“Medical Linear Accelerators and how they work”

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• **Photon Beam (X-Ray):**
  • 4 MV To 22 MV.
  • Single Beam.
  • Dual Beams

• **Electron Beam:**
  • Multi-Beams with energy group between: 4- 22 MeV.
Analogy

• Envisage that electrons as being surfers carried along by a sea wave.
• It is hard for the surfers to catch the right wave at the right time.
• To gain speed they must remain on top.
What is a Linear Accelerator?

- A linear accelerator is a device that uses high Radio-Frequency (RF) electromagnetic waves to accelerate charged particles (i.e. electrons) to high energies in a linear path, inside a tube like structure called the accelerator waveguide.
- The resonating cavity frequency of the medical linacs is about 3 billion Hertz (cycles/sec).
- This is the most common device to treat cancer with external beam radiation.
How does it work?

• The linear accelerator (Linac), uses microwave technology to accelerate electrons in a part of the linac called waveguide, then allows these electrons to collide with a heavy metal target. As a result of these collisions, high energy X-Rays (Photons) are produced from the target.
How does it work?

- These high energy photons will be directed to the patient’s tumor and shaped as they exit the linac to conform to the shape of the tumor.

- Radiation can be delivered to the tumor from any angle by rotating the gantry and moving the treatment couch.
History

• From DC to RF accelerators.
History of medical applications of accelerators

1895 Wilhelm Conrad Röntgen (1845 – 1923) discovers the X-rays on 8th November at the University in Würzburg

1896 On 23rd January Röntgen announced his discovery and demonstrated the new kind of radiation by a photograph of the hand of his colleague Albert von Kolliker

1897 First treatments of tissue with X-rays by Leopold Freund at University in Vienna

1901 Physics Nobel prize for W.C. Röntgen

Schematics of an X-ray tube – an “electrostatic accelerator”
History:
High Voltage Therapy Of Cancer
Heidelberg, 1907
History of medical applications of accelerators

1899  First X-ray treatment of carcinoma in Sweden by Stenbeck and Sjögren

1906  Vinzenz Czerny founded the “Institute for Experimental Cancer research” in Heidelberg – the first of its kind

1913/4  Invention of part- and full-rotation radiation instrumentation

1920´s  Industrially manufactured X-ray apparatus; example from Reiniger-Gebbert & Schall AG (later: Siemens), Erlangen; 1922) with a high-voltage of 150 kV – without shielding!

1930  First linear accelerator principle invented by Rolf Wideroe

1949  Newberry developed first linear accelerator for therapy in England
Radiation „Concentrator“, Heidelberg 1913
Evolution

• DC Voltage Accelerators
• RF-Accelerators
• Linear Accelerators (Linacs)
DC accelerators: Cockcroft–Walton and Van de Graaff Generator

- In 1929/30 J.D.Cockcroft and E.T.S.Walton (Cavendish Labor, E.Rutherford) as well as R.J.Van de Graaff (Princeton) started to develop High Voltage Generators, for generating up to 10 MV.

The tandem Van de Graaff accelerator at Western Michigan University is used mainly for basic research, applications and undergraduate instruction.
Fig. 1.5 Van de Graaff’s very large accelerator built at MIT’s Round Hill Experiment Station in the early 1930s. The spheres stood 43 feet above the ground, supported on steel trucks that ran on a railroad track to make it possible to change the striking distance.
From DC to RF accelerators

• The limit of high-voltage equipment is several million volts. The plants are very complex for higher energy, and higher voltage cause spark discharges.

• Proposal of the Swedish scientist Ising 1924 to use fast-changing high-frequency voltage to accelerate instead of DC.

• The Norwegian scientist Wideröe 1928 successfully tested the first linear accelerator, which is based on this principle.

• Today almost all accelerators use RF systems for accelerating particles.
History of medical applications of accelerators

1950’s Development of compact linear accelerators by Varian, Siemens, GE, Philipps and others later with energies up to around 25 MeV (and above)

radiotherapy (Stanford linac) modern linac for therapy
Early Accelerators

The first one was installed at Hammersmith in 1952.

In 1956, the first patient was treated at Stanford University in the United States.

The Linac had an 8 MV X-ray beam with limited gantry motion.

These linacs were large and bulky.
2nd Generation Linacs

- The second generation, were *isocentric* units, which can rotate 360 degrees around the gantry axis.
- They were built between 1962 and 1982.
- They improved in precision and accuracy of dose delivery.
3rd Generation Linacs

- Better accelerator waveguides and bending magnet systems and more beam modifying accessories.
- Wider range of beam energies, dose rates, field sizes and operating modes.
- Higher reliability and computer driven.
Components
Drive Stand

- The gantry rotates on horizontal axis bearings located inside the Drive Stand, a large rectangular cabinet that is firmly secured to the treatment room floor.

