Corso di
Tecniche Diagnostiche

Corso di laurea in Fisica

A.A. 2002-2003

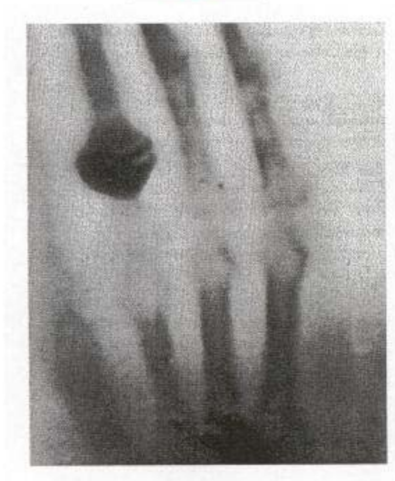
Introduction to Medical Imaging

Specific Goals:

1. Acquiring basic understanding of the physical principles of the image formation. Necessary to:
   - properly utilize any imaging method
   - interpret acquired images
2. Learning medical image terminology

Medical Imaging – Then and Now

1895



2001

Brief History of Medical Imaging (1)

- **1895. X-rays** discovered accidentally by Roentgen. Simple X-ray images, e.g. bones of hand, produced in **early years of 20th Century**. Conventional radiography has been the most widespread medical imaging technique ever since, but the basic technique has only evolved slowly.
- **1896. Natural radionuclides** studied by Becquerel. Artificial radionuclides first studied in 1930’s. First uses of radionuclides were for treatment (therapy) and for metabolic tracer studies, rather than imaging. First γ-ray imaging by a rectilinear scanner, **1950’s**, replaced by a static array of detectors in the 1960’s. This design has only evolved slowly to the present day with no dramatic improvements.

Brief History of Medical Imaging (2)

- **1940’s. Sonar technology from World War 2 (echo location) was readily available, and the possibilities for adapting this to medical imaging were realised very early. For various practical reasons, Ultrasound only became widely available in Medicine in the 1970’s.**
- **20th Century. The mathematical principles behind tomographic reconstruction have been understood for a very long time, but because of the computing power needed tomographic imaging techniques had to await the digital revolution. First practical application in 1960’s for radionuclide imaging, based on rotating and translating detectors. Then in the 1970’s there was an explosion of activity with several techniques being developed simultaneously, most notably positron emission tomography (PET) and X-ray computed tomography (CT). CT is now the most widespread method, although the ideas were applied first in other areas.**

Brief History of Medical Imaging (3)

- **1945. Nuclear Magnetic Resonance discovered by Physicists Block and Purcell. The phenomenon rapidly proved to be more useful to Chemists (1950’s) and later to Biochemists (1960’s) as a spectroscopic technique to study chemical structure and metabolic activity. First proposed as an imaging technique by several groups worldwide around 1973, with developments in Nottingham, Aberdeen, Oxford. Developed sufficiently to be used in hospitals by the 1980’s, and hereafter always called Magnetic Resonance Imaging (MRI) to avoid distressing patients.**

Brief History of Medical Imaging (4)

- **21st Century. The “big 4” of X-ray, radionuclide imaging, ultrasound and MRI continue to dominate, in their many variants, but many other interesting developments in other techniques are occurring, especially when we consider “imaging” to include microscopic as well as macroscopic biological structures (thermal imaging, electrical impedance tomography, scanned probe techniques, etc.) In addition, the emphasis in the future will increasingly be on obtaining functional and metabolic information simultaneously with structural (image) information. This can already be done to some extent with radioactive tracers (e.g. PET) and magnetic resonance spectroscopy.**

Introduction to Medical Imaging

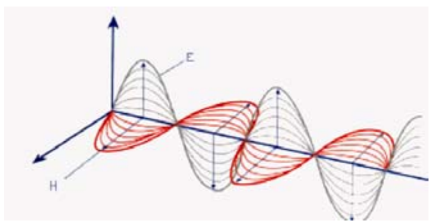
ENERGY in the patient’s body (MATTER)

1. Non-penetrating Energy: visual observation, dermatology (photography), gastroenterology, pathology (microscopy) → Visible Light Imaging
2. Penetrating Energy: diagnostic radiology

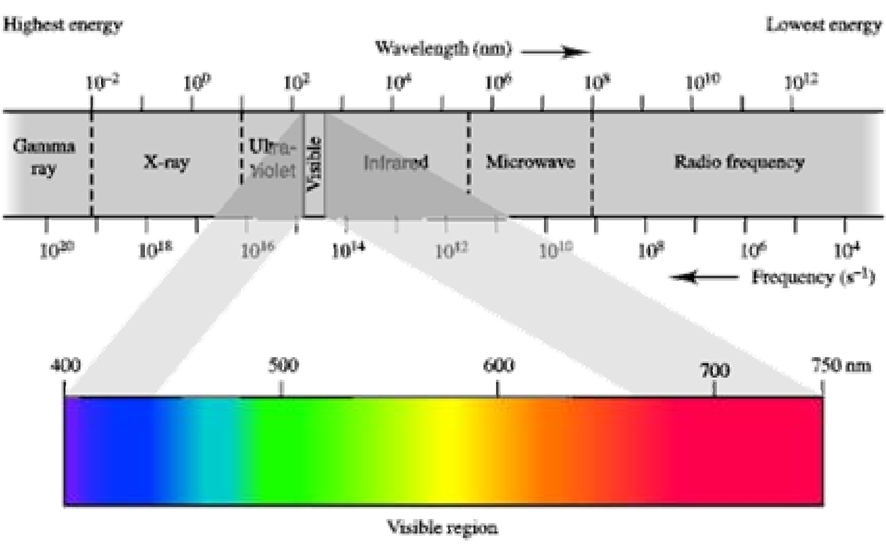
- Electromagnetic: X-ray Imaging, Magnetic Resonance Imaging (MRI), Nuclear Medicine
- Mechanical: Ultrasound

