

ELECTRON BEAM BASIC CONCEPTS



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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

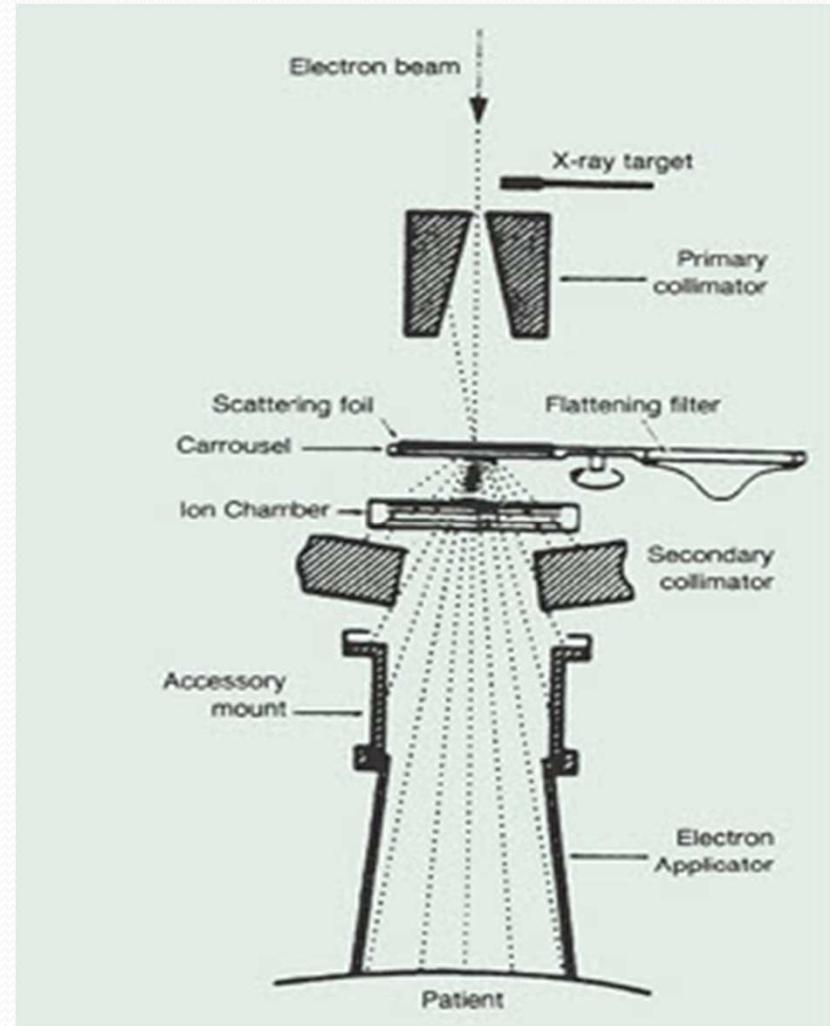
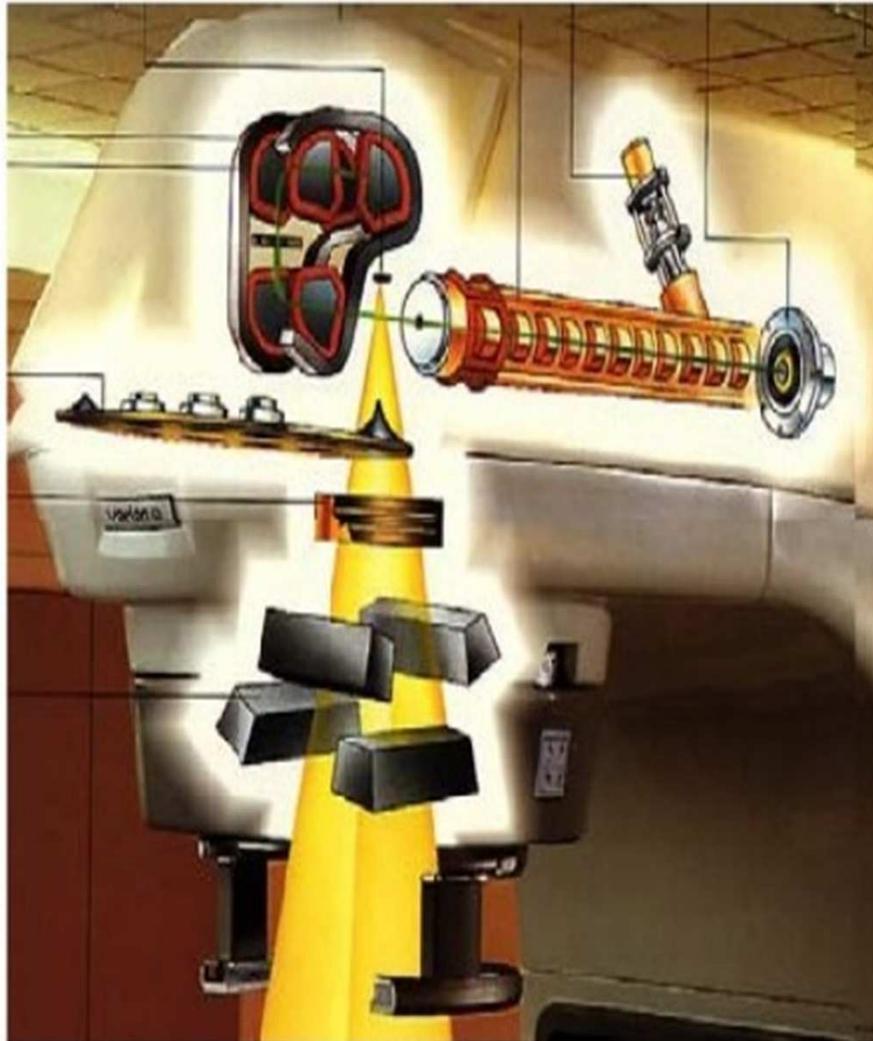
- Delivers a reasonably **uniform dose from the surface to a specific depth** , after which dose falls off rapidly, eventually to a near-zero value.
- Using electron beams allows **disease within approximately 6 cm of the surface to be treated** effectively, sparing deeper normal tissues.
- Electrons 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

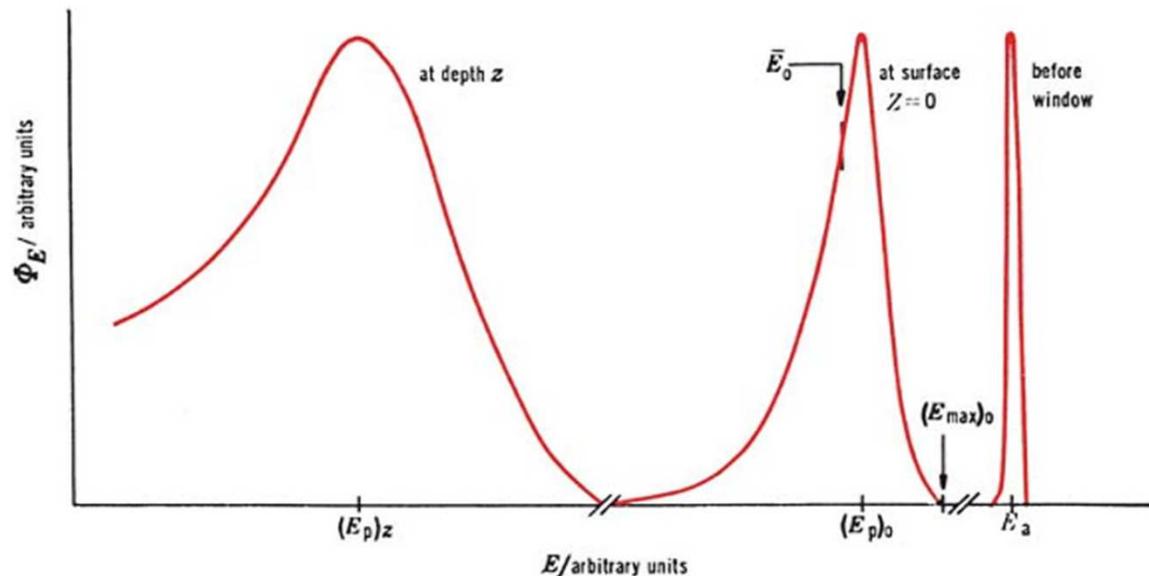
- Electrons are useful in treating cancer of the skin and lips, upper-respiratory and digestive tract, head and neck, breast
- **Skin** : Eyelids, nose, ear, scalp, limbs.
- **Upper-respiratory and digestive tract**: Floor of mouth, soft palate, retromolar trigone, and salivary glands
- **Breast**: Chest-wall 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 PRODUCTION



Energy Specification

- Almost monoenergetic at the exit surface of the window
- A 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

- $(E_p)_0 = C_1 + C_2 R_p + C_3 R_p^2$

$(E_p)_0$ 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

$$\bar{E}_0 = C_4 R_{50} \quad \text{for water, } C_4= 2.33 \text{ MeV}$$

Energy at Depth

The most probable energy and the mean energy of the spectrum decreases linearly with depth.

$$\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)$$

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.

COLLISIONAL & RADIATIVE LOSS

- An electron traveling in a medium loses energy as a result of collisional and radiative processes.
- **Collisional Losses** (Ionization and Excitation) The rate of energy loss depends on the electron density of the medium.
- The rate of energy loss/gm/cm², which is called the mass stopping power, is greater for low atomic number (Z) material.
- **Radiation Losses** (Bremsstrahlung) The rate of energy loss per centimeter is approximately proportional to the electron energy and Z^2 .
- Moreover, the probability of radiation loss relative to the collisional loss increases with the electron kinetic energy and with Z.