- Major components located in the Drive Stand:
  - 1. Klystron or Magnetron
  - 2. RF Waveguide
  - 3. Circulator (connects item 1 and 2 above)
  - 4. Cooling water system.
The Klystron

- Provides the source of microwave power to accelerate the electrons.
- This is done by amplifying introduced Radio Frequency (RF) electromagnetic waves.
RF Generation

• **Klystron**
  
  – Used in High Energy Physics (HEP) and > 6 MeV medical linacs
  
  – Operation – effectively an RF amplifier
    
    • DC beam produced at high voltage
    
    • Low power RF excites input cavity
    
    • Electrons are accelerated or deaccelerated in the input cavity
    
    • Velocity modulation becomes time modulation during drift
    
    • Bunched beam excites output cavity
    
    • Spent beam is stopped
The Magnetron

- Electron tube that provides microwave power to accelerate the electrons.
- Preferred for lower electron energies, 4 MeV to 6 MeV linacs.
- For higher energies the Klystron is a better choice.
RF Generation

- Magnetron

\[ f_{\text{resonance}} \approx \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \]

The cavity exhibits a resonance analogous to a parallel resonant circuit.

Current around the cavity plays the role of an inductor.

Oscillating magnetic and electric fields produced in the cavity.

Charge at ends of cavity plays the role of a capacitor.

Electrons from the hot center cathode arriving at a negatively charged region tend to drive it back around the cavity. "Pumping" the natural resonant frequency.
RF Generation

• Magnetron
  – As seen in your microwave oven!
  – Operation
    • Central cathode that also serves as filament
    • Magnetic field causes electrons to spiral outward
    • As the electrons pass the cavity they induce a resonant, RF field in the cavity through the oscillation of charges around the cavity
    • The RF field can then be extracted with a short antenna attached to one of the spokes
RF Generation

- Magnetron

Hot cathode emits electrons which travel outward

Stable magnetic field $B$

Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.
Electron Gun

Electrons produced by thermionic emission
Accelerator Guide

• This is sometimes called the accelerator structure or accelerator wave guide.
• It can be mounted in the gantry horizontally for high energy single or dual energy machines with klystrons.
• Can be mounted vertically for low energy machines with magnetrons.
• The microwave power produced in the klystron or magnetron is transported to the accelerator structure to accelerate the pulsed electron bunches.
Gantry:

• Helps direct the X-ray (photons) or electron beams to the patient’s tumor.
• It rotates 360 degrees around a line/point, called the Isocenter.
• The gantry has the following components:
  - 1. Electron Gun
  - 3. Treatment Head.
Pulse Forming Network:

- This network stores electrical energy to provide flat topped DC pulses to the Thyatron.
- The Thyatron uses these pulses as a high-tech switch to deliver these pulses to the electron gun.
**Treatment Head:**

- Contains components designed to shape and monitor the treatment beams.
- For photon therapy, they consist of the bending magnet, target, primary collimator, beam flattening filter, ion chambers, secondary collimators, and one or more slots for trays, wedges, blocks, and compensators.
Modulator Cabinet:

• This is the noisiest of the linac system components and is located inside the treatment room.
• Contains 3 subcomponents:
  • Fan Control, cooling the power distribution system.
  • The auxiliary power distribution system, contains the emergency off button that shuts the power to the linac.
  • Primary power distribution system.
Bending Magnet:

• Changes the direction of the electron beam, downwards toward the patient.
• Bends the pulsed electron beam towards the target for X-rays or toward the scattering foil for electron treatments.
• Produces different beam paths for different energies.
• Needed for energies greater than 6 MeV.
X-Ray Target:

• The collision of the electrons with the high density transmission target creates the X-Rays (photons), forming a forward peaking shaped X-ray beam in the direction of the patient’s tumor.
• The X-ray target is located at the focus of the Bending Magnet.
• 94% of the electrons energy goes into heat.
The Water Cooling System

Located in the Drive Stand and Gantry

• Provides thermal stability to the system.
• Allows many components in the Drive Stand and Gantry to operate at a constant temperature.
Beam Flattening Filter:

- It is a conical shaped metal absorber, that absorbs more forward peaking photons than the ones in the periphery.
- Shapes the X-rays in their cross sectional shape.
- It is required to create a flattened beam of sufficient area, uniformity and symmetry.
- It is usually made of Tungsten, Steel, Lead, Uranium and Aluminum.
- In dual energy photon linacs, two flattening filters are required for the low and the higher photon energies.
Scattering Foils:

• The electron beams have pencil-like shapes.
• These narrow pencil beams need to be broadened to clinical useful beams and need to be made uniform.
• There is a different scattering foil for each electron beam energy produced.
• Made out of Aluminum or Cooper.
• A thin foil (or multiple ones) are used, they are measured in mils, i.e. 8 mils of Al is about 0.2 millimeters.
Monitor Ionization Chambers:

• They monitor integrated Dose, Dose Rate and Field Symmetry.