Radiation in Medical Imaging

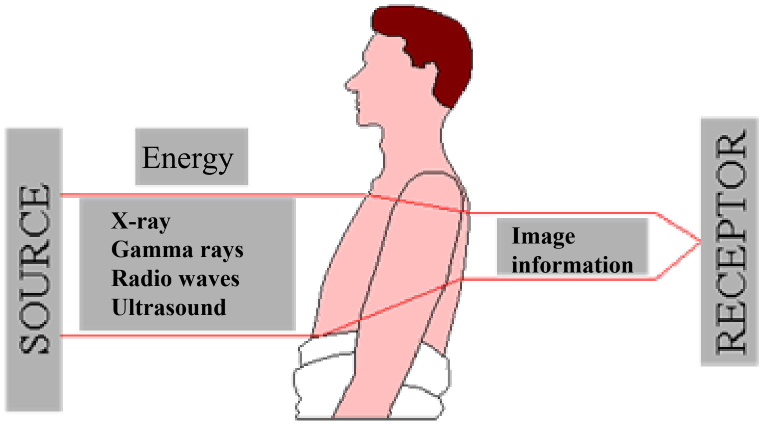
- Transfer of energy from a source to another object
- Electromagnetic Radiation
  – visible light, radio waves, x-rays, γ-rays,…
  – Speed: $c = 2.998\ 10^8$ m/s; Period (T) [sec]
  – Wavelength: λ=cT=c/n   [m, nm,…]
  – Frequency: n = c/λ = 1/T [cycles/s, s^{-1}, Hz]



The Electromagnetic Spectrum



Principles of Medical Imaging



Medical Imaging Considerations

- Diagnostic Utility (image contrast and localization, sensitivity & specificity)
- Patient and Personnel Safety (radiation exposure, toxicity, other side-effects)
- Invasiveness (less = better)
- Practicality (availability, complexity, imaging time,…)
- Support (service, image processing,…)
- Cost

Medical Imaging Modalities

- Ability to visualize specific anatomic structures or physiologic (biochemical, hemodynamic) processes depends on
  - imaging technique or “Modality”
  - imaging parameters
- Medical Imaging is an optimization procedure with trade-offs among various aspects of image quality as well as…

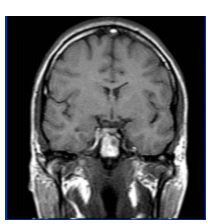
Medical Imaging Modalities

- Radiography/Fluoroscopy, Mammography
- Computed Tomography (CT)
- Nuclear Medical Planar Imaging
- Single Photon Emission Computed Tomography (SPECT)
- Positron Emission Tomography (PET)
- Magnetic Resonance Imaging (MRI)
- Ultrasound

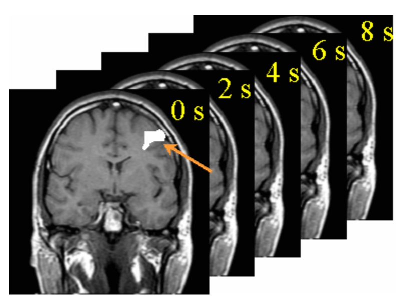
Medical Imaging Types

1. Transmission vs. Emission Imaging
   – External Energy Attenuation (Absorption and Scattering) → Transmission Imaging
   – Internal (Metabolic or Physiologic) Interactions → Emission Imaging
2. Static vs. Dynamic (Functional) Imaging
   – Spatial Only → Static: Structure, Anatomy
   – Spatial and Temporal Information → Functional Imaging
3. Tomographic vs. Projection Imaging

Static vs. Dynamic Imaging



Static - Structure



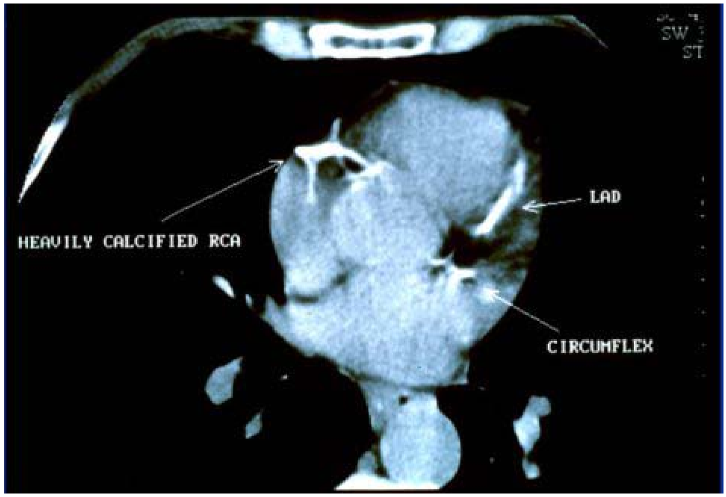
Dynamic – function

Projection Imaging vs. Tomography

- Projection Imaging
  - Images formed by projecting energy through the patient’s body and forming a single image
  - Structures superimposed on top of each other
- Tomographic Imaging
  - tomos (part, slice) + graphos (picture)
  - Images of selected planes or slices of tissue
  - Increased visibility of objects in a single image but many images needed for an entire organ system

Projection Imaging

Tomographic Imaging



CT Cross-sectional view of the heart

The Modalities

Radiography, Mammography	X-rays	Projection	Transmission
Fluoroscopy	X-rays	Projection	Transmission
Computer Tomography	X-rays	Tomographic	Transmission
SPECT	X, γ-rays	Tomographic	Emission
PET	β+, γ-rays	Tomographic	Emission
MRI	γ (10-300 MHz)	Tomographic	Both
Ultrasoud	γ (10 MHz)	Tomographic	Both

