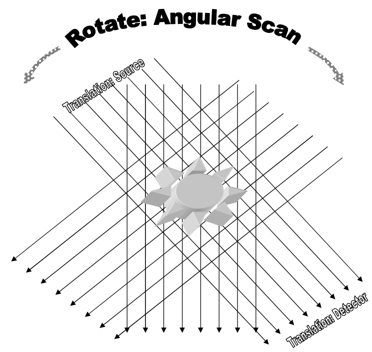


25 years later

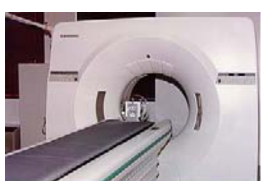
Original CT image (128x128) from the CT scanner circa 1975. In 1975 physicians were fascinated by the ability to see the soft tissue structures of the brain.

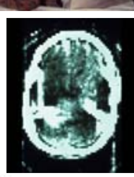
CT image (512 x 512) *using a state-of-the-art CT system. Note the two black "pea-shaped" ventricles and the subtle delineation of gray and white matter.*

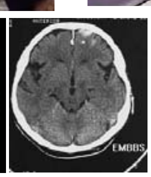
Principle of a CT Scanner



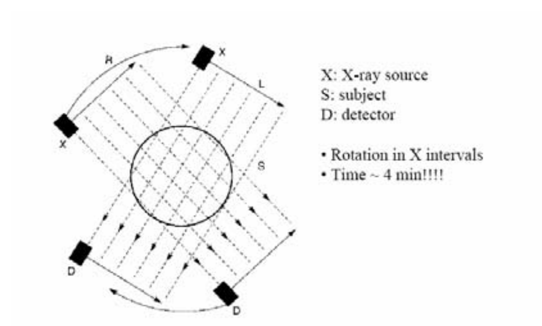
30 Years of CT



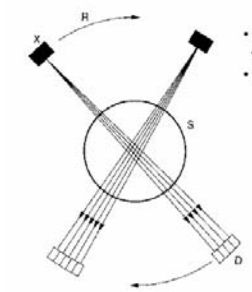




First Generation Scanners



Second Generation Scanners



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

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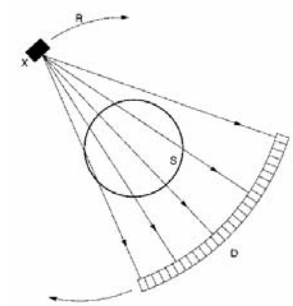
Third Generation Scanners



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

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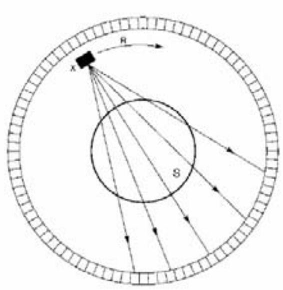
Fourth Generation Scanners



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

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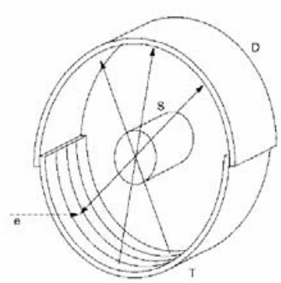
Fifth Generation Scanners



- 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

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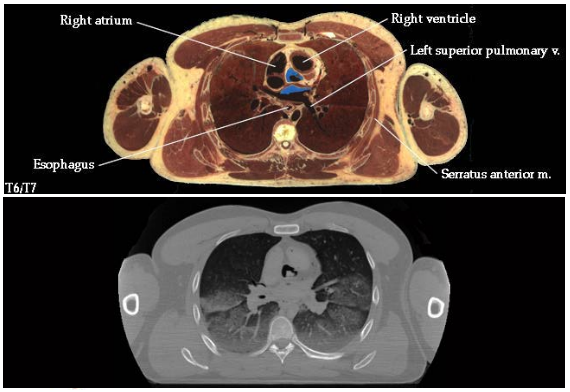
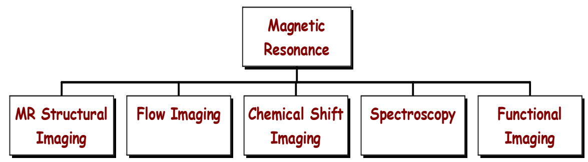
CT Chest Images



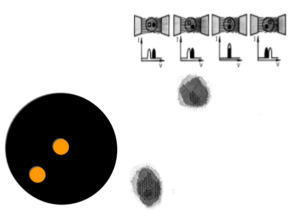
Magnetic Resonance Imaging

Basic Principle: The electromagnetic induction based rf signals are collected through nuclear magnetic resonance from the excited nuclei with magnetic moment and angular momentum present in the body. Most common is proton density imaging.



