X-ray Tube and Generator –

Basic principles and construction

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OBJECTIVES

- Production of X-rays
- X-ray tube construction
- Anode - types, efficiency
- X-ray tube working characteristics
- Intensity of X-ray beam, housing and filtration
- Classical X-ray generator (block diagram)
- Medium frequency X-ray generator (block diagram)
- Principle of radiographic contrast formation
- X-ray film and film/screen combination
- Mammographic contrast and X-ray tubes
- Various radiographic contrasts (definitions)
Estimated annual collective dose to UK population from Diagnostic Radiology for 1990 is approx. 20,000 manSv. On the basis of risk estimate this could be responsible for up to 700 cancer deaths/year!

Safety in Diagnostic Radiology, IPEM, 1995

Approximately 90% of the total collective dose to UK population from man-made radiation sources arises from Diagnostic Radiology

Safety in Diagnostic Radiology, IPEM, 1995

In most industrialised countries there are between 300 and 900 X-ray examinations for every 1000 inhabitants every year. Over half of these are chest examinations (these figures does not include dental X-ray examinations or mass screening programs).

Doses varies widely from hospital to hospital, even in the same country, sometimes by a factor of 100.

Radiation and You, EU, Luxembourg 1990
Distribution of X-ray dose from the Tube through the Patient to the X-ray film

Exposure ~ 80 kV, 30 mAs @ 1m

Distribution of X-rays and Bremsstrahlung (stopping radiation) – thermal electron emission in vacuum (10⁻⁶ mbar) and target bombardment

White X-ray spectrum (gamma quanta with all energies) and its final view (after tube filtration)
<table>
<thead>
<tr>
<th></th>
<th>Imaginary model</th>
<th>Real (approximate)</th>
<th>Scaled-up approx. model (linear)</th>
<th>Volume ratio:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron radius</td>
<td>$10^{-15}$ m</td>
<td>1 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nucleus radius</td>
<td>$10^{-14}$ m</td>
<td>10 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atom radius</td>
<td>$10^{-10}$ m</td>
<td>100 000 mm (100 m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-atom dist in crystal</td>
<td>$10^{-10}$ m</td>
<td>100 m</td>
<td></td>
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</table>

Space charge effect -
X-ray tube function characteristics

PRE-Heating of Cathode

Volume ratio: $e \text{ vs } A \sim 10^{15}$

High temp. : Electron cloud
Cathode – W wire filament (~10x0.2 mm)
Anode – W plate (melting at 3370°C)
Construction: stationary and rotation

ANODE: X-ray tube focal spot -
Line focus principle
Stationary – anode angle determines focal spot – less power

Rotational – increased thermal focus – more power

Anode angle

Effective focus : Thermal (Actual) focus

Anode angle

EF = sin α . AF

Anode heat - storage and dissipation (cooling)

\[ P_{\text{max}} \sim f^{3/2} D^{1/2} n^{1/2} / \sin \alpha \]

The maximal power of the rotating anode \( P_{\text{max}} \) depends on:
- the effective focal spot size \( f \);
- the diameter of the target track \( D \);
- the angle of the anode \( \alpha \);
- the speed of rotation \( n \) - r.p.m.;
X-ray Intensity distribution:
- In all directions inside the Tube housing (only a fraction of X-rays used – output dose)
- The overall output intensity decreases with ageing of Tube
- Decreased intensity at Anode site (Heel effect) – it is more obvious with old Tubes

Intensity of X-ray radiation: \( W \sim I \cdot U^2 \cdot Z \)

Anode efficiency: \( \eta \sim k \cdot U \cdot Z \) (Z-anode atom. No.)

(intensity per energy unit - \( \eta = W/IU \))

X-ray Tube Housing – Insulating Oil; Output window; Pb lining; Leakage radiation

Tube and Housing cooling and T^2 protection
Max. power of the tube:
\[ P = kV \times mA \ (100x300=30kW) \]

Max anode heat capacity
\[ HU = kV \times mAs \ (100x1000=100kHU) \]
\( 1HU = 1.4 \) Joules

X-ray Tube characteristics:
Using of single exp. chart

X-ray image resolution depends on the size of the X-ray tube focal spot (effective focus)

Fine (~0.5mm) or Broad (~1mm)
The BF smears the contours of the imaged objects (this increases with the increase of object-to-film distance)
Superb electron focusing and heat dissipation (cooling) = small focal spot (resolution) + high X-ray tube power (penetration and long exposures)
kVp and Dose pulses (waveforms) from various X-ray generators

