Electron Beam Therapy

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Introduction

- Mega voltage electron beams represent an important treatment modality in modern radiotherapy, often providing a unique option in the treatment of superficial tumors (less than 5 cm deep).
- Electrons have been used in radiotherapy since the early 1950s, first produced by betatrons and then by microtrons and linacs.
- Modern high energy linacs typically provide, in addition to megavoltage photon energies, several electron beam energies in the range from 4 to 22 MeV.
- Electron-beam therapy is advantageous because it delivers a reasonably uniform dose from the surface to a specific depth, after which dose falls off rapidly, eventually to a near-zero value.

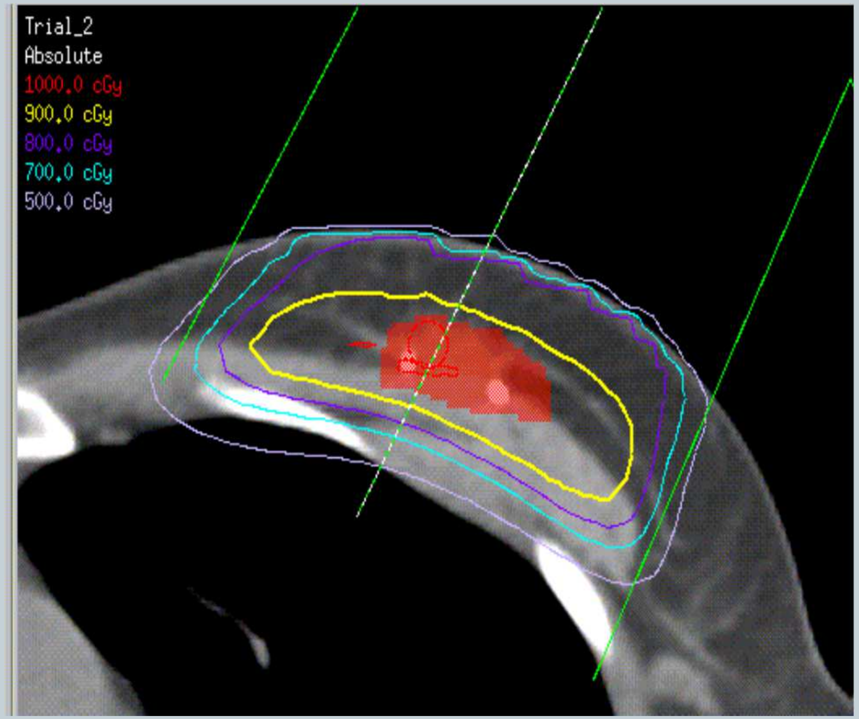
Clinical utility

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 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 (intra operative therapy).

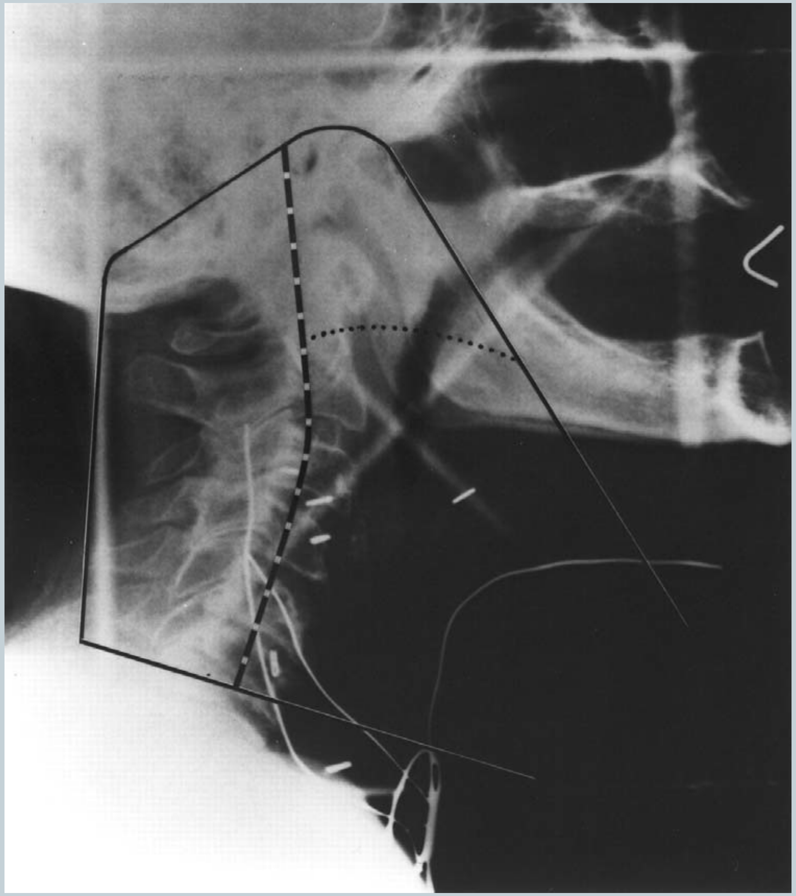
Why treat with electrons?