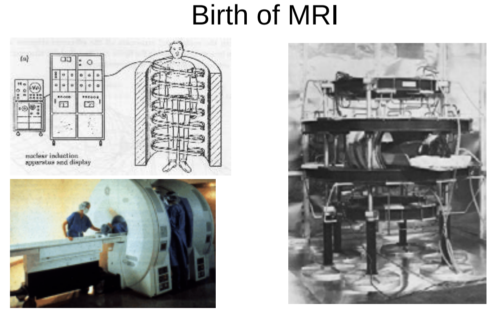
Birth of MRI

- Paul Lautebur 1975
  - Presented at Stanford CT meeting
  - “Zeugmatography”
- Raymond Damadian 1977 –
- Sir Peter Mansfield early 1980’s



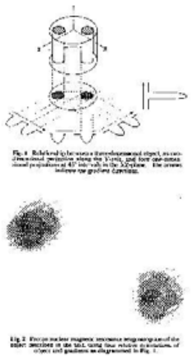
Early Thorax Image Nottingham

Birth of MRI



- Electro Magnetic signal emitted (in harmless radio frequency) is acquired in the time domain
- image has to be reconstructed (Fourier transform)

Birth of MRI



In 1978, Mansfield presented his first image through the abdomen.

Lauterbur and the first magnetic resonance images (from *Nature*)

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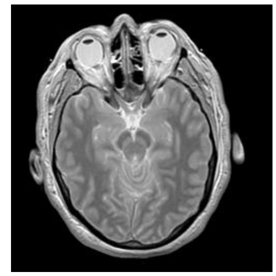
30 Years of MRI

First brain MR image



Typical T2-weighted MR image

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NMR

- The principle of nuclear magnetic resonance (NMR) for medical imaging was first demonstrated by Raymond Damadian in 1971 and Paul Lauterbur in 1973.
- NMR is a phenomenon of magnetic systems that possesses both a magnetic moment and an angular moment.
- All materials consist of nuclei which are protons, neutrons or a combination of both. Nuclei that contain an odd number of protons, neurons or both in combination possess a nuclear spin and a magnetic moment. Most materials are composed of several nuclei which have the magnetic moments such as ^{1}H, ^{2}H, ^{13}C, ^{31}Na, ^{31}P, etc.

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NMR…

- When such material is placed number a magnetic field, randomly oriented nuclei experience an external magnetic torque which aligns the nuclei either in a parallel or an antiparallel direction in reference to the external magnetic field. The number of nuclei aligned in parallel is greater by a fraction than the number of nuclei aligned in an antiparallel direction and is dependent on the strength of the applied magnetic field. Thus a net vector results in the parallel direction.
- The nuclei under the magnetic field rotate or precess like spinning tops precessing around the direction of the gravitational field. The rotating or precessional frequency of the spins is called the Larmor precession frequency and is proportional to the magnetic field strength.
- The energy state of the nuclei in the antiparallel direction is higher than the energy state of the nuclei in the parallel direction.

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NMR….

- When an external electromagnetic radiation at the Larmor frequency is applied through the rf coils (because the natural magnetic frequency of these nuclei fall within the radiofrequency range), some of the nuclei directed in the parallel direction get excited and go to the higher energy state, becoming in the direction antiparallel to the external magnetic field to the antiparallel direction.
- The lower energy state has the larger population of spins than the higher energy states.

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NMR…..

- Thus, through the application of the rf signal, the spin population is also affected.
- When the rf excitation signal is removed, the excited portions tend to return to their lower energy states through the relaxation resulting in the recovery of the net vector and the spin population.
- The relaxation process causes the emission of a rf frequency signal at the same Larmor frequency which is received by the rf coils to generate an electric potential signal called the free-induction decay (FID). This signal becomes the basis of NMR imaging.

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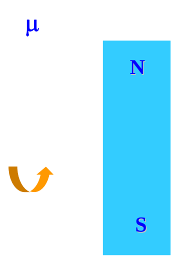
Spinning Protons



Protons with a spinning property behave like small magnets.

Spinning around their own axes results in generation of a magnetic moment, μ.

When placed in external magnetic field, spinning protons align themselves either along or against the external magnetic field.

In addition, placing spinning proton in an external magnetic field causes the magnetic moment to precess around an axis parallel to the field direction.

