PHYSICS OF ELECTRON BEAM THERAPY

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OUTLINE..

- Basics of electron Beam
- Dose distribution in water
- Dose distribution in patients
- Effect of tissue heterogeneity
- Treatment Planning

CLINICAL ELECTRON BEAM

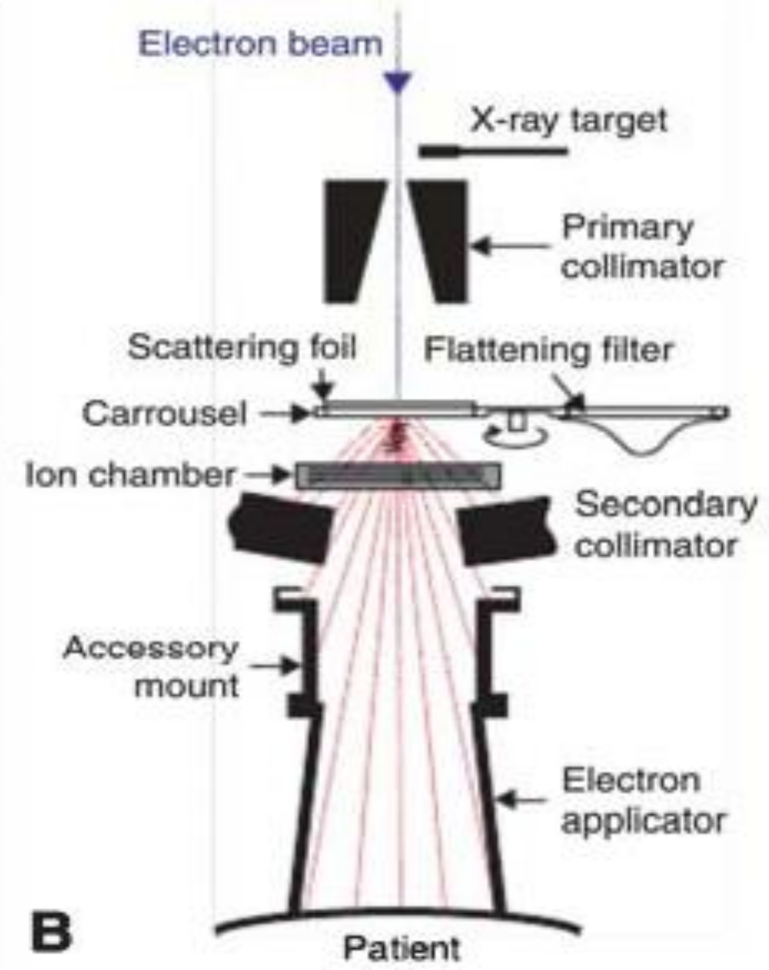
- Delivers a reasonably uniform dose from the surface to a specific depth , after which dose falls off rapidly, eventually to a near-zero value.
- Using electron beams allows disease within approximately 6 cm of the surface to be treated effectively, sparing deeper normal tissues.
- Electrons have been used in radiotherapy since the early 1950s.
- Modern high-energy linacs typically provide, in addition to two photon energies, several electron beam energies in the range from 4-25 MeV

CLINICAL USE

- Skin : Eyelids, nose, ear, scalp, limbs.
- Upper-respiratory and digestive tract: Floor of mouth, soft palate, retromolar trigone, and salivary glands
- Breast: Chest-wall irradiation following mastectomy; Nodal irradiation, Boost to the surgical bed
- Other sites: Retina, orbit, spine (craniospinal irradiation), Pancreas and other abdominal structures (intraoperative therapy) Cervix (intracavitary irradiation)

Electron Beam in accelerator

- Target retracted
- Carousel rotated to the appropriate scattering foil position
- Ion chamber monitors the beam
- Electron applicator is inserted
- X-ray collimator **jaws** set and **interlocked** to subtend a field few cms larger than the field defined by applicator
- Cutout defines final electron field size/shape



Broadening & flattening of electron beam

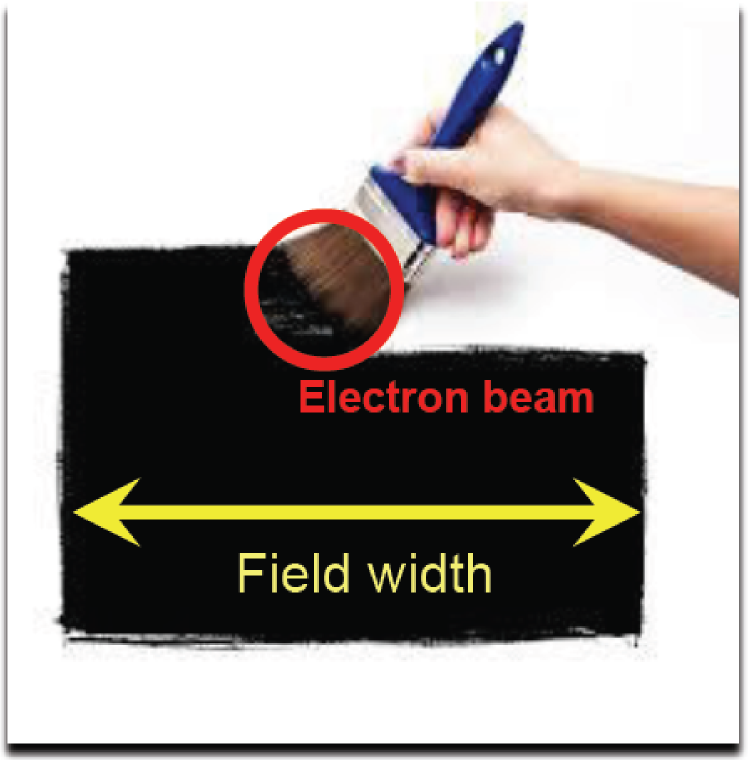
- Electron beam at the beryllium exit window is a **pencil beam** about **1 to 2 mm in diameter**

- Necessary to have a flat beam as large as 25 x 25 cm^2

- Two approaches:
  - Scanned beam technique *(obsolete now)*
  - Scattering foil(s) – *very thin metal sheets*
    - **Single scattering foil** *(obsolete now)*
    - **Dual scattering foil**

Scan beam method

- Electrons are charged particles
- Electron pencil beam from the exit window is magnetically deflected
- Scanned across the entire field
- Clinical machines
  - Sagittaire
  - Saturne



- *Scanned beams disappeared following accidents with Sagittaire and Therac*

Scattering foil method: Single foil

- **Single**, high atomic number scatterer will adequately flatten the beam
  - Early days linacs used this technique

- Different scattering foils having different thicknesses – mounted on a carousel – facilitate optimization for different energies

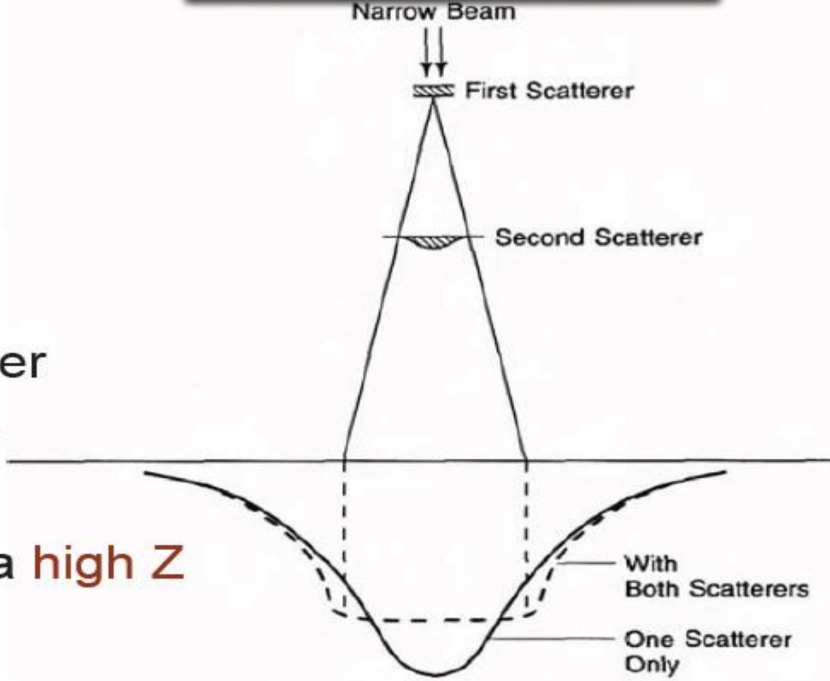
- ***X-ray contamination was higher than scanned beam!***

Scattering foil method: Dual foil

- **Dual-foil** scattering system — few centimeters or more between the two foils — **significantly improves** electron **beam flatness** characteristics
- Additional benefit: Reduced x-ray contamination
  - Particularly above 15 MeV
  - Field sizes ≥ 15 cm in dia

Dual scattering foil

- First, high atomic number (Z) scatterer is selected to minimize energy loss for a given scattering distribution
- Second scatterer
  - Low Z composite
  - Thicker in axis
  - Functions more as a field flattening filter
    - Preferentially scattering electrons to the periphery
  - Thicker portion may be in the form of a high Z "button" on a low Z foil

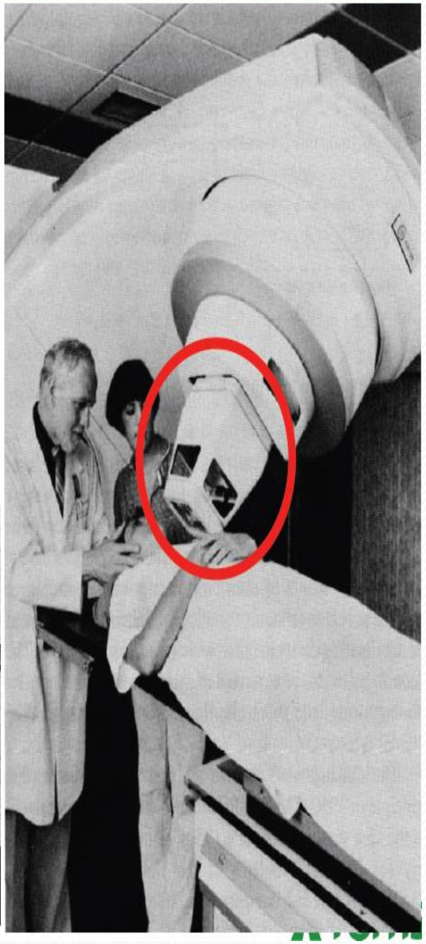


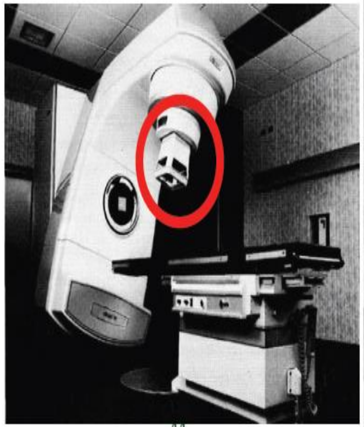
X-ray contamination was comparable to scanned beam

Electron Applicators

- Need for **all-sides-closed** applicators faded with the single scattering foil accelerators

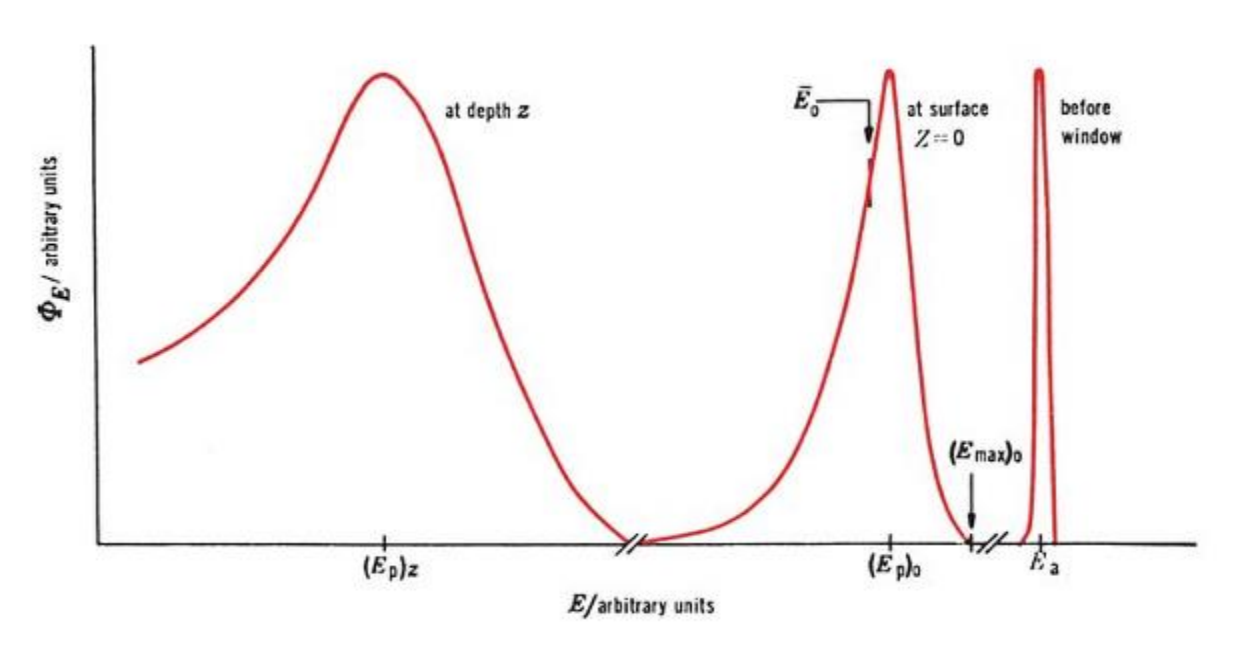
- Modern accelerators using dual scattering foils do not require them
  - They use all-sides-open applicators





Energy Specification

- Almost monoenergetic at the exit surface of the window
- A narrow spectrum of energies at the phantom surface
- Usually characterized by the energy at the phantom surface
- Energy spreads at depth



Energy Specification

Most Probable Energy

- $(E_p)_0 = C_1 + C_2R_p + C_3R_p^2$

$(E_p)_0$ the most probable energy at the phantom surface

R_p the practical range in centimeters

For water, C_1=0.22 MeV, C_2=1.98 MeV cm^{-1},

C_3=0.0025 MeV cm^{-2}

Mean Energy

$$\overline{E}_0 = C_4 R_{50}$$

for water, C_4= 2.33 MeV

Energy at Depth

The mean energy of the spectrum decreases linearly with depth.

$$\overline{E}_z = \overline{E}_0 (1 - \frac{z}{R_p})$$

INTERACTION WITH MEDIUM

- Interact with atoms by a variety of processes owing to Coulomb force interactions.

The processes are

- (a) inelastic collisions with atomic electrons
  (ionization and excitation),
- (b) inelastic collisions with nuclei (bremsstrahlung),
- (c) elastic collisions with atomic electrons, and
- (d) elastic collisions with nuclei.