Basic diagram of Classical X-ray Generator with the Tube
Contemporary medium-frequency X-ray Generator
(smaller HV transformer; frequency varies the kV)

\[ U / f \sim A \cdot n \]

- \( U \) is the voltage
- \( f \) is the frequency
- \( A \) is the cross section of the transform core
- \( n \) is the number of transformer windings

(smaller HV transformer; frequency varies the kV)
SUMMARY

X-ray tube:
- Focal spot (spatial resolution; power)
- Total filtration at tube output (pat. dose)
- Tube housing (leakage radiation)

X-ray Generator:
- kV control (image contrast, pat. dose²)
- mA control (image brightness, pat. dose)
- Time (msec) control (image brightness and patient dose)

X-ray output spectrum
The X-ray source radiation $I_o$ passes through the object (the body) and is modulated by the body tissues ($\mu\cdot d$) on its way. This modulated radiation beam $I_x$ interacts with the detector, where the modulated radiation is transformed into modulated light – the X-ray image.

The contrast of the image depends on the energy of the X-ray beam.

\[ I_x = I_o \cdot e^{-(\mu\cdot d)} \]
Photoemulsion: The lattice Ag and Br atoms are fixed. The individual silver halide crystals within the emulsion contain: 1. interstitial +Ag ions (mobile) and 2. electron traps (usually silver sulfide).

Light (X-ray) photon excites a Bromine atom (and it looses an e-). These free e- are trapped into crystal defects (traps). The (+) Silver ions are attracted into these (–) defects, where they are neutralised and become Ag atoms (sensitised grains). The combination of areas in the film with different number of sensitised grains forms a LATENT IMAGE. During the process of film development the sensitised grains are stabilised (the exposed AgBr crystals are reduced to stable Ag atoms). During the next process of film fixing the remaining un-sensitised grains (which had not been exposed to light photons) are removed and washed out. The final visible image contains areas with various opacity/darkness (depending on the concentration of Ag atoms).

X-ray film characteristics:
- Exposure latitude (dynamic range);
- Resolution (grain size)
- Sensitivity (film speed)

Cassette intensifying screen influence
Development process influence
X-ray Film Type influence

kV-mAs

reading

processing

storage

Un-processed image

Influence of the characteristic curve

RX breast screen film reading processing

DO

Un-processed image

DO
**Basic Principles of Mammography**

- Use of low kV due to the type of imaged tissue

Photoelectric absorption:

\[ \tau_m \approx 8(Z_{\text{eff}} \lambda)^3 \]

Total absorption = Photoelectric + Compton:

\[ \mu = \sigma + \tau \approx \rho[0.2 + 8(Z_{\text{eff}} \lambda)^3] \]

- Some specific parameters of mammographic X-ray equipment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>X-ray Generator</td>
<td>Medium frequency or at least 3 phase (~ 5 kW)</td>
</tr>
<tr>
<td>X-ray tube Anode + added filtration</td>
<td>Mo/ 30 µm Mo Rh/ 50 µm Rh W/ 60 µm Mo W/ 50 µm Rh</td>
</tr>
<tr>
<td>Focal spot</td>
<td>Small 0.1-0.3 mm, Large 0.4-0.6 mm</td>
</tr>
<tr>
<td>kV</td>
<td>20-35 kV, steps - 0.5-1 kV</td>
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</table>
X-ray spectrum from W anode with 0.06 mm Mo or 0.05 mm Rh filtration – 30 kV

X-ray spectrum from Mo anode with 0.06 mm Mo or 0.05 mm Rh filtration – 30 kV

The characteristic radiation is predominant (compared with stopping radiation)

The additional energy gained with Rhodium filter for enhanced penetration.
X-ray mammo tube positioning and compression of the breast

Fig. 20-5. Use of compression in mammography has these advantages: uniform image receptor exposure, reduced focal-spot blur, and reduced absorption and scatter.

Radiographic contrast
\[ \Delta C = \frac{[D_2 - D_1]}{D_1} \]

Film contrast
\[ \gamma = \frac{[D_2 - D_1]}{[\log E_2 - \log E_1]} \]

Subject Contrast
\[ \Delta C = I_2 - I_1 \]

Visual contrast
\[ \Delta C = \log I_2 - \log I_1 \]
Automatic Exposure Control (AEC) system

Anatomical X-ray contrast >>

Artificial X-ray contrast:
(Various contrast agents)
<<< Barium-based (ex. stomach)

Iodine-based >>>
(ex. heart/vessels)

<<< Interventional Radiology
Contrast and Resolution of various X-ray detectors and methods

Contrast:
1. CT
2. Film
3. Fluo

Resolution:
1. Film
2. Fluo
3. CT