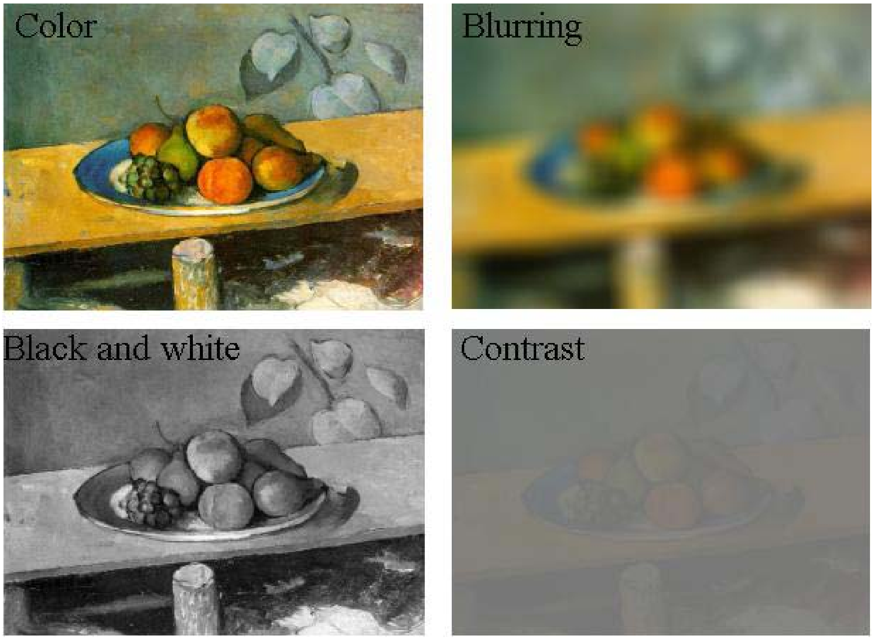
The Medical Imaging Process

Major components in the medical imaging:

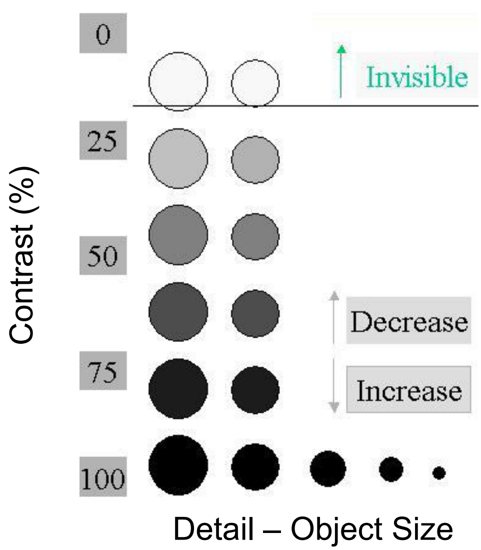
- Object (phantom) or Subject (patient)
- Imaging System (scanner – hardware and software components)
- Operator (parameter selection, skill)
- Image (acquisition, processing, display…)
- Observer (image interpretation)

Image Characteristics

- Quality – applies to all types of images
- Quality – subjective, dependent on the function of the image. In radiology, primarily defined via its diagnostic utility
- Properties – objective measures:
  1. Contrast
  2. Resolution
  3. Noise, Artifacts, and Distortion



Contrast



Difference in intensity of an object with respect to the immediate background

Imaging system translates a specific tissue property into image shades of GRAY or COLOR

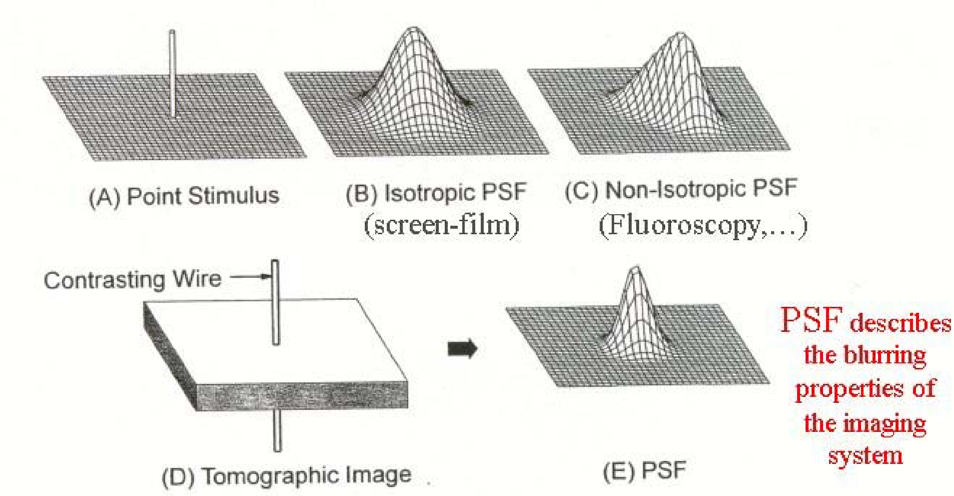
Contrast

- The medical image contrast is the result of many steps that occur during image acquisition, processing, and display
- Subject contrast (Cs)
  - The difference in some aspect of the signal before it is recorded
  - Result of the energy used by the modality and the patient's anatomy or physiology
  - The amount of contrast can be adjusted by changing parameters on the imaging system

Resolution

- The ability of an image system to distinctly depict two objects as they become smaller and get closer together
- Spatial resolution (x,y,z dimensions)
  - object's width, length, and height
- Temporal resolution (t dimension)
  - time distinction in case of dynamic imaging

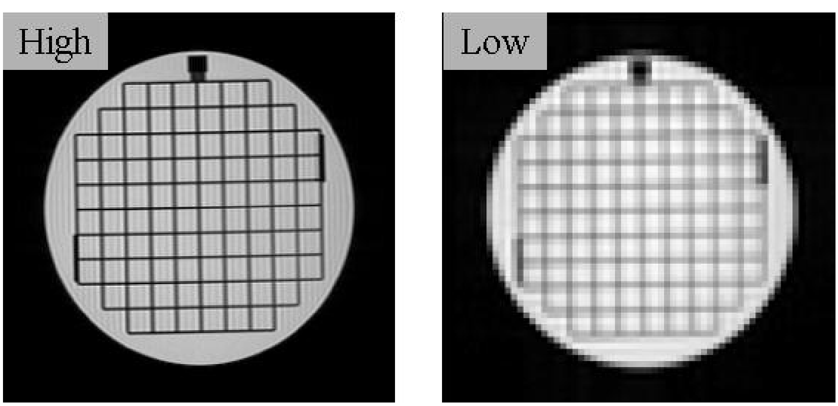
Resolution



Point response function or point spread function (PSF) – image of a single point stimulus

