RAD 416

Treatment Machines

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Introduction

- This lecture discusses the equipment used in external beam radiotherapy.
- The treatment devices used for radiation production are either kilovoltage X-ray units, cobalt-60 teletherapy machines, and megavoltage linear accelerators (LINACs).

Kilovoltage X-Ray Machines

- Kilovoltage x-ray units played an important role in the early development of radiotherapy, mainly between **1910** and **1950**.
- They indeed were the earliest attempt at external beam therapy.
- Although still useful for the treatment of superficial lesions, they have been superseded for most treatments by linear electron accelerators, emitting megavoltage x-ray beams and possibly electron beams.

Kilovoltage x-rays

- Kilovoltage x-rays are generated by stopping electrons accelerated across the potential difference between a cathode and an anode.
- The energy or beam quality can generally be described in terms of the magnitude of this potential difference (kV).
- The spectrum of radiation can be significantly altered by placing metal filters in the path of the beam, and beams of different penetrative quality can be produced from the same accelerating potential.
- It is. therefore, customary to define the beam quality in terms of the thickness of a given material (usually aluminium or copper) that will reduce the beam intensity to half of its initial value. This is called the half value layer or HVL.

Kilovoltage x-rays

- The kilovoltage range covers x-ray beams generated between 10 kV and 400 kV and is usually subdivided into categories according to increasing beam penetration.
- The divisions reflect the type of treatments that each range is suited for as well as other physical considerations such as equipment design, beam characteristics, and the method employed in determining the dose rate.

Classification of kilovoltage x-rays

- **GRENZ RAYS**
  - Covers a range of 10 kV to 20 kV with added filtration of 0.02 mm to 0.15 mm Al HVL
  - They lie between the hardest ultraviolet rays and x-rays and are named from the German word Grenze (meaning boundary).
  - Also called border x-rays. At such energies, absorption in air can be appreciable. This range is rarely used in modern radiotherapy.
- **SHORT DISTANCE OR CONTACT THERAPY X-RAYS**
  - (10 kV to 60 kV with added filtration of 0.02 mm to 3.3 mm Al HVL.
  - Originally developed to reproduce the conditions of surface Radium treatment.
  - The very short source skin distance (SSD) of typically 1.5 cm to 5.0 cm ensures a rapid fall-off in depth dose, even over a wide range of qualities, providing a useful treatment depth up to several millimetres.

SUPERFICIAL THERAPY X-RAY

- Covers a range of 50 kV to 150 kV with added filtration of 1 mm to 8 mm Al HVL.
- This energy range has probably been least affected by the introduction of high energy linear accelerators providing the treatment of choice for many superficial lesions, and in many other cases, an adequate alternative to electrons.
- The beam characteristics enable lesions to a depth of around 5 mm to be encompassed by 90%of the surface dose.

ORTHOVOLTAGE THERAPY OR DEEP THERAPY X-RAY

- Covers a range of 150 kV to 400 kV
- Most clinical units in this range are operated with generating potentials from 160 kVp to 300 kVp corresponding to added filtrations of 0.5 mm to 4 mm Cu HVL.
- The 90% dose in this range lies 1 cm to 2 cm beneath the incident skin surface at the usual treatment distance of 50 cm SSD. The percentage depth dose gradually varies with applied tube potential in this range. It changes by 2% or less of the local dose down to 50% of the peak dose per 50 kV change in tube voltage
- Multi-energy units covering both the superficial and orthovoltage ranges are now used in many departments.

Kilovoltage x-ray production

- When a high speed electron penetrates a target material, three main interactions can occur.
- The electron is subjected to small deflections by the electron cloud of the target material. These energy losses cause excitation and heat production, and they account for the majority of interactions.
- The incoming electron interacts with an inner shell orbital electron and has sufficient energy to eject it. The resultant vacancy is filled by an electron from an outer shell that emits a photon of energy equal to the difference in energy between the two shells. This is termed **characteristic radiation** as the energy difference between orbital shells depends on atomic number and is characteristic of the target material. An electron from a shell still farther from the nucleus will then fill this new vacancy. This process is repeated, leading to the emission of a series of discrete lines of characteristic x-rays. Characteristic radiation accounts for only a small percentage of the x-rays produced.
- **Bremsstrahlung (braking radiation)** accounts for the majority of x-ray photons emitted, and it occurs when the incoming electron passes close enough to the positive charge of the target nucleus to be attracted and, consequently, decelerated. The energy lost because of this braking effect is emitted as an x-ray photon. The electron can lose all of its incident energy in a single collision with a nucleus