- Region of fairly uniform dose, then rapid falloff
- Treat superficial targets
- Avoid dose to deep and/or adjacent tissues

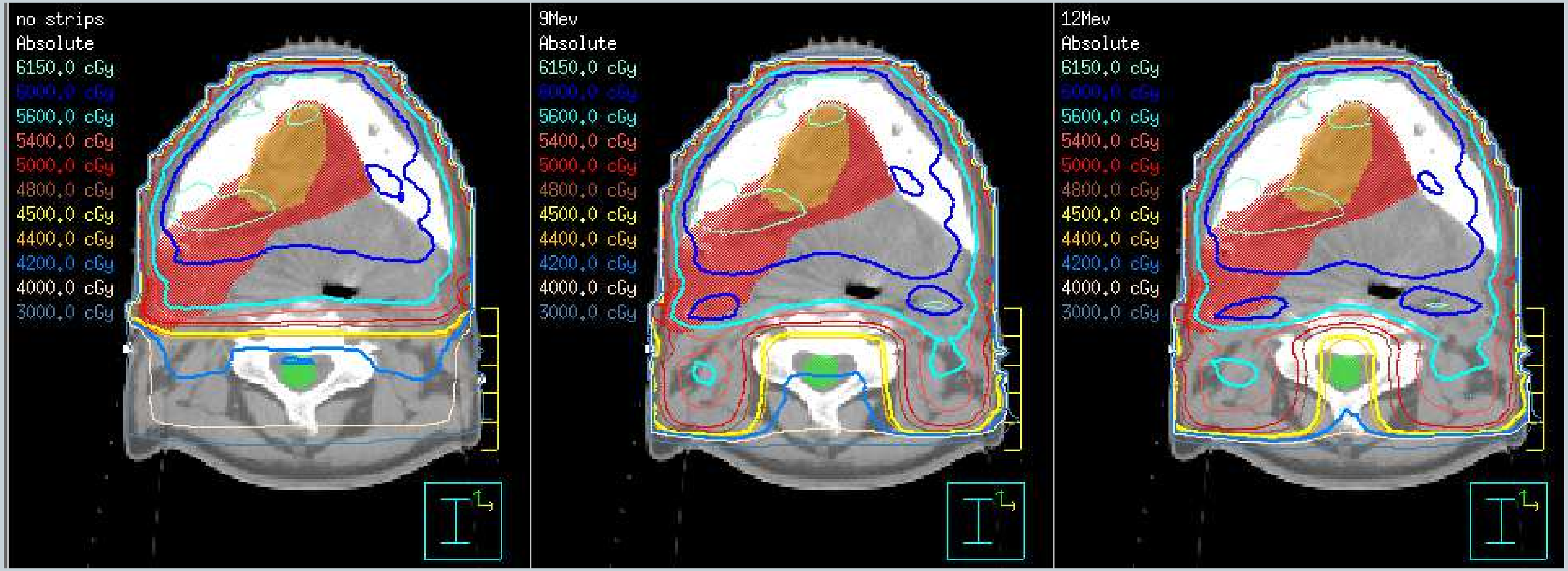


Head and neck

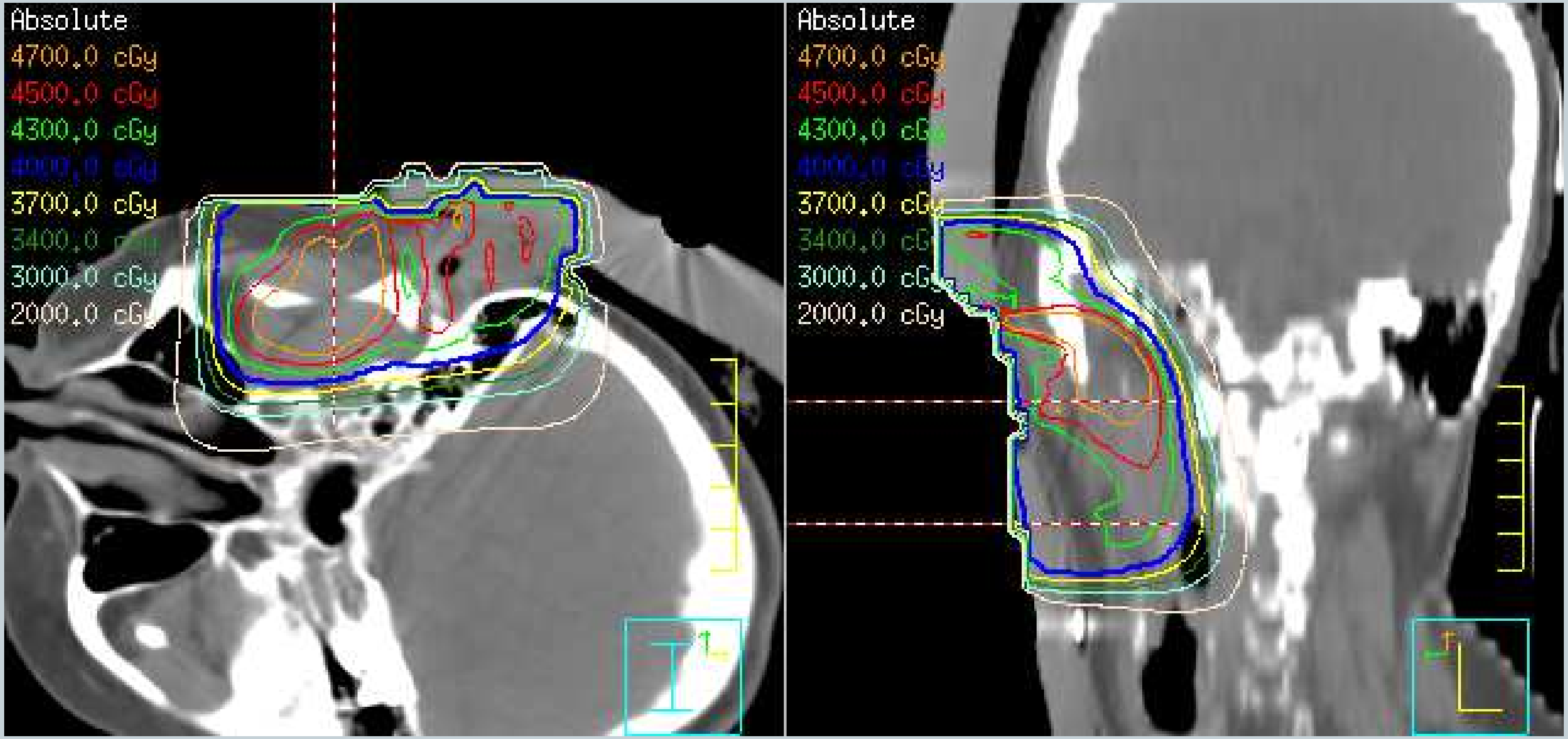
- Fields for postoperative irradiation of a patient with advanced cancer of the laryngopharynx.
- Electrons used for off cord reduction.