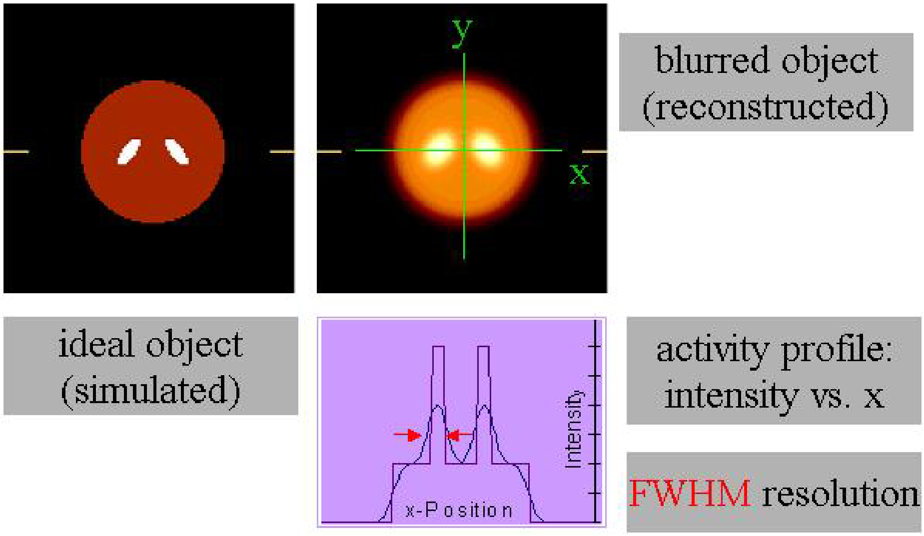
Resolution

Evaluation – example: MR phantom



256x256 acquisition matrix (left) and 64x64 matrix (right). Pixel dimensions are 0.9375mm and 3.75mm, respectively.

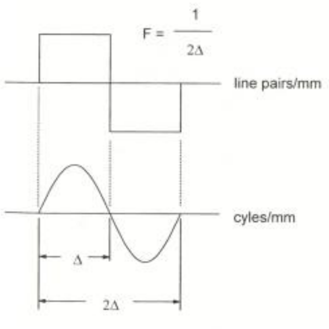
Resolution

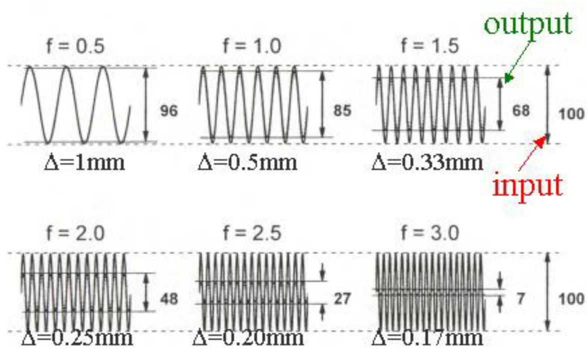


Resolution

- Physical sources of blurring
  - Scattering → physics
  - Motion → time, correction algorithms,...
  - Geometry → Tomographic modalities
- The frequency domain
  - temporal frequency (υ, f)
  - spatial frequency, (F, k)

Resolution

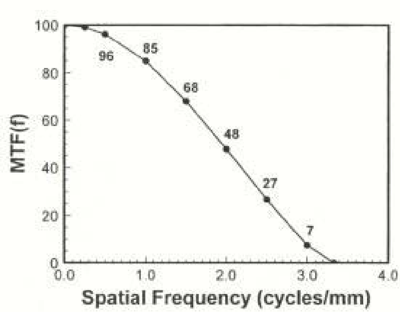


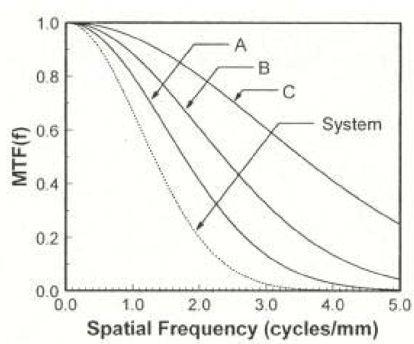


Definition of the Spatial Frequency, $F = 1/(2\Delta)$
Small $\Delta \rightarrow$ higher F
Large $\Delta \rightarrow$ lower F

A series of sine waves of various spatial frequencies. The contrast (peak-to-valley difference) of the input waves is 100%. Output wave amplitudes are reduced.

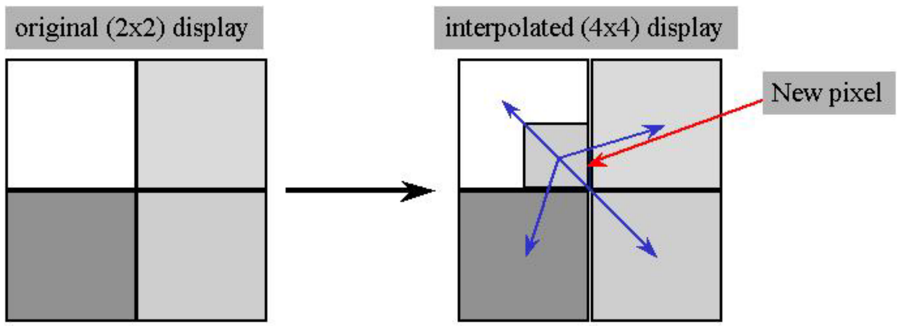
Resolution





The output amplitude of the sine waves as a function of the frequency. Modulation Transfer Function (MTF) describes how an imaging system response depends on the size of an object. MTF(System) = MTF(A)×MTF(B) ×MTF(C)

Resolution



Interpolation is useful when improving display, but does not improve spatial resolution !!!