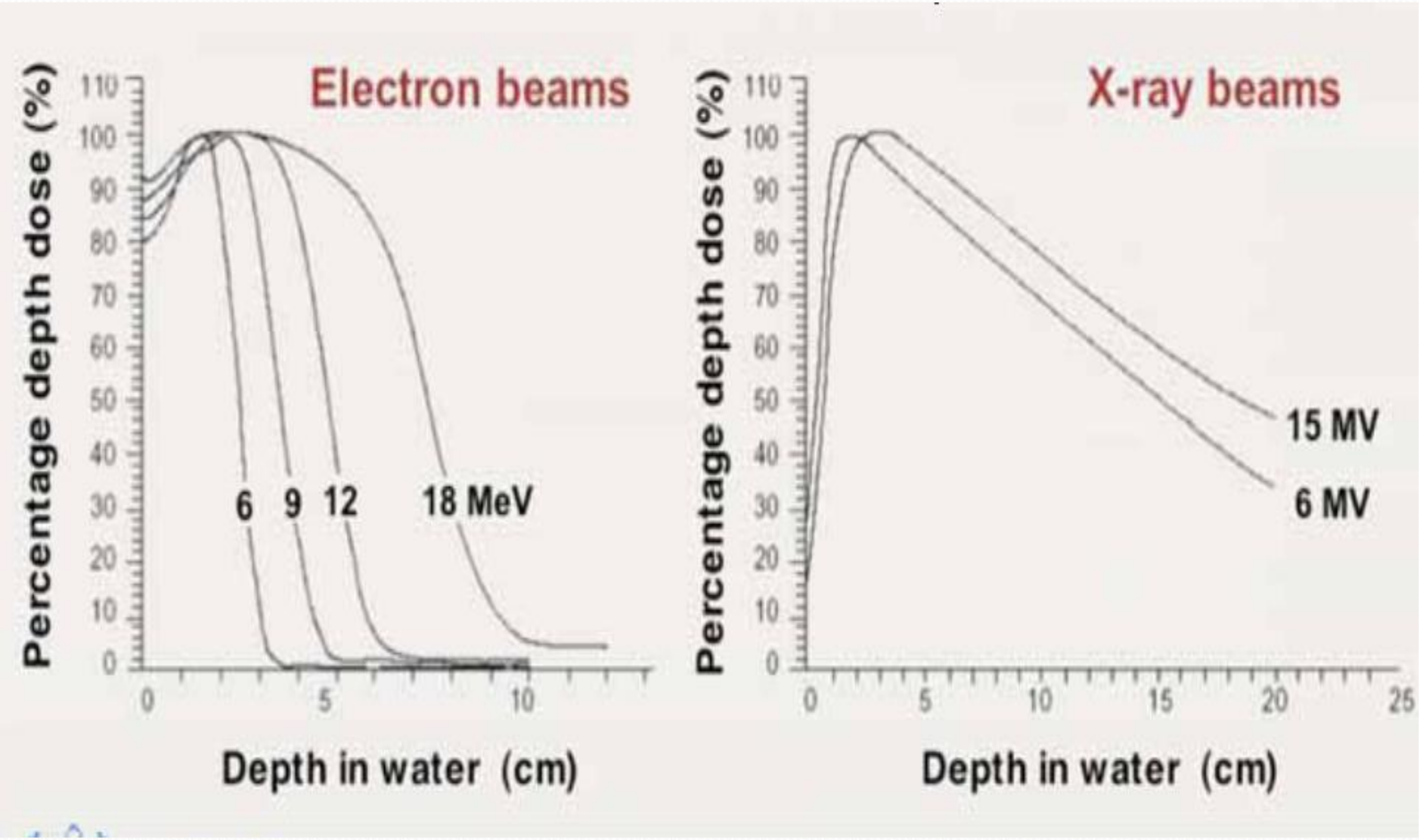
Output Calibration

- Ion Chamber
  - Plane-parallel ionization chambers for energies less than 10 MeV
  - Plane-parallel or cylindrical chambers for higher-energy beams
- Phantom
  - Water, or plastic phantoms such as polystyrene and Lucite
  - Dimensions large enough to provide full scatter for all field sizes and energies

Output Calibration

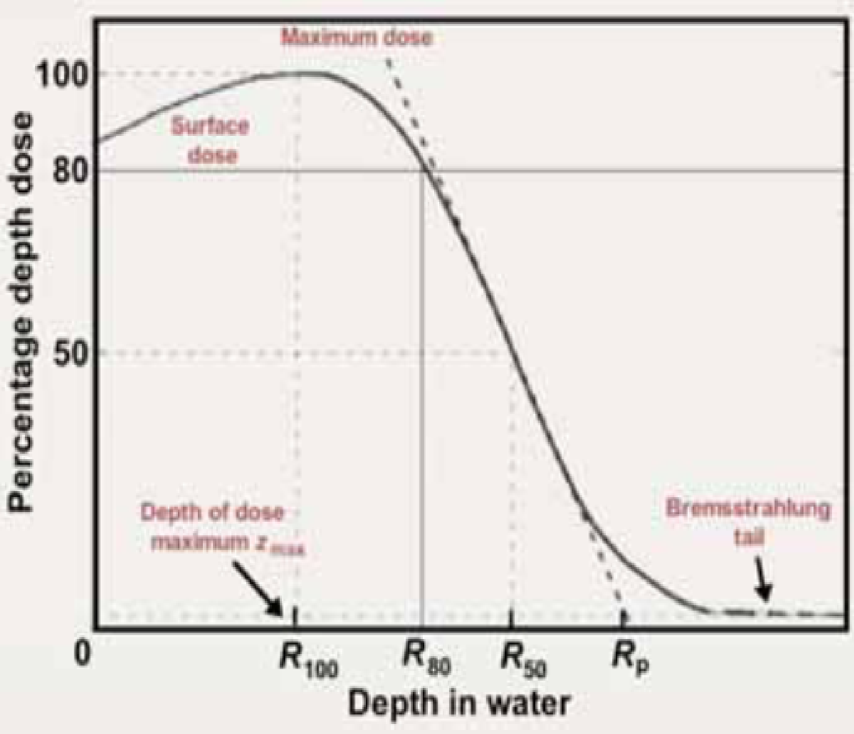
- Reference depth
  - The point of reference depth on the central axis
  - $Z_{ref} = 0.6 R_{50} - 0.1cm$
  - The deepest part of the maximum
    - To avoid low-energy electron contamination problems close to the phantom
- field size
  - 10×10 cm as reference field
  - The maximum dose at d_{max} set at 1 cGy/MU
  - Another cone is expressed as an output factor.

Dose distribution in water



Electron beam PDD

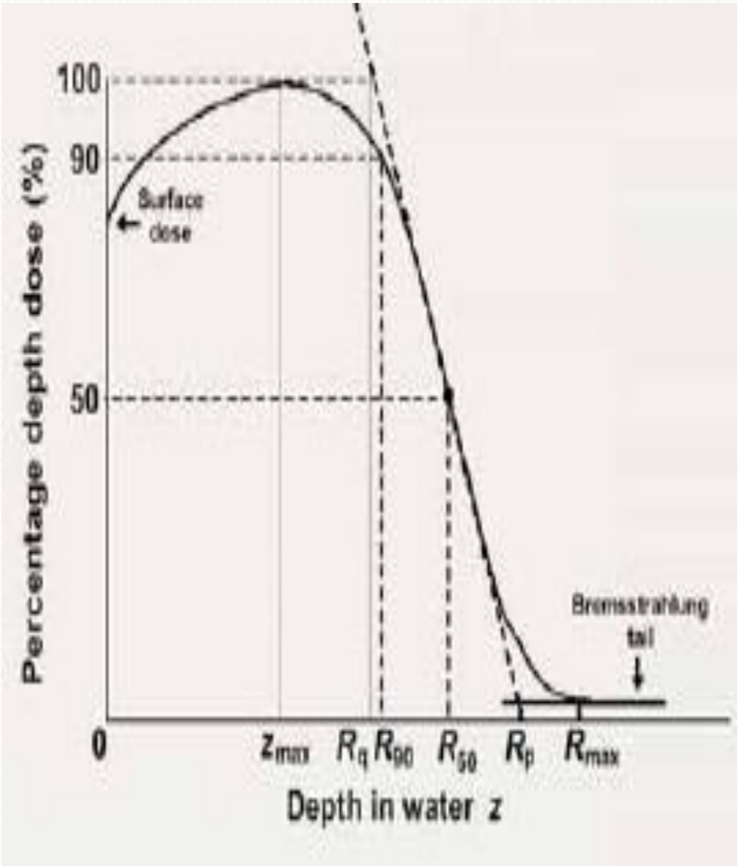
- The electron beam central axis percentage depth dose curve exhibits the following characteristics:



- The surface dose is relatively high (of the order of 80 - 100%).
- Maximum dose occurs at a certain depth referred to as the depth of dose maximum z_{max}.
- Beyond z_{max} the dose drops off rapidly and levels off at a small low level dose called the bremsstrahlung tail (of the order of a few per cent).

Components in PDD

- Maximum Range R_{max} – Depth at which the extrapolation of the tail meets the bremsstrahlung background.
- Practical Range R_p – Depth at which the tangent plotted through the steep portion intersects with the extrapolation of bremsstrahlung tail.
- Therapeutic Range R_{85} – Depth at which the PDD value is 85% of D max value.



- The bremsstrahlung dose depends on electron beam energy

  4 MeV - 1%

  10 Mev - 2.5%

  20 MeV – 4%

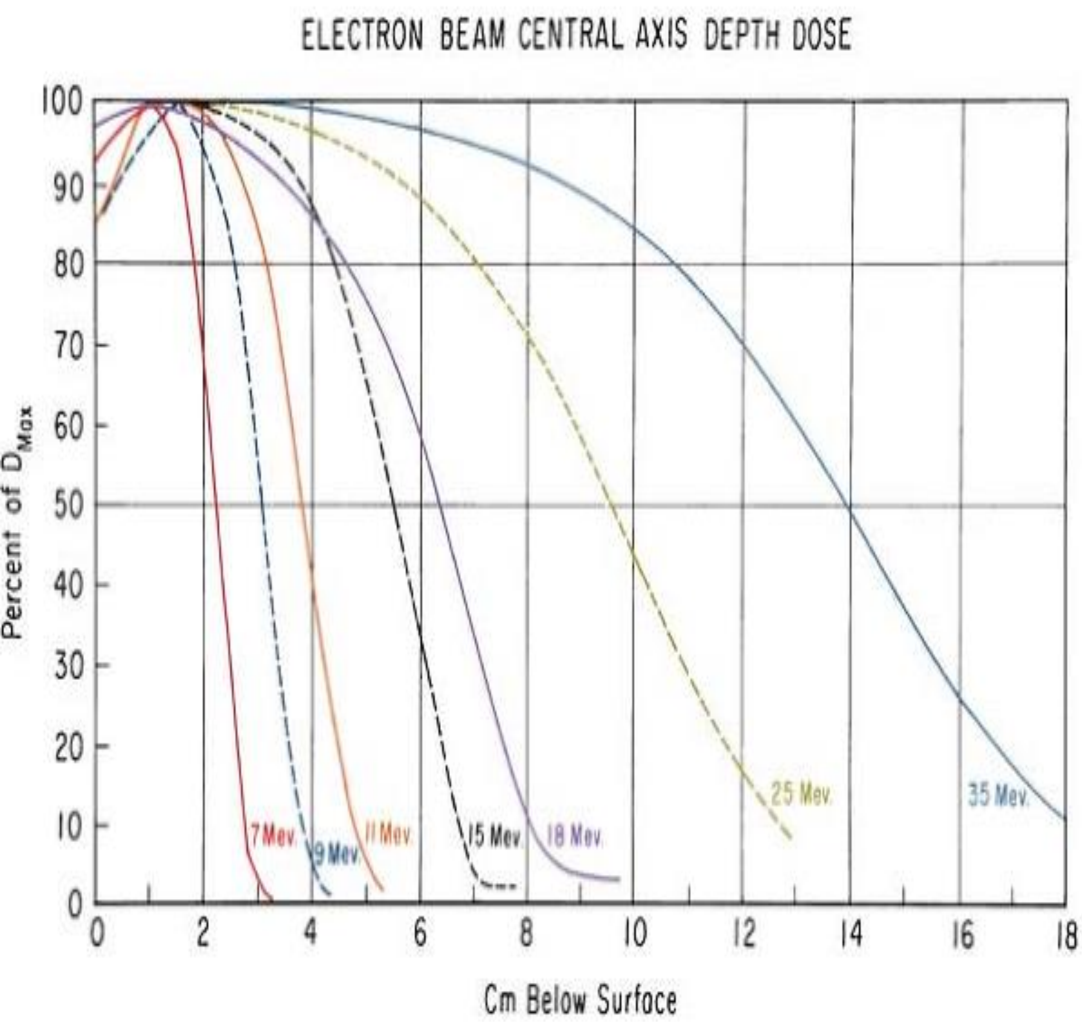
Rule of Thumb with electron beam

- The depth in cm at which electrons deliver a dose 85% isodose level , is equal to approximately one-third of the electron energy in MeV.
- The depth in cm at which electrons deliver a dose 90% isodose level , is equal to approximately one-fourth of the electron energy in MeV.
- The range of electrons in cm is equal to approximately one half of the electron energy in MeV.
- The rate of energy loss is about 2 MeV/cm

Electron Energy and Treatment Depth

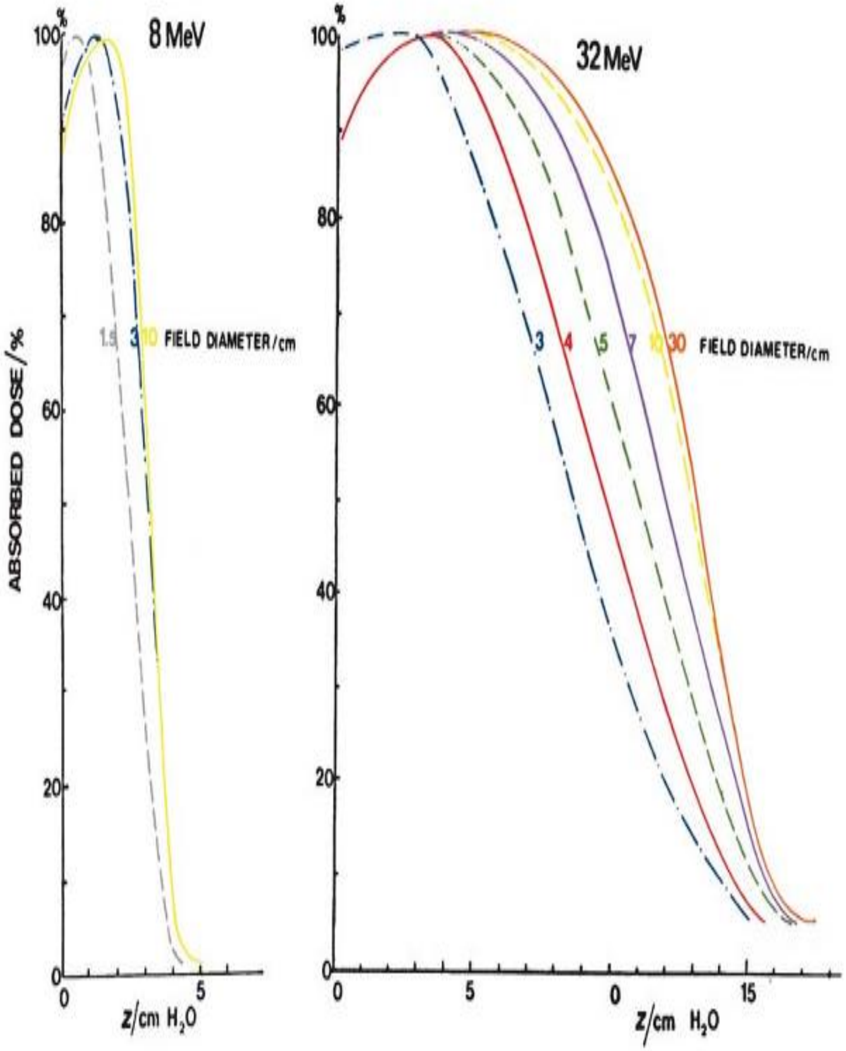
- Most useful treatment depth, or therapeutic range , of electrons is given by the depth of the 85% depth dose.
- Because the dose decreases abruptly beyond the 85% dose level, the treatment depth and the required electron energy must be chosen very carefully .
- The guiding principle is that, when in doubt, use a higher electron energy to make sure that the target volume is well within the specified isodose curve.

