PD233: Design of Biomedical Devices and Systems

(Lecture-8 Medical Imaging Systems)
(Imaging Systems Basics, X-ray and CT)

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Course Website:
http://cpdm.iisc.ac.in/utsaah/courses/
Medical Imaging Systems

- X-ray
- Computed Tomography (CT)
- Magnetic Resonance Imaging (MRI)
- Ultrasound (US)
- Photoacoustics (PA)
- Optical Coherence Tomography (OCT)

- Provide a window into the body to see **anatomy** and **signs of pathology**
- No window is perfect

Image credit http://www.sprawls.org/resources/
IMAGE QUALITY CHARACTERISTICS

THAT AFFECT VISIBILITY

Detail (blurring)
Contrast sensitivity
Spatial
Artifacts
Noise

Image credit: http://www.sprawls.org/resources/
RESOLUTION TEST PATTERN

1 2 3 4 5 6 7 8
SPATIAL FREQUENCY (LP/MM)
CONTRAST TRANSFER FUNCTION

High Blur

Medium Blur

High Blur

SPATIAL FREQUENCY (LP/MM)
### Accuracy of Diagnostic System

**Clinical questions:**

- Is the bone fractured?
- Is a kidney stone present?
- Is there a blockage in the artery?

<table>
<thead>
<tr>
<th>Imaging Test Result</th>
<th>Disease Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>a (True Positive)</td>
</tr>
<tr>
<td>-</td>
<td>c (False Negative)</td>
</tr>
</tbody>
</table>

**Sensitivity** ➔ Probability of positive test given patient is sick

**Specificity** ➔ Probability of negative test given patient is well

What is Total accuracy?
Accuracy of Diagnostic System

Positive Predictive Value:

If the test is positive what is the probability that the disease is present.

Negative Predictive Value:

If the test is negative what is the probability that the disease is absent.

Prevalence: Number of diseases present in a given population at a given time

<table>
<thead>
<tr>
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<th>Imaging Test Result</th>
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<tbody>
<tr>
<td>+</td>
<td>+</td>
</tr>
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<td>+</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Positive Predictive Value: \( \frac{a}{a+b} \)
- Negative Predictive Value: \( \frac{d}{c+d} \)

\( a \): True Positives
\( b \): False Positives
\( c \): False Negatives
\( d \): True Negatives
X-Ray Imaging

"First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand" by Wilhelm Röntgen.

Reading material: Chapter 1, Kirk Shung
Electromagnetic (EM) wave Spectrum

\[ \frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 B}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 B}{\partial t^2} \]

for the electric Field

for the magnetic Field

where \( \frac{1}{c^2} = \varepsilon_0 \mu_0 \)
X-Ray as Particle

Energy of a single photon

\[ E = hf \]

\[ h = \text{Planck's Constant} \]

\[ = 4.13 \times 10^{-18} \text{ keV-sec} \]

What is eV?

Calculate energy of single 1nm X-ray Photon
Attenuation of X-Ray beam

Beam of intensity $I$ and cross-sectional area $A$

$$dI = -\beta I dx$$

$\beta$ = Linear attenuation coefficient

At what distance will the Intensity become half?
What will happen is material changes state/density?
Attenuation of X-Ray beam

Half Layer Value = \( \frac{0.693}{\beta} \)

<table>
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<tr>
<th>Material</th>
<th>HVL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 keV</td>
</tr>
<tr>
<td>Tissue</td>
<td>20.0</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.3</td>
</tr>
<tr>
<td>Lead</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Mass-attenuation coefficient = \( \frac{\beta}{\rho} \)

\( \rho \) = density

\( \beta = n\sigma \)

Material has \( n \) atoms per unit volume each with cross section \( \sigma \)
Intensity of X-ray beam

Intensity $\propto$ energy of the photons
$\propto$ number of photons

X-Ray Dose – should also account for time of exposure

Roentgen (R): total number of ions produced in 1cc of air at (760mm Hg and 0°C)

Radiation Absorbed Dose (rad): X-Ray energy absorbed per kg of material

$1 \text{rad} = 0.01 \text{ Joules absorbed per kg}$
$1 \text{ gray (Gy)} = 100 \text{ rad}$
X-ray Generation

X -Rays can be generated by bombarding metal targets with high energy electron

White Radiation:
Energy lost by striking electron interact with the positivity charged metal
targets inelastically
Also know as Bremsstrahlung or stopping radiation

Characteristic Radiation:
When inner shell electrons are removed
by interaction striking electrons

This phenomenon similar to
photoelectric effect
X-ray Generators

X-rays can be generated by bombarding metal targets with high energy electrons.

**Line Focus Principle**
Large focal spot on the surface but small effective spot

\[ F = f \sin(\theta) \]

**Rotating Anode**
3000 to 10000 rpm

**X-ray Tube Characteristics**
- Target material
- Tube voltage
- Tube current
- Filament current

Striking electrons heat up the metal target.
Beam Restrictors

Needed to regulate size and shape of the x-ray beam

**Beam Restrictors:**
- Aperture diaphragms
- Cone and cylinders
- Collimators

Collimators provide moveable opening
Light used a guide to see the region to be exposed by x-ray

Note Finite focal spot leads to penumbra along edges
Grids

Used to remove effect scattered emissions

Early image of x-ray with grid

Snap on grid, attaches to the x-ray film cassette
**X-ray Detectors**

**X-Ray (Photographic) films**

X-Ray produces free electrons, which reduces silver halide in the exposed region. Silver halide is black, hence region less exposed appear bright.