• The radiation that leaves the X-Ray Target or the electron Scattering Foils will pass through dual monitor ionization chambers, and they produce an ionization current.

• This ionization current is proportional to the X-ray of electron beam intensity.
Collimators:

• The radiation beams are collimated by adjusting the upper and lower collimator jaws.
• The jaws are made of High Z number, like Tungsten or Lead.
• The jaws can define a rectangular shaped beam up to 40 cm by 40 cm for X-ray beams.
Multi Leaf Collimators (MLC’s)

• They are heavy metal field-shaping devices with independent moving mechanisms used to create a custom like block to spare normal tissue and direct the radiation dose to the tumor.

• The MLC’s became a key element in the treatment delivery of X-ray beams with IMRT (Intensity Modulated Radiation Therapy).
Multileaf Collimators:-( continue)

Outline of the prostate

40 independently positioned Tungsten leaves.

Sketch of a multileaf collimator.
Treatment Couch:

- The treatment couch or table is where the patient lays still to receive the radiation treatment.
- It moves Up/Down, Right/Left and In/Out.
- Robotic couches are being used in some linacs nowadays for 3 more degrees of freedom.
Medical Linac

• Block diagram

Electron source

Pulse modulator

Accelerating structure

Klystron or magnetron

Bending magnet

Treatment head
Klystron Standing Wave Linac
Electron gun
Accelerator Wave guide
Target
Bending magnet
Carrousel with flattening filters and foils
Transmission Ion Chambers
MLC’s
Photon Beam path

Electron beam accelerated in wave guide

Forward peaked X-ray beam

X-Ray Target

Flattening Filter

Electron scattering foil

Secondary Collimator jaws

Accessory Holder Slot

X-ray Beam central axis
Accelerated electron beam

X-ray target removed

Electron Beam Central Axis

Scattering Foil

Transmission monitor ion chambers

Accessory Mount

Electron cone or applicator
electron beam after acceleration in wave guide

270° bending magnet

flattening filter mounted on the carousel: depending on the radiation quality different filters or scattering foils can be brought into the beam

target

primary collimator

transmission monitor ion chambers

two orthogonal sets of movable collimators allow definition of a rectangular field

beam intensity modifier: compensator or wedge as shown here

customized blocking for individual patients

block tray

X-rays

patient
Beam Modification Effects: Attenuation and Scattering

- Radiation reaching any point is made up of primary and scattered photons.
- Any introduction of the modification devices results in alteration of dose distribution, due to these two phenomena.
- The phenomena scattering results in an "blurring" of the effect of the beam modification.
- Scattering is more in kilovoltage radiation than in megavoltage radiation therapy.
Types of Beam Modification

There are four main types of beam modification:

- **Shielding**: To eliminate radiation dose to some special parts of the zone at which the beam is directed.

- **Compensation**: To allow normal dose distribution data to be applied to the treated zone, when the beam enters a or obliquely through the body or where different types of tissues are present.

- **Wedge filtration**: Where a special tilt in isodose curves is obtained.

- **Flattening**: Where the spatial distribution of the natural beam is altered by reducing the central exposure rate relative to the peripheral.
Types of Beam Modification Devices

- Field blocking and shaping devices:
  - Shielding blocks.
  - Custom blocks.
  - Asymmetrical jaws.
  - Multileaf collimators.
- Compensators.
- Beam spoilers

- Wedge filters.
- Beam flattening filters.
- Bolus
- Breast cone.
- Penumbra trimmers.
- Electron beam modification
Shielding: Collimators and Blocks

The higher scale contribution to the dose results in lower adjacent to the shields in kilovoltage radiation.