Energy dependence of depth dose



- The Percentage Depth dose increases as the energy increases.
- However, unlike the photon beams , the percent surface dose for electrons increases with energy.

Field Size dependence of Depth dose



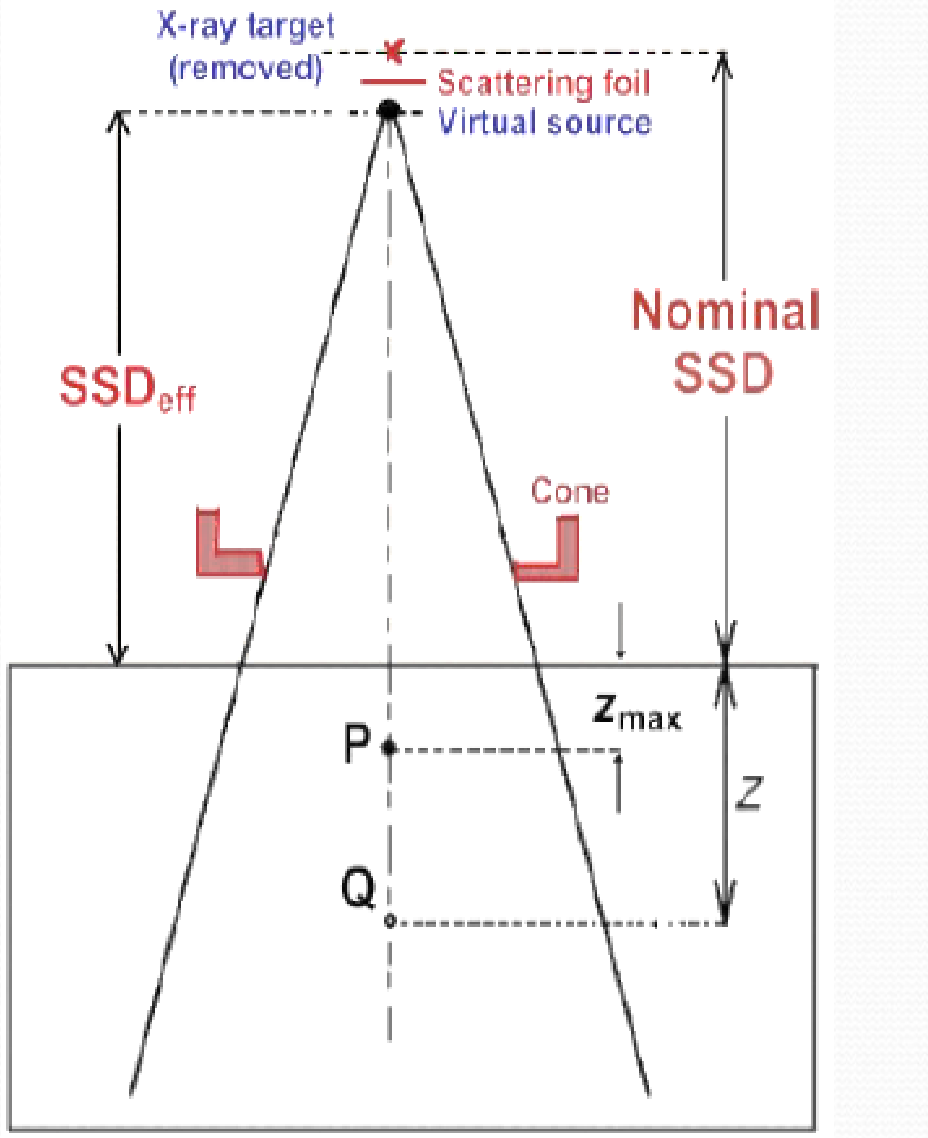
- Depth dose has a significant dependence on field size, and the dependence varies with incident electron energy.
- Loss of side-scatter equilibrium , results in R_{100} shifting toward the surface as field size decreases .
- The shift also increases the R_{90-10} distance, as R_{10} changes only slightly.

Surface dose with electron beams

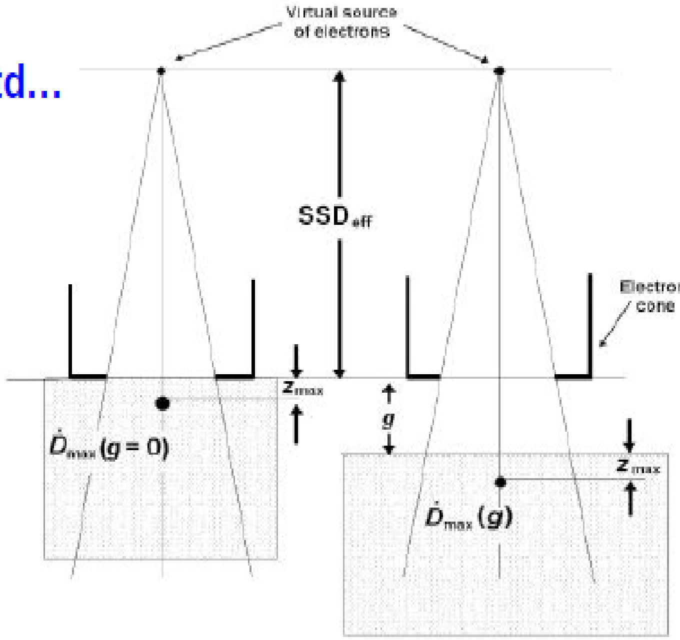
- Unlike in photon beams, surface dose increases with energy
  - 70-75% for 4 to 6 MeV beams
  - >90% for high energy beams
- Why?
  - At low energies pronounced dose deposition at d_{max}
  - Hence surface dose becomes lesser compared to this high dose at d_{max}
  - At high energies, the effect is not significant
  - Surface dose, as compared to low energies, becomes higher

Electron Virtual Source

- Photon beams originate from the accelerator x-ray target
- Electrons appear to originate from a point which does not coincide with the scattering foil or accelerator exit window
- The virtual or effective source to surface Distance is called **SSD**eff
- **SSD**eff helps in correcting output due to inverse square law (up to 120 cms)

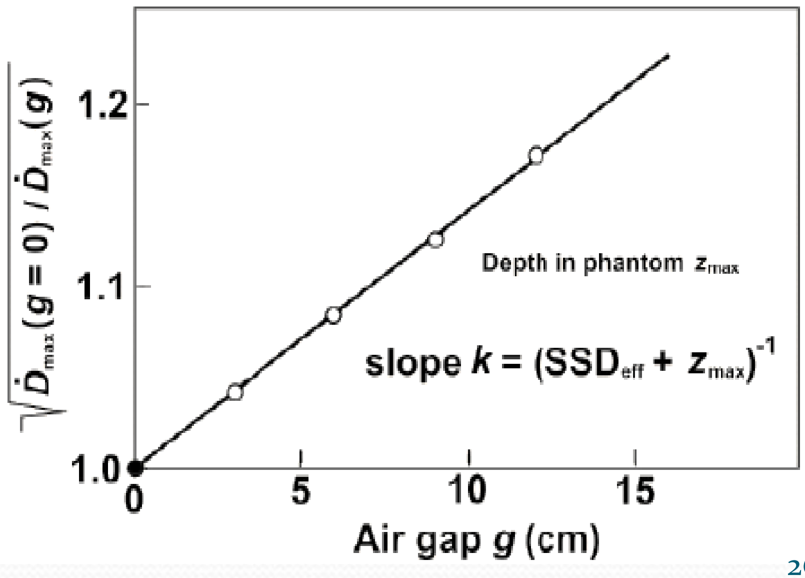


Virtual Source Position Contd...

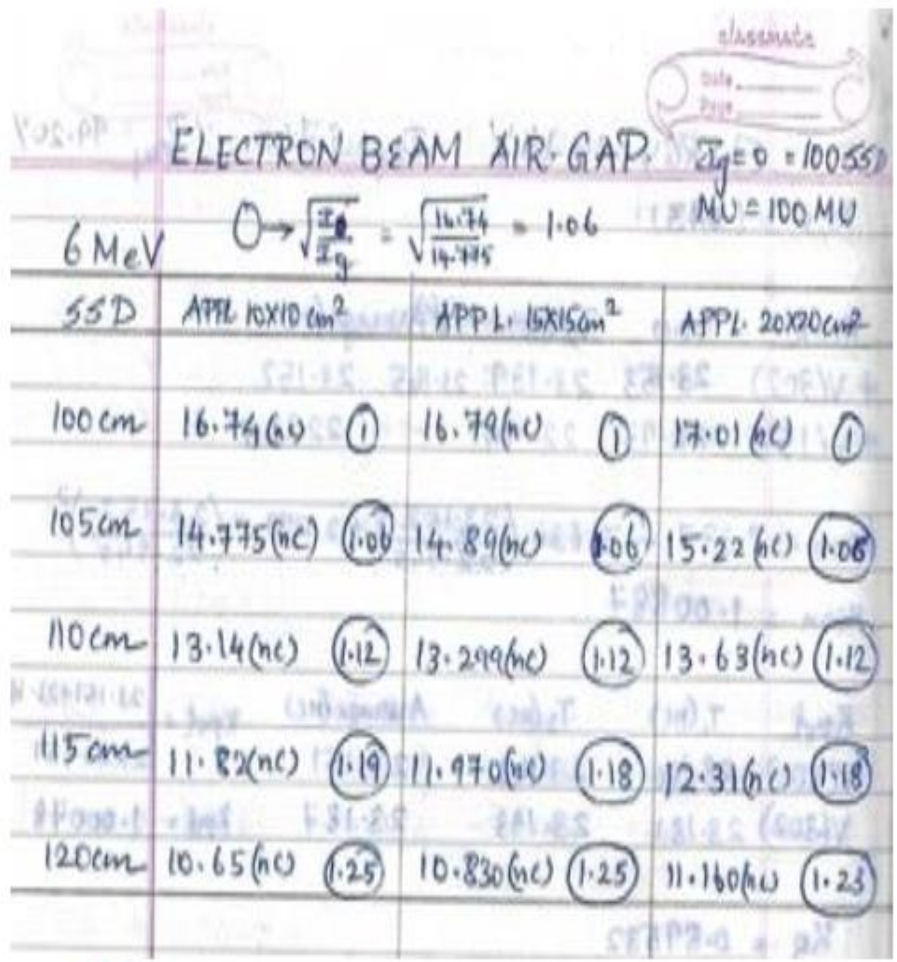


- ✓ A common method for determining SSD_{eff} consists of measuring the dose rate at Z_{max} in phantom for various air gaps *g* starting with at the electron cone
- ✓ Dose Measuring at various distances with electron applicator by varying the gap between the phantom surface and the applicator (gaps ranging from 0 to 15 cm).

$$\frac{I_0}{I_g} = \left(\frac{SSD_{eff} + z_{max} + g}{SSD_{eff} + z_{max}} \right)^2 \quad \text{or} \quad \sqrt{\frac{I_0}{I_g}} = \frac{g}{SSD_{eff} + z_{max}} + 1$$



