X-ray Emission Spectrum

Dr. Ahmed Alsharef Farah
• X-ray photons produced by an X-ray tube are heterogeneous in energy.
• The energy spectrum shows a continuous distribution of energies for the bremsstrahlung photons superimposed by characteristic radiation of discrete energies.
There are two types of X-ray spectrum:

1. Bremsstrahlung or continuous spectrum.
2. Characteristic spectrum.
• A bremsstrahlung spectrum consists of X-ray photons of all energies up to maximum in a continuous fashion, which is also known as white radiation, because of its similarity to white light.

• A characteristic spectrum consists of X-ray photons of few energy, which is also called as line spectrum.

• The position of the characteristic radiation depends upon the atomic number of the target.
Characteristic X-ray Spectrum:

• The discrete energies of characteristic x-rays are characteristic of the differences between electron binding energies in a particular element.
• A characteristic x-ray from tungsten, for example, can have 1 of 15 different energies and no others.
Characteristic X-rays of Tungsten and Their Effective Energies (keV).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>L Shell</th>
<th>M Shell</th>
<th>N Shell</th>
<th>O Shell</th>
<th>P Shell</th>
<th>Effective Energy of X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>57.4</td>
<td>66.7</td>
<td>68.9</td>
<td>69.4</td>
<td>69.5</td>
<td>69</td>
</tr>
<tr>
<td>L</td>
<td>9.3</td>
<td>11.5</td>
<td>12.0</td>
<td>12.1</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>M</td>
<td>2.2</td>
<td>2.7</td>
<td>2.8</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>0.52</td>
<td>0.6</td>
<td></td>
<td>0.08</td>
<td>0.6</td>
</tr>
<tr>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
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</tbody>
</table>
Characteristic x-ray emission spectrum for tungsten contains 15 different x-ray energies.
• Such a plot is called the characteristic x-ray emission spectrum.
• Five vertical lines representing K x-rays and four vertical lines representing L x-rays are included.
• The lower energy lines represent characteristic emissions from the outer electron shells.
• The relative intensity of the \textbf{K x-rays} is greater than that of the \textbf{lower energy characteristic x-rays} because of the nature of the interaction process.

• \textbf{K x-rays} are the only \textbf{characteristic x-rays} of tungsten with \textbf{sufficient energy} to be of value in \textbf{diagnostic radiology}.

• Although there are five \textbf{K x-rays}, it is customary to represent them as one with a single vertical line, at \textbf{69 keV}. 
The characteristic x-ray emission spectrum is represented by a line at 69 keV.
Bremsstrahlung X-ray Spectrum:

• If it were possible to measure the energy contained in each bremsstrahlung x-ray emitted from an x-ray tube, one would find that these energies range from the peak electron energy all the way down to zero.
• In other words, when an x-ray tube is operated at 90 kVp, bremsstrahlung x-rays with energies up to 90 keV are emitted.
• A typical bremsstrahlung x-ray emission spectrum is shown in Figure below.
Question:
• At what kVp was the x-ray imaging system presented in Figure above operated?

Answer:
• Because the bremsstrahlung spectrum intersects the energy axis at approximately 90 keV, the imaging system must have been operated at approximately 90 kVp.
• The general shape of the bremsstrahlung x-ray spectrum is the same for all x-ray imaging systems.
• The maximum energy (in keV) of a bremsstrahlung x-ray is numerically equal to the kVp of operation.
• The greatest number of x-rays is emitted with energy approximately one third of the maximum energy.
• The number of x-rays emitted decreases rapidly at very low energies.
• The energy of an x-ray is equal to the product of its frequency \((f)\) and Planck’s constant \((h)\). X-ray energy is inversely proportional to its wavelength. As x-ray wavelength increases, x-ray energy decreases.

• The minimum wavelength of x-ray emission corresponds to the maximum x-ray energy, and the maximum x-ray energy is numerically equal to the kVp.
Question

• What would be the expected emission spectrum for an x-ray imaging system with a pure molybdenum (Mo) target (effective energy of K x-ray = 19 keV) operated at 90 kVp?
Answer

• The spectrum should look something like Figure below.
The curve intersects the energy axis at 0 and 90 keV and has the general shape shown in Figure below.
• The bremsstrahlung spectrum is much lower because the atomic number of Mo is low (Z = 42), and x-ray production is much less efficient.
• A line extends above the curve at 19 keV to represent the K-characteristic x-rays of molybdenum.
Factors affecting the x-ray emission spectrum

- The total number of x-rays emitted from an x-ray tube could be determined by adding together the number of x-rays emitted at each energy over the entire spectrum, a process called integration.
• **Graphically**, the total number of x-rays emitted is equivalent to the area under the curve of the x-ray emission spectrum.

• The **general shape** of an emission spectrum is always the same, but its relative position along the energy axis can change.

• The farther to the right a spectrum is, the **higher the effective energy or quality of the x-ray beam.**
• The **larger** the area under the curve, the **higher** is the x-ray intensity or quantity.
• A number of factors under the control of radiographers influence the **size** and **shape** of the x-ray emission spectrum and therefore the **quality** and **quantity** of the x-ray beam.
Factors that affect the size and relative position of x-ray emission spectrum.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube current</td>
<td>Amplitude of spectrum</td>
</tr>
<tr>
<td>Tube voltage</td>
<td>Amplitude and position</td>
</tr>
<tr>
<td>Added filtration</td>
<td>Amplitude; most effective at low energy</td>
</tr>
<tr>
<td>Target material</td>
<td>Amplitude of spectrum and position of line spectrum</td>
</tr>
<tr>
<td>Voltage waveform</td>
<td>Amplitude; most effective at high energy</td>
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</tbody>
</table>
Factors affecting the x-ray emission spectrum:

1. **Effect of mA and mAs:**
   
   - If one changes the current from 200 to 400 mA while all other conditions remain constant, twice as many electrons will flow from the cathode to the anode, and the mAs will be doubled.
   - This operating change will produce twice as many x-rays at every energy.
• In other words the x-ray emission spectrum will be changed in **amplitude** but not in shape.