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Required lead thickness</th>
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<tbody>
<tr>
<td>4 MV</td>
<td>6.0 cm</td>
</tr>
<tr>
<td>6 MV</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>10 MV</td>
<td>7.0 cm</td>
</tr>
<tr>
<td>Co\textsuperscript{60} (1.25 MeV)</td>
<td>5.0 cm</td>
</tr>
</tbody>
</table>

Lesser amount scattered radiation megavoltage radiation means that the attenuation produced by shielding is also more.
Asymmetric or Independent Jaws

- Used when we want to block off the part of the field without changing the position of the isocenter.
- Independently movable jaws, allows us to shield a part of the field, and this can be used for "beam splitting".
- Here beam is blocked off at the central axis to remove the divergence.
- Use of independent jaws and other beam blocking devices results in the shift of the isodose curves.
- This is due to the elimination of photon and electrons scatter from the blocked part of the field.
Multi Leaf Collimators (MLC)

- Multileaf collimators are a bank of large number of collimating blocks or leaves.
- Can be moved automatically independent of each other to generate a field of any shape.
- 40 pairs of leaves or more having a width of 1 cm on less (projected at the isocenter).
- Thickness = 6 - 7.5 cm
- Made of a tungsten alloy.
- Density of 17 - 18.5 g/cm³.
- Primary x-ray transmission:
  - Through the leaves < 2%.
  - Interleaf transmission < 3%.
  - For jaws 1%
  - Cerrogebend blocks 3.5%.
Compensators 2D and 3D

Two-dimensional compensators

- Used when proper mould room facilities are not available.
- Thickness varies, along a single dimension only.
- Can be constructed using thin sheets of lead, lucite or aluminum. This results in production of a **laminated** filter.
Beam Spoilers

- Special beam modification device where **shadow trays** made from **Lucite** are kept at a certain distance from the skin.
- Based on the principle that **relative surface** dose increases when the surface to tray distance is **reduced**.
- First used by Doppke to **increase** dose to superficial neck nodes in head and neck cancers using 10 MV photon beams.
The wedge isodose angle ($\theta$) is the **complement** of the angle through which the isodose curve is tilted with respect to the **central ray** of the beam at any specified depth.

This depth is important because the angle will **decrease** with increasing depth.

The choice of the reference depth varies:

- **10 centimeters**.
- $1/2 - 2/3^{\text{rd}}$ of the beam width.
- At the 50% isodose curve (kV).
X-ray Beam Flattening Filter

- A beam flattening filter reduces the **central** exposure rate relative to that near the edge of the beam.
- Used for **Linear accelerators**.
- Due to the lower scatter the isodose curves are exhibit “forward peaking”.
- The filter is designed so that the **thickest** part is in the centre.
- Material: copper or brass.
- Penetrating power **should not** increase as this will alter the PDD as well as reduce the flattening.
- In cobalt beams:
  - The beam is almost monoenergetic.
  - Source emits uniform radiation all around.
Standard (STD) Linac and Flattening Filter Free (FFF) Linac

Linac-head components used in a Monte Carlo Simulation. Building a 6 MV and 10 MV FFF linac model by tuning incident beam parameters and matching them with measured data in a flattening filter removed standard linac.
Varian True Beam FF and FFF beams

- 3D, IMRT, IGRT, SRS, SBRT, RapidArc
- Photons with FF: 6, 10 and 15 MV
- Photons in FFF mode: 6 and 10 MV
- Electrons: 6, 9, 12, 16 and 20 MeV
- Max dose rates & Dose per beam pulse:
  - MU/min  | mGy/pulse
  - 6, 10, 15 | 600 | 0.28, 0.28, 0.56
  - 6 FFF  | 1400 | 0.65
  - 10 FFF  | 2400 | 1.11
  - Electrons  | 1000
  - Cone Beam CT (CBCT)
  - kV Imaging
  - Electronic Imaging Device (EPID)
Other modern FFF linacs

Cyberknife

Thomotherapy
Mitsubishi Vero Linac

Combined infrared and fluoroscopy-guided Real-Time Tumor Tracking*
Dose Monitoring and Beam Stabilization

- Transmission Ionization chambers.
- Integrated Dose and Dose Rate.
- Field uniformity control (flattening and symmetry).
- Multimodality treatment units.
- Treatment beam stabilization (constancy).
- Electrical and magnetic interference (pacemakers).
Accelerator Control and Safety Interlocking

• Computer Control.
• Miniaturization.
• Accelerator operational states.
• Interlock system.
• Protection against extreme dose.
• Control Console.
• Motion control system.
• Record and verify system.
• Patient record keeping (Electronic charts).
• Computer integration of Radiotherapy.
Information Flow in Radiotherapy
Linac Treatment Quality Assurance

- Linac QA protocols have become extensive through modern Linac development and implementation.
- AAPM TG-40 report still function as the base lines.
- AAPM TG-142 has gradually been emerging into modern clinical practice (tough on busy clinics).
- Regulatory agencies still have a hard time to follow due to manpower, training and budgeting constraints.
- End to End (local and independent) dose delivery verification tests with antropomorphic phantoms, may be a simpler way to tackle the new complexities with accurate dosimetry, mechanical precision, imaging, moving targets and special devices/procedures with higher tech Linacs.
References

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• Image pictures googled from the internet.
THANK YOU