Practical example

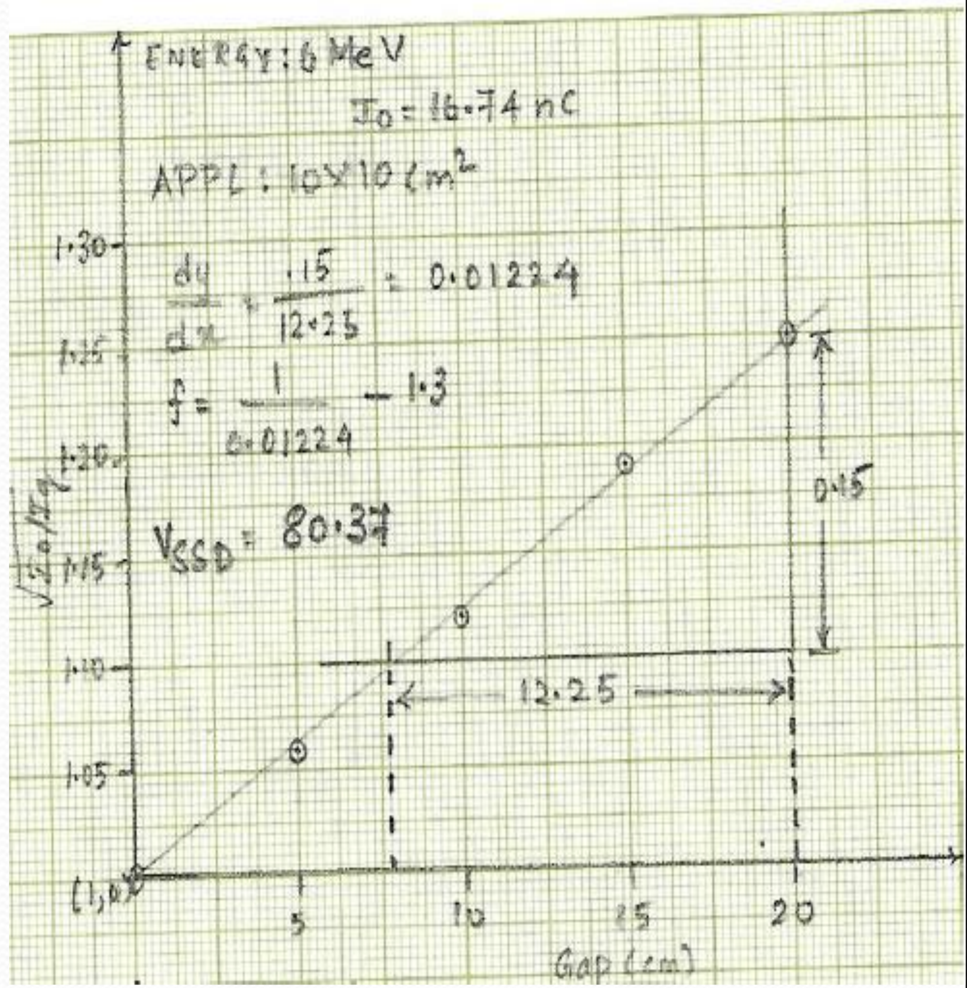


ELECTRON BEAM AIR-GAP $I_{g=0}$ = 100 SSD

MU = 100 MU

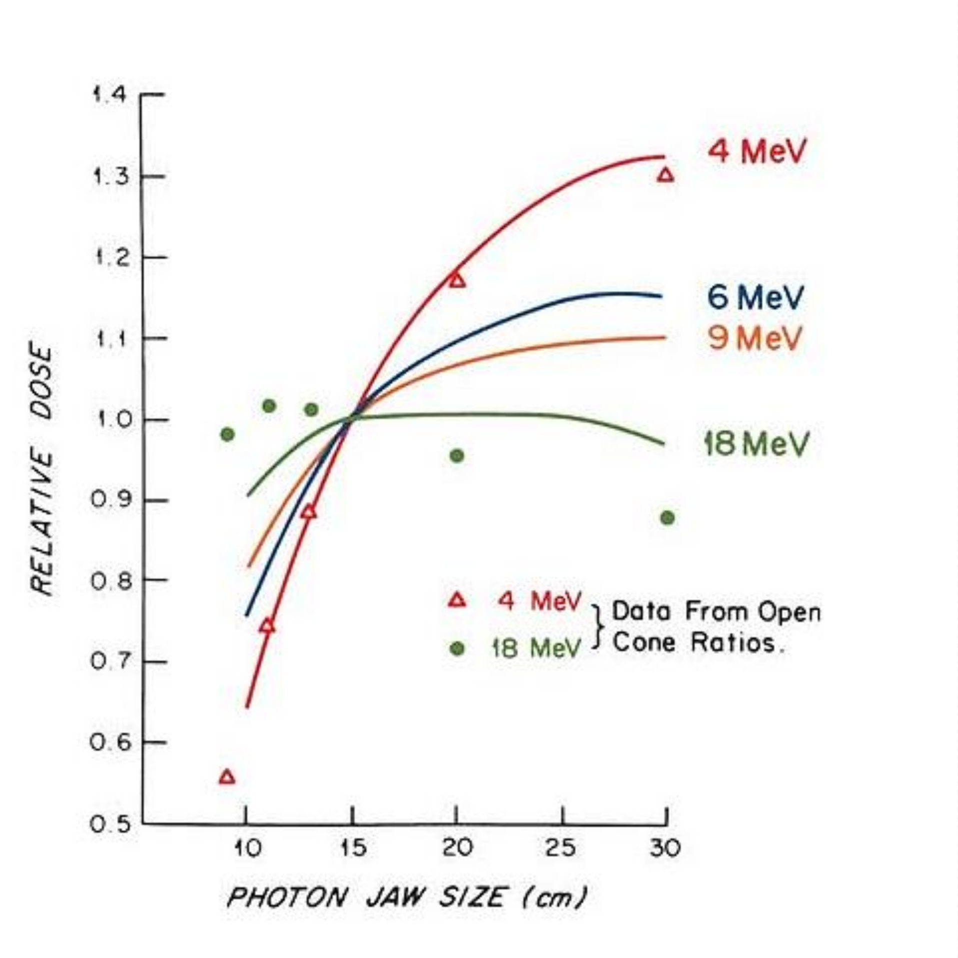
6 MeV $\quad \textcircled{1} \rightarrow \sqrt{\frac{I_0}{I_g}} = \sqrt{\frac{16.74}{14.775}} = 1.06$

SSD	APPL 10X10 cm²		APPL 15X15 cm²		APPL 20X20 cm²	
100 cm	16.74(nC)	1	16.79(nC)	1	17.01(nC)	1
105 cm	14.775(nC)	1.06	14.89(nC)	1.06	15.22(nC)	1.06
110 cm	13.14(nC)	1.12	13.299(nC)	1.12	13.63(nC)	1.12
115 cm	11.82(nC)	1.19	11.970(nC)	1.18	12.31(nC)	1.18
120 cm	10.65(nC)	1.25	10.830(nC)	1.25	11.160(nC)	1.25



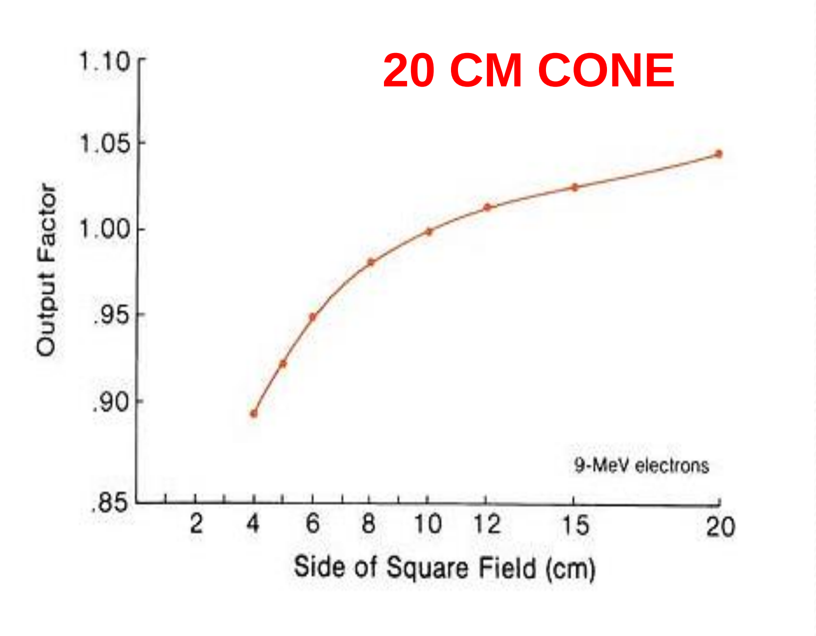
Output variation with Field size

- The dose increases with field size because of the increase scatter from the collimator and phantom.
  - If the x-ray jaw setting changed with the field, the output would vary widely, especially for lower-energy beam.

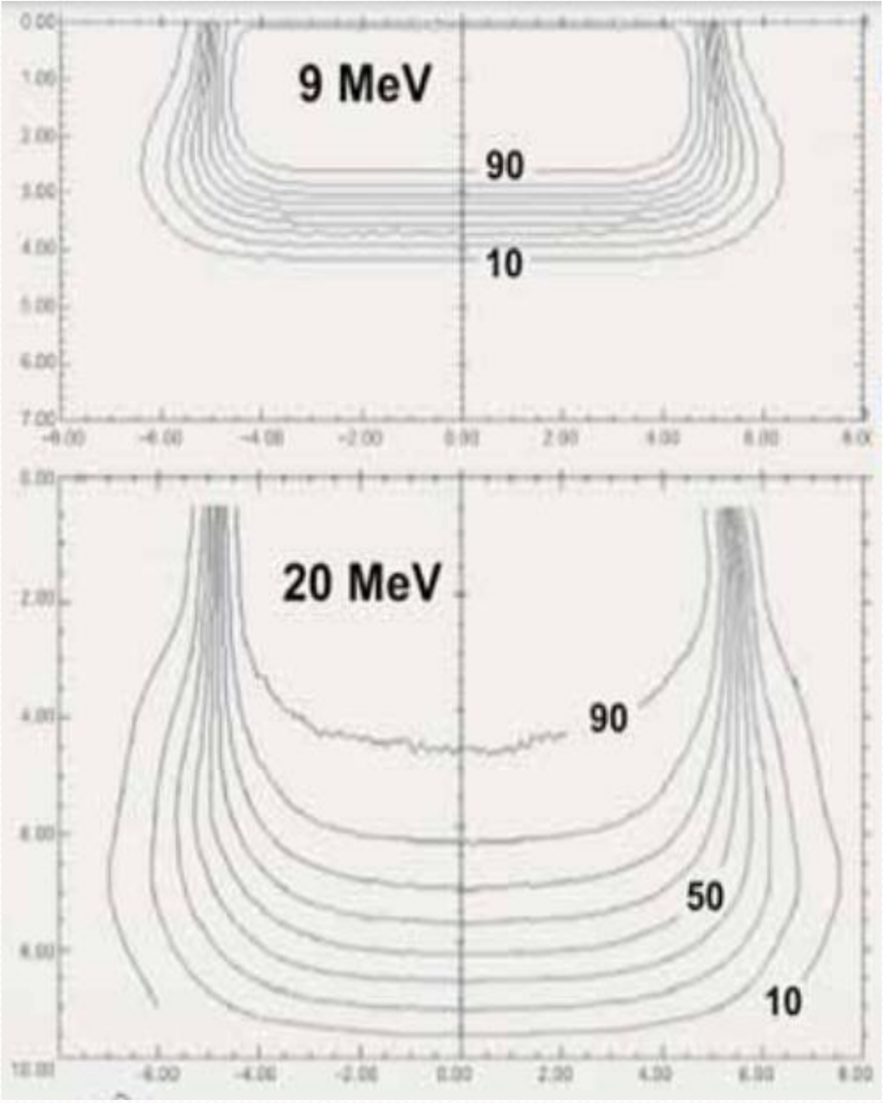


Field Size Dependence

- Various size cone with a fixed jaw opening minimizes the variation of collimator scatter

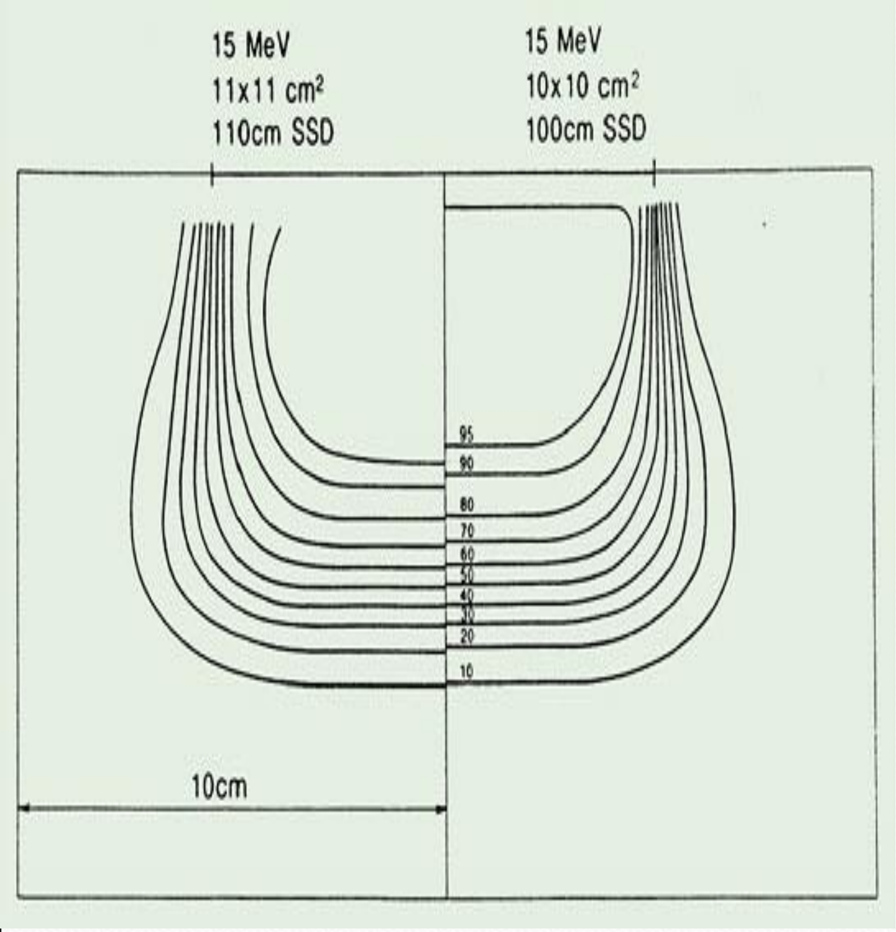


Isodose curves



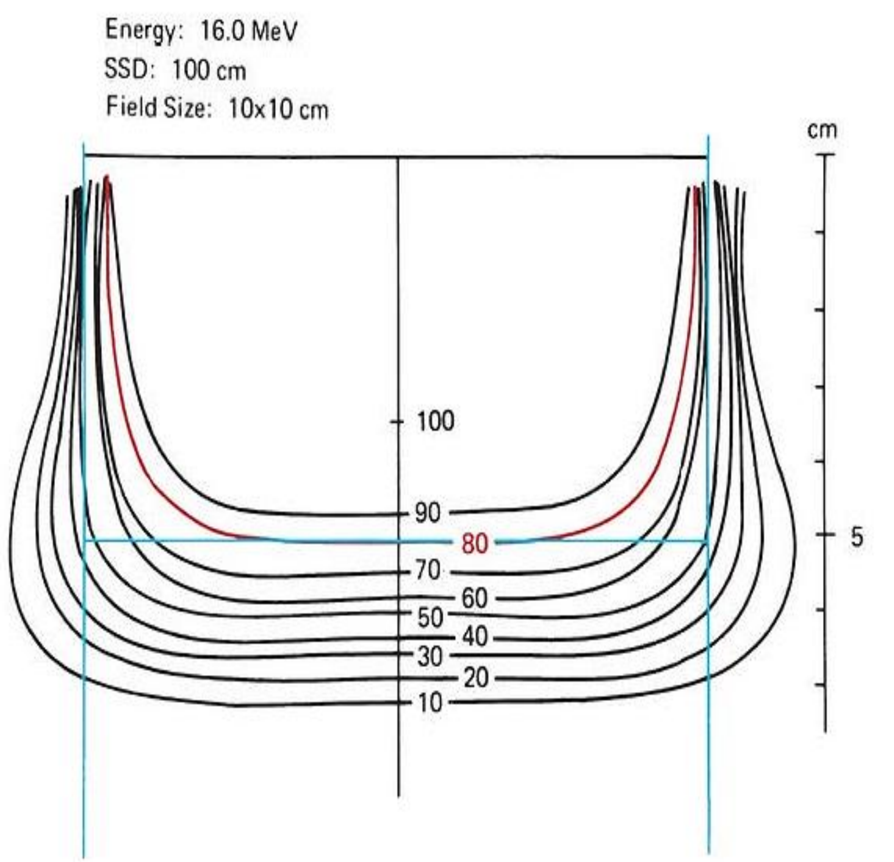
- As electron beam penetrates the isodose curves expands due to scattering.
- Low value isodose curves (<20%)bulges out as the result of increase in electron scattering angle with decreasing electron energy.
- Above 15 MeV electrons exhibit lateral constriction of higher value isodose curves (>80%)
- Penumbra is the distance between 80%-20% isodose level at a depth of $R_{85}/2$

SSD dependence of depth dose



- Depth-dose variations with SSD are usually insignificant .
- Differences in the depth dose resulting from inverse square effect are small because electrons do not penetrate that deep .
- The significant growth of penumbra width with SSD restricts the SSD in clinical practice to typically 115 cm or less.
- The primary effect of inverse square is that R_{90} penetrates a few millimeters deeper at extended SSD at the higher energies .

Choice of Field Size

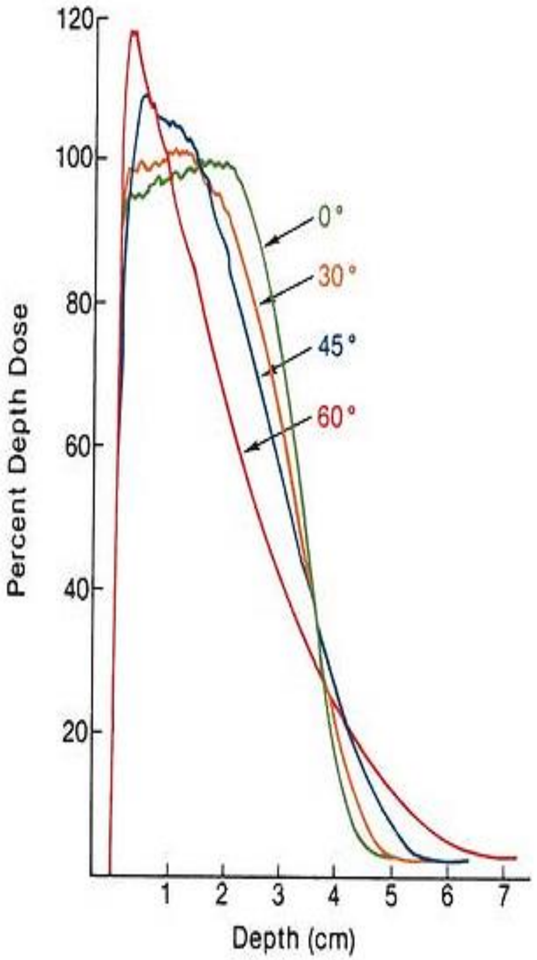


- A significant tapering of the 80% isodose curve at energies above 7 MeV
- A larger field at the surface may be necessary to cover a target area adequately.