Resolution

Modality	**Δ(mm)**	**Comment**
Radiography	0.08/0.17	Screen film/digital
Fluoroscopy	0.125	
Mammography	0.03/0.08	Screen film/digital
Computed Tomography	0.4	
Nuclear Medicine Planar	7	~ detector distance
SPECT	7	
PET	5	
MRI	1	(1.5 T)
Ultrasound	0.3	5 MHz

Noise

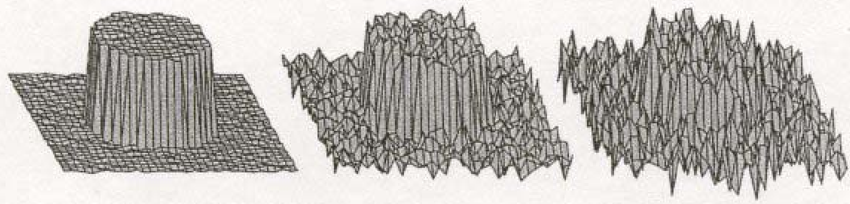


FIGURE 10-23. The concept of noise is illustrated using isometric display. A low noise image is shown on the *left*, with increasing amounts of noise added to the "images" toward the *right*.

Information obtained in the image (measurement) that does not contribute in its usefulness and interpretation

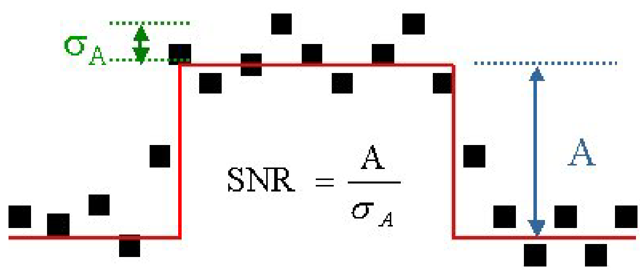
Noise

- Nature and extent of noise vary significantly for different imaging modalities.
  - Noise effects:
  - reduced ability to discern low contrast objects
- increased masking of smaller objects (higher frequencies)
- Sources: quantum noise, receptor sensitivity, electronic noise, image integration,…

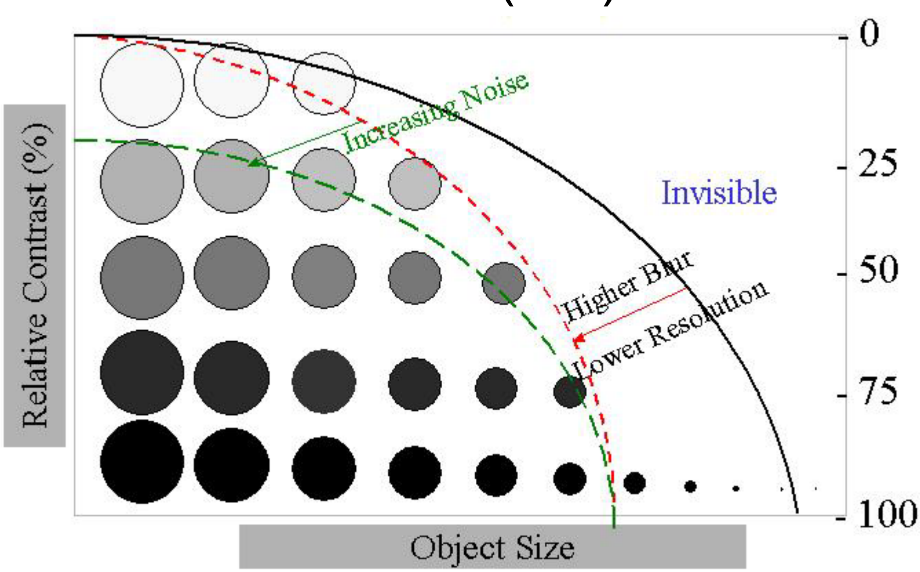
Noise

Relative Noise = σ / N

Signal-to-Noise Ratio: SNR = N / σ = N / $(N)^{1/2}$ = $N^{1/2}$



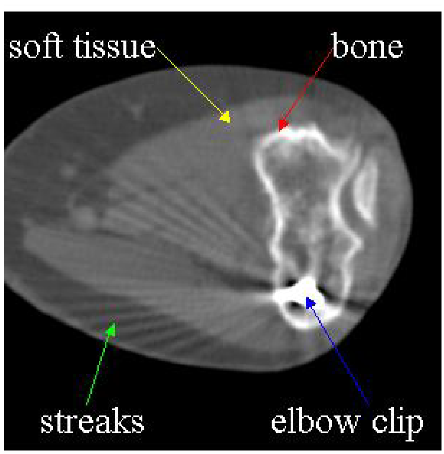
Contrast-Detail (CD) Curves



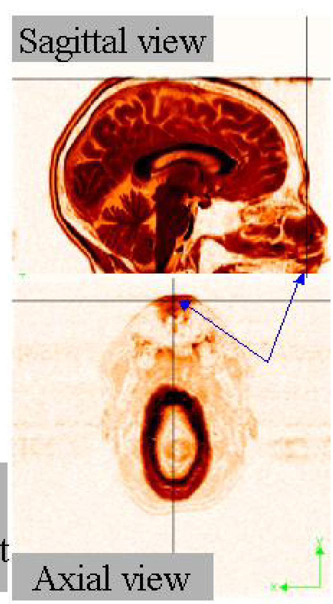
Artifacts and Distortion

- Artifacts
  - Image object created by an imaging method rather than structure of object itself
  - Suppression or absence of object image
- Distortion
  - Image must give accurate impression of object size, shape and its relative position. If that is not a case, image is distorted and its diagnostic usefulness is **severely reduced**