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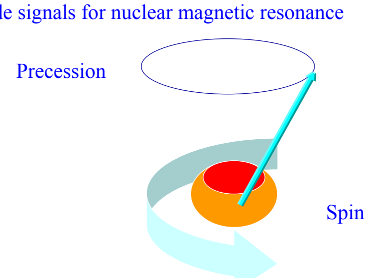
Spinning Proton

Protons possessing properties of angular and magnetic moments provide signals for nuclear magnetic resonance



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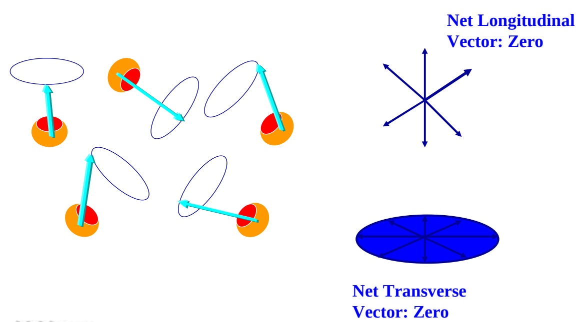
Protons With Random Effect



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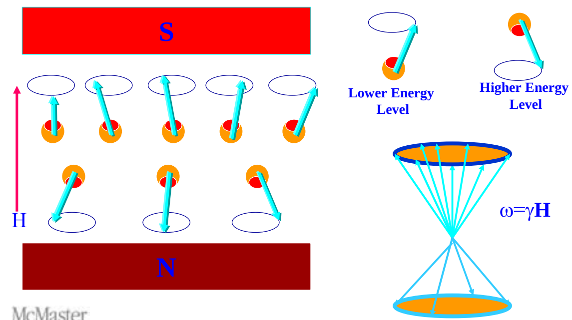
Protons Under External Magnetic Field



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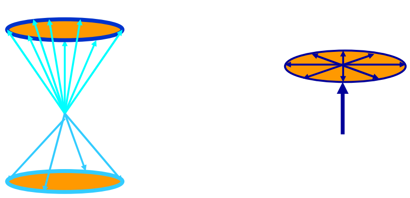
Net Vector Under Thermal Equilibrium

Larmor (Precession) Frequency $\omega=\gamma \mathbf{H}$



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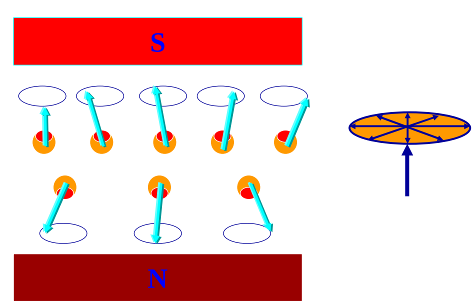
Protons Under Thermal Equilibrium



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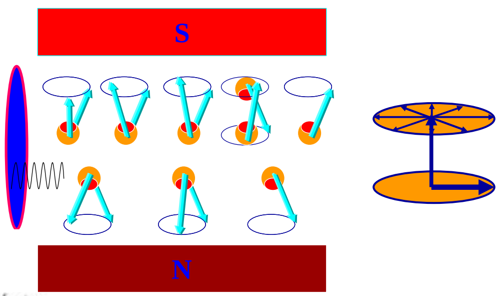
Protons With External RF Excitation: 90 Degree Pulse



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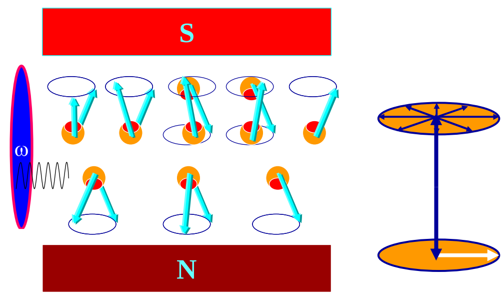
Protons With External RF Excitation: 180 Degree Pulse



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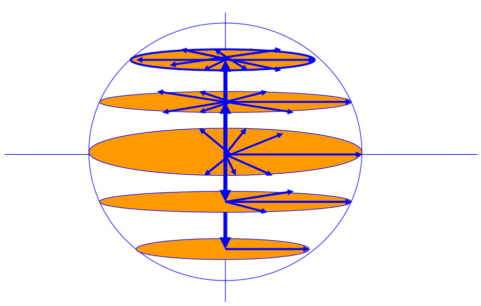
Longitudinal Relaxation Parameter: T1



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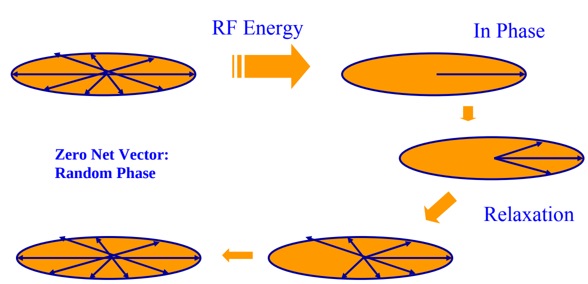
Transverse Relaxation Parameter: T2