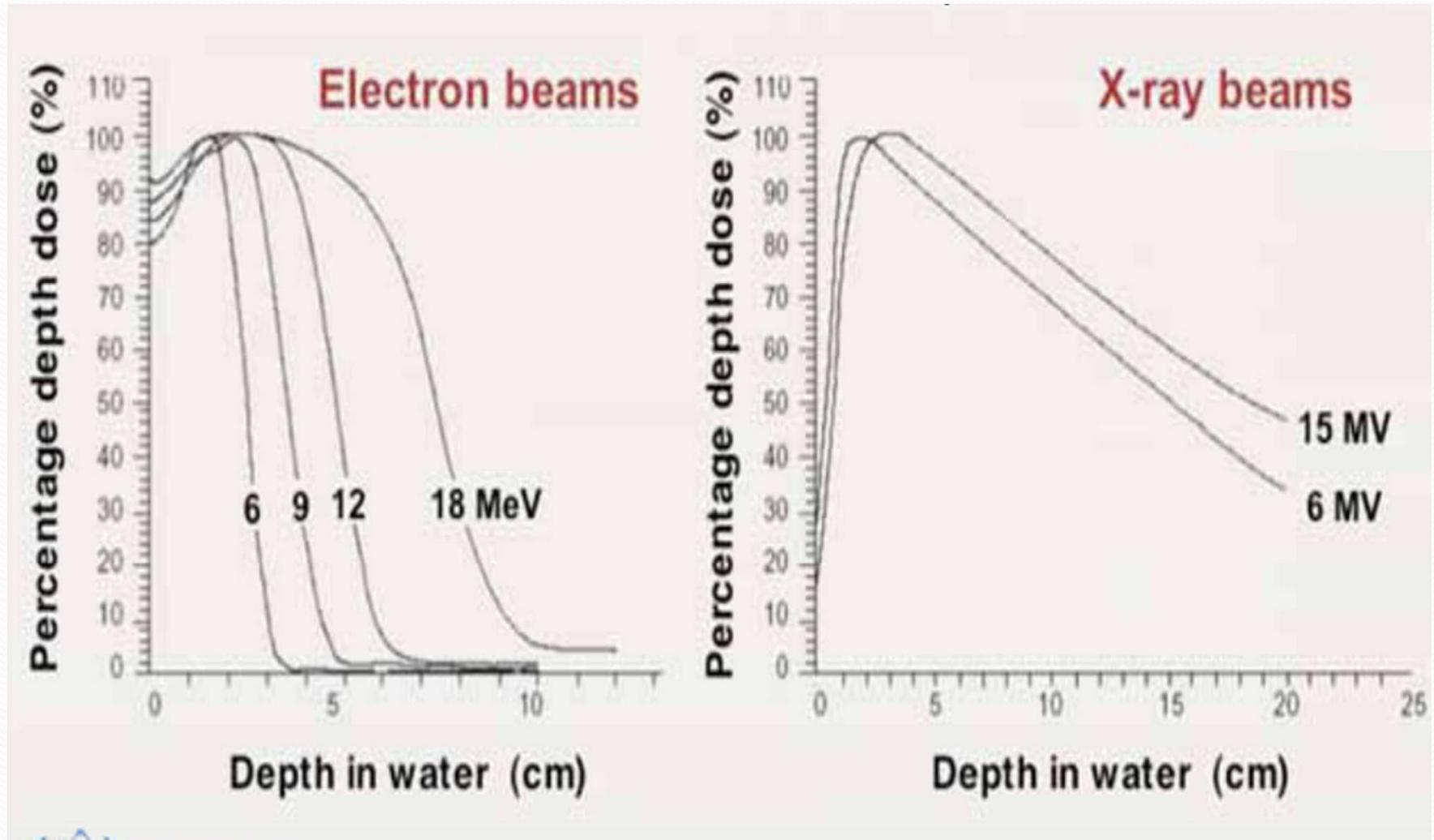
Output Calibration

- **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

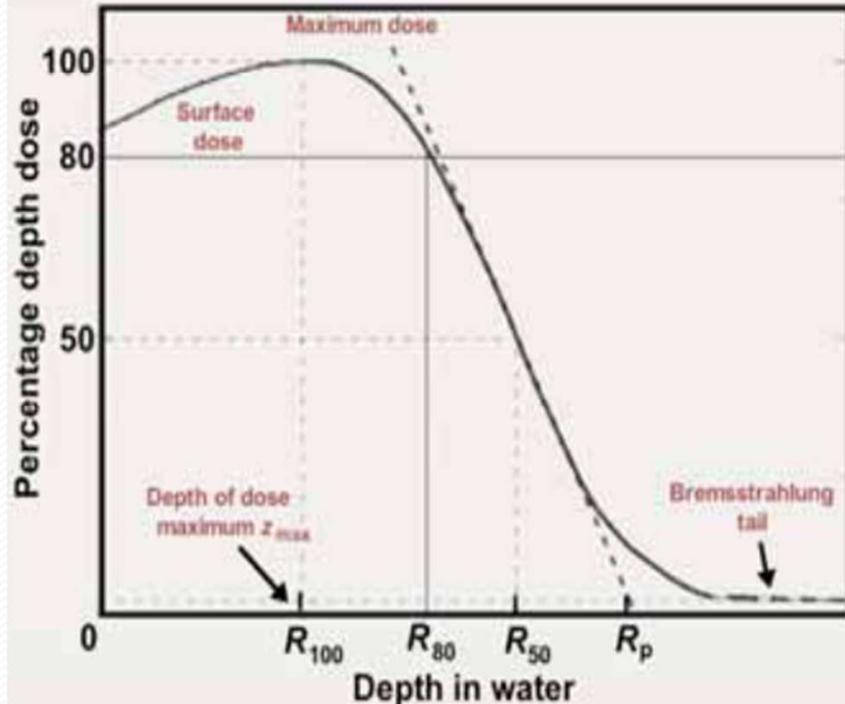
- Reference depth
 - The point of **reference depth** on the central axis
 - $Z_{\text{ref}} = 0.6 R_{50} - 0.1\text{cm}$
- field size
 - 10×10 cm as reference field
 - The maximum dose at d_{max} set at 1 cGy/MU
 - Output for another cone is expressed in terms of **output factor**.

Dose distribution in water



Electron beam PDD

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

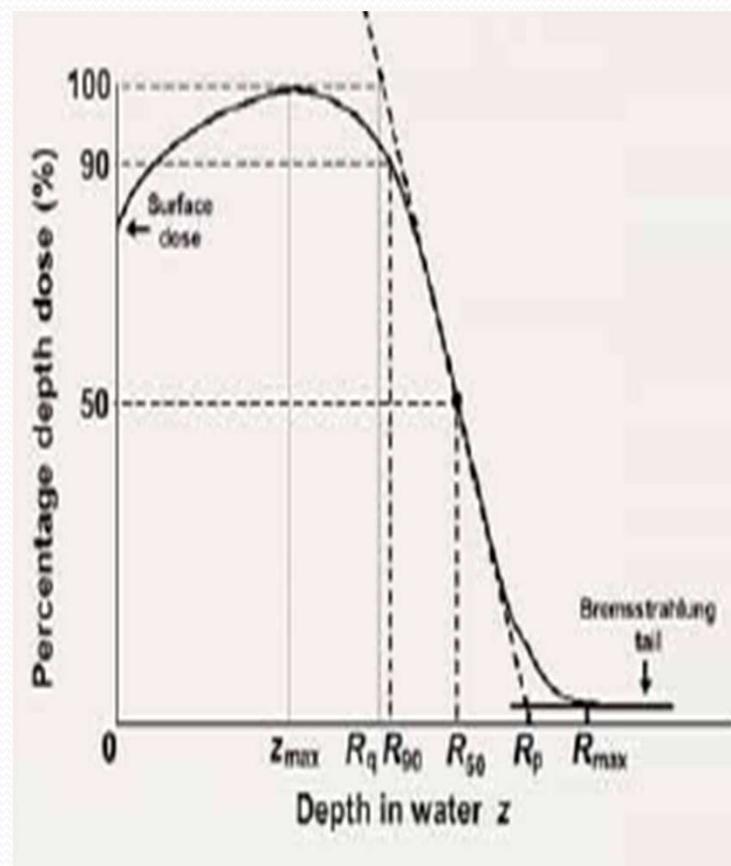


- The surface dose is relatively high (of the order of 80 - 100%).
- Maximum dose occurs at a certain depth referred to as the depth of dose maximum z_{max} .
- Beyond z_{max} the dose drops off rapidly and levels off at a small low level dose called the bremsstrahlung tail (of the order of a few per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

- The deepest part of the maximum
 - To avoid low-energy electron contamination problems close to the phantom

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%

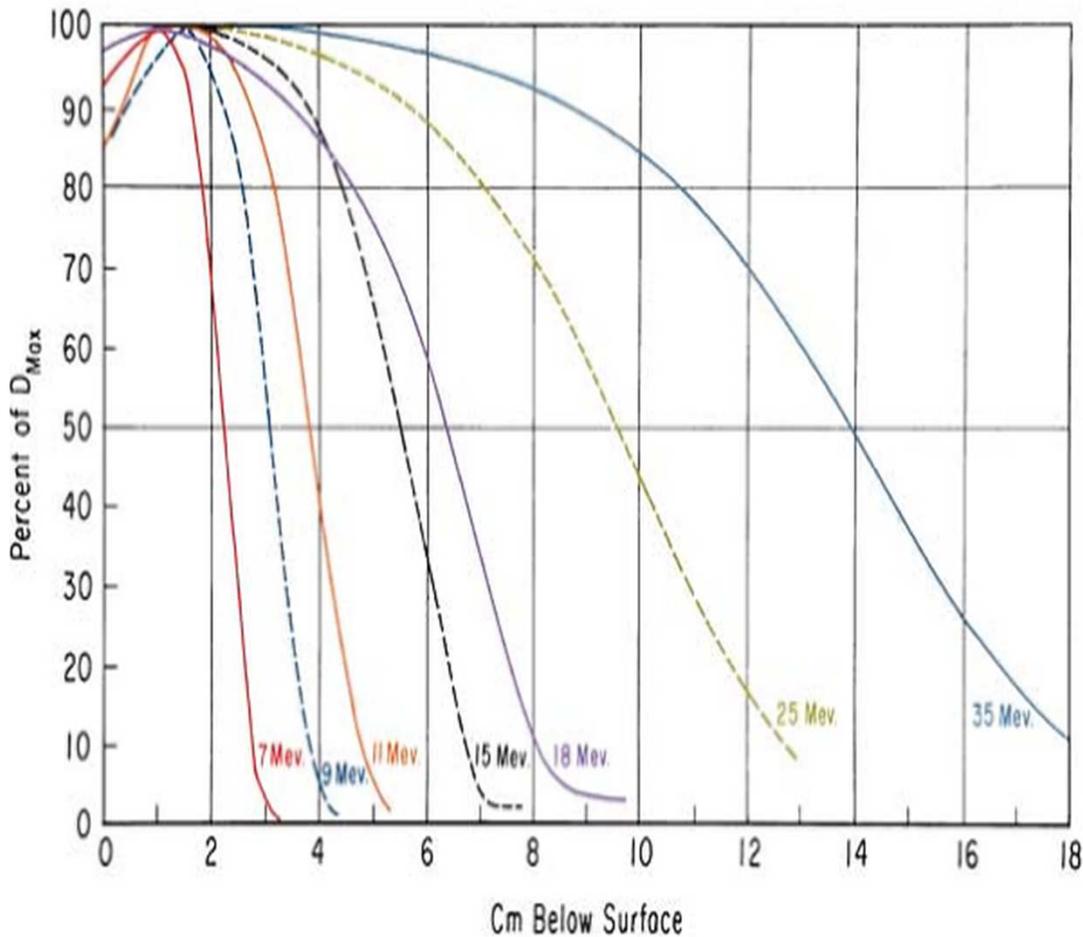


Continued...

- 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 **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**
- 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.

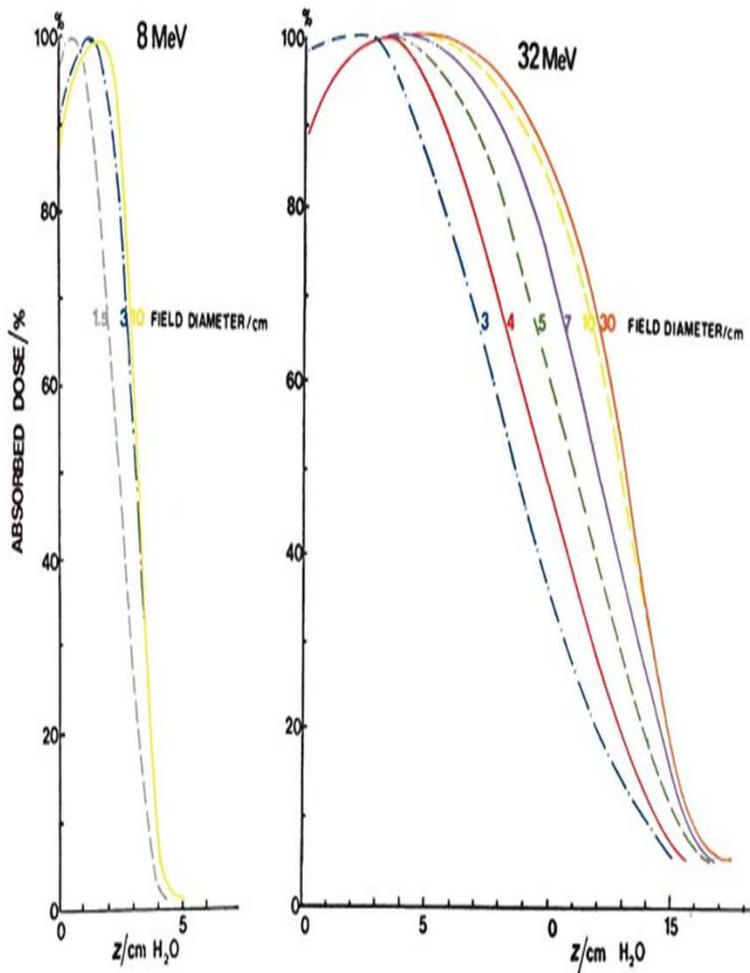
Energy dependence of depth dose

ELECTRON BEAM CENTRAL AXIS 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.

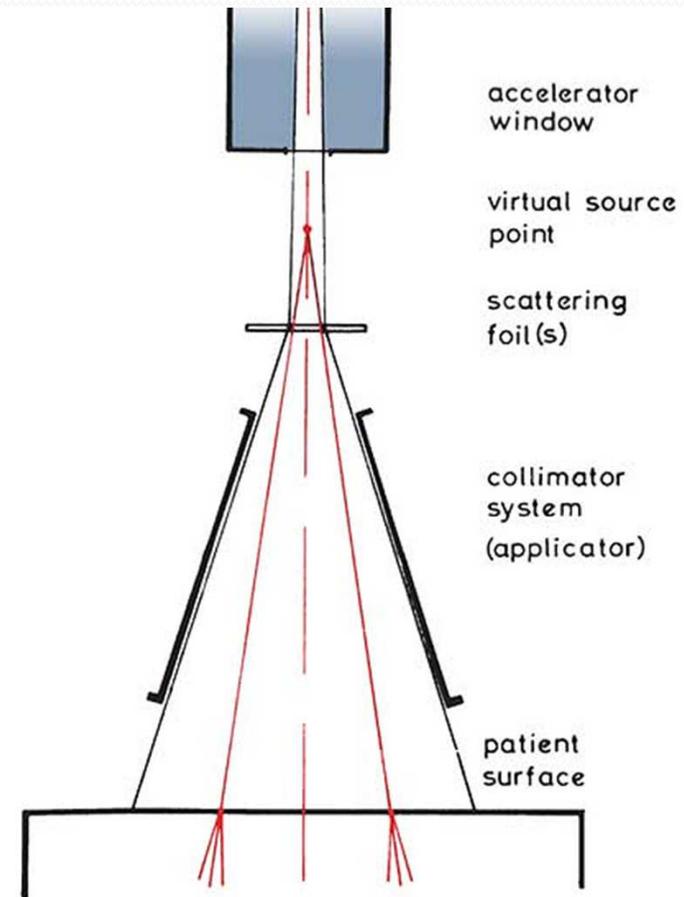
Field Size dependence of Depth dose



- **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_{90} shifting toward the surface as field size decreases.
- The shift also **increases the R_{90-10} distance**, as R_{10} changes only slightly.
- As the **field size gets even smaller**, the maximum dose decreases, and when it is normalized to 100%, the relative dose at the surface, **D_s** , increases.