Special features of radiotherapy kilovoltage x-ray machines

- **Metal–Ceramic Tube Design**: The x-ray tube (tube insert) is made of metal-ceramic.
- Metal ceramic tubes are manufactured with an integral beryllium window (2 mm to 5 mm thick) that has a low atomic number (Z=4) and physical density.
- For the same tube operating conditions, this lower inherent filtration results in increased output compared with glass envelope tubes. Consequently, metal–ceramic tubes can be run at lower tube currents and allow lower beam qualities to be produced for a given tube kVp.

- **Contact Therapy Tubes**: The design of contact therapy tubes is based on bringing the target as close as possible to the treatment surface.
  - This leads to quite different configurations that have involved the use of both transmission targets and reflection targets.
  - This equipment is not commonly used today.
- **Target Angle and Radiation Distribution in Air:**
  - The inverse-square law and the amount of oblique filtration through attenuating materials in the beam path will govern the directional distribution of the beam.
  - The beam profile perpendicular to the anode–cathode direction should be symmetric. This is unlikely to be the case in the anode–cathode direction where x-rays will be differentially absorbed within the target depending on the angle where they emerge. This heel effect can result in increased or reduced beam intensity on the anode side of the beam axis compared with that on the cathode side.
  - The magnitude of this effect depends on both the target angle and applied kV, and it is additionally constrained by the need for a large useful beam at relatively short SSDs. The target angle is typically **40^o** for superficial x-rays and **30^o** for orthovoltage equipment.

X-ray Tube Housing

- Permissible leakage levels through the shield at 1 m from the focal spot are 1 mGy/h and 10 mGy/h for equipment running up to 150 kVp and 300 kVp, respectively.
- A filter holder and applicator mount are attached to the tube housing at the beam exit aperture. The filter holder usually contains one or more micro-switches to enable the system control unit to recognize coded external metal filters.
- For orthovoltage equipment with applicators of SSD above 40 cm, a radiation monitor should be provided to indicate the tube output rate.

Tube Cooling System

- Heat is conducted through the target into the copper anode block and, in the case of the metal–ceramic tube, efficiently removed by direct water (or oil) cooling of the copper block.
- Some units may also incorporate secondary cooling of the pumped coolant using a remote heat exchanger. Interlocks prevent the beam from running if the coolant temperature gets too high or if its flow rate drops below an acceptable level.

Cobalt-60 Teletherapy Machine

- Teletherapy cobalt-60 units were first used for patient treatment in 1951 in Canada.
- Although megavoltage x-ray units had been available for some years prior to this date, they were not in widespread use, whereas, cobalt units became the mainstay of external beam therapy for the next 30 years or so world-wide.
- Cobalt-60 is manufactured by irradiating cobalt-59 in a high neutron flux nuclear reactor. The main reasons for its suitability for teletherapy are the availability of relatively small, high specific activity, sources that minimize the beam penumbra; its relatively long half-life (5.27 years); and the almost monochromatic high-energy photon emission (photons of 1.173 MeV and 1.333 MeV in equal quantity).

- Cobalt units offer poorer geometrical precision in treatment compared to LINAC because of a larger penumbra and greater mechanical inaccuracy.
- Cobalt beams are less penetrating than those from LINACS
- Cobalt units lack the flexibility in the control of the radiation output offered by LINACS.
- Currently, commercially available cobalt units may be quite adequate for many non-radical treatments, and there are even some applications where cobalt sources have been used in specially designed equipment to give a performance that could be argued to be superior to that obtainable from a conventional LINAC, for example stereotactic radiosurgery with the Elekta Gamma Knife and total body irradiation with custom-designed extended source skin distance (SSD) units

- In countries where facilities for the maintenance of linear accelerators are lacking, cobalt-60 therapy may be the most appropriate choice for radiotherapy.
- Many of the major techniques and advances in the physics of external beam therapy were developed on cobalt units including arc therapy; conformal therapy; transmission dosimetry; the development and measurement of tissue air ratios and the subsequent derivation of scatter air ratios; and differential SARs and the associated algorithms for treatment planning based on the separation of primary and secondary radiation.
- A recent study shows that conformal therapy, and even IMRT, could be adequately delivered with a cobalt-60 unit except for the most deep-seated tumours.