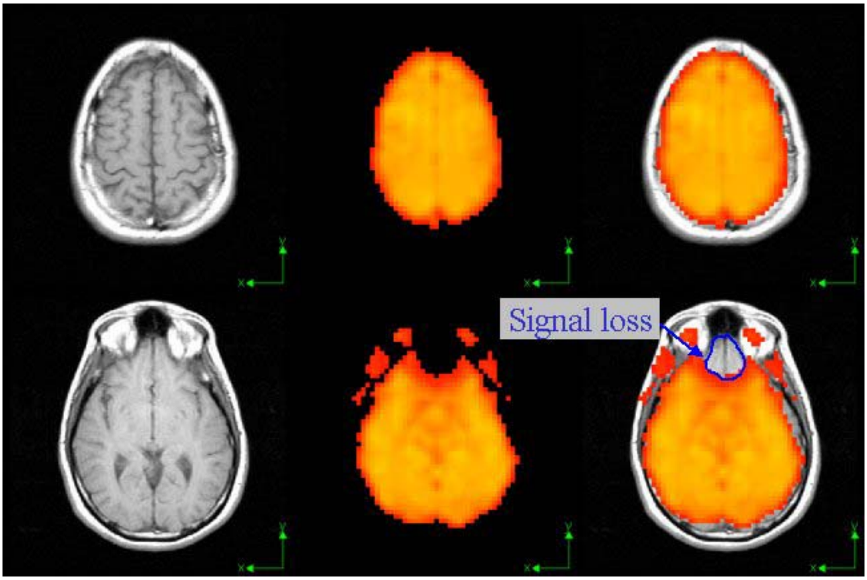
Artifacts and Distortion



Top: CT Streaking artifact
Right: MR Phase-wrap artifact



Artifacts



Observer Performance

- Specific problem - does a patient have a breast cancer ?
- Best-available approx. to a true answer
- Decision making in the total procedure of image interpretation:

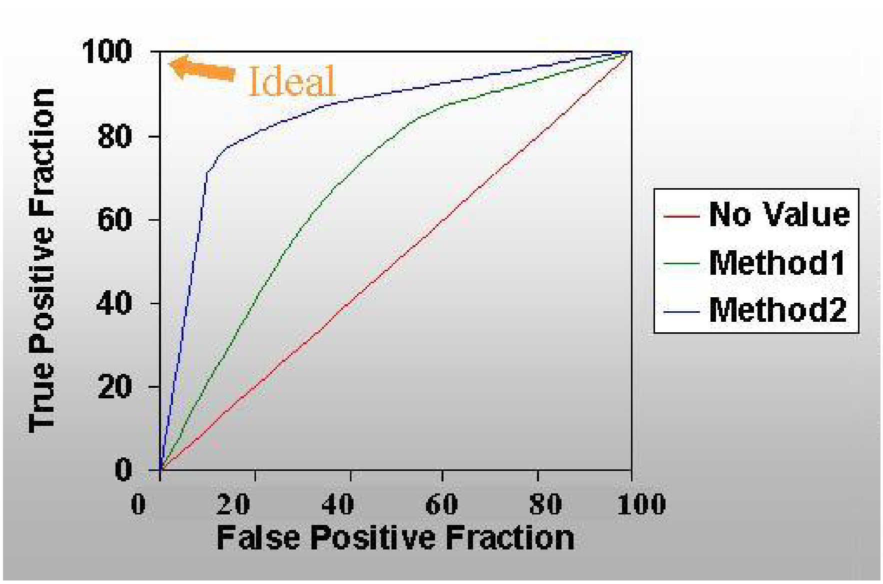
1. Detection – abnormality present or absent
2. Localization – where is the abnormality ?
3. Classification – what sort of abnormality ?

Measures of Performance

Number of test assessments of presence of abnormality	Number of ‘true’ assessments of presence of abnormality	
	Yes	No
Yes	True Positive (TP)	False Positive (FP)
No	False Negative (FN)	True Negative (TN)

Statistical Decision Matrix, showing the four possible situations

Measures of Performance



Measures of Performance

- Points on a single curve – repeating the test with different degrees of bias (threshold)
- Different curves – different quality in the decision process
- ROC analysis can be used to compare the detectability and to compare performance of imaging systems, operators, or both – slow !
- Faster rating procedure – observers level of confidence (definitely there, maybe there, uncertain, maybe not there, definitely not there)

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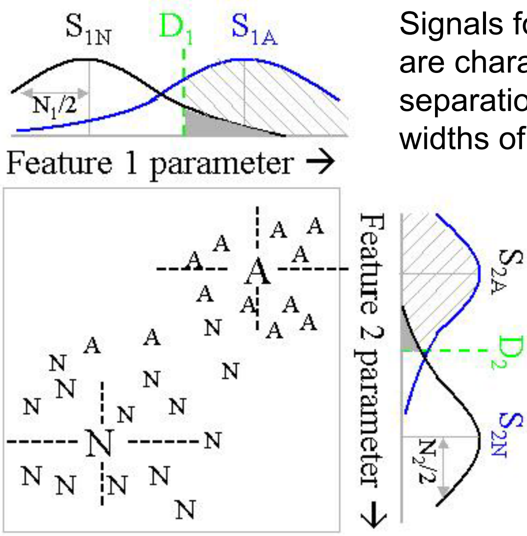
Measures of Performance



Signals for two different features are characterized by their separations (S_{1A}-S_{1N}) and the widths of their noise spectra (N_1)

Imposing a Decision threshold, D_1 defines TPF (hatched area) & FPF (solid gray area)

Illustration of 'Noise'-limited feature separation

Most common imaging modalities

- Film X-ray, Digital X-ray, Fluoroscopy, Digital Substraction Angiography (DSA)
- Ultrasound -- 2D and 2.5D (stack of slices)
- Computed Tomography (CT)
- Magnetic Resonance Imaging (MRI)
- Nuclear Medicine (NM)
  - PET -- Positron Emission Tomography
  - SPECT -- Single Photon Emission Tomography

Medical images: characteristics (1)

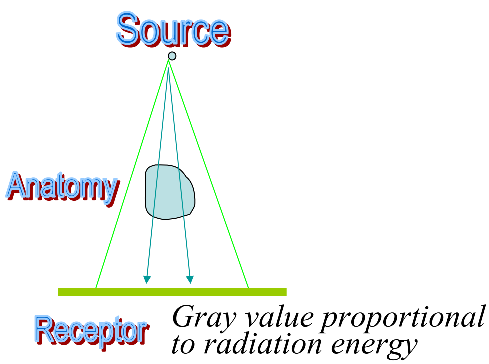
- Dimensionality: 2D, 2.5D, 2D+time
  - projection, cross section, stack of projections, time sequence
- Image quality
  - pixel intensity and spatial resolution
  - amount of noise; signal/noise ratio
  - spatial distortions and intensity bias