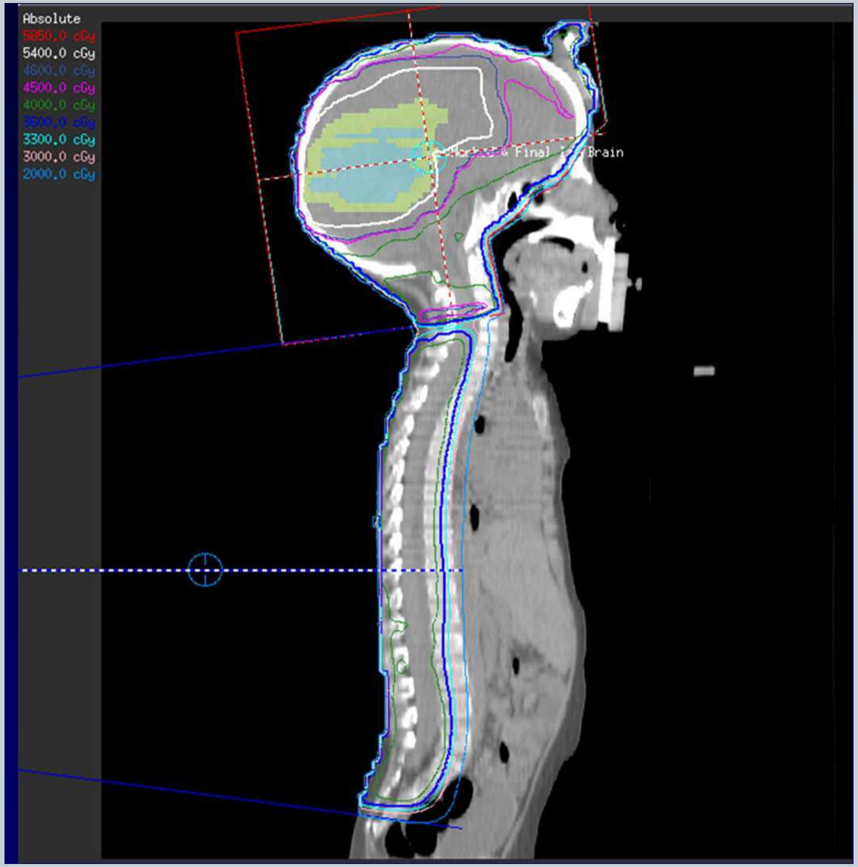
Head & Neck Posterior Strips (9 & 12 MeV)