Electron Source

- Virtual source
 - An intersection point of the back projections along the most probable directions of electron motion at the patient
 - The **Virtual SSD** helps to predict dose at extended SSDs
 - The Virtual SSD is a function of FS and energy



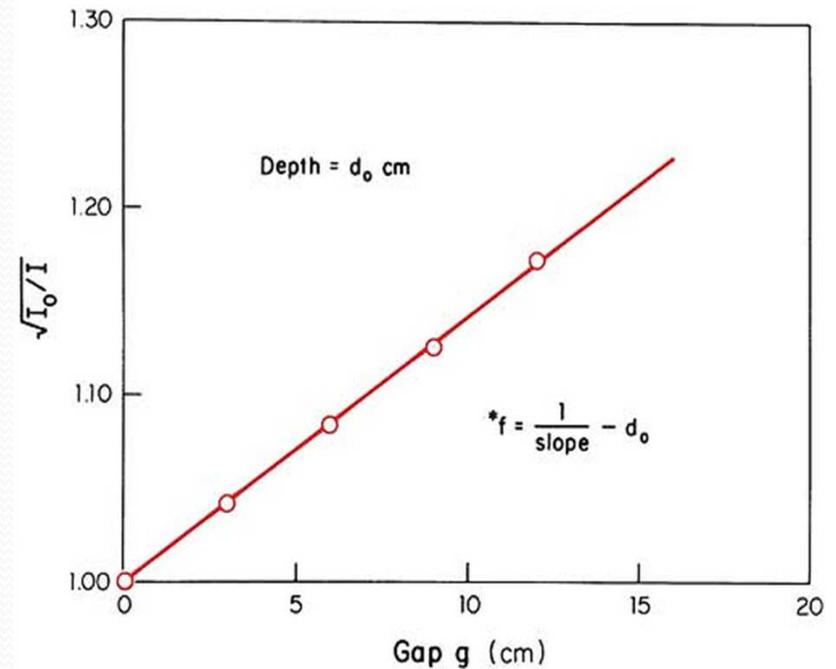
Virtual source

Effective SSD

To correct air gap

$$\frac{I_0}{I_g} = \left(\frac{f + d_m + g}{f + d_m} \right)^2$$

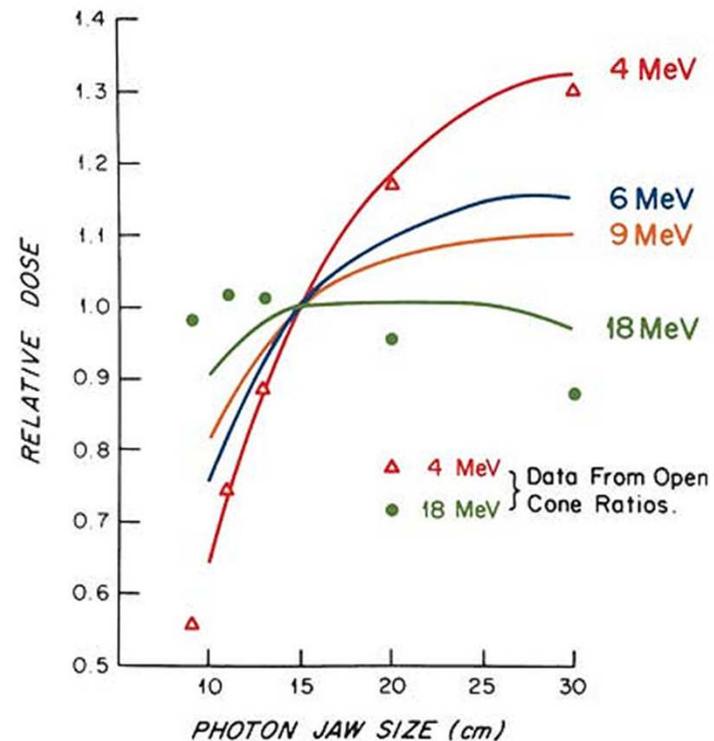
$$\sqrt{\frac{I_0}{I_g}} = \frac{g}{f + d_m} + 1$$



A function of energy and FS

Output variation with Field size

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

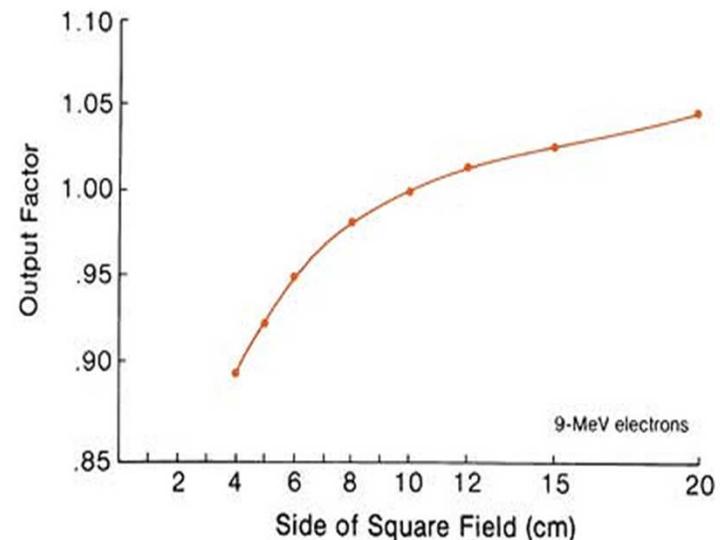


Field Size Dependence

- If the distance between the point of measurement and the edge of the field is shorter than the range of the laterally scattered electrons

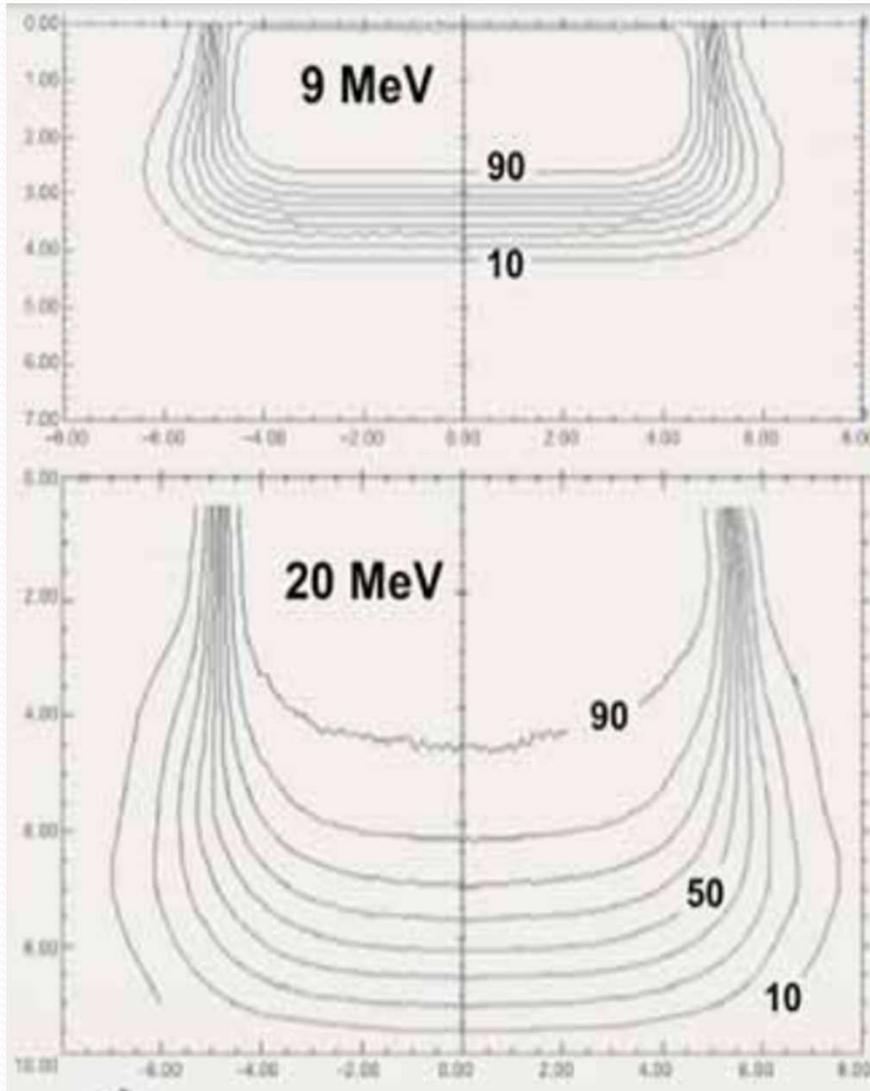
⇒ phantom scatter ↓

⇒ The effects of field size on output and the central axis depth dose curve is significant.



Primary collimator fixed, secondary collimators (trimmers) close to the phantom varied to change the field size