Dose distribution in patient

- The ideal irradiation condition is for the electron beam to be incident normal to a flat surface with underlying homogeneous soft tissues , which is seldom encountered clinically.
- As the angle of incidence deviates from normal, as the surface becomes irregular , and as internal heterogeneous tissues (e.g., air, lung, and bone) become present, the qualities of the dose distribution deviate from that in the phantom.
- Internal heterogeneities can change the depth of beam penetration .
- Both irregular surfaces and internal heterogeneities create changes in side-scatter equilibrium , producing volumes of increased dose (hot spots) and decreased dose (cold spots).

Oblique Incidence

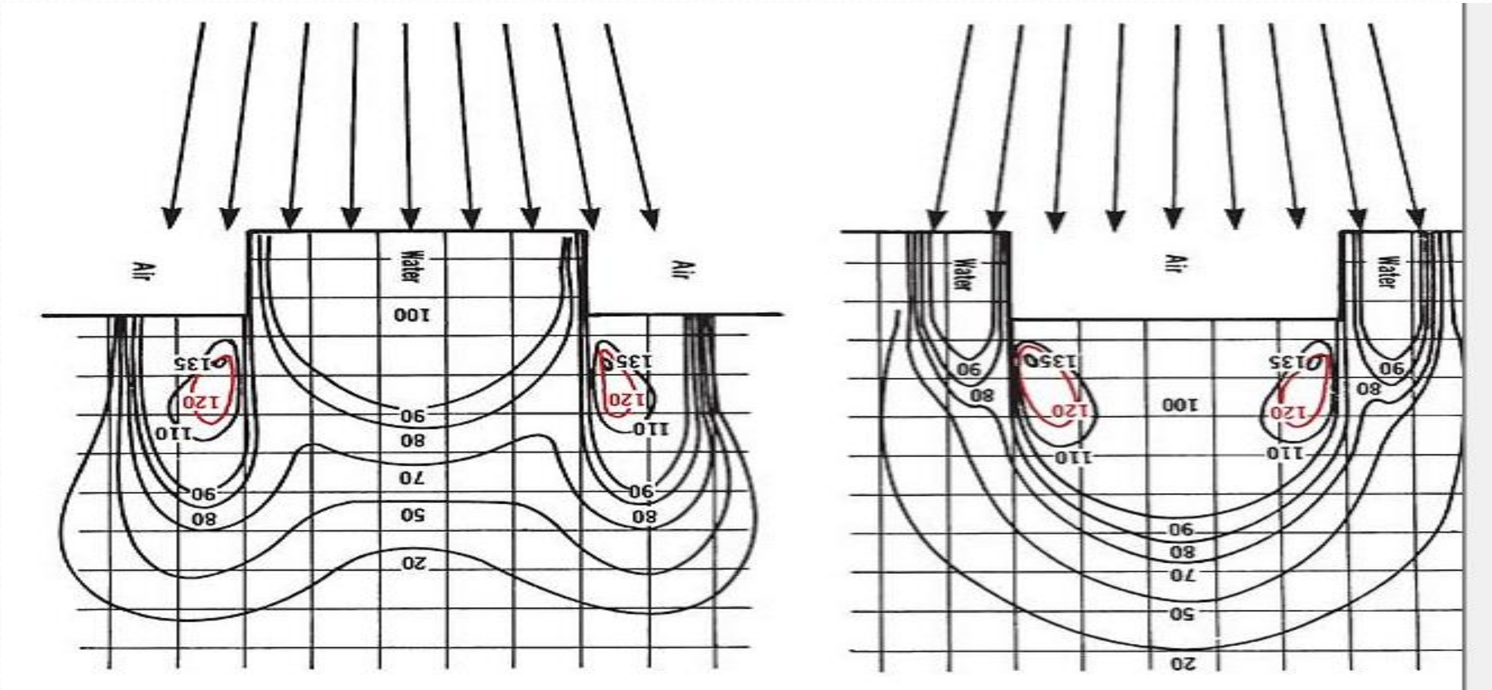


10MeV

- For obliquely incident beams whose angle of incidence is greater than 30°, there is a significant change in the shape of PDD.
- As the angle of beam incidence increases, the d_{max} decreases .
- As the angle of incidence increases beyond 60°, the shape of the PDD curve changes significantly, and the D_{max} increases dramatically.
- Clinical examples where sloped or curved surfaces are encountered include chest wall treatments, treatment of the limbs , and treatments of the scalp .

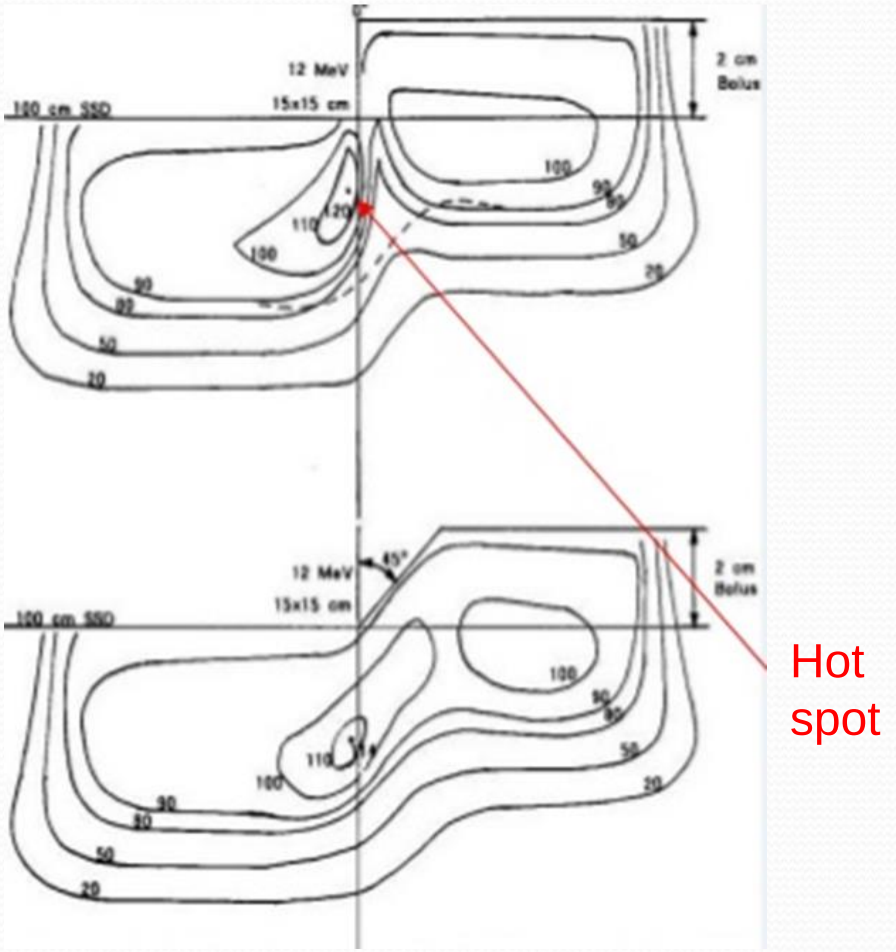
Surface Irregularities

- Sharp surface irregularities produce localized hot and cold spots in the underlying medium due to scattering.
- Electrons are predominantly scattered outward by steep projections and inward by steep depressions.
- In practice, such sharp edges may be smoothed with an appropriately shaped bolus .



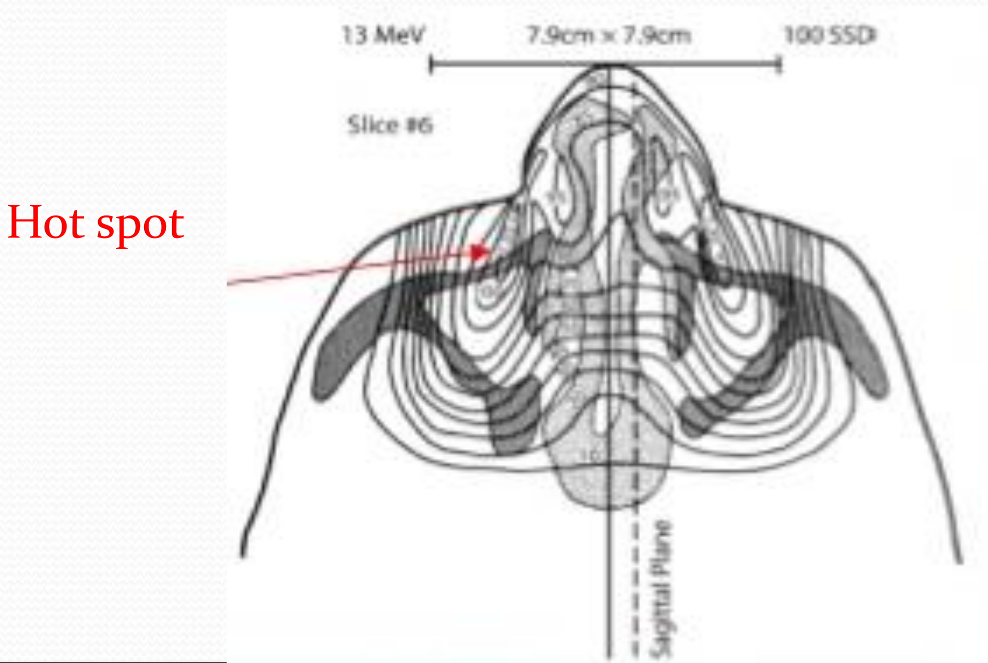
Use of bolus for Electrons

- If a bolus is used to reduce beam penetration in a selected part of the field, its edges should be tapered.



Surface Irregularities

- Irregular skin surfaces in the patient are encountered primarily during the treatment of the nose, eye, ear and ear canal, and in the group area
- Surgical excisions can also create treatment areas with abrupt changes in the surface of the body.



Tissue Heterogeneity

- It is difficult to determine dose distribution within or around small inhomogeneities because of enhanced scattering effects. However, for large and uniform slabs, dose distribution beyond the inhomogeneity can be corrected by using the coefficient of equivalent thickness (CET) method.

$$d_{eff} = d - z(1 - \text{CET})$$

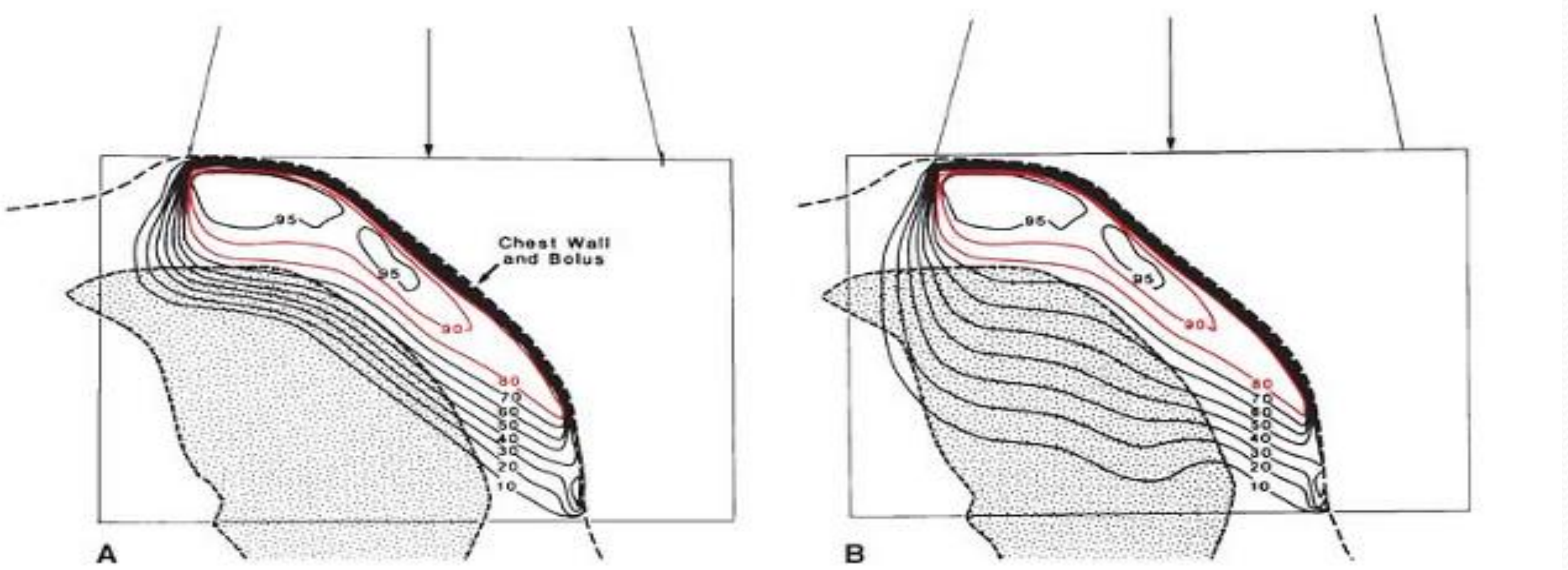
- Where, d is the actual depth of point of interest, Z the thickness of inhomogeneity
  - CET of a compact bone = 1.65
  - CET of a spongy bone = 1
  - CET of lung = 0.25
- Thus, a beam that would penetrate 1 cm of normal, unit density material such as water would penetrate to a 4-cm depth in lung having a density of 0.25 g/cm^3.

Tissue Heterogeneity

Lungs

- Electron beam results in an increased penetration of electron beams into lung tissue.
- Left Figure shows a 12-MeV beam incident on the chest wall of a patient without taking the density of the lung into account .
- Right Figure shows the dramatic increase in dose to the lung when this inhomogeneity is taken into account in the calculation.