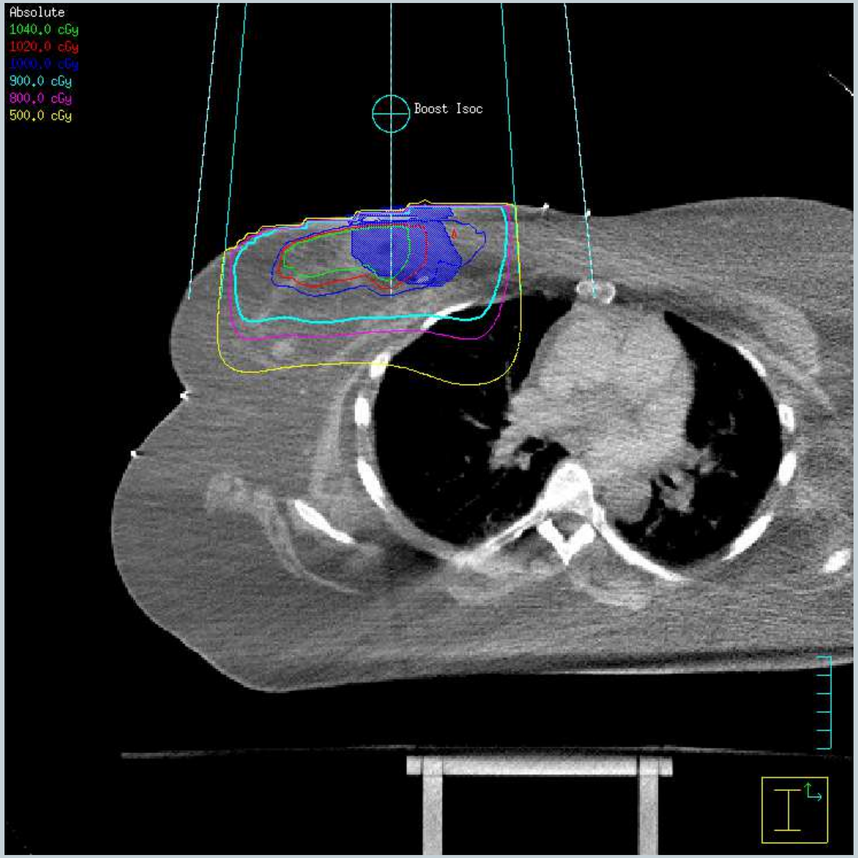
Treatment of Ca Parotid (16MeV with bolus)



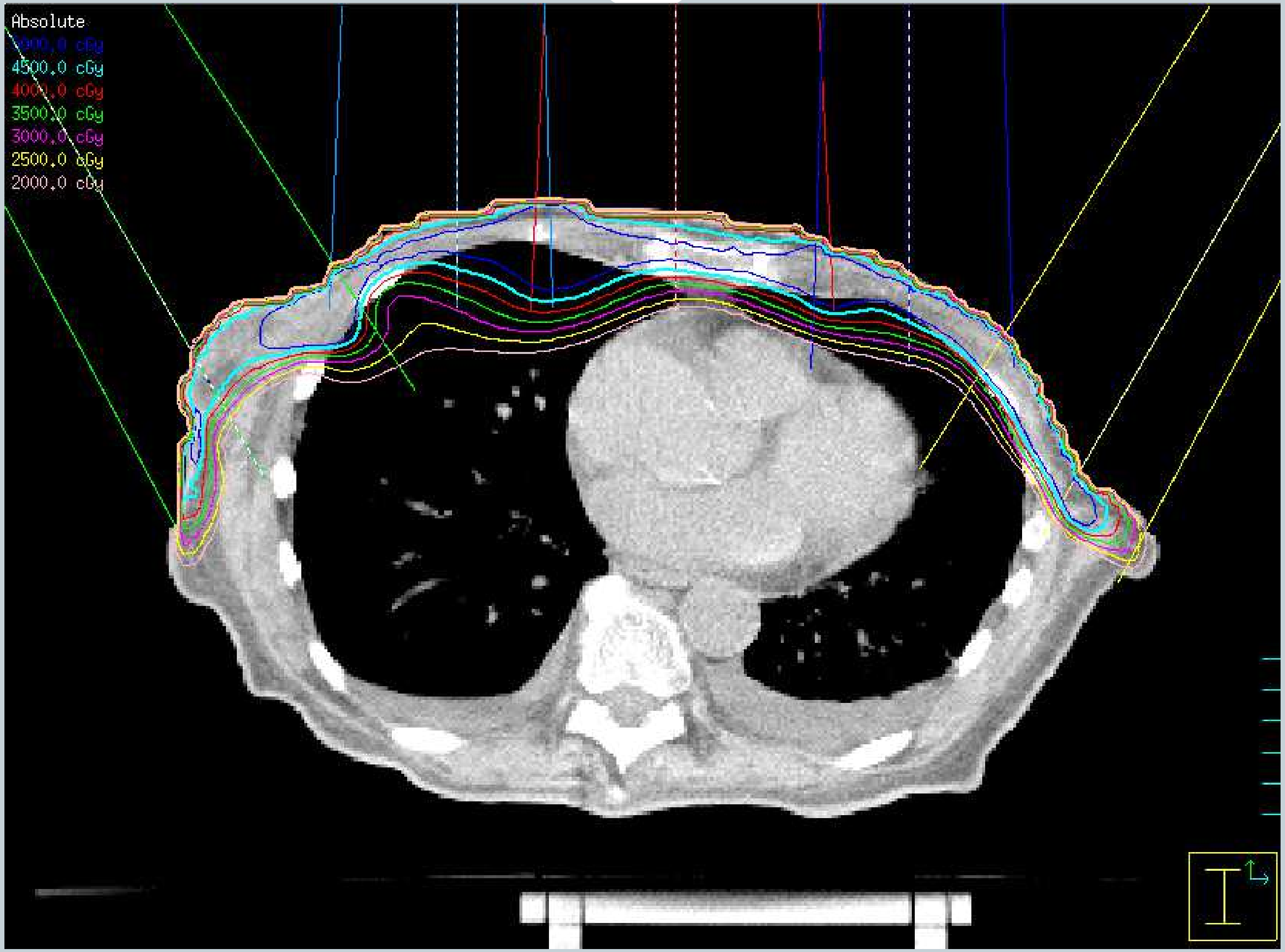
Pediatric CNS (12 MeV)



