Chapter 2
The Production and Properties of X Rays
Radiation Dosimetry I

http://www.utoledo.edu/med/depts/radtherapy

X-ray tube design

- Filament is heated, releasing electrons via thermionic emission \( V_f \approx 10V, I_f \approx 4A, \) resulting in \( T \approx 2000\)°C
- X rays are produced by high-speed electrons bombarding the target
- Typically < 1% of energy is converted to x-rays, the rest is heat

X-ray tube current

- Electron cloud near the filament creates space charge region, opposing the release of additional electrons
- Increase in tube voltage increases tube current, limited by filament emission
- High filament currents and tube voltage of 40 to 140kV must be used

Alternating currents and voltages

- Phase changes from 0 to 360° during the 1 cycle time of 1/60 s
- Negative wave is suppressed or rectified
- Averaging: \( V_{av} = \frac{1}{\pi} V_0 \) or \( V_{rms} = \frac{1}{\sqrt{2}} V_0 \)

Alternating currents and voltages

- High voltage from secondary of transformer with peak value of 120 kV
- The inverse part of the cycle is ABC: \( v \) Tube current for the circuit of Figure 2.2 when the x-ray tube has the characteristics of curve 2 of Figure 2.1b and the tube voltage is given by Figure 2.3. The intensity of the resulting x-ray pulses calculated assuming x-ray production is proportional to \( V^2 \) is also given. Curve 6 is the current pulse using the transmission curve 5 of Figure 2.1b.
Rectification

Figure 2.4. Schematic diagram of a p-n silicon rectifier. The operating characteristics are for the MB2772, a typical silicon rectifier. Note that the voltage and current scales are different for the forward and reverse directions. In the inset is shown a Machlett rectifier, which consists of some 500 rectifiers in series in a tube 25 cm long and capable of withstanding an inverse voltage of 150 kV.

Three phase units

- Need to increase pulse repetition rate to deliver high x-ray flux in a short period of time
- Three phase units: voltage between any pair of 3 wires

Tube potential is almost constant, with a “ripple”

Example 1

- Which type of x-ray generator produces the highest effective tube voltage, assuming the peak voltage is applied across the tube?
  
  A. One-phase
  B. Three-phase
  C. Constant potential
  D. The effective voltage is the same for all types above.

In C - effective voltage = peak voltage

Example 2

Ratio of the turns in a transformer is \( N \). Given an input RMS (primary) voltage, what is the peak output (secondary) voltage?

Faraday’s law:

\[
V_p = N_p \frac{\Delta P}{dt} \quad \text{and} \quad V_s = N_s \frac{\Delta P}{dt}
\]

\[
V_s = V_p \cdot \sqrt{2}
\]

Example 3

- What energy (kJ) is imparted to a rotating anode (0.25 kg) during a 2 s exposure that produced a temperature of 2500°C. Specific heat of tungsten is 0.035 kcal/kg°C, and 1 cal = 4.186 J

\[
E = m \cdot c \cdot \Delta T
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E = 0.25 \cdot 4.186 \times 10^3 \cdot 0.25 \cdot 2500 = 91.5 \times 10^3 = 91.5 \text{ kJ}
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Diagnostic X-ray tubes

- X-rays that are emitted from the target travel through different thickness of cathode material
- **Heel effect**: radiation intensity toward the cathode side of the x-ray tube is higher than on the anode side
- Cathode is typically mounted over the thicker part of the patient to balance the amount of transmitted photons on the imager

Rating of diagnostic tubes

- Focal spot loading determines the maximum permissible exposure: there is a maximum power that can be tolerated before target starts melting ($T_{\text{melting}} = 3400^\circ \text{C}$ for tungsten)
- Anode cooling and housing cooling rates determine the number of exposures that may be given in a sequence

Rating of diagnostic tubes

- The combination of current and voltage must lie to the left of the appropriate curve
- The maximum duration of a single exposure depends on spot size, anode rotation speed, current, voltage, power supply type

X-ray tubes for radiotherapy

- Mostly for superficial treatments
- No need for a small spot source
- The instantaneous energy input is small (about 1/10) but the average energy input is ~ 10 times greater compared with a diagnostic tube
- Due to much higher energy (>200keV) of electrons bombarding the target, there is a problem of secondary electrons emerging from the target
  Solution: the target is placed in a “hood” - hollow tube with copper shielding intercepting the secondary electrons

X-ray spectra

- Observed spectra from a diagnostic x-ray tube excited at 60, 80, 100, and 110 kVp, due to Kα (Y). added filter 2 mm A1
Interactions of electrons with the target to give x rays

Most probable; no x-rays produced

Breaking radiation

Figure 2-14. Typical electron interactions with a target. (a) Electron suffers instantaneous losses, giving rise to delta rays and eventually heat. (b) The electron ejects a K electron, giving rise to characteristic radiation. (c) Collisions between an electron and a nucleus, leading to bremsstrahlung of energy E. The electron escapes from the "collision" with energy E - E0.

Bremsstrahlung interaction

Thin target approximation: one collision per electron
Thick target approximation: \( I(E) = C Z \left( E_{\text{max}} - E \right) \)

Figure 2-15. Relative energy or intensity, I, in each photon energy interval produced when a beam of monochromatic electrons of energy E interacts with a target. The energy of bremsstrahlung is determined by the average energy of the electrons as they emerge from the target, given by the electron energy loss, \( E_{\text{max}} \).

Example 4

The energy levels of K, L, and M shells in tungsten are 69.5, 11.0, and 2.5 keV. What photon energies will be present in its characteristic X-ray spectrum?

A. 67.0, 58.5, 8.5 keV
B. 80.5, 72.0, 13.5 keV
C. 69.5, 11.0, 2.5 keV
D. Continuous spectrum from 2.5 to 69.5 keV
E. Continuous spectrum below 2.5 keV

Photon energies are equal to the differences between corresponding energy levels.

Example 5

In the graph below, the two X-ray spectra shown have the same

1. Filtration
2. Target material
3. HVL
4. KVp

A. 1, 2, 3, 4
B. 1, 3
C. 2, 4
D. 3, 4
E. 4 only

Different intensity – different filtration and HVL

Example 6

A target material has the following binding energies: K=30 keV, L=4 keV, M=0.7 keV. If 40.0 keV electrons are fired at the target, what kind of X-rays can the following energies?

- 6: 34 keV
- 6: 26 keV
- 6: 40.7 keV

A. Characteristic only
B. Bremsstrahlung only
C. Both A and B
D. Neither A nor B

Answers:
A. 6: 1
B. 6: 2
C. 6: 3

Characteristic radiation

Table 2-3

<table>
<thead>
<tr>
<th>K Lines</th>
<th>L Lines</th>
</tr>
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<tbody>
<tr>
<td>Transition</td>
<td>Symbol</td>
</tr>
<tr>
<td>K-(\text{N})</td>
<td>K(_{\alpha})</td>
</tr>
<tr>
<td>K-(\text{M})</td>
<td>K(_{\beta})</td>
</tr>
<tr>
<td>K-(\text{M})</td>
<td>K(_{\beta})</td>
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<tr>
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<td>K-(\text{L})</td>
<td>K(_{\beta})</td>
</tr>
<tr>
<td>K-(\text{L})</td>
<td>K(_{\gamma})</td>
</tr>
<tr>
<td>K-(\text{M})</td>
<td>K(_{\alpha})</td>
</tr>
</tbody>
</table>

From Storm and Israel (SI):

- Different transitions have different probabilities, according to quantum mechanics selection rules (some transitions are forbidden).