Without lung correction	With lung correction



Tissue Heterogeneity: Air Cavities

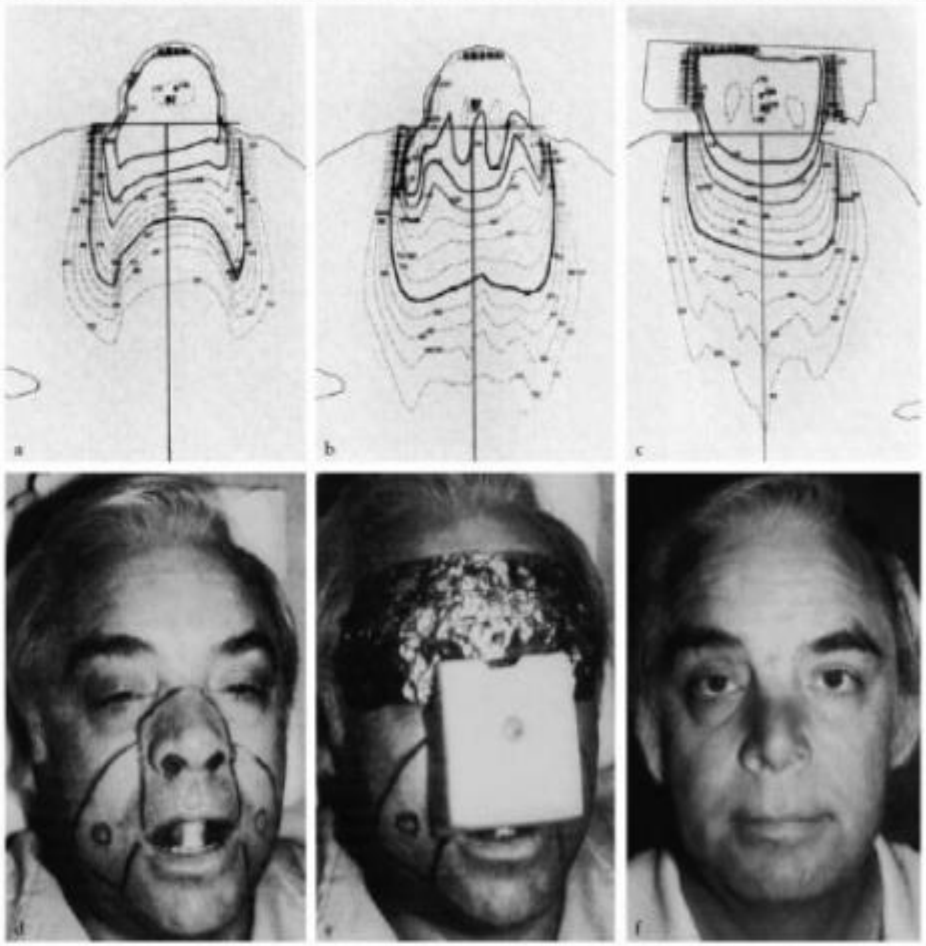
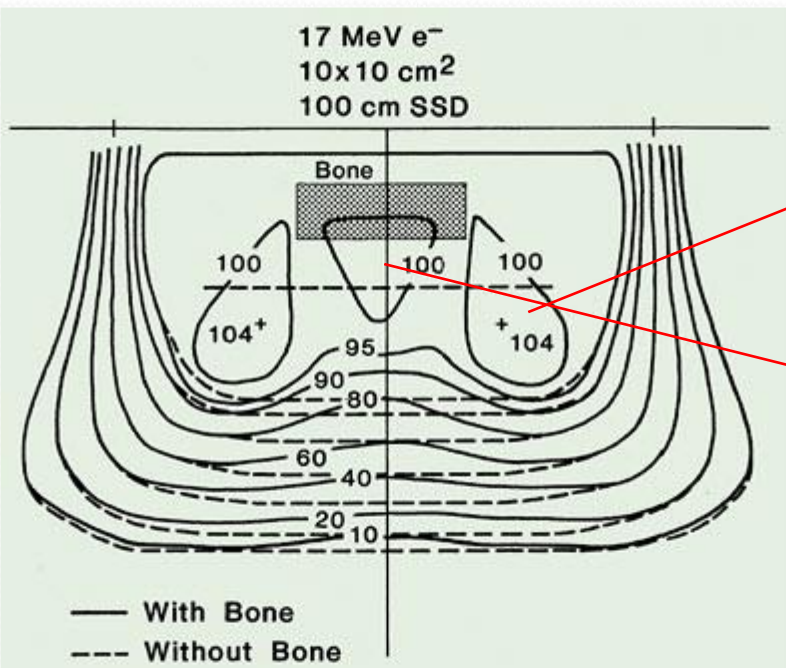


Fig. 7.15a–f. a Dosimetry without heterogeneity correction gives false impression of isodose distribution. b Dosimetry with heterogeneity correction shows more accurate isodose distribution. c Improved isodose distribution with use of internal and external bolus. d Actual treatment fields, with bolus placed in nostrils and intraoral stent in place. [Reprinted with permission from McNeese (1989)]. e Completion of treatment setup with external wax bolus and lead eyeshield in place. f 2 years after completion of therapy. [Reprinted with permission from McNeese (1989); Chobe et al. (1988)]

- Because of the low physical density of air (0.0013 g/cm3), electrons pass easily through this medium.
- Very high doses penetrating into the brain and other underlying tissues can easily be seen from this diagram.
- Use of bolus can reduce dose to deep lying structures

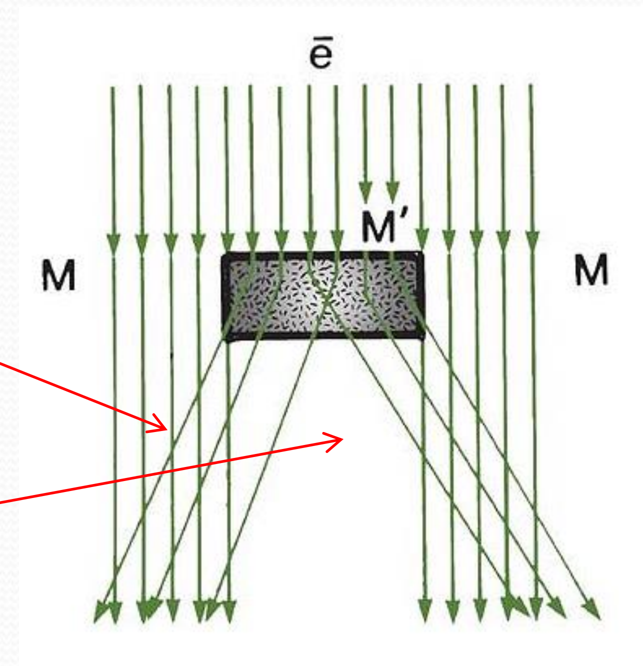
Tissue Heterogeneity:Bones

- Bone density can range from 1.0 g/cm ^{3} to 1.10 g/cm ^{3} for the spongy bone of the sternum to 1.5 g/cm ^{3} to 1.8 g/cm ^{3} for hard bones such as those of the mandible, skull.
- Beneath the bone, the electron isodoses are shifted toward the surface due to extra attenuation.



Hot spot

Cold spot



Treatment planning-Target definition

- As with photon beam treatments, the first step in the initiation of electron therapy is to determine accurately the target to be treated .
- All available diagnostic, operative, and medical information should be consulted to determine the extent and the final planning target volume (PTV) with appropriate margins to be treated before simulation and placement of the electron fields is initiated

Treatment Planning : Selection of Beam Energy

- The electron energy for treatment should be selected such that the depth of the 85% isodose line covers the distal or deepest portion of the region to be treated in addition to an approximate 5-mm additional depth beyond the treatment region.

- This depth of R_{85} can be approximated by dividing the energy of the electron beam in MeV by three (Eo /3) in centimeters of water.

Treatment Planning: Field Shaping and Collimation

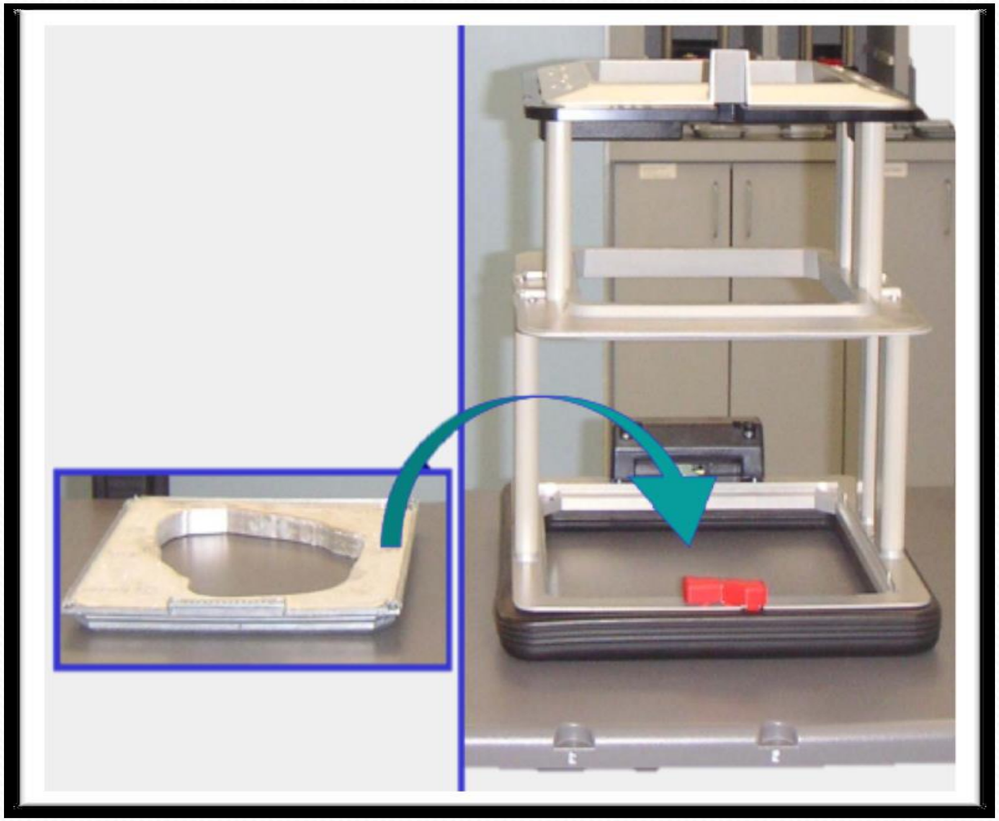
- Electron collimation consists of multiple collimating components; however, the electron field shape usually is defined by an applicator's collimating insert and/or skin collimation.
- The lead thickness in millimeters required to stop the primary electrons is given by ,

$$T_{lead} = 0.5 Eo + 1$$

- For example, an 10-MeV beam requires 5 mm of lead.
- Lipowitz metal has a density 20% less than that of lead; therefore, its thickness should be 20% greater. For example, an 10-MeV beam requires 6 mm of Lipowitz metal.
- Lipowitz metal collimating inserts usually are fabricated at a constant thickness that is sufficient for the greatest energy on the treatment machine.
- For a machine whose maximum energy is 20 MeV, the Lipowitz metal thickness should be a minimum of 12 mm.

. Treatment Planning: Beam Field Shaping and Collimation

Cone attached to the gantry



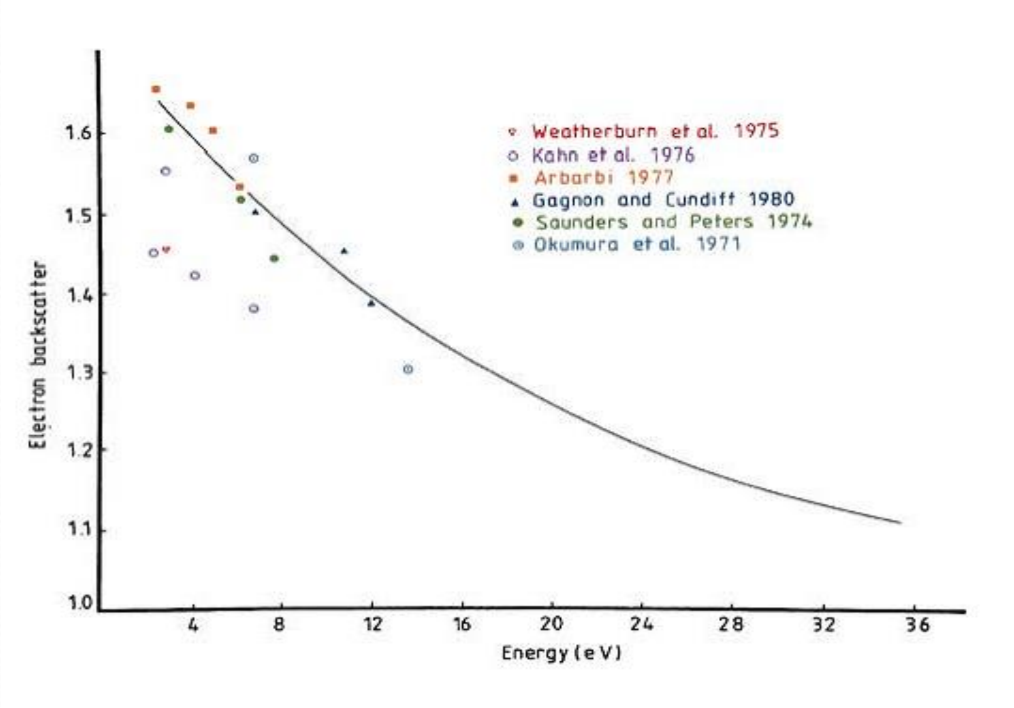
Cones of different size with insert

Treatment Planning: Internal Shielding

- In some instances, internal shields need to be used to protect underlying sensitive structures.
- This is most commonly seen when using fields to treat the lip, buccal mucosa, and eyelid lesions.
- Lead is the most common material used for the production of internal shields because of its availability and ease of use.
- The required thickness of the shield depends on the energy of the electron beam at the location of the internal shield, the fact that electrons decrease in energy by 2 MeV/cm in muscle, and that 1 mm of lead is required as shielding for every 2 MeV of electron energy (plus 1 mm for safety).
- Thus, if 9 MeV of electrons are used to treat the buccal mucosa of thickness 1 cm, a shield placed beneath the cheek to protect the oral cavity would have to be 4.5 mm thick. This is because the electrons would decrease to 7 MeV after penetrating 1 cm of tissue, and that 3.5+1 = 4.5 mm of lead would be required to shield7 MeV electrons.

Internal Shielding : Electron Backscatter

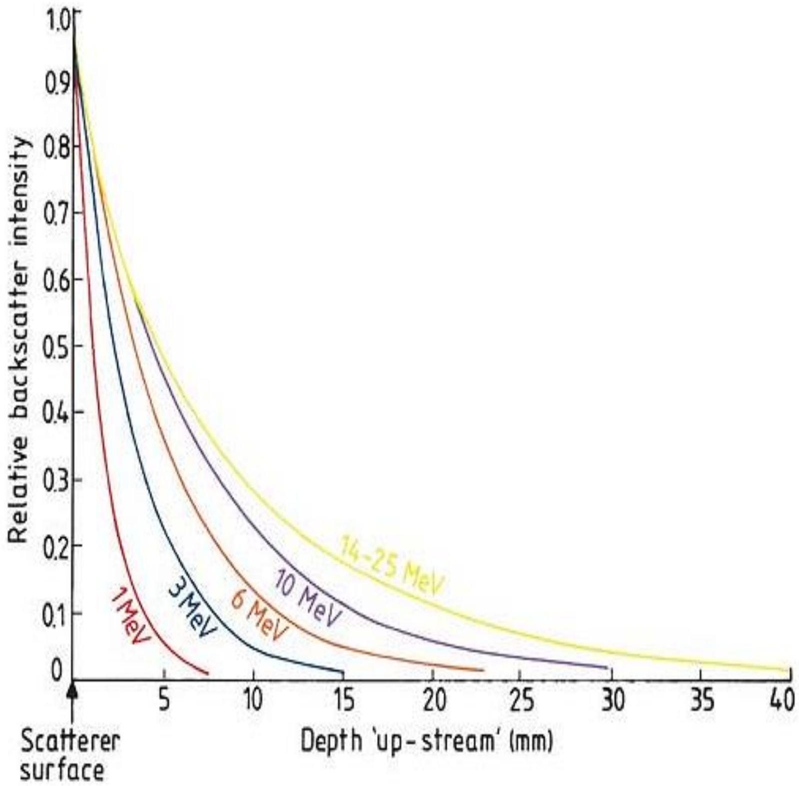
- The electron backscatter from lead enhances the dose to the tissue near the shield
  - 30% - 70% in the range of 1 – 20 MeV, having a higher value for the lower-energy beams



For the polystyrene-lead interface

$$ESF = 1 + 0.735e^{(-0.052\ Ez)}$$

Relative backscatter intensity v.s.the thickness of absorber (polystyrene)