Breast Boost (20 MeV)

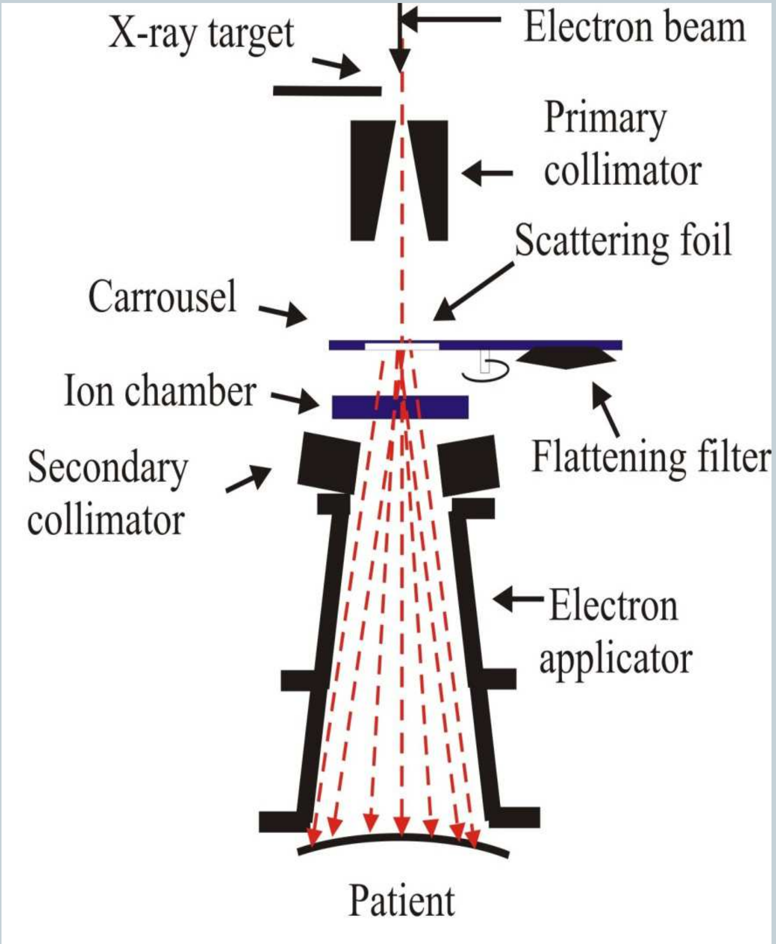


Bi-Lat Chest Wall Electron (6 & 9 MeV)



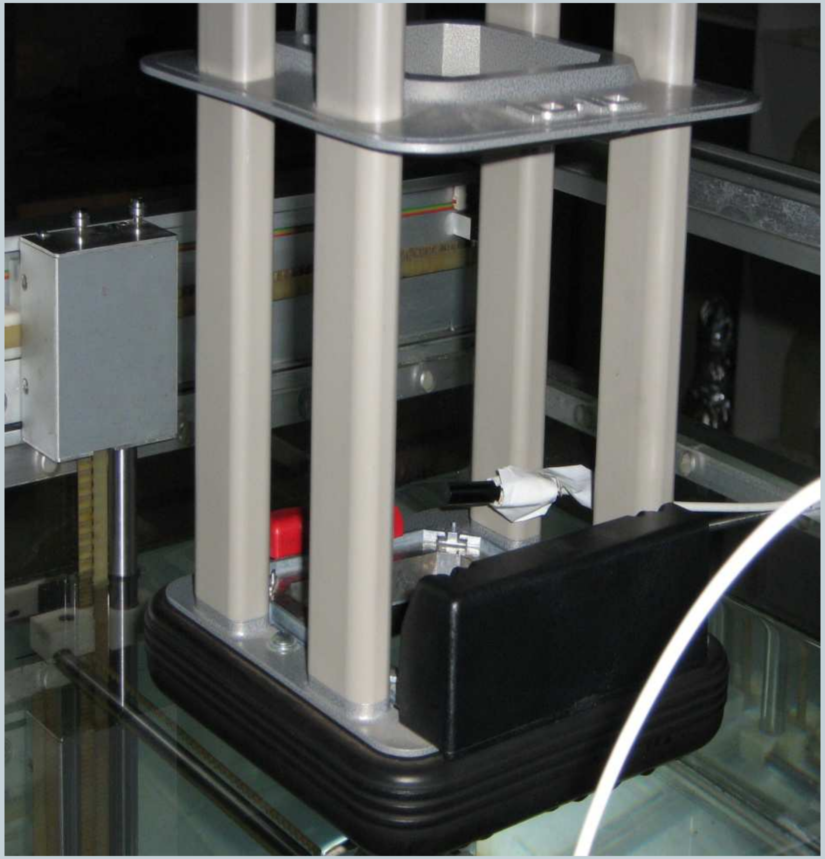
LINAC in e- Mode

- Scattering Foil
- Monitor ionization chambers
- Field defining Light
- Collimator System
  - 2nd degree collimation = cone, downstream of photon
    Collimators placed close to skin to decrease e- scatter in air.
  - 3rd degree collimation cutout downstream of cone custom shape field to match Rx site.