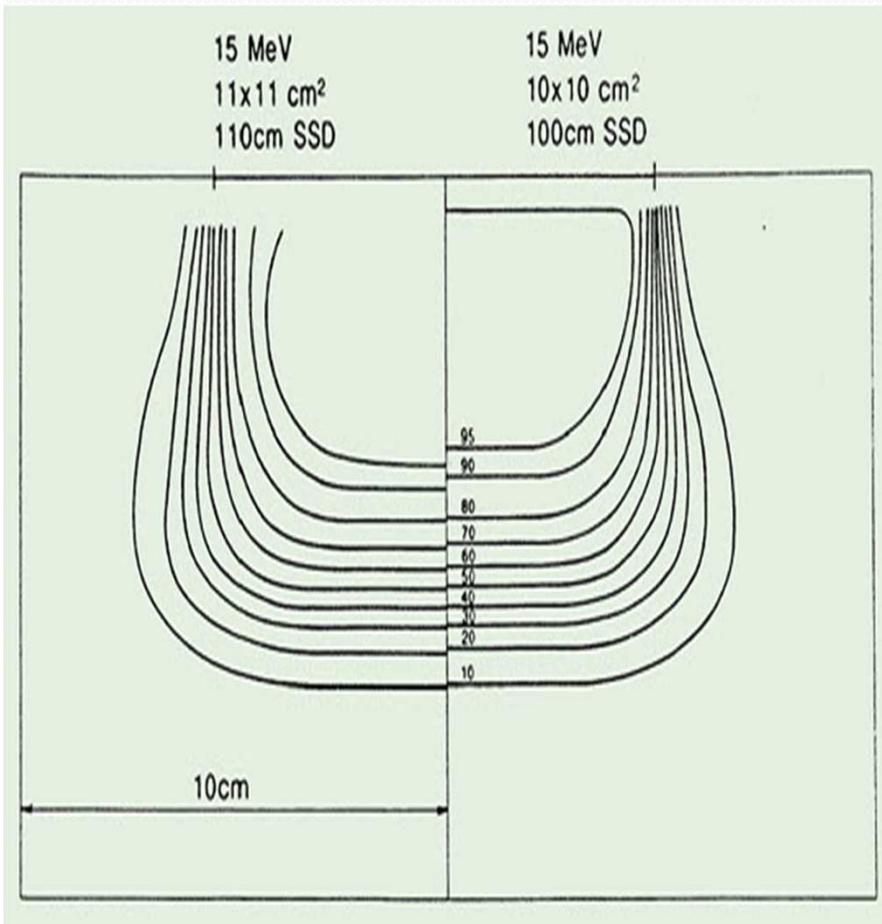
Isodose curves



- 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 $R_{85}/2$

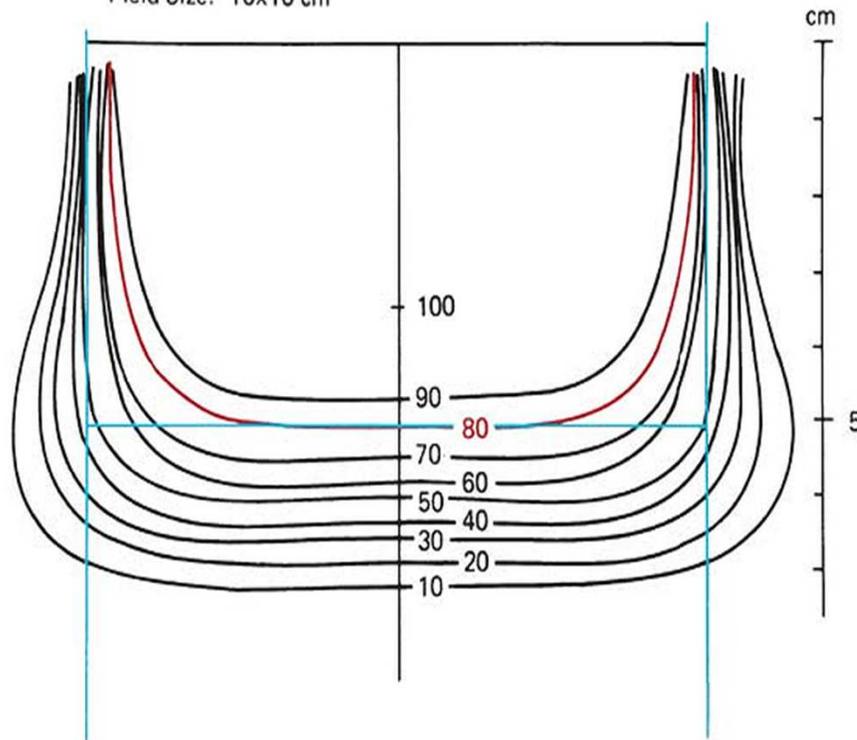
SSD dependence of depth dose

- **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

Energy: 16.0 MeV
SSD: 100 cm
Field Size: 10x10 cm

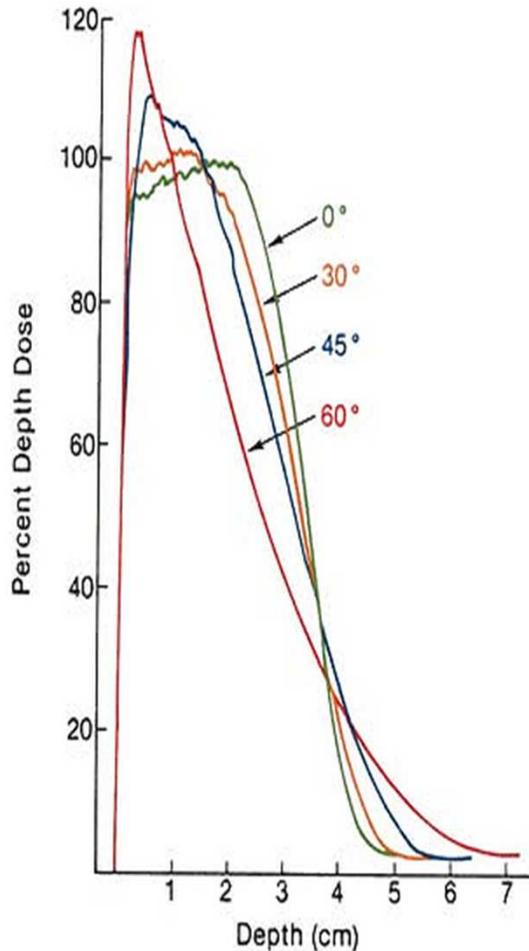


- A significant **tapering** of the **80% isodose** curve at energies **above 7 MeV**
- The constriction of the useful treatment is worse for the smaller fields.
- A **larger field at the surface** may be necessary to cover a target area adequately.

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).

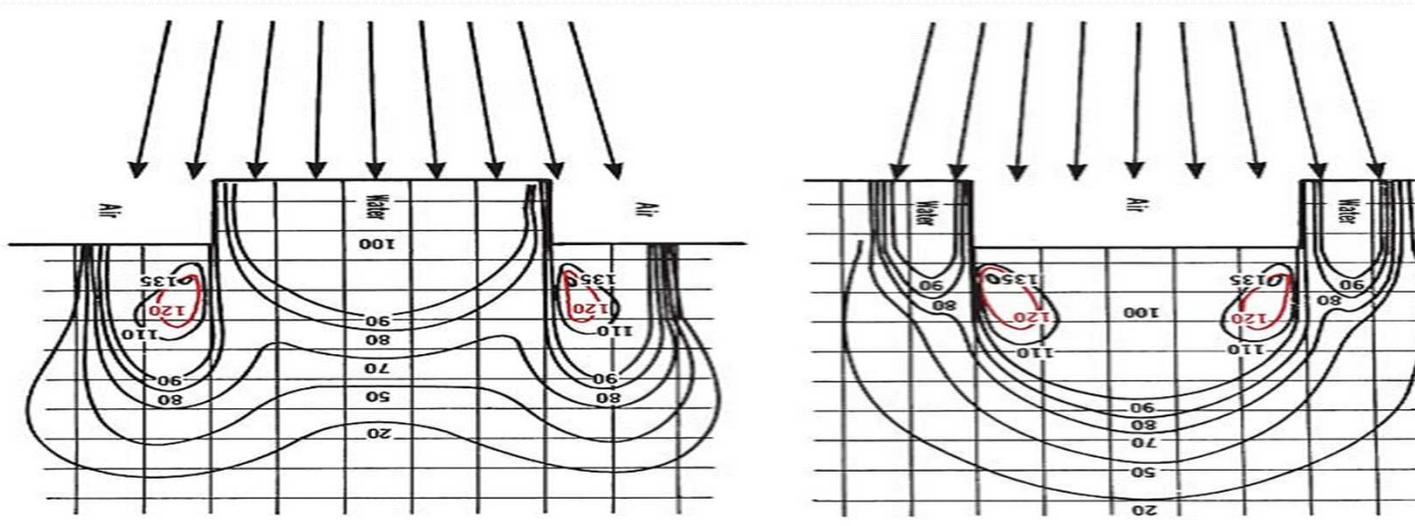
Oblique Incidence



- 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.

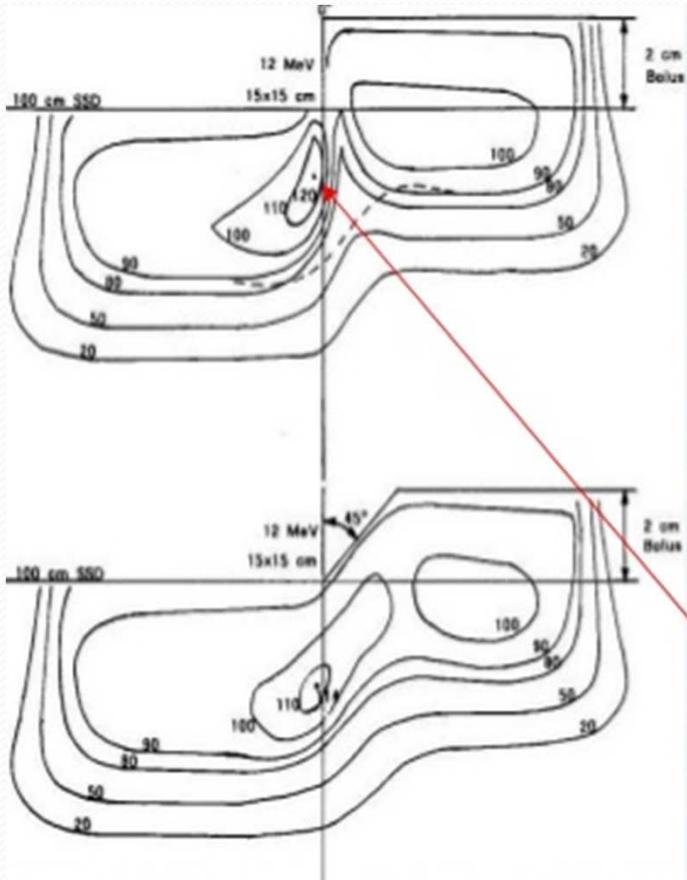
Surface Irregularities

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

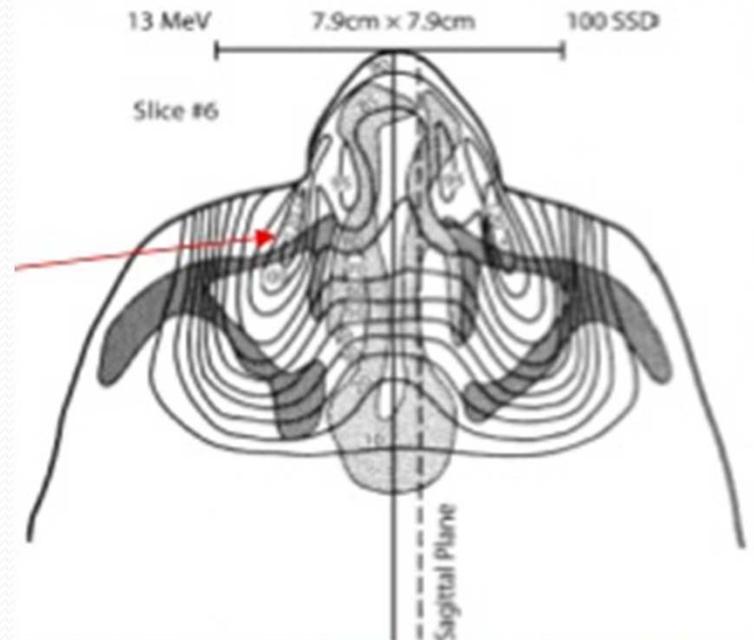


Surface Irregularities

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



Hot spot



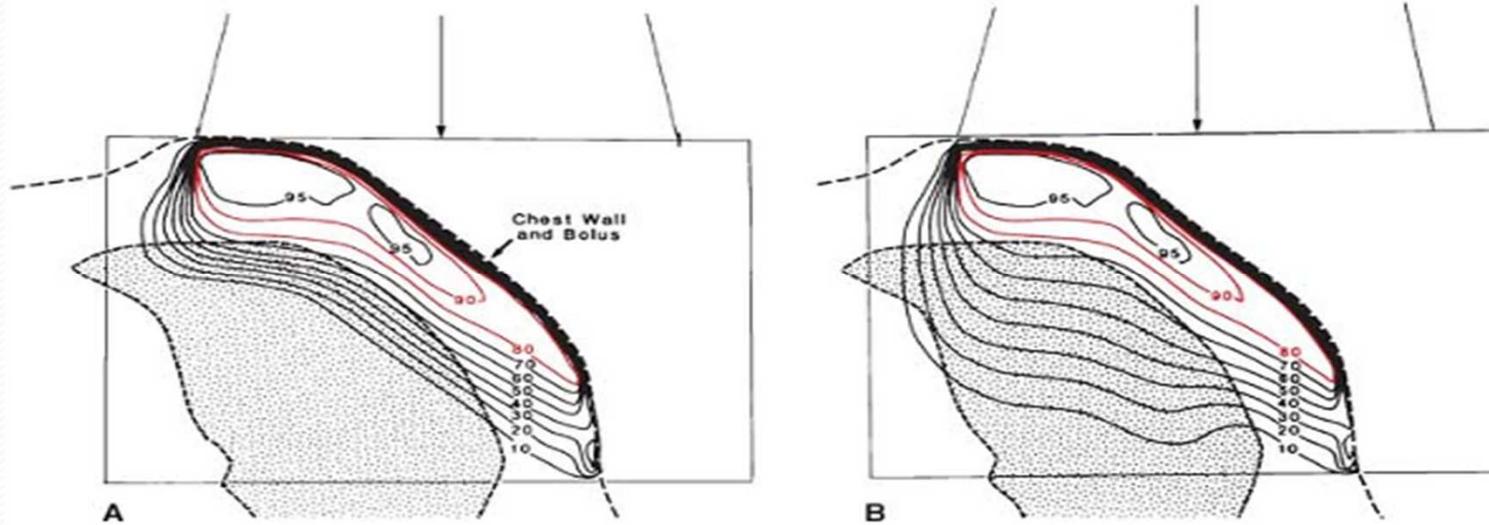
Tissue Heterogeneity

- 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.**

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

- 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



Without lung correction

With lung correction

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.