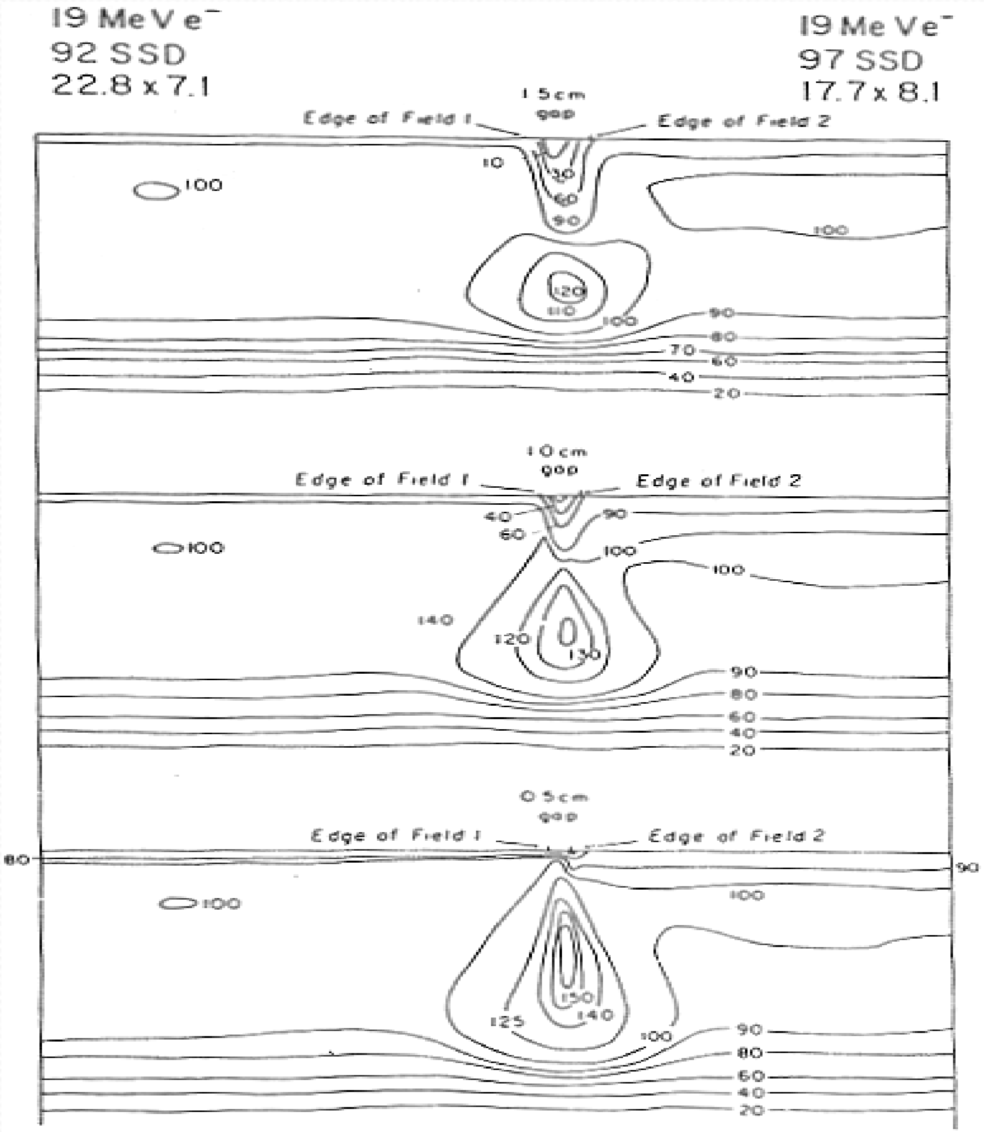
To dissipate the effect of electron backscatter, a suitable thickness of low Z absorber may be placed between the lead shield and the preceding tissue surface

Intensity of backscattered electrons from lead transmitted through polystyrene in the upstream direction of the primary beam

Treatment Planning: Bolus

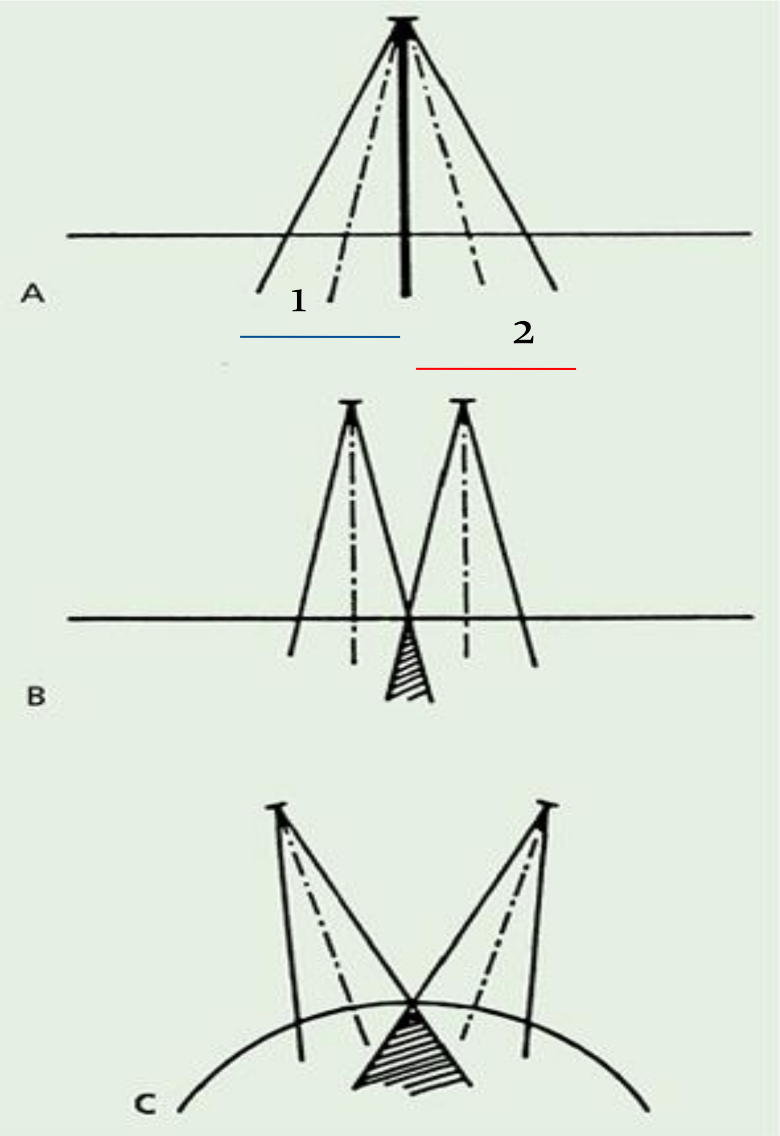
- A bolus is used for several reasons in electron beam treatments:
- To increase the dose on the skin surface ,
- To replace missing tissue due to surface irregularities and
- As compensating material to shape the coverage of the radiation to conform as closely as possible to the target volume while sparing normal tissue.
- Several commonly available materials like paraffin wax, polystyrene, acrylic (PMMA), Super Stuff, Superflab, and Super-flex can be used.

Treatment Planning : Field Abutment



- The decision about the gap is based on the uniformity of the combined dose distribution across the target volume

Treatment Planning : Field Abutment



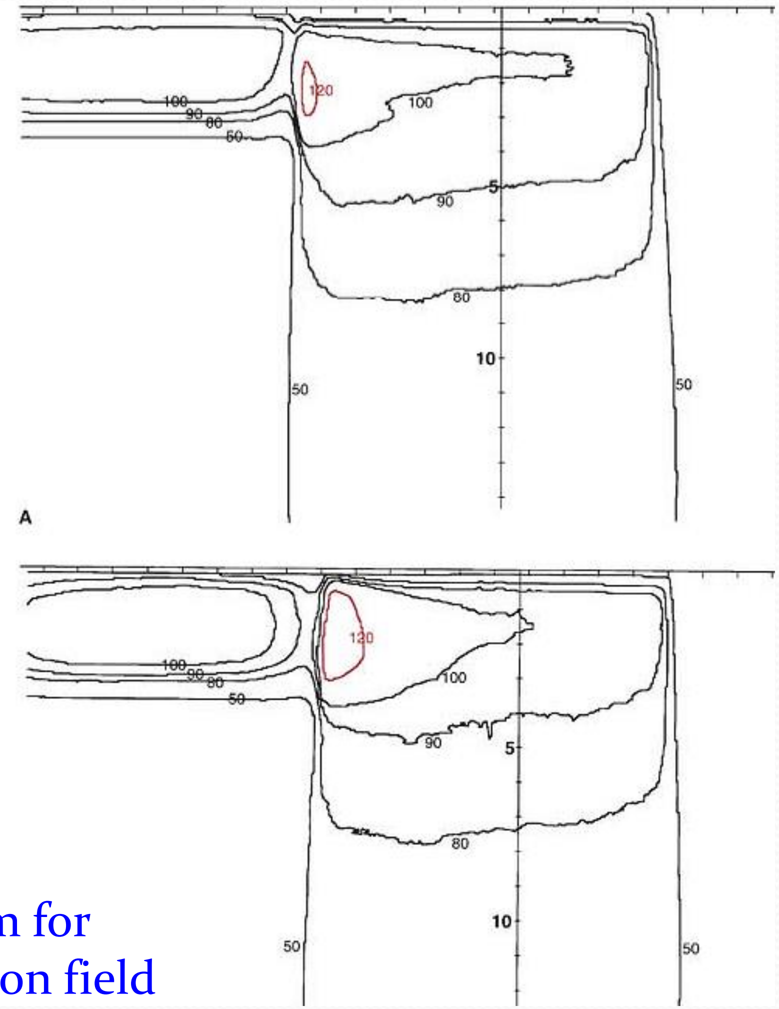
- Extent and magnitude of the high-dose region can be minimized by angling the central axis of each beam away from each other so that a common beam edge is formed

- Overlap that can occur when the central axis of the beams are parallel

- Converging beam central axes that result in the greatest amount of overlap with the highest doses and largest high-dose regions.

Treatment Planning : Photon & Electron Field Abutment

- A hot spot on the side of the photon field
- A cold spot on the side of the electron field
- Outscattering of electrons from the electron field increases hot spot



120 cm for electron field

Intracavitary Irradiation

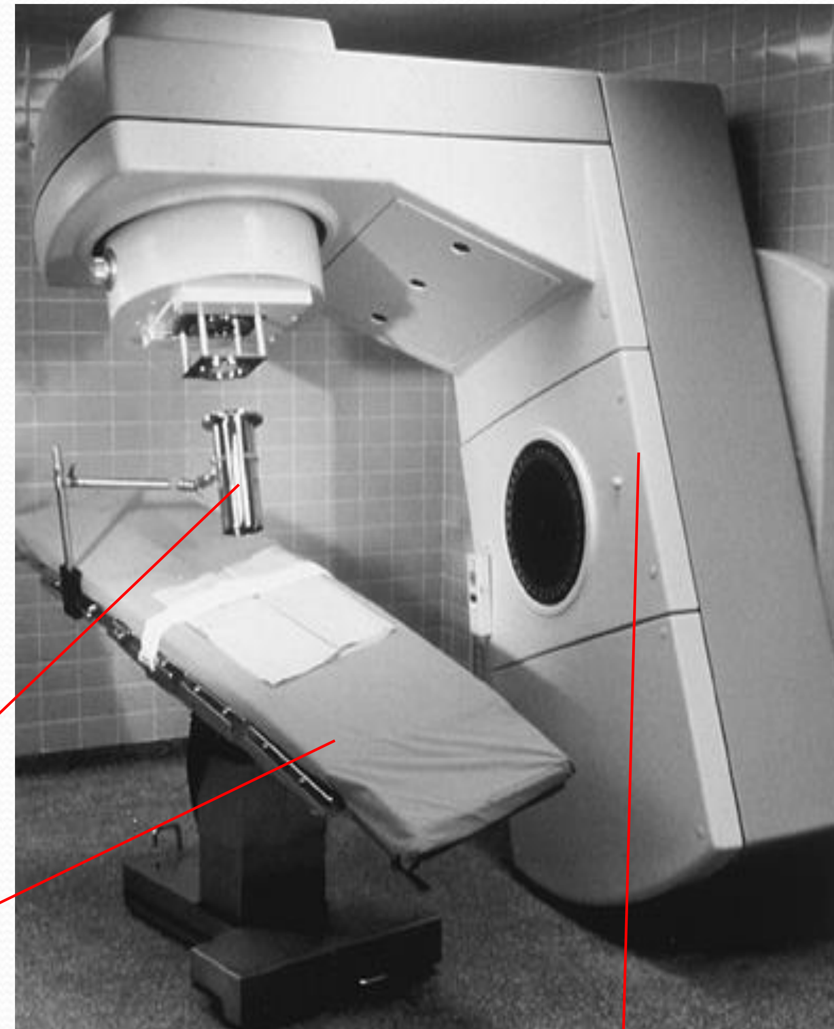
- Intracavitary radiation is performed for treatment of intraoral or transvaginal areas of the body.
- Additionally, IORT can be considered an intracavitary electron technique.
- It is used in the treatment of oral lesions presenting in the floor of the mouth, tongue, soft palate, and retromolar trigone.
- For all intracavitary irradiation, specially designed treatment cones and adapter to attach to accelerator are required .

cones

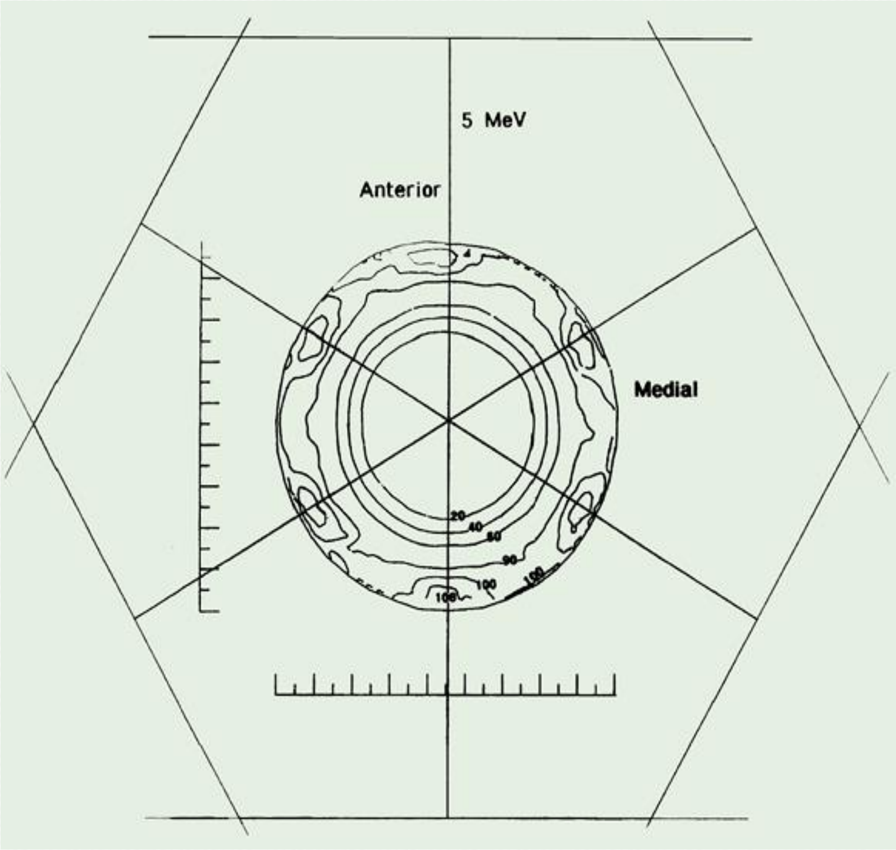
Cone with adapter

Requirement for IOERT

- A dedicated linear accelerator room that can meet the requirements of operating room (OR)
- sterile conditions or new mobile electron linacs that can be transported to a shielded OR need to be used.