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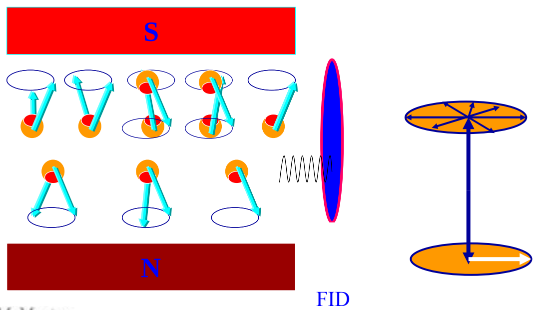
Relaxation Process Provides FID or MR Signal



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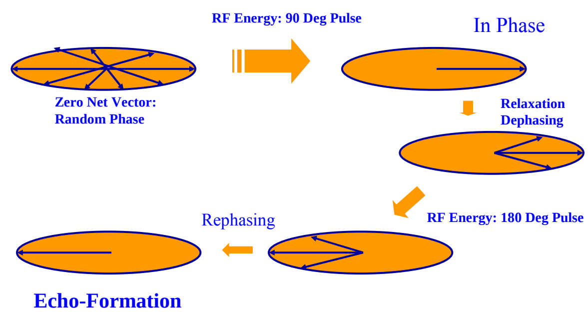
Spin Echo Imaging Sequence



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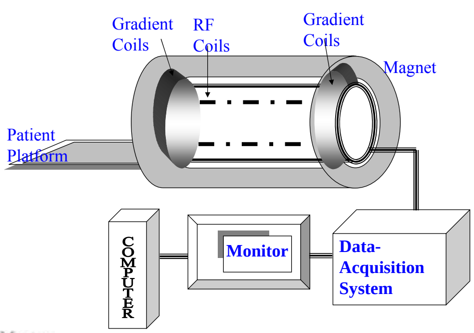
MR Imaging



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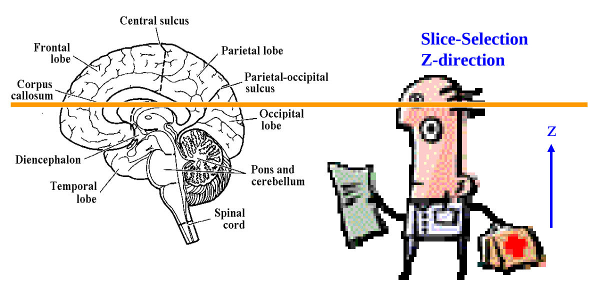
Spin-Echo Imaging Sequence



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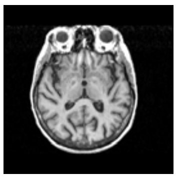
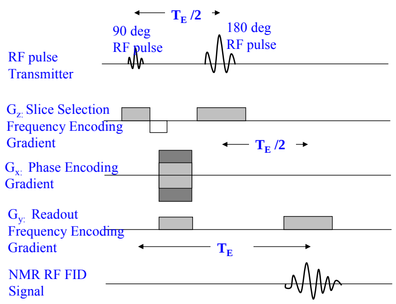
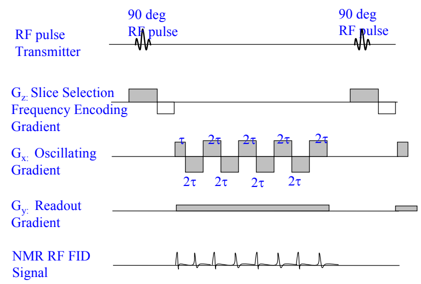
Imaging Through MR: Spin Echo





MR Imaging: Single Shot EPI

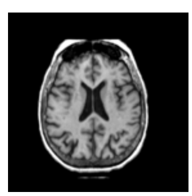


T1 and T2 Contrast

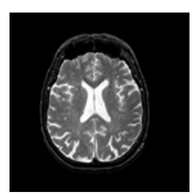
Tissue	T1 msec	T2 msec	SD %
Fat	150	150	10.9
Liver	250	44	10.0
White Matter	300	133	11.0
Gray Matter	475	118	10.5
Blood	525	261	10.0
CSF	2000	250	10.8