Basic construction and features of Cobalt-60 machine

- A major advantage of cobalt units is the basic simplicity of their design and construction that generally makes them inherently reliable.
- Nevertheless, care must be taken to ensure that they are robustly built and carefully maintained to minimise the potential hazards from the high activity source and the associated heavy shielding.
- It is essential that the physicists responsible for its performance understand the way that the unit is constructed and operates so that they will be aware of its capabilities and limitations.

The source

- The cobalt source usually consists of a series of either millimetre-size cylindrical pellets or thin, metallic discs sealed within a double capsule of stainless steel and manufactured to meet certain standards regarding protection from impact, corrosion, and heat.
- Active source diameters are generally in the region of 15 mm to 20 mm, being a compromise between achieving a high enough activity to obtain a reasonable output and keeping the source small enough to minimize the beam penumbra.
- The source length may be longer than the diameter, but this is not such a critical dimension because the photons from the rear of the source contribute relatively less to the clinical beam than those from the front.
- In a typical source, about 25% of the primary photons are lost due to self-attenuation. The space behind the active cobalt material in the capsule must be tightly packed with blank discs to eliminate movement. The low-energy β-ray emission from the source is filtered out by the capsule walls.

❑ The head

- The head of a cobalt unit has three basic functions: to shield the source, to expose the source as required, and to collimate the beam to the correct size.
- Shielding is achieved by surrounding the source and exposure mechanism with lead and, in many designs, with alloys of a higher density metal such as tungsten in order to reduce the volume.
- In some earlier designs, depleted uranium alloy (with a high percentage of U-238, density approximately 19 x 10^3 kg/m^3) was used, but this has been discontinued because of the problems with stability of the alloy as some of it became powdery and also because of the difficulties associated with eventual disposal.
- The source exposure mechanism is usually one of two types where either the source is moved between a safe and exposed position or where the source remains stationary, and a moving shutter opens or closes the beam.

❑ Gantry

- Modern cobalt units are manufactured in a standard isocentric configuration, with a source axis distance of 80 cm being the most common, to obtain a reasonable compromise between output, depth dose, and clearance around the patient.
- Units with an SAD of 100 cm are also practical if high activity sources can be afforded and offer the advantages of greater depth dose, larger field sizes, greater clearance around the patient, and geometrical compatibility with LINACs.
- To increase their versatility, isocentric units have often been made with the ability to swivel the head about a horizontal axis through the source.
- The swivel motion keeps the beam axis in a vertical plane, and when used with an appropriate gantry angle, may be useful for extended SSD treatments or for treating immobile patients in a bed or chair.

❑ Beam modifiers

- Beam flattening filters can, in principle, be successfully used on cobalt units. They are rarely employed in practice because of the consequent reduction in output.
- Without a flattening filter, the beam homogeneity is relatively poor across a large area beam, especially at greater depths, because of scattering in the tissue and the greater distance from the source to the field edges compared to the centre for a constant depth.
- Fixed wedge filters may be inserted into the beam below the end of the collimator to give a range of wedge angles, typically between 15^{o} and 60^{o}.
- Other beam modifiers and accessories such as the beam-defining light, range finder, accessory tray, laser positioning system, front and back pointers, etc., will be very similar to those employed on LINACs.