Tissue Heterogeneity: Air Cavities

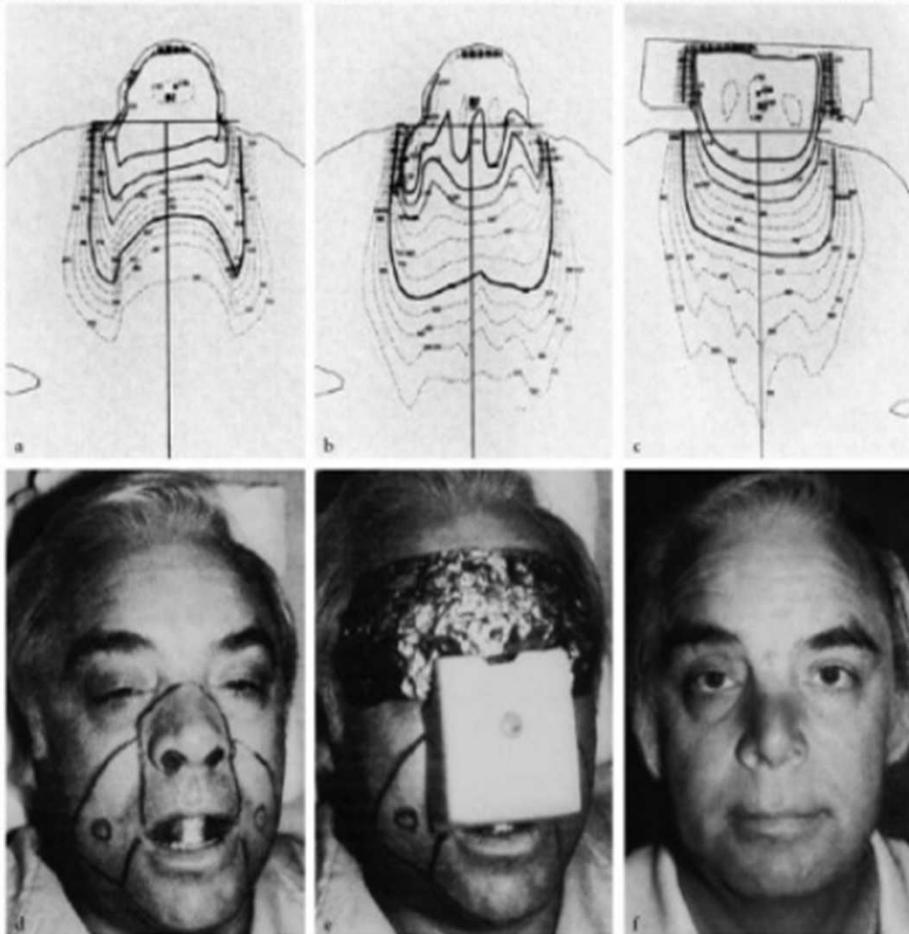
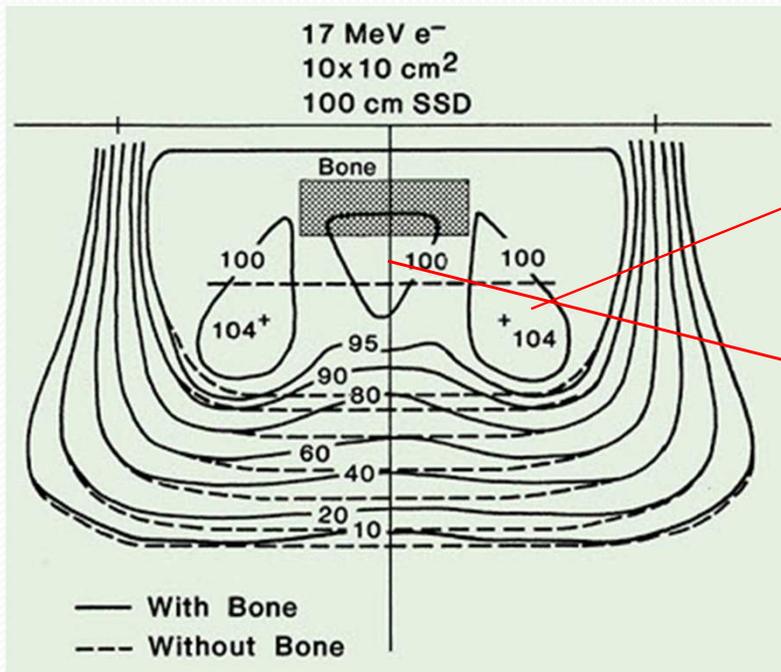


Fig.7.15a-f a Dosimetry without heterogeneity correction gives false impression of isodose distribution. b Dosimetry with heterogeneity correction shows more accurate isodose distribution. c Improved isodose distribution with use of internal and external bolus. d Actual treatment fields, with bolus placed 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); CHOI et al. (1988)]

- Because of the low physical density of air (0.0013 g/cm^3), electrons pass easily through this medium.
- Very high doses penetrating into the brain and other underlying tissues can easily be seen from this diagram.
- If this increased dose is not considered, large doses to these underlying structures can result.

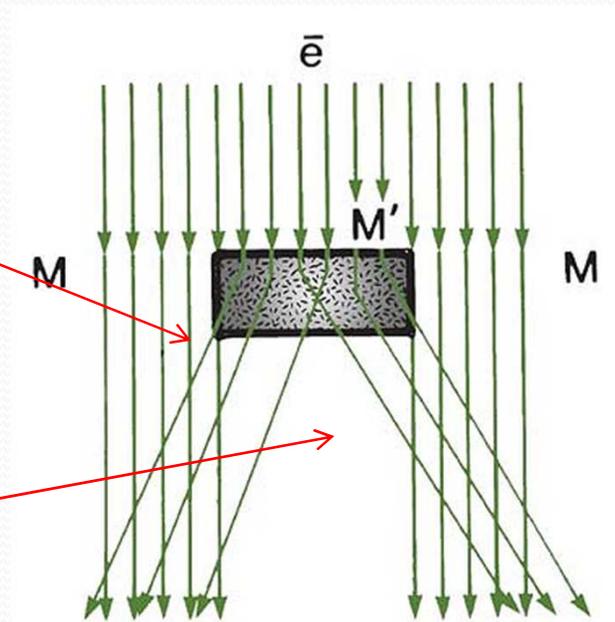
Tissue Heterogeneity: Bones

- 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** ($E_0 / 3$) 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 ,

$$T_{\text{lead}} = 0.5 E_0 + 1$$

- For example, an **18-MeV** beam requires **10 mm of lead**.
- **Lipowitz metal** has a **density 20% less** than that of lead; therefore, its thickness should be **20% greater**. For example, an **18-MeV** beam requires **12 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 13 mm.

- Treatment Planning: Beam Field Shaping and Collimation

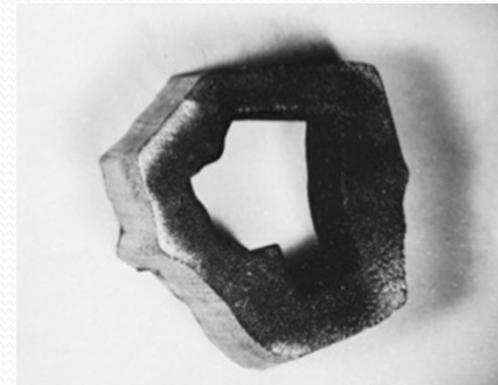
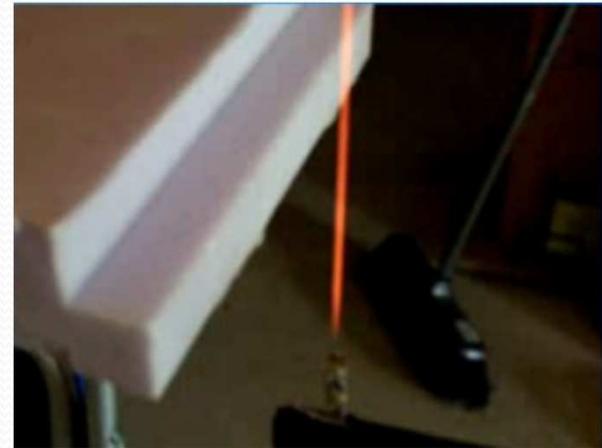
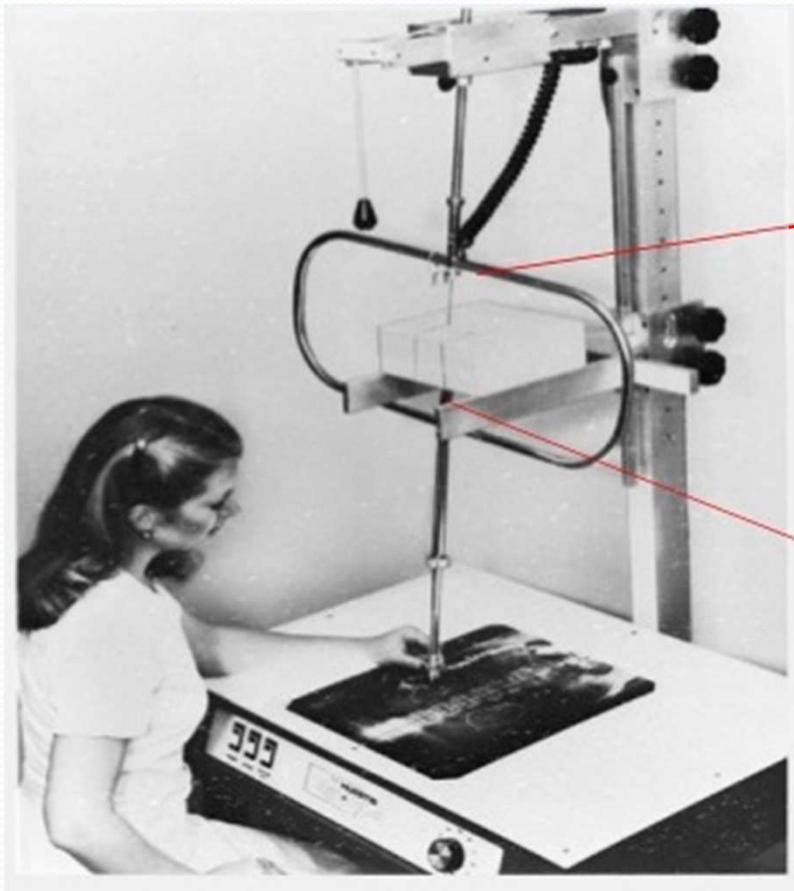


Cone attached to the gantry



Cones of different size with insert

Treatment Planning: Field Shaping and Collimation

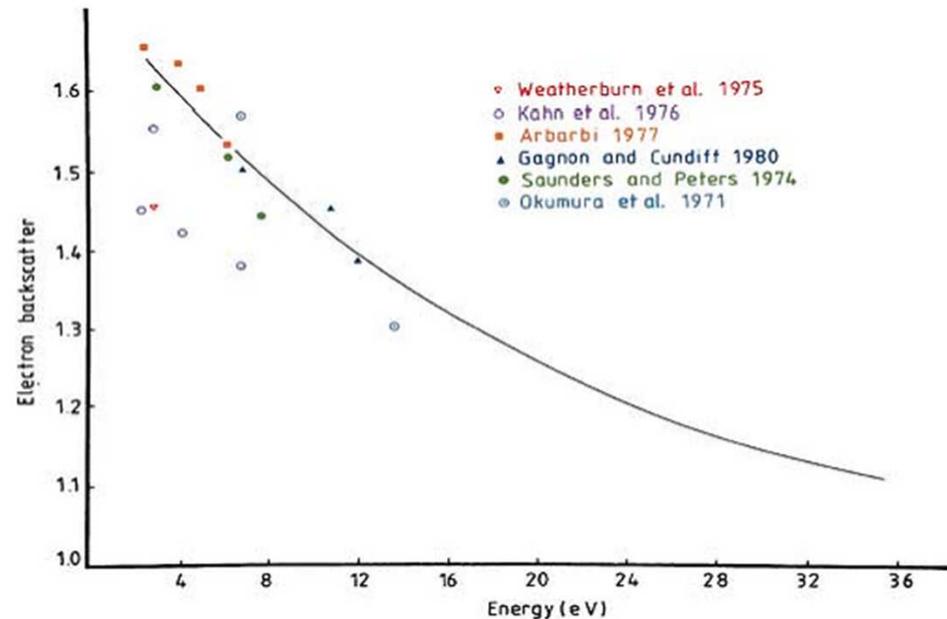


Treatment Planning: Internal Shielding

- 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 shield 7 MeV electrons.