Typical NMR Tissue Values at 0.15 T

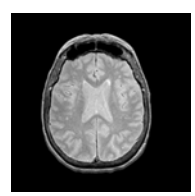
MR Images



T1 Weighted

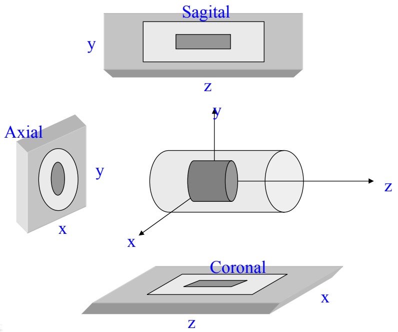


T2 Weighted



Spin Density Image

3-Directioanl Imaging



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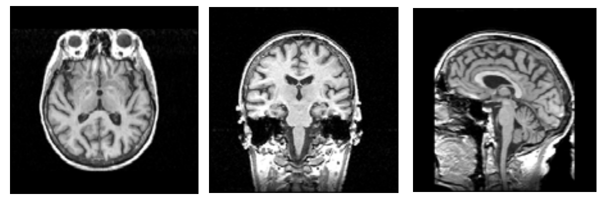
3-D MR Imaging



Axial **Coronal** **Sagittal**

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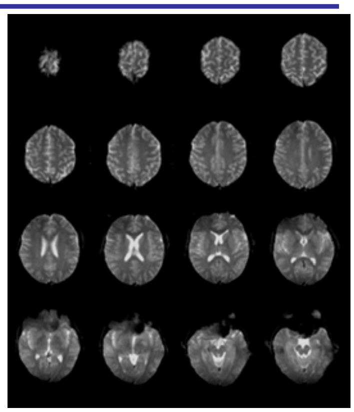
SEPI MR Imaging



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MRI: modalities

There are several imaging modalities within MRI, except for T1 and T2:

- MRA - Magnetic resonance angiography
  - images of vessels
- MRS - Magnetic resonance spectroscopy
  - images of chemistry of the brain and muscle metabolism
- fMRI - functional magnetic resonance imaging
  - image of brain function
- PW MRI – Perfusion-weighted imaging
- DW MRI – Diffusion-weighted MRI
  - images of nerve pathways

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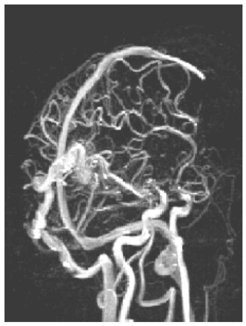
Magnetic Resonance Angiography

- MR scanner tuned to measure only moving structures
- "Sees" only blood - no static structure
- Generate 3-D image of vasculature system
- May be enhanced with contrast agent (e.g. Gd-DTPA)



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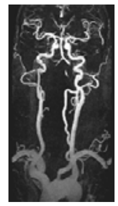
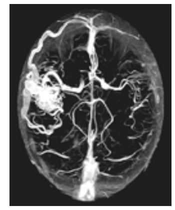
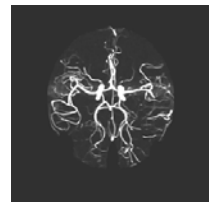
MR Angiography



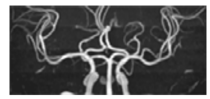
GD-enhanced



GD-enhanced



Phase-contrast



In-flow

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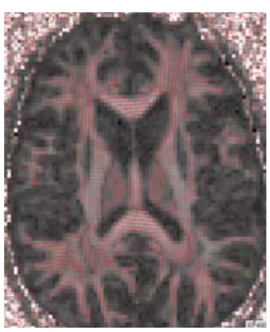
Diffusion-Weighted MRI

- Image diffuse fluid motion in brain
- Construct "Tensor image" – extent of diffusion in each direction in each voxel in image
- Diffusion along nerve sheaths defines nerve tracts.
- Create images of nerve connections/pathways



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Functional MRI (fMRI)

- Active brain regions demand more fuel (oxygen)
- Extra oxygen in blood changes MRI signal
- Activate brain regions with specific tasks
- Oxygenated blood generates small (~1%) signal change
- Correlate signal intensity change with task
- Represent changes on anatomical images

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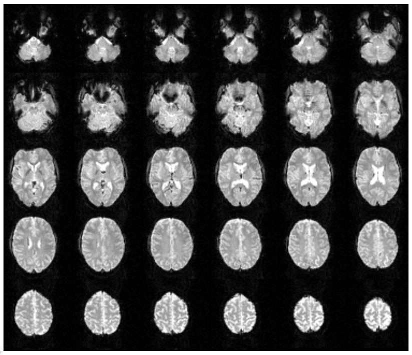
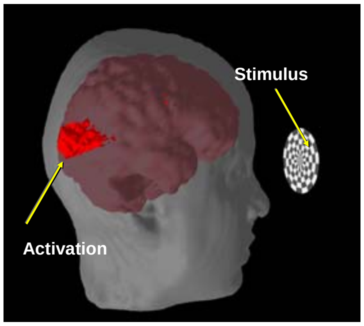
fMRI