• **Increasing the mA** does not affect the shape of the spectrum but **increases the output of both bremsstrahlung and characteristic radiation proportionately.**

• The area under the x-ray emission spectrum varies in proportion to changes in mA or mAs, as does the x-ray quantity.
Change in mA or mAs results in a proportionate change in the amplitude of the x-ray emission spectrum at all energies.
2. **Effect of kVp:**

- As the kVp is raised, the area under the curve increases to an area approximating the **square of the factor** by which kVp was increased.
- Accordingly, the x-ray quantity increases with the **square of this factor**.
• When kVp is increased, the relative distribution of emitted x-ray energy shifts to the right to a higher average x-ray energy.
• The maximum energy of x-ray emission always remains numerically equal to the kVp.
• Increasing the kV shifts the spectrum upwards and to the right.
• It increases the maximum and effective energies and the total number of x-ray photons.
• Below a certain kV (70 kV for a tungsten target), the characteristic K-radiation is not produced.
Effect of tube kilovoltage (kV) on X-ray spectra for three tube potentials: A, 40 kV; B, 80 kV; and C, 120 kV.
• A 15% increase in kVp does not double the x-ray intensity but is equivalent to doubling the mAs to the image receptor.
• To double the output intensity by increasing kVp, one would have to raise the kVp by as much as 40%.
• **Radiographically**, only a 15% increase in kVp is necessary because with increased kVp, the *penetrability* of the x-ray beam is increased.

• Therefore, **less radiation is absorbed** by the patient, leaving a proportionately **greater number of x-rays** to expose the image receptor.
3. **Effect of Added Filtration:**

- Adding *filtration* to the useful *x-ray beam* reduces *x-ray beam intensity* while increasing the *average energy*.
- Added *filtration* more effectively *absorbs low-energy x-rays* than *high-energy x-rays*; therefore, the *bremsstrahlung x-ray emission spectrum* is reduced further on the left than on the right.
Adding filtration to an x-ray tube results in reduced x-ray intensity but increased effective energy.
The emission spectra represented here resulted from operation at the same mA and kVp but with different filtration.

Effect of increasing aluminium filtration on the X-ray spectrum.

Effect of a 0.1 mm erbium filter on the spectrum at 80kV compared with the same beam filtered by 2.5 mm Al.
• Adding filtration is sometimes called hardening the x-ray beam because of the relative increase in average energy.
• The characteristic spectrum is not affected, nor is the maximum energy of x-ray emission.
4. **Effect of Target Material:**

- The **atomic number of the target** affects both the number (**quantity**) and the effective energy (**quality**) of x-rays.
- As the **atomic number** of the target material increases, the **efficiency of the production of bremsstrahlung radiation** increases, and **high-energy x-rays** increase in number to a greater extent than **low-energy x-rays**.
• The change in the bremsstrahlung x-ray spectrum is not nearly as pronounced as the change in the characteristic spectrum.

• After an increase in the atomic number of the target material, the characteristic spectrum is shifted to the right, representing the higher energy characteristic radiation. This phenomenon is a direct result of the higher electron binding energies associated with increasing atomic number.
• **Changing the target to one of lower atomic number** reduces the output of bremsstrahlung but does not otherwise affect its spectrum, unless the filtration is also changed.

• The **photon energy** of the characteristic lines will also be less.

• Elements of **low atomic number** also produce **low-energy characteristic x-rays**.
Discrete **emission spectrum** shifts to the right with an increase in the **atomic number** of the **target material**.
• **Tungsten** is the primary component of x-ray tube targets, but some specialty x-ray tubes use gold as target material.
• The **atomic number** for **tungsten** is 74 and gold is 79.
• Molybdenum \((Z = 42)\) and rhodium \((Z = 45)\) are target elements used for mammography.

• In many dedicated mammography imaging systems, these elements are incorporated separately into the target.

• The x-ray quantity from such mammography target material is low owing to the inefficiency of x-ray production.
5. **Effect of Voltage Waveform:**

- There are **five voltage waveforms:**
  I. Half-wave–rectified.
  II. Full-wave–rectified.
  III. Three-phase/six-pulse.
  IV. Three-phase/ 12-pulse.
  V. High-frequency waveforms.
Waveforms of high-voltage generators:
(a) singlephase, half wave–rectified; (b) single-phase, full wave–rectified; (c) three-phase, six-pulse; and (d) high-frequency generator.
Whatever the kV waveform, the maximum and minimum photon energies are unchanged.
Three-phase and high-frequency operations are considerably more efficient than single-phase operation.
• The number of x-rays emitted is **low at lower voltages and increases at higher voltages**.
• The **quantity of x-rays** is much **greater at peak voltages** than at lower voltages.
• Consequently, voltage waveforms of **three-phase** or **high-frequency** operation result in considerably more intense x-ray emission than those of **single-phase** operation.
• The relationship between x-ray quantity and type of high-voltage generator provides the basis for another rule of thumb used by radiologic technologists.

• If a radiographic technique calls for 72 kVp on single-phase equipment, then on three-phase equipment, approximately 64 kVp — a 12% reduction — will produce similar results.