Internal Shielding : Electron Backscatter

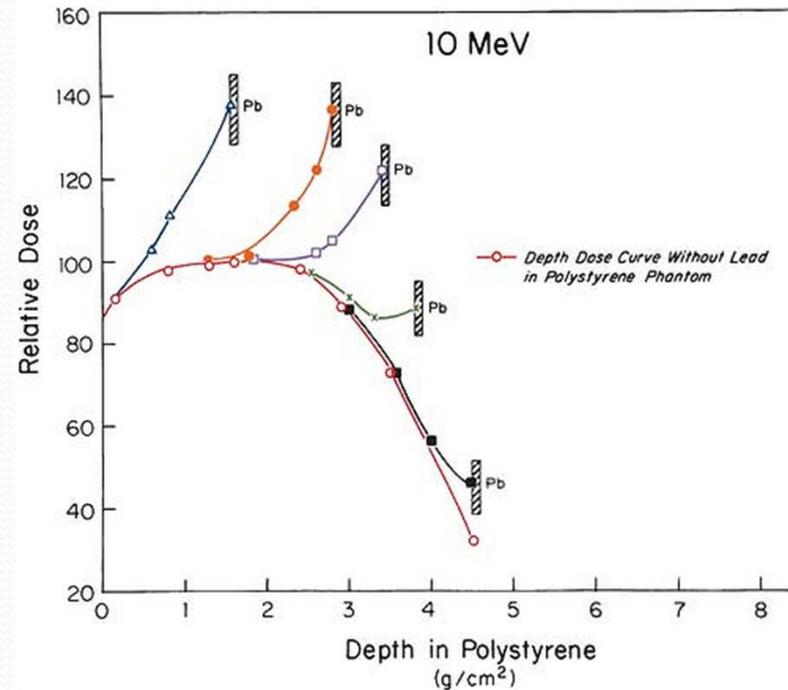
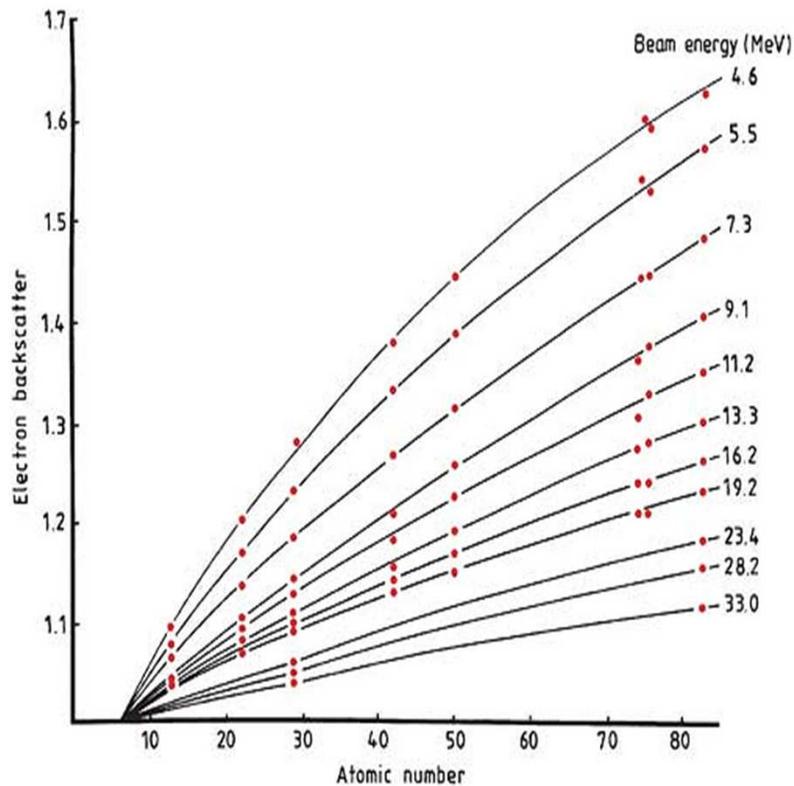
- The electron backscatter from lead enhances the dose to the tissue near the shield
 - 30% - 70% in the range of 1 – 20 MeV, having a higher value for the lower-energy beams



For the polystyrene-lead interface

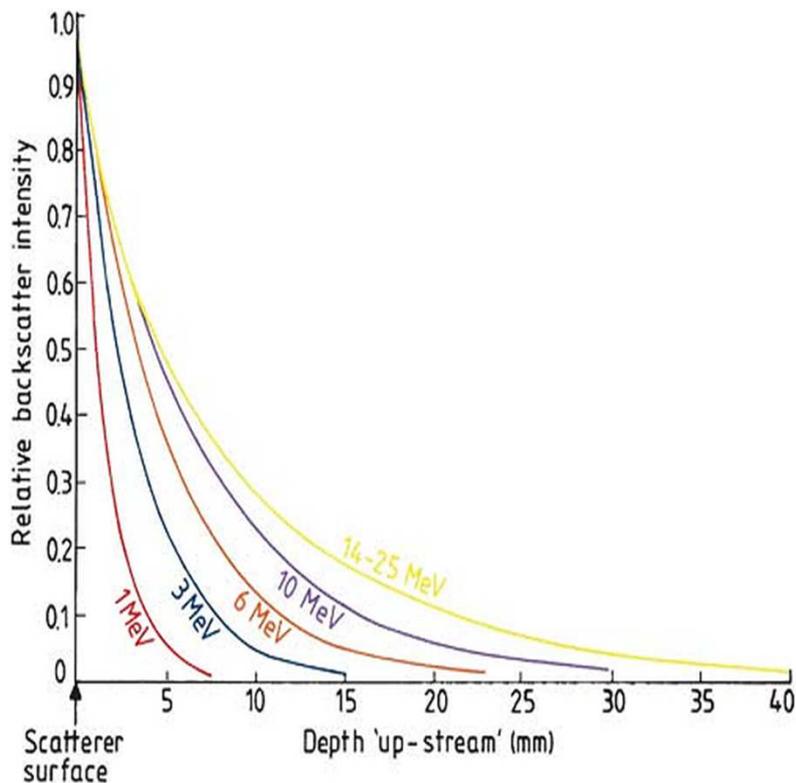
$$ESF = 1 + 0.735e^{(-0.052 E_z)}$$

Internal Shielding : Electron Backscatter



The dose enhancement drops off exponentially with the distance from the interface on the entrance side of the beam.

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



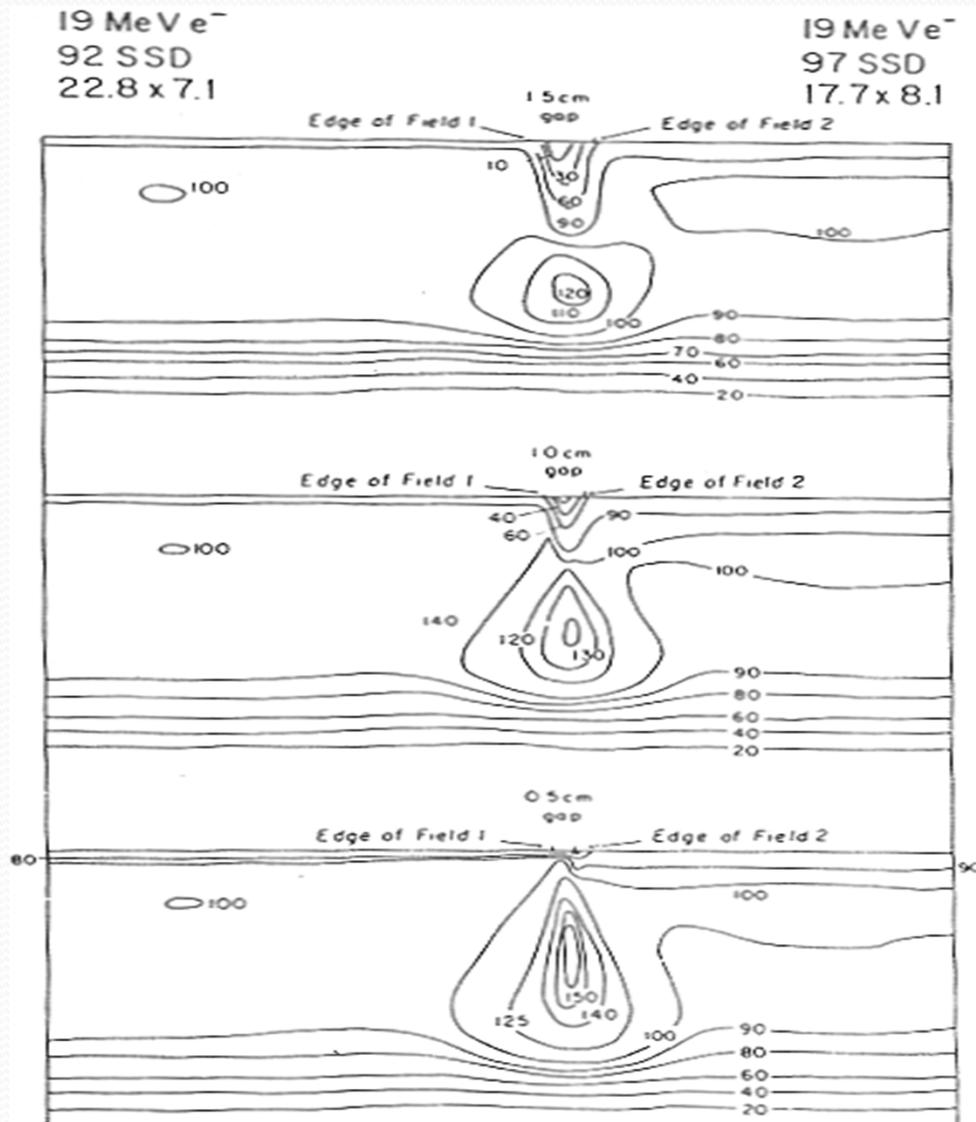
To dissipate the effect of electron backscatter, a suitable thickness of **low Z absorber** may be placed **between the lead shield and the preceding tissue surface**

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

Treatment Planning: Bolus

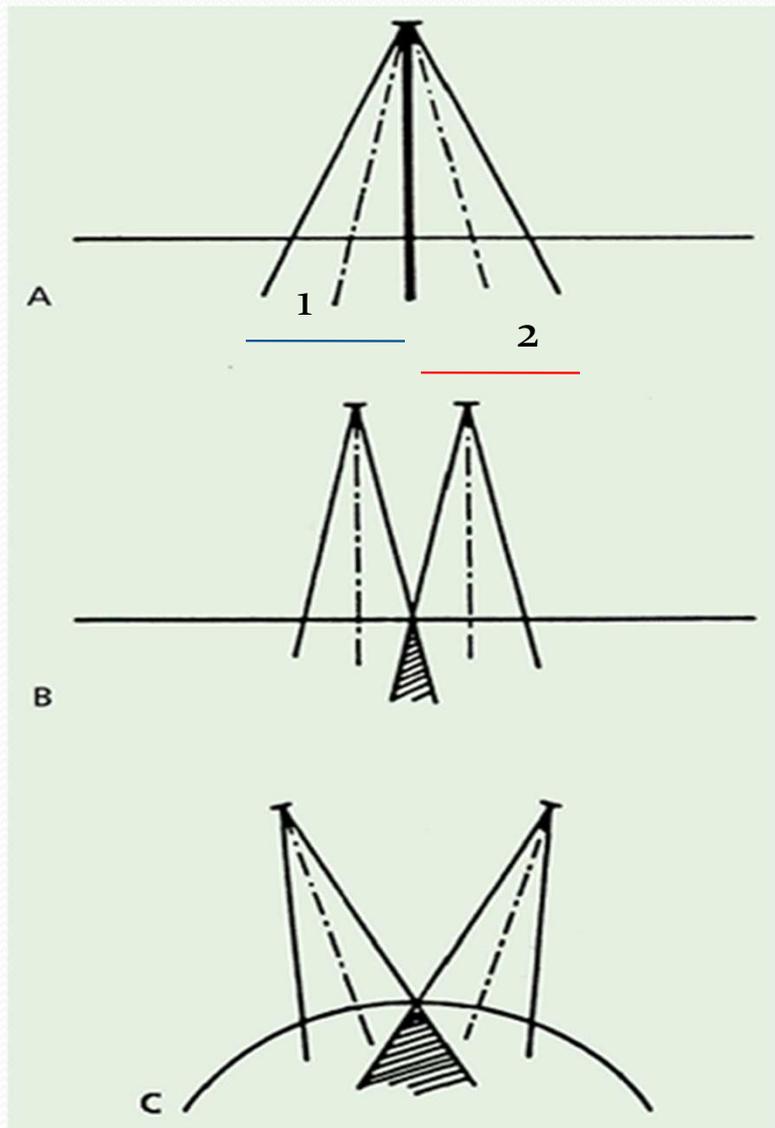
- A **bolus** is used for several reasons in electron beam treatments:
 - To **increase** the **dose on the skin surface** ,
 - To **replace missing tissue** due to surface irregularities and
 - As **compensating material** to shape the coverage of the radiation to conform as closely as possible to the 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



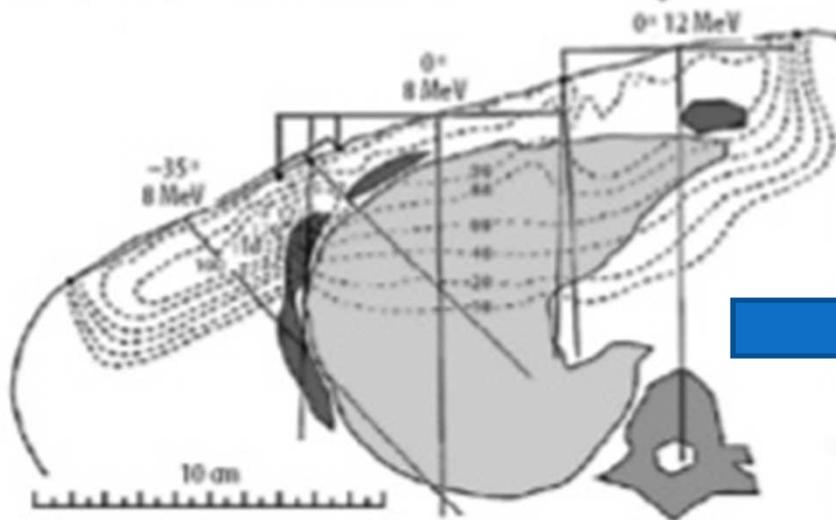
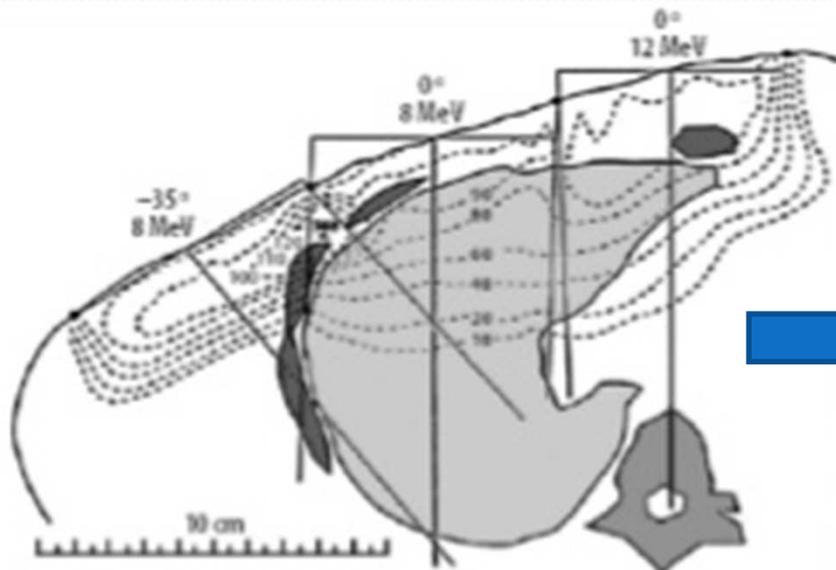
- The **decision** about the **gap** is based on the **uniformity of the combined dose distribution** across the target volume

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.