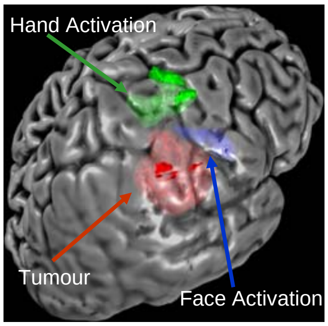


fMRI

Subject looks at flashing disk while being scanned
"Activated" sites detected and merged with 3-D MR image



fMRI in Neurosurgery Planning



MRI Advantage

- The most important advantage of the MRI is its ability to provide unprecedented contrasts between various organs and tissues and the three-dimensional nature of imaging methods.
- Selective 3-D imaging is provided by appropriate selection of gradient fields and phase encoding methods.
- A variety of contrast images can be created by different combinations of weighting of T1, T2 and echo images
- MR spectroscopy provides a great potential for meaningful tissue characterization.
- Functional MRI holds great promise for the future.

Ultrasound Imaging

Basic Principle: Backscattered echo and Doppler shift principles are more commonly used with the interaction of sound waves with human tissue. Sometimes the scattering information is complemented with transmission or attenuation related information such as velocity in the tissue.

- Acoustic Energy
  - Ultrasound Transmission
  - Ultrasound Echo

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Ultrasound imaging

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Acoustic Energy

- Velocity of propagation of sound in water and in most body tissues is about 1.5×10^3 m/sec. Thus, the wavelength based resolution criterion is not satisfied from electromagnetic radiation concept.
- The resolution capability of acoustic energy is therefore dependent on the frequency spectrum.
- The attenuation coefficient in body tissues varies approximately proportional to the acoustic frequency at about 1.5 dB/cm/MHz.
- Thus, at much higher frequencies, the imaging will not be meaningful because of excessive attenuation.

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Ultrasound Imaging

- For thicker parts of the body such as abdominal imaging, frequencies of about 1.0 to 3.0 MHz are used to provide reasonable attenuation.
- Unlike X-rays, in ultrasound imaging, the images are produced through the reflection or echo using the known velocity of propagation to calculate the depth.
- In ultrasound imaging, air causes excessive attenuation and therefore cannot be used to study some anatomical structures, such as lungs.
- Ultrasound imaging operates close to the diffraction limit because of its larger wavelength compared to X-rays.

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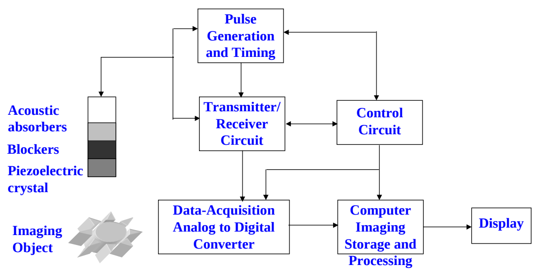
Ultrasound Imaging System



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B-Mode Imaging of Heart

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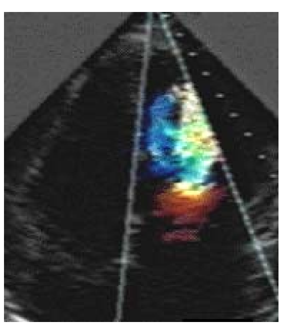
Doppler Imaging of Beating Heart



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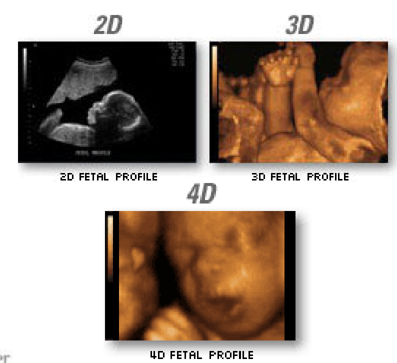
There is more …



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Ultrasound Advantage

- Non-invasive nature and capability of providing excellent information forobjects immersed in fluids.
- Low velocity of propagation as compared to the free-space velocity of X-rays which is $3X10^8$ m/sec. This makes the time of flight measurements possible using ultrasound with pulse echo techniques.
- Unlike X-rays, the velocity of propagation of ultrasound is dependent on the material. Ultrasound provides a variety of refractive indices of materials. Thus, selective imaging of specific planes is feasible with ultrasound through the construction of so-called lens systems to provide images of focused structures.