Medical images: characteristics (2)

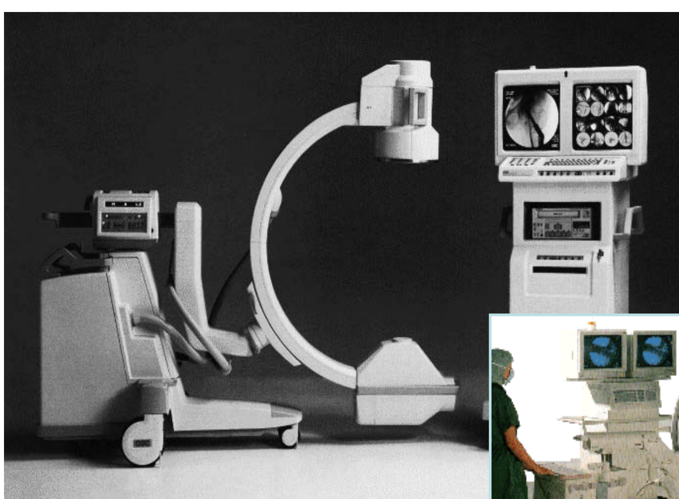
- Field of view
- Radiation to patient and to surgeon
- Functional or anatomical imaging
  - neurological activity, blood flow, cardiac activity
- What it's best at for
  - bone, soft tissue, fetus, surface/deep tumors, etc
- Clinical use
  - diagnosis, surgical, navigation,

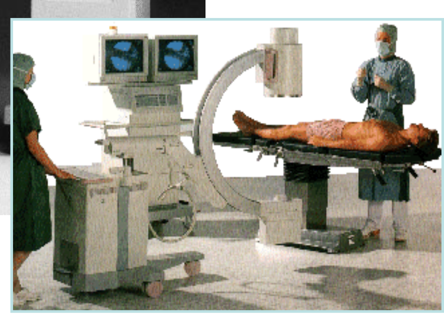
X-ray images

- Measure absorption of x-ray radiation from source to set of receptors
- Film X-ray has very high resolution

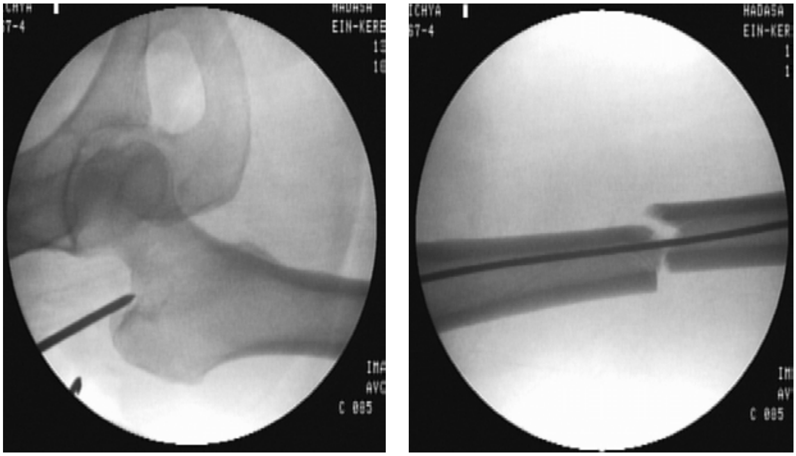


X-ray Fluoroscopy





Fluoroscopic images



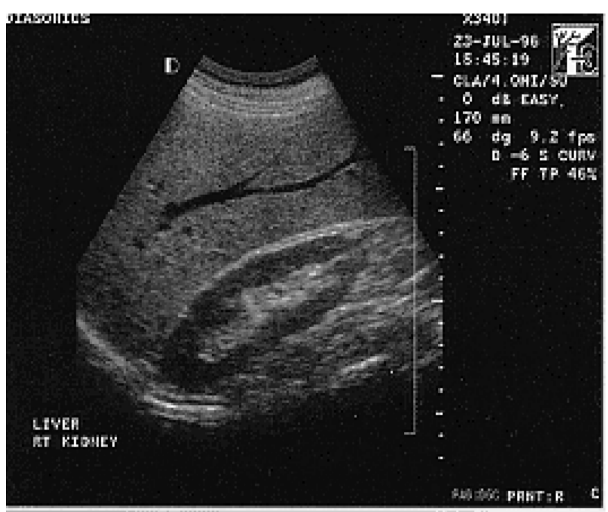
X-ray image properties

- Traditional, cheap, widely available
- Two-dimensional projections (at least two required)
- High resolution, low noise (more fluoroscope)
  - film size, 64K gray levels
  - fluoroscopic images: TV quality, 20cm field of view
- Relatively low radiation
- Bone and metal images very well
- Fluoroscopy used for intraoperative navigation

Ultrasound imaging (US)

- Measure refraction properties of an ultrasound wave as it hits tissue
- No radiation
- Poor resolution, distortion, noise
- Low penetration properties
- One 2D slice or several slices (2.5D)
- Relatively cheap and easy to use
- Preoperative and intraoperative use

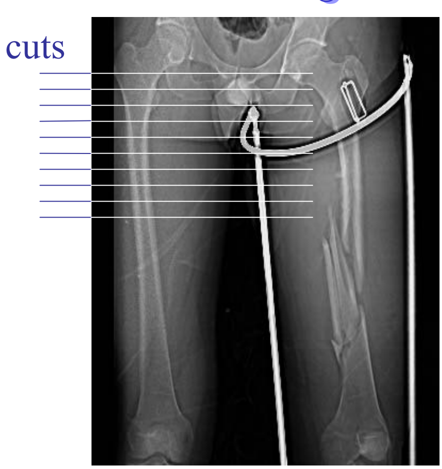
Ultrasound imaging



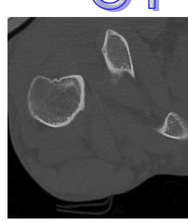
Computed Tomography (CT)