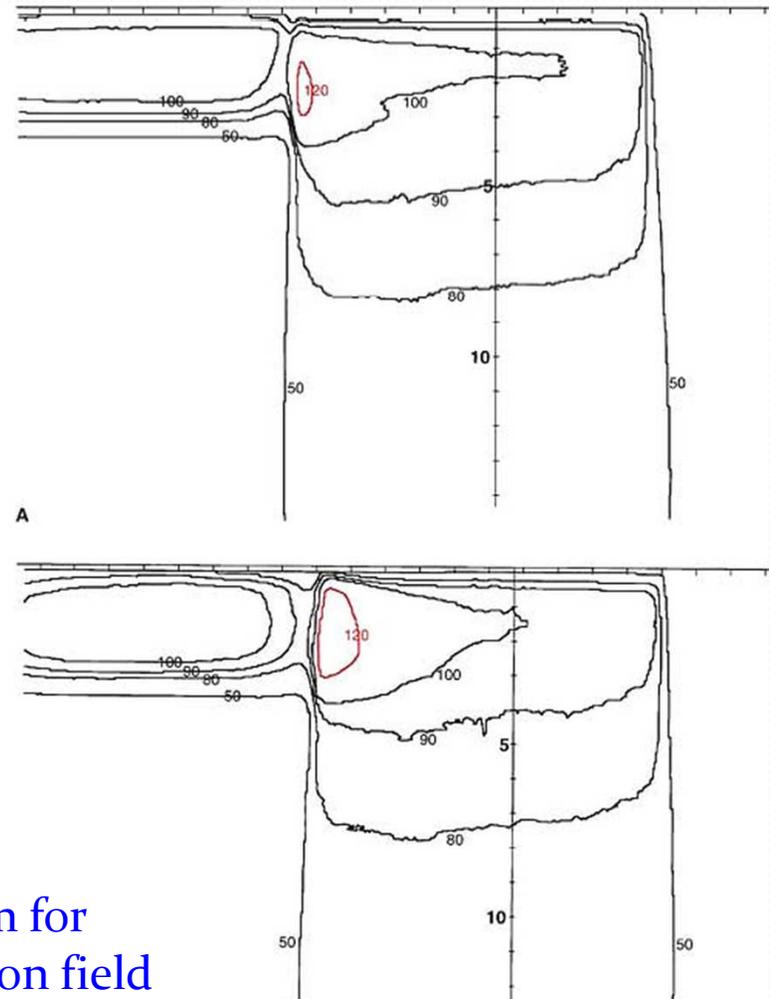
Treatment Planning : Field Abutment



- Example of abutting electron fields in chest wall treatment .
- The dose homogeneity is acceptable at the border of the IMC and medial chest wall fields because central axes are parallel and field widths are small.
- Dose homogeneity is unacceptable at the border of the medial and lateral chest wall fields because the central axes are converging.
- Figure shows the smoothing effect of moving the junction by 1 cm twice during the treatment. A 50% high-dose region can be reduced to +27% by moving the junction in this manner.

Treatment Planning : Photon & Electron Field Abutment

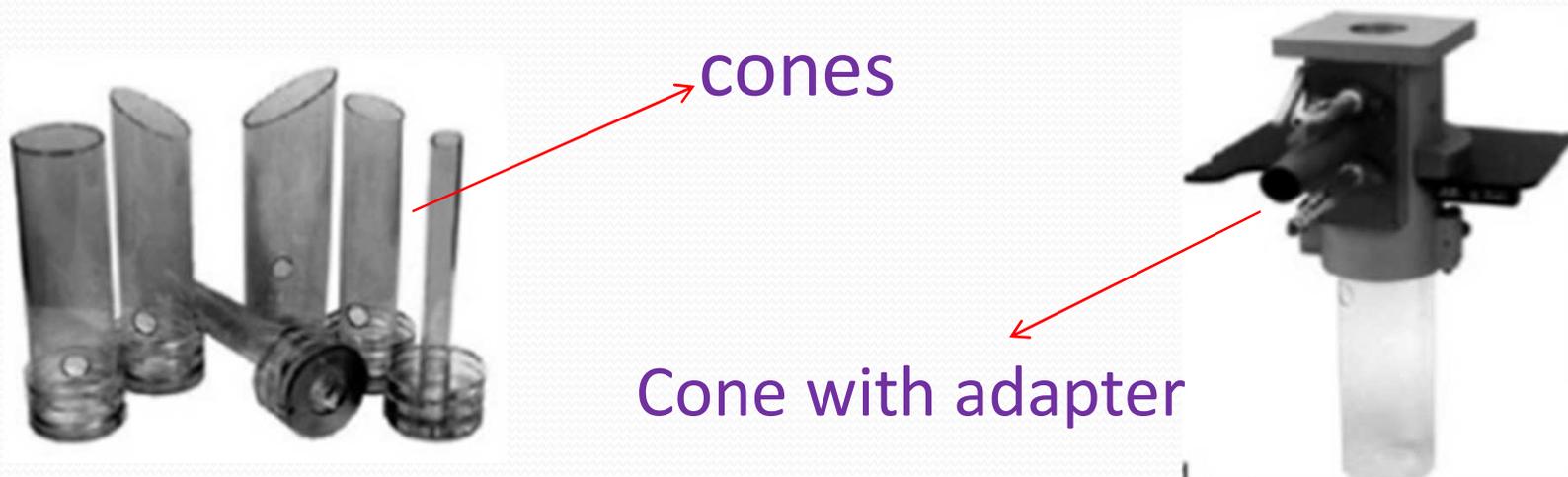
- A hot spot on the side of the photon field
- A cold spot on the side of the electron field
- Outscattering of electrons from the electron field increases dose in photon portal side



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 by 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 .



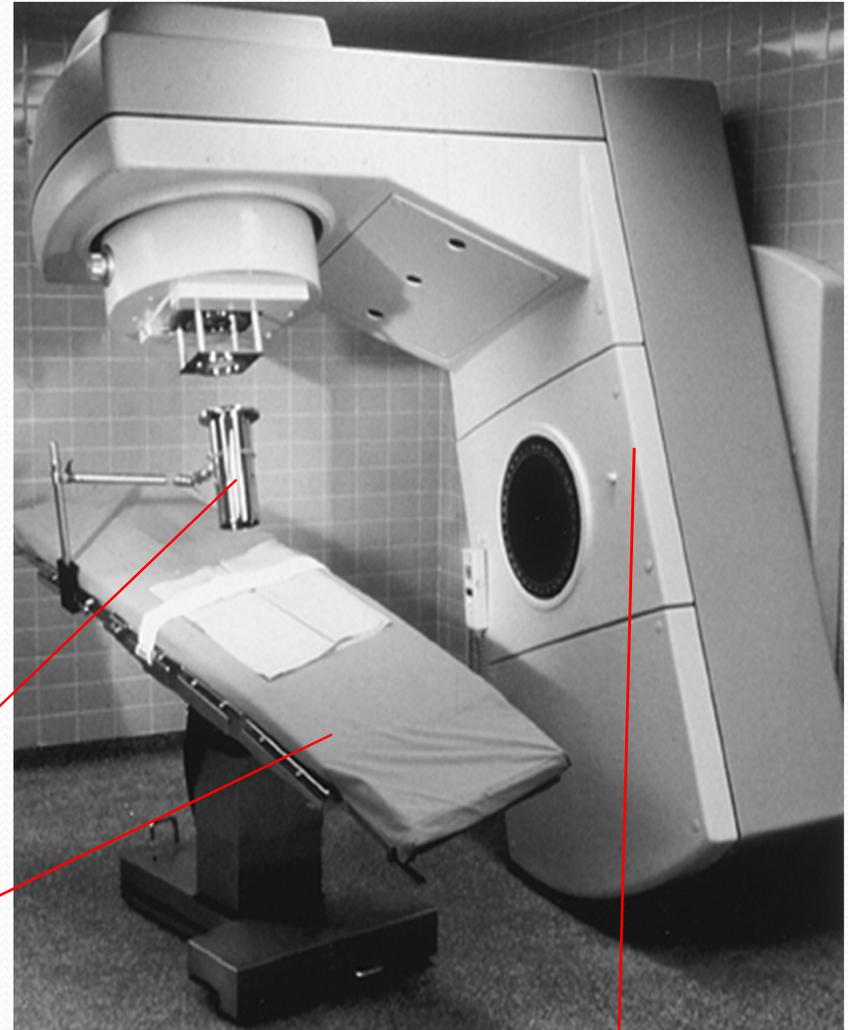
Requirement for IOERT

- A dedicated linear accelerator room that can meet the requirements of operating room (OR)
- New mobile electron linacs that can be transported to a shielded OR can also be used.
- 3, 5, 7 and 9 MeV (Novac7) & 4, 6, 8 and 10 MeV (Liac)

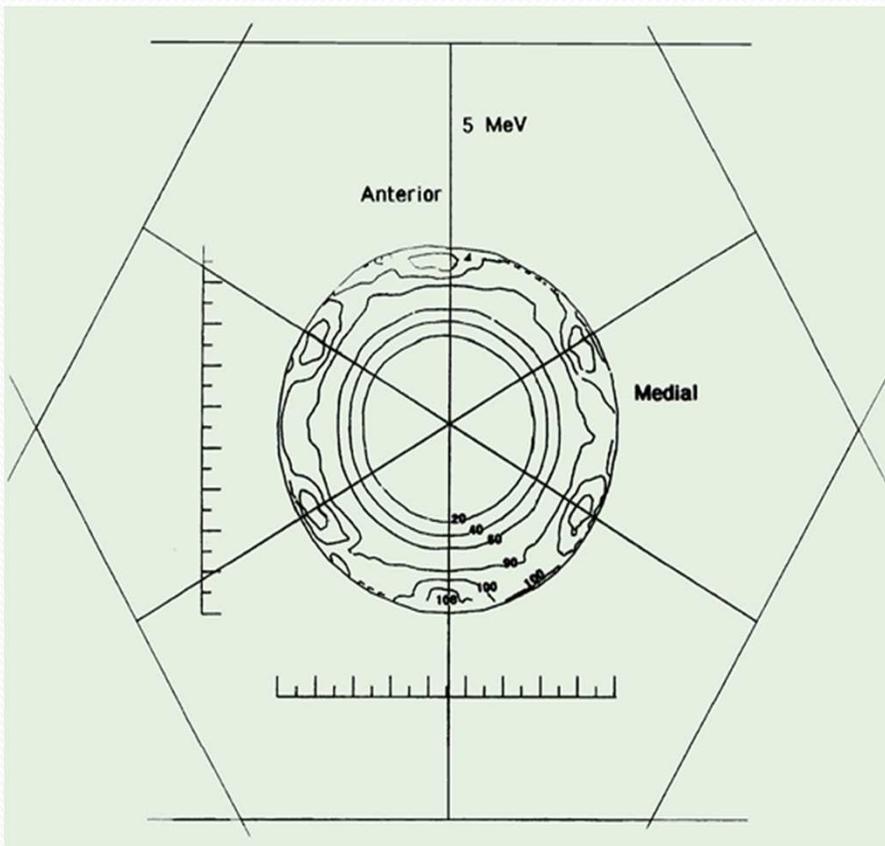
Operating table

Cone

Linac



Total Limb Irradiation

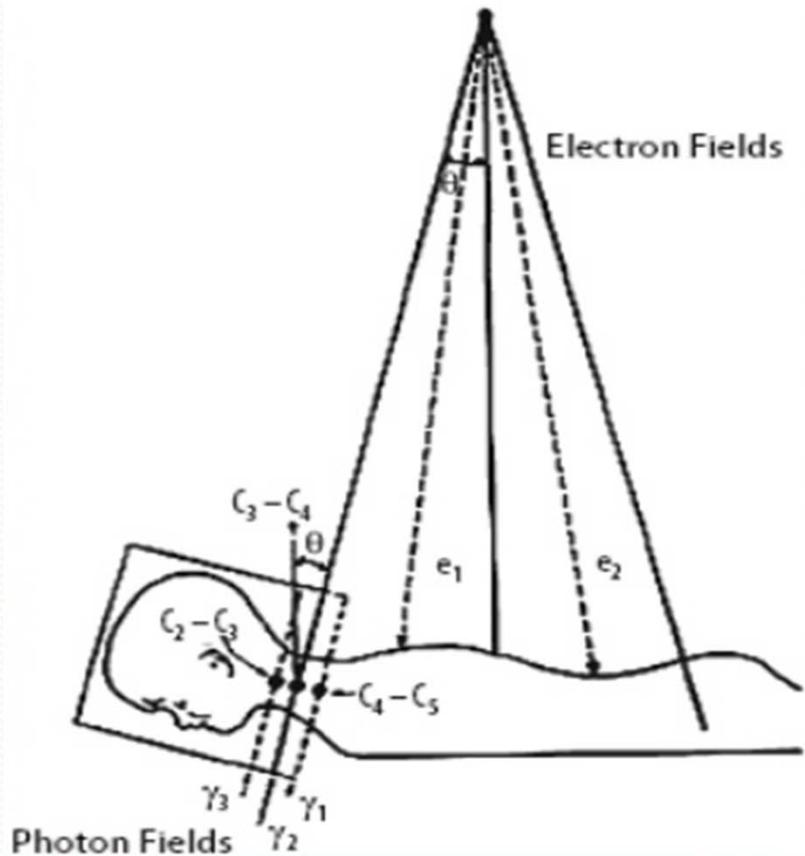


- Treatment of the entire periphery of body extremities (e.g., melanoma, lymphoma, Kaposi's sarcoma) can be carried out using electron fields spaced uniformly around the limb.
- Delivers a uniform dose while sparing deep tissues and structures which are uninvolved.