Electron Applicator

Electron beam applicators or cones are usually used to collimate the beam, and are attached to the treatment unit head.

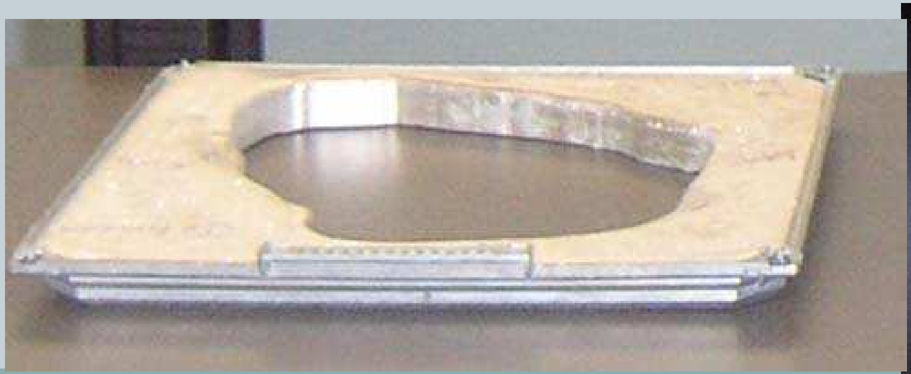


Electron Applicator

- Normally the photon beam collimators on the accelerator are too far from the patient to be effective for electron field shaping.
- After passing through the scattering foil, the electrons scatter sufficiently with the other components of the accelerator head, and in the air between the exit window and the patient, to create a clinically unacceptable penumbra. Hence electron applicators are used.
- Several cones are provided, usually in square field sizes ranging from 5×5 cm^2 to 25×25 cm^2.

Electron Applicator

- For a more customized field shape, a lead or metal alloy cut-out may be constructed and placed on the applicator as close to the patient as possible.
- Standard cut-out shapes may be pre constructed and ready for use at the time of treatment.
- Field shapes may be determined from conventional or virtual simulation, but are most often is decided first day of the treatment.



Electron Interaction

- Inelastic collisions with atomic electrons, resulting in ionization and excitation of atoms and termed collisional or ionizational loss.
- Elastic collisions with atomic nuclei, resulting in elastic scattering that is characterized by a change in direction but no energy loss.
- Inelastic collisions with atomic nuclei, resulting in bremsstrahlung production and termed radiative loss.
- Elastic collisions with atomic electrons.

Electron Interaction

- The kinetic energy of electrons is lost in inelastic collisions that produce ionization or is converted to other forms of energy, such as photon energy or excitation energy.
- In elastic collisions kinetic energy is not lost; however, the electron's direction may be changed or the energy may be redistributed among the particles emerging from the collision.
- The typical energy loss for a therapy electron beam, averaged over its entire range, is about 2 MeV/cm in water and water-like tissues.

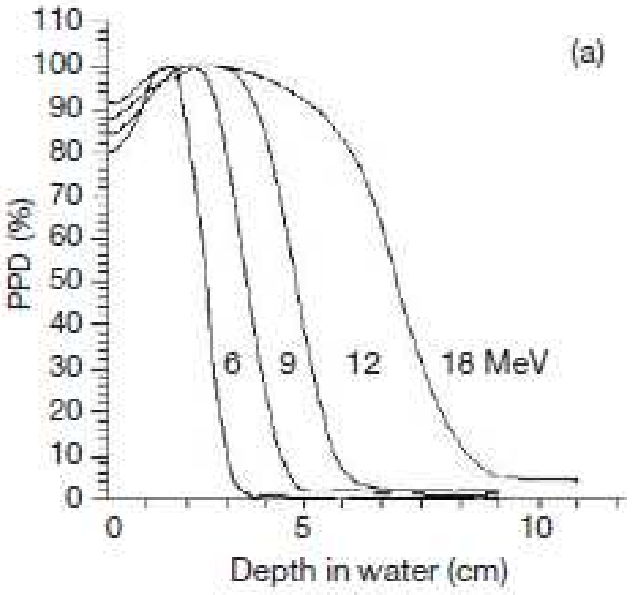
Stopping Power (Rate of energy loss)

- The rate of energy loss for collisional interactions depends on the electron energy and on the electron density of the medium.
- The rate of energy loss per gram per square centimetre, $MeV/g/cm^2$ (called the mass stopping power), is greater for low atomic number materials than for high atomic number materials.
- The rate of energy loss for radiative interactions (bremsstrahlung) is approximately proportional to the electron energy and to the square of the atomic number of the absorber.
- The scattering power of electrons varies approximately as the square of the atomic number(Z^2) and inversely as the square of the kinetic energy($1/E^2$).