Computed Tomography Images

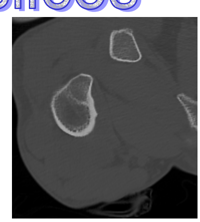
Scout image



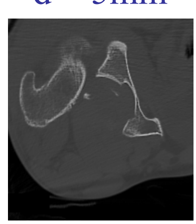
CT slices



d = 5mm



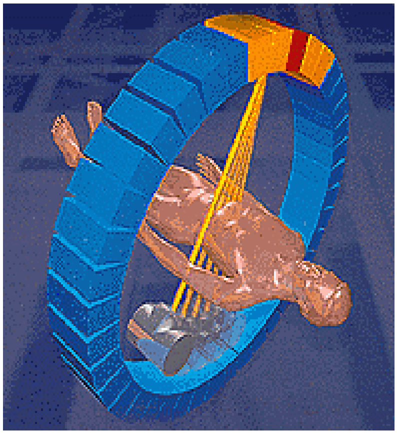
d = 15mm

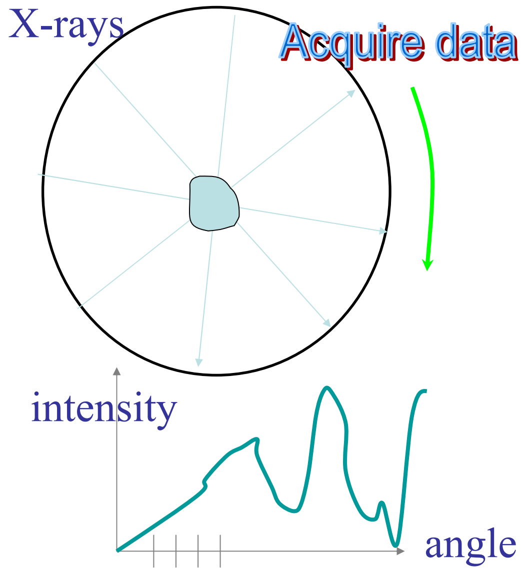


d = 25mm

d = 35mm

Computed Tomography Principle





Reconstruct image
with Fourier Transform

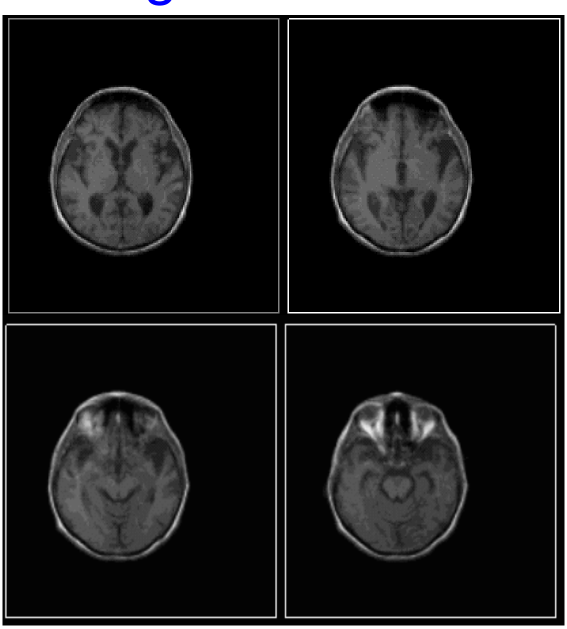
Computed Tomography Properties

- Specifications:
  - 512x512 12bit gray level images; pixel size 0.5mm
  - slice interval 1-10mm depending on anatomy
  - 50-200 slices per study
  - noise in the presence of metal (blooming)
- All digital, printed on X-ray film
- Acquisition 1sec/slice (spiral models)
- 15mins for image reconstruction

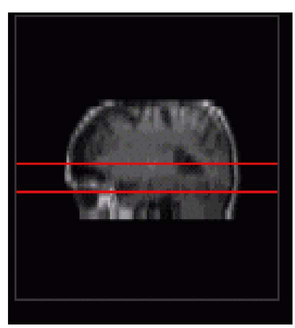
Magnetic Resonance Imaging

- Similar principle and construction than CT machine, but works on magnetic properties of matter
  - magnetic fields of 0.1 to 4 Teslas
- Similar image quality characteristics as CT
- Excellent resolution for soft tissue
- Open MR: intraoperative device (only 15 to date)

Magnetic Resonance Images



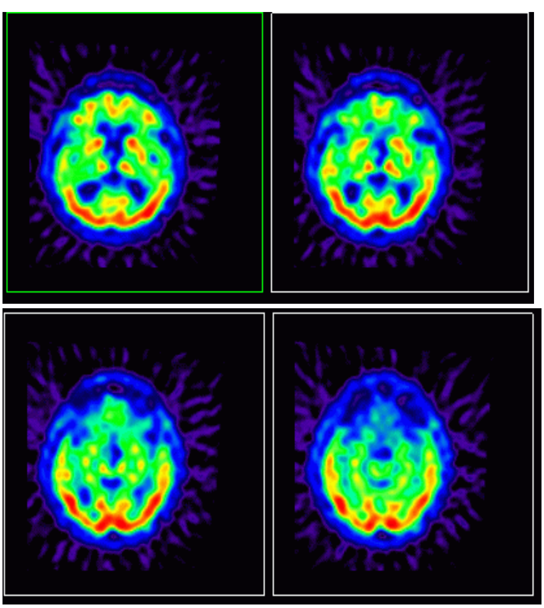
Lateral Reconstruction



Nuclear Medicine Imaging (NMI)

- Same slices principle
- Source of photons or positrons is injected in the body. Shortly after, radiation of metabolism is measured
- Poor spatial resolution
- Expensive machine AND installation
- Expensive and time-consuming
- Provides functional info no other source does

Nuclear medicine images



Lateral Reconstruction

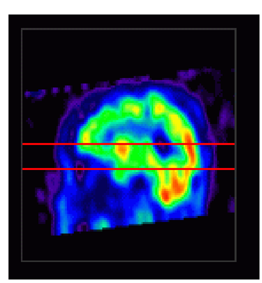


Image Fusion: MRI and NMI