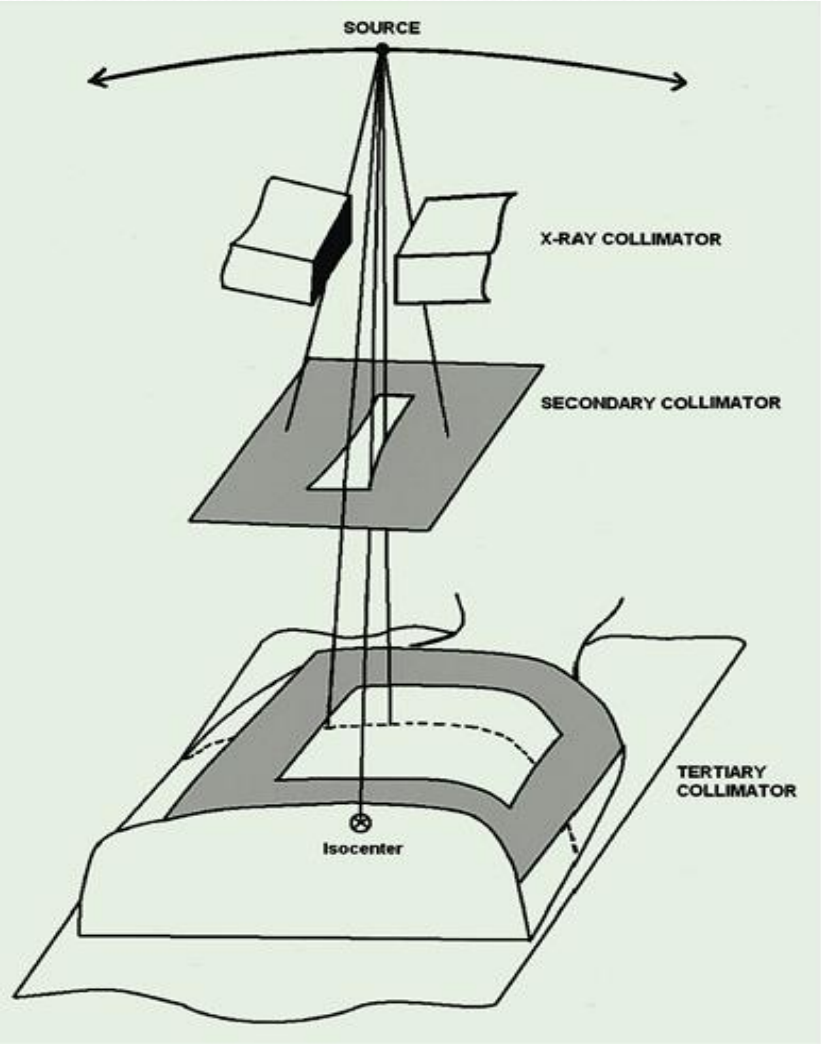


Total Limb Irradiation



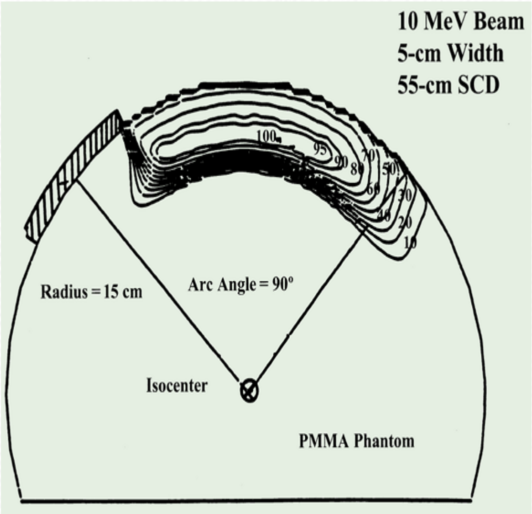
- Treatment of the entire periphery of body extremities(e.g., melanoma, lymphoma, Kaposi’s sarcoma) can be carried out using electron fields spaced uniformly around the limb.
- Delivers a uniform dose while sparing deep tissues and structures which are uninvolved.

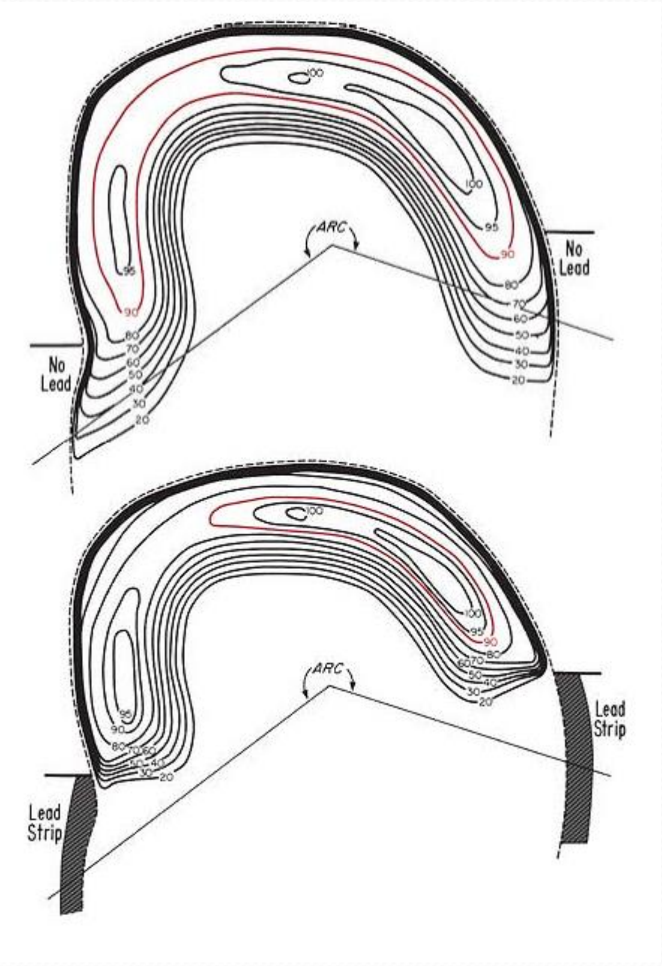
Electron Arc Therapy



- Electron arc therapy is useful for treating postmastectomy chest wall
- It is more useful in barrel-chested women , where tangent beams can irradiate too much lung
- There are three levels of collimation in electron arc therapy: the primary x-ray collimators, a shaped secondary Cerrobend insert , and skin collimation

Electron Arc Therapy



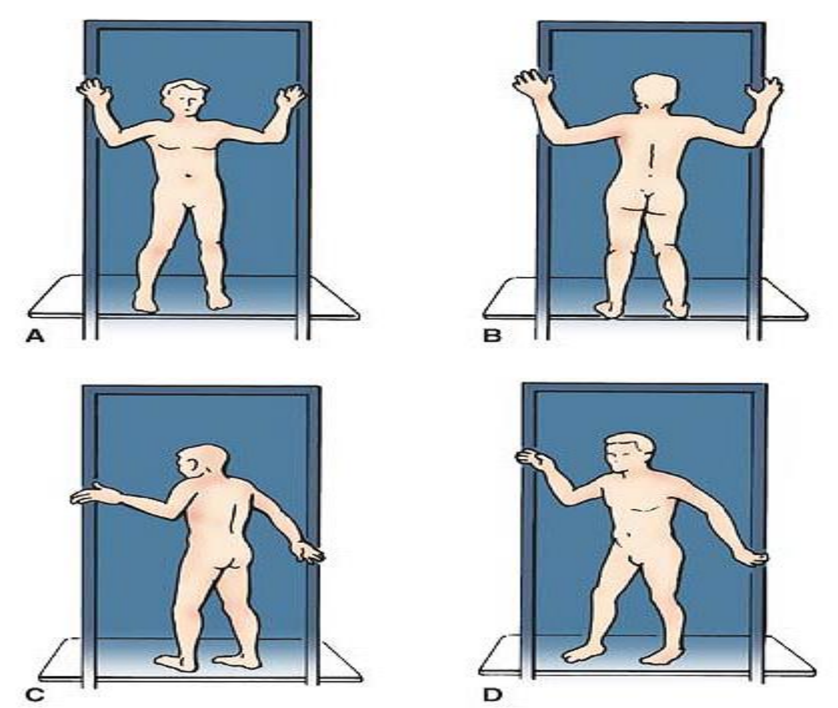


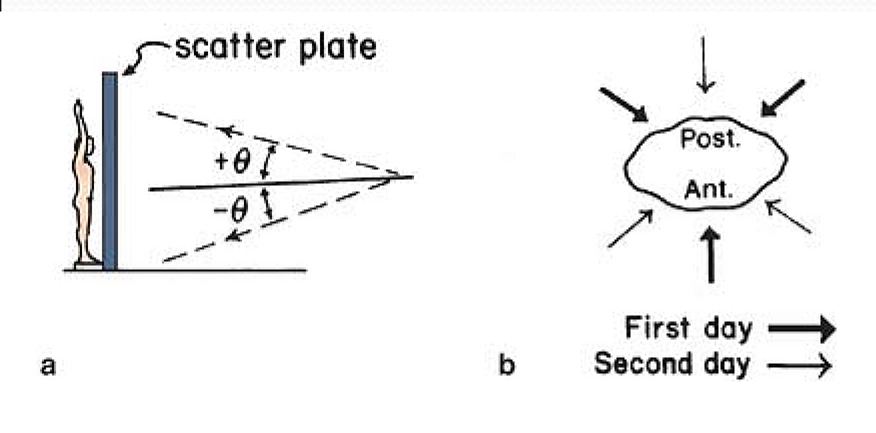
- Comparison of dose distribution with and without skin collimation
- The uncollimated edge has a slow dose falloff
- The skin collimation restores the beam edge but requires rotating the beam 15 degrees beyond the edge of the skin collimator.

Total Skin Irradiation

- Total skin electron treatments are employed in the management of mycosis fungoides
- The first requirement for total skin electron treatments is a uniform electron field large enough to cover the entire patient in a standing position from head to foot and in the right to left direction.
- This is accomplished by treating the patient at an extended distance (410 cm), angling the beams superiorly and inferiorly, and using a large sheet of plastic (1 cm thickness acrylic at 20 cm from the patient surface) to scatter the beam.

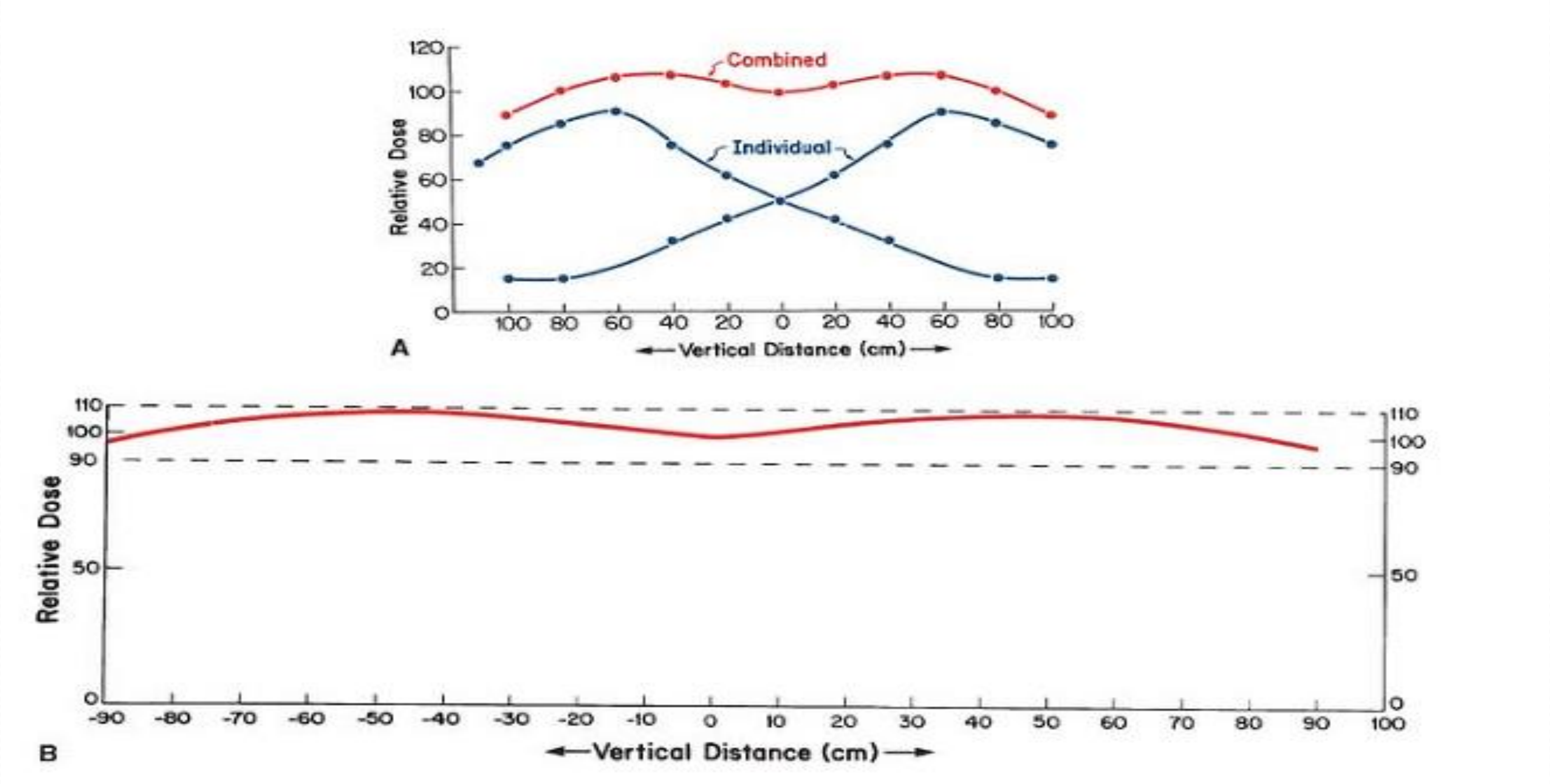
Total Skin Irradiation





- The beam is made uniform from head to foot by abutting two fields at the 50% dose profile
- By aiming the beams up and down, the largest bremsstrahlung contribution (central axis) misses the patient
- The dose is made uniform around the circumference of the patient by irradiating from six different directions
- Placed upstream of the patient is a plastic screen that serves as both an energy degrader and a scatterer

TSET



- Combining individual beam profiles to obtain a composite profile with ±10% dose variation in the vertical direction.
- Data for 9 MeV; source to surface distance = 410 cm; scatter plate to phantom distance = 20 cm; individual profile beam angle relative to horizontal axis= 12 degrees

Future of Electron Therapy

- Availability of MLC for irregular shaped electron therapy.
- Work is in progress to implement IMRT with electrons.
- Advances in electron dose calculations and methods for electron-beam optimization will enable accurate planning and delivery

THANK YOU FOR YOUR ATTENTION