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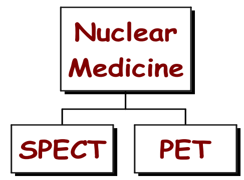
Nuclear Medicine Imaging

Basic Principle: Radioactive pharmaceuticals are injected in the body which selectively metabolize with the tissue or medium to generate radioactive emission such as gamma rays in Single Photon Emission Computed Tomography (SPECT) or positrons in Positron Emission Tomography (PET). Finally, the emitted photons are captured by the detectors outside the body for generating maps of radioactivity tracers.



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SPECT

- Radioactive materials are administered into the body and are selectively taken up in a manner designed to indicate a specific metabolism or disease. In SPECT imaging, gamma rays are emitted from these materials absorbed by the tissue or body, which then becomes a radioactive source. External detectors are used to reconstruct images of the radioactive source.

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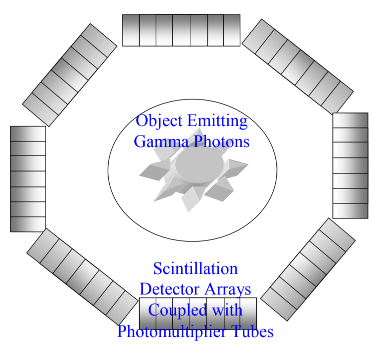
SPECT Imaging



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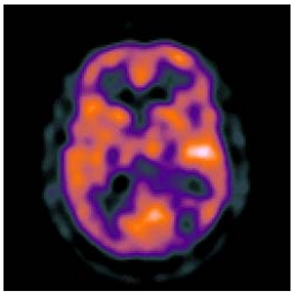
$^{99m}T_c$ (140 keV) SPECT Image



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Positron Emission Tomography

- In PET imaging, the radioactive pharmaceuticals which decay by emitting positrons are administered in the body. When these radioactive materials are taken up by the body, positrons are emitted which, after losing some energy through kinetic motion, annihilates with the free electrons of the biomaterial within the body. The annihilation results in the emosion of two photons, which travel in almost opposite directions and escape from the body to be detected by external detectors. This is called the coincidence detection.
- In PET, images are reconstructed from the coincidence detection to represent the distribution of the emission of photons within the body. Since the emission of photons is very close to the emission of positron, the reconstructed images are considered the representation of the radioactivity source or tracer.

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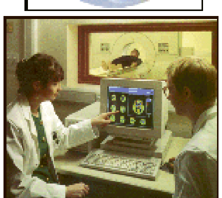
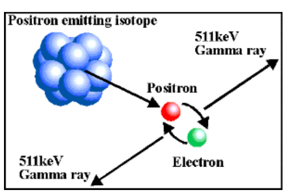
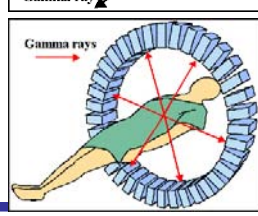
PET







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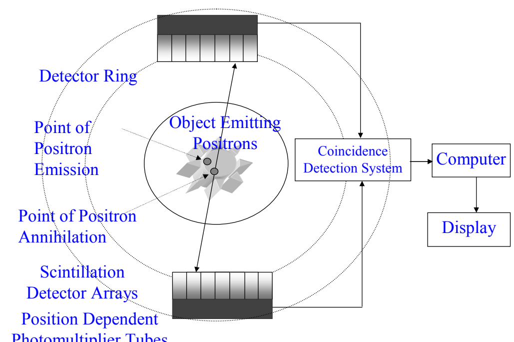
PET Imaging



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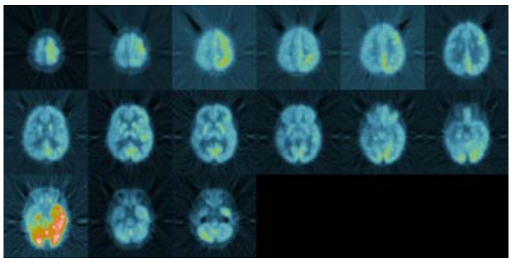
FDG PET Imaging

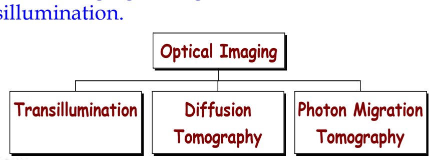


Nuclear Medicine Images

- In general, the resolution of the emission images are poor because of inherent uncertainty of the computation of the source of emission, which is corrupted by scattering and absorption.
- The photon energy of gamma rays must be high enough to escape the body but energy photons are difficult to detect. The energy range between 25 kev to 1.0 Mev is usually used.
- The main advantage of nuclear medicine imaging is its capability to provide information about the specific metabolism to study the functional aspects of the human body.
- The radioactive pharmaceuticals can be produced in a manner so that they are only taken by the diseased part of the organ/tissue/ biomaterial, which helps in studying the functional aspects.
- However, the nuclear medicine images provide poor resolution and poor anatomical information making them complementary to anatomical or radiographic imaging.