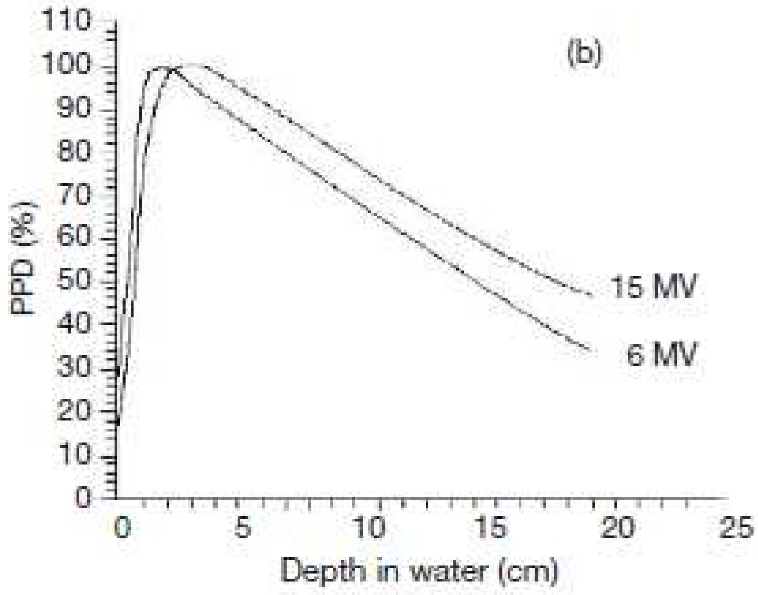
Dose Distribution in Water

To appreciate the clinical use of electron beams, their dose distributions in water must be understood. Understanding the properties of depth dose, off-axis ratios, and two-dimensional (2D) isodose contour plots will clarify the concept of dose distribution in water.

Depth Dose



Electron beam PDD



Photon beam PDD

Dose Distribution in Water

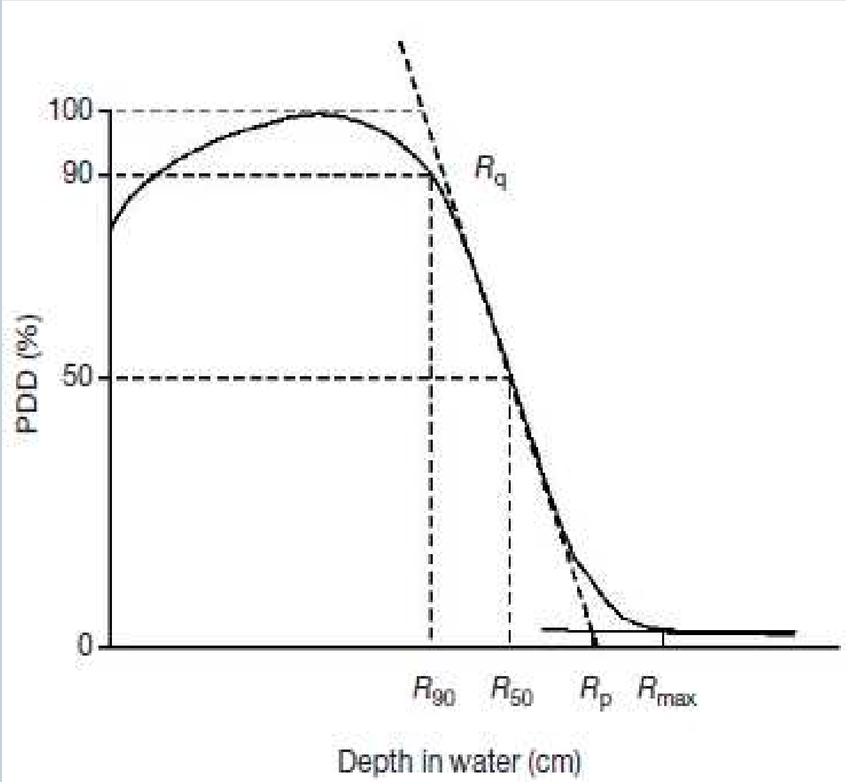
- The electron beam central axis depth dose curve exhibits a high surface dose (compared with megavoltage photon beams), and the dose then builds up to a maximum at a certain depth referred to as the electron beam depth of dose maximum D_{max}.
- *Beyond D_{max} the dose drops off rapidly and levels* off at a small low level dose component referred to as the bremsstrahlung tail.
- These features offer a distinct clinical advantage over the conventional X-ray modalities in the treatment of superficial tumors.

Dose Distribution in Water

- The practical range ***Rp*** *(cm or g/cm2) is defined as the depth at which the* tangent plotted through the steepest section of the electron depth dose curve intersects with the extrapolation line of the background due to bremsstrahlung. ***Rp*** increases as energy increases.

- The maximum range ***Rmax*** *(cm or g/cm2) is defined as the depth at which* extrapolation of the tail of the central axis depth dose curve meets the bremsstrahlung background.