Linear Accelerator

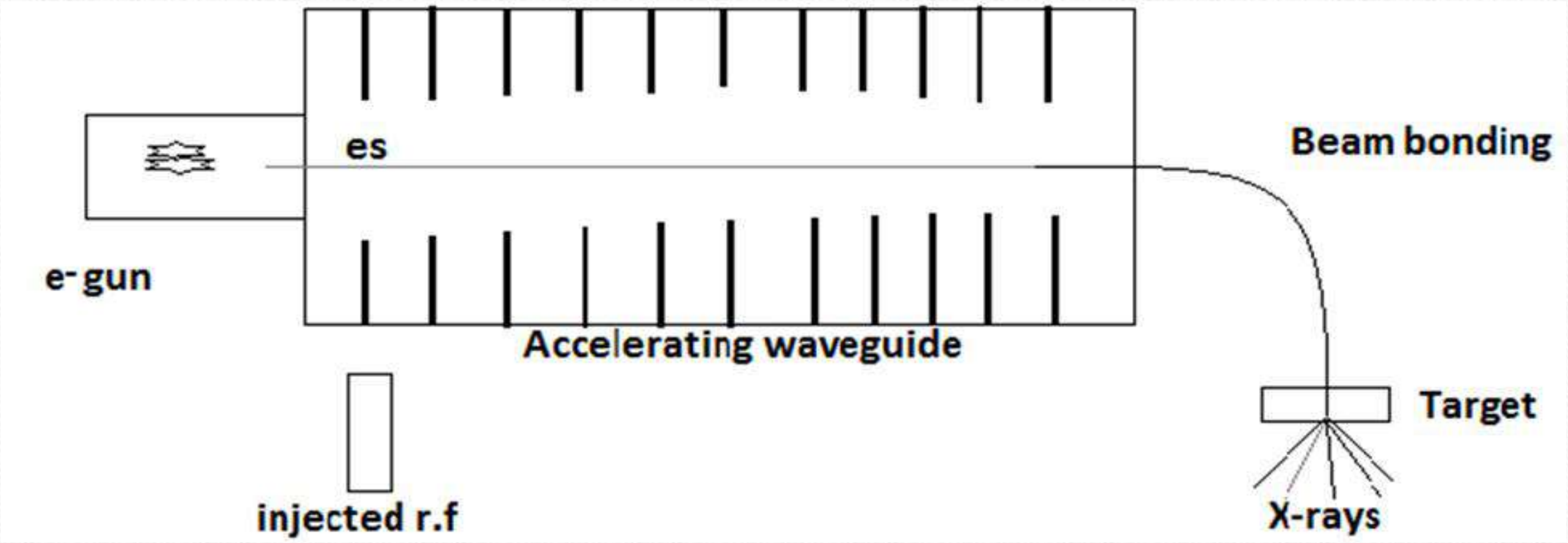
- Kilovoltage x-ray beams are useful for the treatment of skin lesions and shallow tumuors, but for deep-seated tumuors, where the dose that can be delivered is limited by the high skin dose.
- Megavoltage beams are not only more penetrating, but they have the major benefit that the maximum dose is delivered below the skin surface.
- Additionally, because the principal interaction with the tissue is through the Compton effect, the locally absorbed dose is not dependent on the atomic number of the tissue, and the dose to bone is not enhanced.
- It is not practicable to use transformer-based high voltage x-ray generators for energies above 300 kV and another method of accelerating the electrons must be used. One of the methods of accelerating electrons to high energies to produce megavoltage beams is by the use of linear accelerators.

❑Principles of operation of LINACs

- Linear accelerators are radiotherapy machines capable of producing beams of 4-18 MeV energies. Beams of higher energies are also available.
- In a linear accelerator designed for radiotherapy, electrons gain energy by interacting with a synchronized radio-frequency electromagnetic field rather than by acceleration by direct potential. The electrons are injected from one end into the accelerating waveguide. These electrons are accelerated to near the speed of light by radio frequency waves traveling through the waveguide.
- The waveguide consists of a long cylindrical tube containing a series of circular baffles. The waveguide is designed in such a way that the speed of propagation increases in the first part of the tube until it eventually reaches velocities close to the speed of light.
- The electrons injected into the waveguide are produced by a device called the electron gun.

❖ **See slide #22 for illustrative diagram**

Simplified diagram of linear accelerator designed for radiotherapy (beam bending pls.)



- The high-energy electron beams produced can be used directly for therapy or used for x-ray production.
- A target can be placed in the part of the electron beam leading to bremsstrahlung emission in the forward direction.
- The use of LINAC to produce X-rays for treatment is known as photon mode and is used for more deep-seated tumuors that cannot be treated adequately with an electron beam.

Advantages of LINAC over kilovoltage X-ray and Cobalt-60 teletherapy machines

- **Advantages**
  - It produces deeper penetration radiation
  - It has skin-sparing effect of the entrance side of the beam
  - There is homogenous absorption of its radiation by different tissues.
  - It operates in dual mode – particulate (electron) and photon (X-ray) modes
- **Disadvantage**
  - A major disadvantage of the linear accelerator is that because of the highly penetrating beam a relatively high-intensity beam is produced at the opposite side of the entry point.

End

Thank you