Optical Imaging

Basic Principle: Optical photons are transmitted into the tissue for transillumination. As a result of photon-cell interaction, diffusion of photons results in forward and backward scattering, and absorption. The backscattered light photons are recovered as remittance to provide data for imaging. Examples include Nevoscopy and breast imaging through transillumination.



Optical Imaging..

- Range of visible light provides an attractive alternative for non-invasive imaging.
- Because of the nm wavelength range, the photon energy is not very high to guarantee straight line transmission.
- The light photons interact with the cells and other objects in the body resulting in several types of forward and backward scattering including Rayleigh and Mie scattering.
- The reflection is thus a dominant phenomenon in optical imaging.

Optical Imaging …

- The imaging resolution is not as good as X-rays, but for certain kinds of non-invasive imaging, it is sufficient to provide meaningful information. Examples include endoscopic and Nevoscopic imaging.
- Infrared imaging specifically provides additional information about the temperature of the object because of its smaller photon energy.
- Ultraviolet rays, along with dyes, are used for fluorescence imaging. The dyes absorbed by the tissue cause the tissue or cell to absorb ultraviolet radiation resulting in the emission of electromagnetic radiation in visible range to form the image.

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Nevoscopy: Imaging by Transillumination

- Optical Imaging Technology for Imaging Skin-Lesions
- Non-Invasive, Cost Effective, Easy-to-Use for Screening
- Light (complete visible or narrow band spectrum) penetrates skin area surrounding the lesion.
- Backscattered light re-emerges from the skin forming images of the transilluminated skin-lesion.
- Images of skin-lesions can be captured through rotatble optical mirror geometry from different angles.
- Images are treated as 2-D projections of 3-D transilluminated lesion for 3-D reconstruction using Photon Diffusion Model and iterative reconstruction algorithms.

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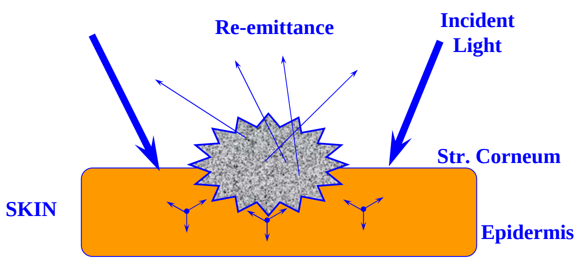
Optical Transillumination Imaging



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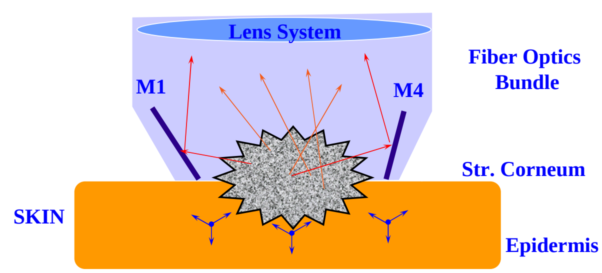
Nevoscope



Nevoscope provides both transillumination and surface-illumination and any regulated combination of these two illumination methods.

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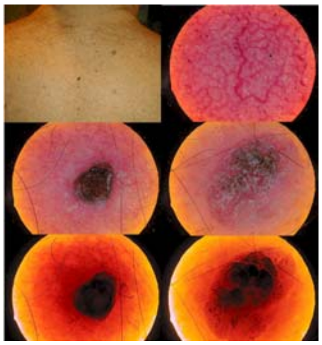
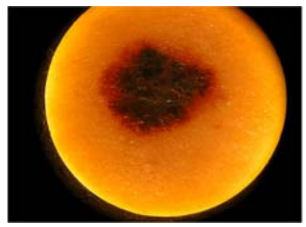
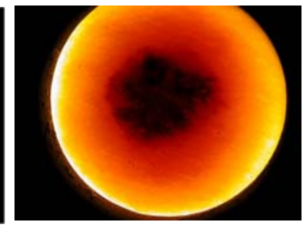
Nevoscope Imaging



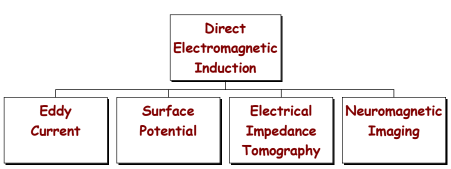
Nevoscope Imaging…





Emerging Technologies

Basic Principle: The cells in the human body and organs generate electric currents and potentials as well as magnetic fields. The bioelectric current or potential and biomagnetic fields can be measured through very sensitive instrumentation to provide information about the underlying physiological process.



End of Lecture