**Digital Radiography (DR)**

Uses reversible chemistry. Exposed film is scanned by variety of means - camera, drum scanner, laser scanning.

Alternatively, x ray detectors can be electronics/digitals.

Self study!

X Ray film characteristics: response curve, speed, fog, speed.
X-ray Detectors

**Scintillation Detectors**

X-Ray photon can produce visible photon in scintillation material (NaI, Th)
Visible photons and amplified by photomultiplier tube (PMT) - 85% efficient

**Ionization Chamber Detectors**

X Ray ionizes inert gases in confined chamber place between charged electrodes.
Amount of ions produced result in a current which digitized
Limitation of Conventional X-ray imaging

1) 2d Projection of 3D object – i.e. multiple planes are mapped on to one plane – depth information is lost
2) Limited use to distinguish soft tissue
3) Conventional X ray is not quantitative
   -Image intensity/size depend on source-object-detectors distance
Biological Effects of X-Ray

Factors affecting biological effects:

**Threshold:**
Quantitative level above which tissue damage happens

**Exposure Time:**
**Exposure Area:**

**Biological Variation:**
Response varies from species to species, tissue to tissue
Lethal dose vs short term effects
Biological Effects of X-Ray

LD 50/30:
Dose of substance or radiation which will kill 50% of the individual over a 30 day period.

Lethal dose for humans is ~450 rad
Short term effects like nausea, vomiting can happen at dose of 100 rad
- carcinogenic effects
- genetic effects

Even diagnostic X ray is harmful!!
Conventional Tomography
1st Gen. Computed Tomography

- Few minutes for each scan
- Pencil beams
- Motion artifacts
- Translate and Rotate Scanner

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf
2nd Gen. Computed Tomography

- Multiple detector for single beam
- Initial versions with 3 detectors later upto 50+ detectors
- Still uses translate and rotate scanner
3\textsuperscript{st} Gen. Computed Tomography

- 300-500 detectors
- Designed for pure rotational scanning
- X ray tube collimated for fan-beam
- Scanning time reduced to 2 sec per slice
- Got rid of translate and rotate scanning – even used in most recent configurations

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf
4th Gen. Computed Tomography

- Circular array of fixed detectors
- Only source rotates
- 600-4800 detectors
- Less efficient as only ¼ of detectors used at any point in time.
1\textsuperscript{st} generation CT scanner (Parallel beam, translate-rotate)

2\textsuperscript{nd} generation CT scanner (Fan beam, translate-rotate)

3\textsuperscript{rd} generation CT scanner (Fan beam, rotate only)

4\textsuperscript{th} generation CT scanner (Fan beam, stationary circular detector)
5th Gen. Computed Tomography

Cine CT/ millisecond CR/ultrafast CT

- Stationary-Stationary configuration – no mechanical scanning
- X-ray source single tube with array of tungsten targets
- Reduced scanning time to 50ms, cardiac scanning made possible

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd.presentation_final.pdf
6th Gen. Computed Tomography

Spiral/Helical CT

- Table translation with source rotation
- Slip ring technology X-ray source continuously
- Volume data interpolation algorithms developed
- Whole abdomen in 30sec (1BH)
6th Gen. Computed Tomography

Spiral/Helical CT

- Table translation with source rotation
- Slip ring technology: X-ray source continuously
- Volume data interpolation algorithms developed
- Whole abdomen in 30 sec (1BH)

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7th Gen. Computed Tomography

MDCT/ Cone beam CT

Multi-row Detector CT
Collimator opened even more
Key advance in detector technology – 2D arrays rather than one 1D array

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf
7th Gen. Computed Tomography

MDCT/ Cone beam CT
War on slices!!

1-slice CT 4-slice CT 16-slice CT 64-slice CT

focal spot

collimator

axis of rotation

1 x 5 mm 4 x 1 mm 16 x 0.75 mm 64 x 0.5 mm

detector

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf
5th, 6th, 7th Gen. Computed Tomography

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf
<table>
<thead>
<tr>
<th>Gen.</th>
<th>Source</th>
<th>Source Collimation</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Single X-ray Tube</td>
<td>Pencil Beam</td>
<td>Single</td>
</tr>
<tr>
<td>2nd</td>
<td>Single X-ray Tube</td>
<td>Fan Beam (not enough to cover FOV)</td>
<td>Multiple</td>
</tr>
<tr>
<td>3rd</td>
<td>Single X-ray Tube</td>
<td>Fan Beam (enough to cover FOV)</td>
<td>Many</td>
</tr>
<tr>
<td>4th</td>
<td>Single X-ray Tube</td>
<td>Fan Beam covers FOV</td>
<td>Stationary Ring of Detectors</td>
</tr>
<tr>
<td>5th</td>
<td>Many tungsten anodes in single large tube</td>
<td>Fan Beam</td>
<td>Stationary Ring of Detectors</td>
</tr>
<tr>
<td>6th</td>
<td>3G/4G</td>
<td>3G/4G</td>
<td>3G/4G</td>
</tr>
<tr>
<td>7th</td>
<td>Single X-ray Tube</td>
<td>Cone Beam</td>
<td>Multiple array of detectors</td>
</tr>
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