Craniospinal Irradiation

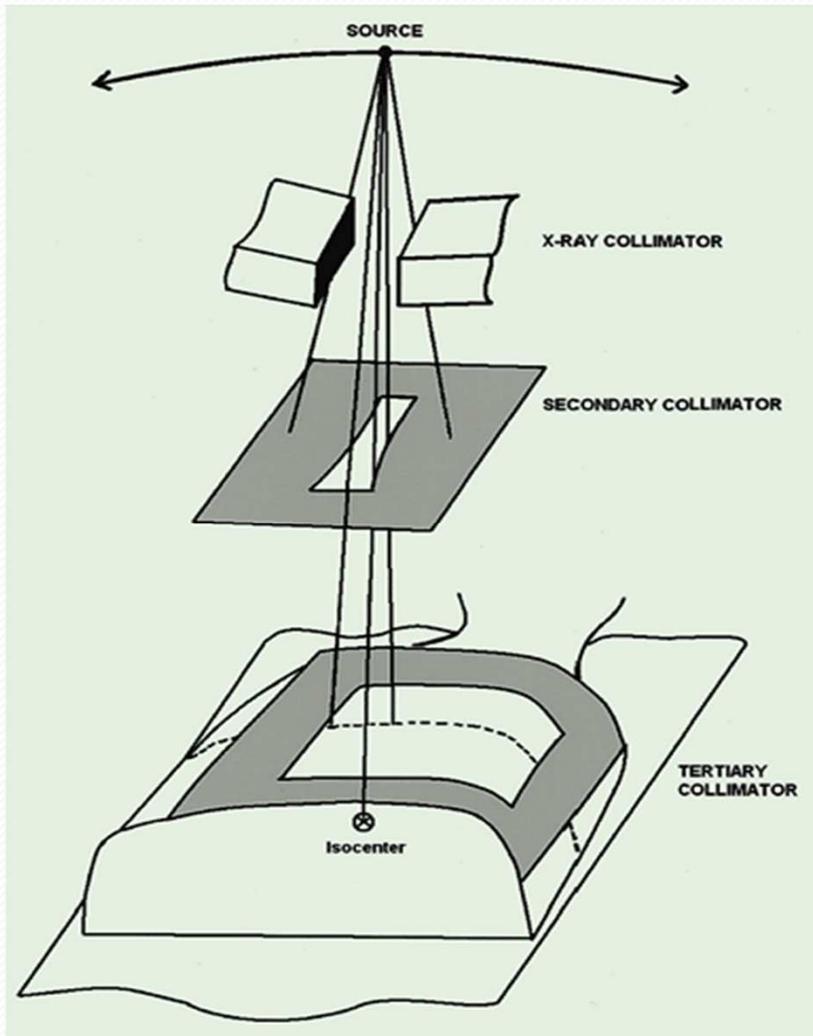
- Replacement of the posterior photon field with a high-energy electron field can reduce greatly the exit dose to the upper thorax region, especially the heart, and the lower digestive tract. This is especially important for pediatric patients and results in reductions of both acute and late complications.
- The lateral photon fields are rotated through an angle to match the divergence of the posterior electron field.
- One-third of the photon treatments are delivered with the inferior border of the two photon fields coincident with the electron field edge.
- The next one-third of the photon treatments are delivered with the edge of one photon field moved 9 mm superior to the electron field edge and the edge of the second photon field moved 9 mm inferiorly to the electron field edge.
- The final one third of the photon treatments are delivered with the edges of the photon fields reversed from their previous position.

Craniospinal Irradiation



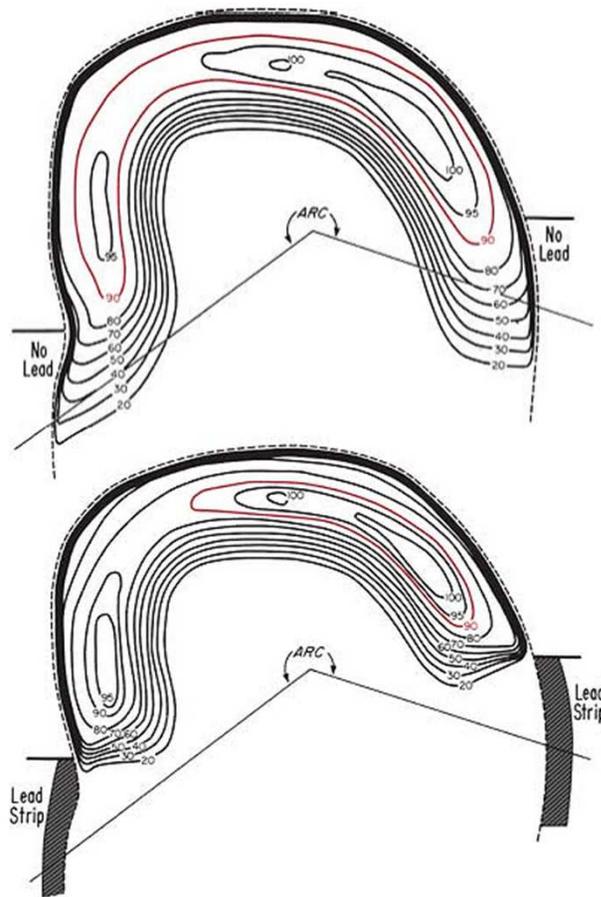
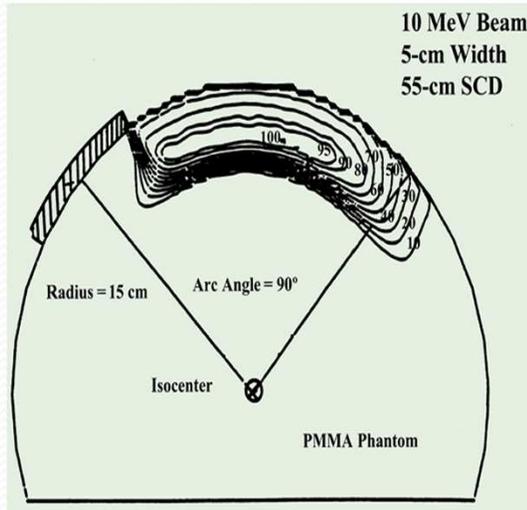
- The angle of the two photon fields are rotated by an angle to account for the divergence of electron field and to produce a common field edge.

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

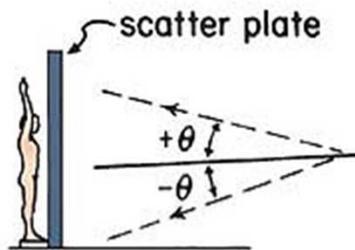
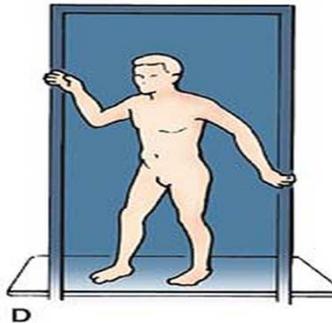
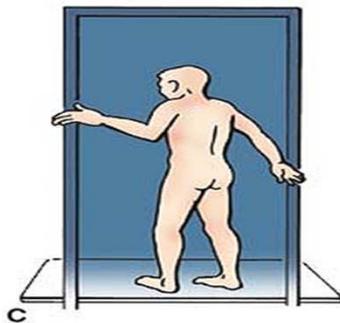
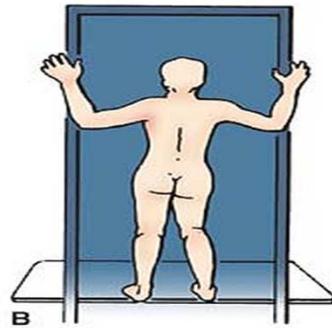
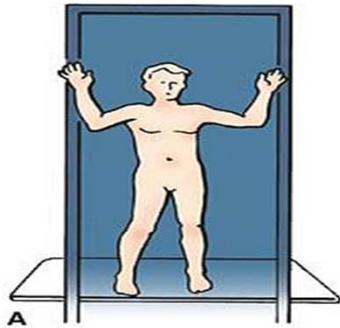


- The uncollimated edge has a slow dose falloff
- The skin collimation restores the beam edge but requires rotating the beam 15 degrees beyond the edge of the skin collimator.

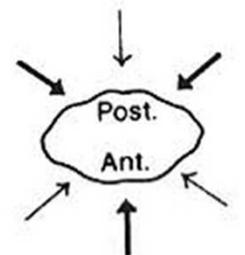
Total Skin Irradiation

- 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



a

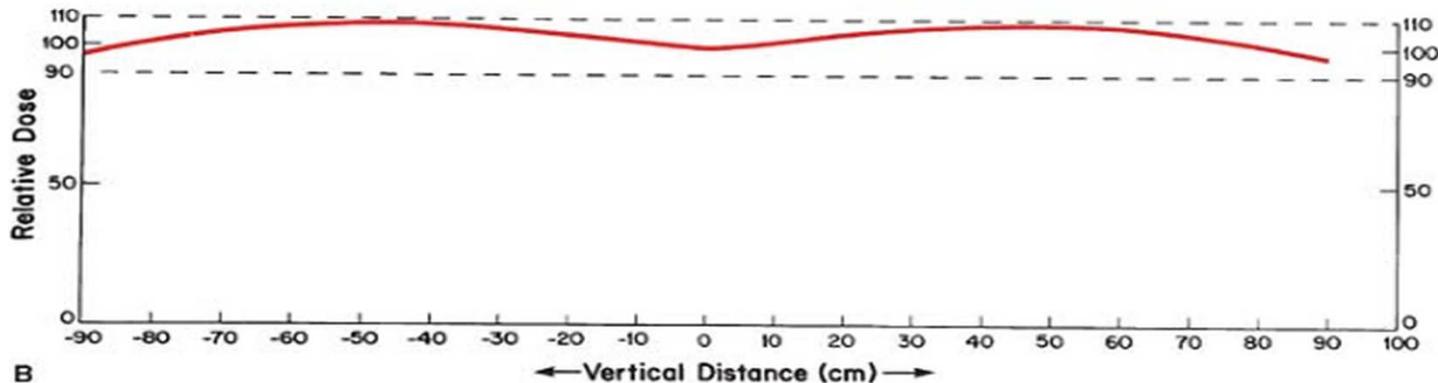
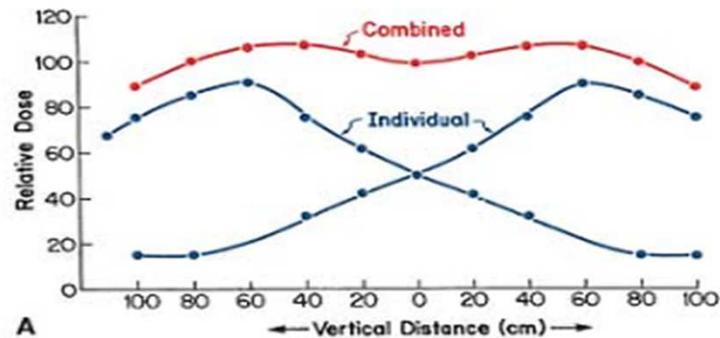


b

First day →
Second day →

- 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*