- The depths $\boldsymbol{R_{90}}$ *and* $\boldsymbol{R_{50}}$ *(cm or g/cm2) are defined as depths on the* electron PDD curve at which the PDDs beyond *Dmax attain values of 90% and* 50%, respectively.



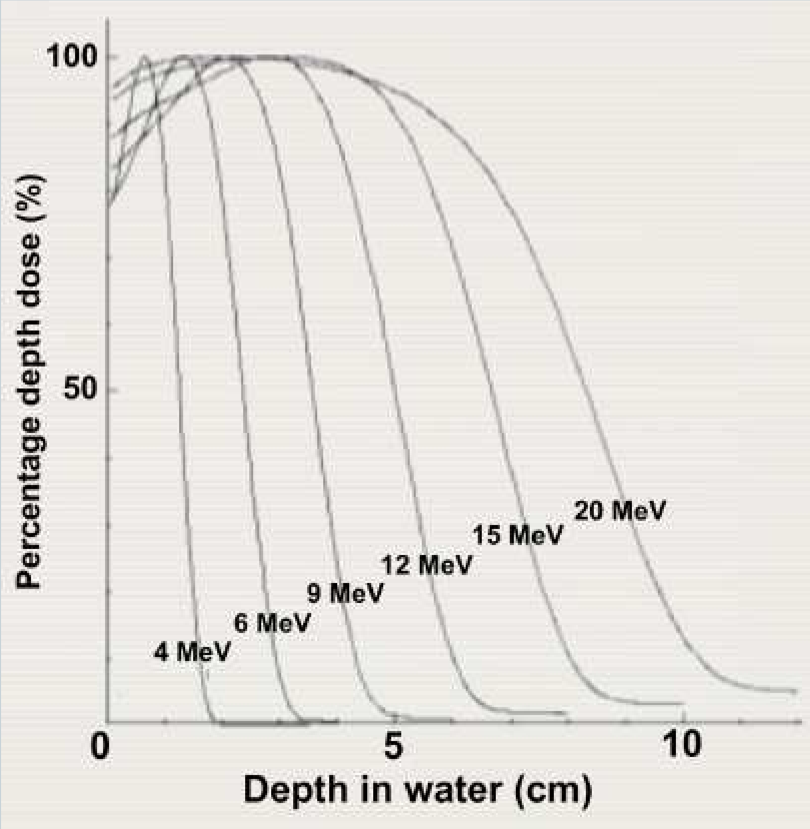
Dose Distribution in Water

- Electron beams are almost monoenergetic as they leave the linac accelerating waveguide.
- In moving toward the patient through:
  - Waveguide exit window
  - Scattering foils
  - Transmission ionization chamber
  - Air

and interacting with photon collimators, electron cones (applicators) and the patient, bremsstrahlung radiation is produced. This radiation constitutes the bremsstrahlung tail of the electron beam PDD curve.

Dose Distribution in Water

- Bremsstrahlung contamination of electron beams depends on electron beam energy and is typically:-
  - Less than 1 % for 4 MeV electron beams.
  - Less than 2.5 % for 10 MeV electron beams.
  - Less than 4 % for 20 MeV electron beams.



Measured and calculated data of a typical Linear accelerator

Nominal Energy	Measured E_o (MeV)	Measured E_p (MeV)	R_{90}: Depth of 90% (cm)	R_{50}: Depth of 50% (cm)	*Rp* (cm)	*Dx* (%)
6	5.55	6.08	1.53	2.38	2.95	0.1
9	8.41	8.84	2.69	3.61	4.33	0.3
12	11.77	12.23	3.85	5.05	6.02	0.9
16	15.63	16.02	5.10	6.71	7.900	1.6
20	19.62	20.78	6.14	8.42	10.25	2.1

- Where **Eo** is Average(mean) energy at the surface ($Eo = C_4.R_{50}$ MeV) ; C4= 2.33MeV/cm
- **Ep** is Most probable electron energy at the surface, ($E_p = C_1 + C_2 R_p + C_3 R_p^2$) where C_1, C_2, and C_3, are constants, with C_1 = 0.22 MeV, C_2 = 1.98 MeV/cm, and C_3 = 0.0025 MeV/cm^2.

Characteristics of Clinical Electron Beams

- The most useful treatment depth, or therapeutic range, of electrons is given by the depth of the 90% depth dose.
- For modern accelerators with trimmer-type applicators this depth of 90% is approximately given by E/3.2 cm,
- The depth of the 80% depth dose occurs approximately at E/2.8 cm.

where E is the most probable energy in MeV of the electron beam at the surface.

Characteristics of Clinical Electron Beams

- **Depth of the 80% Dose is approximately $E_{nom}/2.8$**

$E_{nominal}$	$E_{nom}/2.8$	Actual
6	2.14	2.20
9	3.21	3.30
12	4.28	4.30
16	5.71	5.50
20	7.14	7.00

- **Depth of 90% is approximately $E_{nom}/3.2$**

$E_{nominal}$	$E_{nom}/3.2$	Actual
6	1.88	2.00
9	2.81	3.00
12	3.75	4.00
16	5.00	5.00
20	6.25	6.10

Characteristics of Clinical Electron Beams

- Depth of maximum dose (R_{100}):

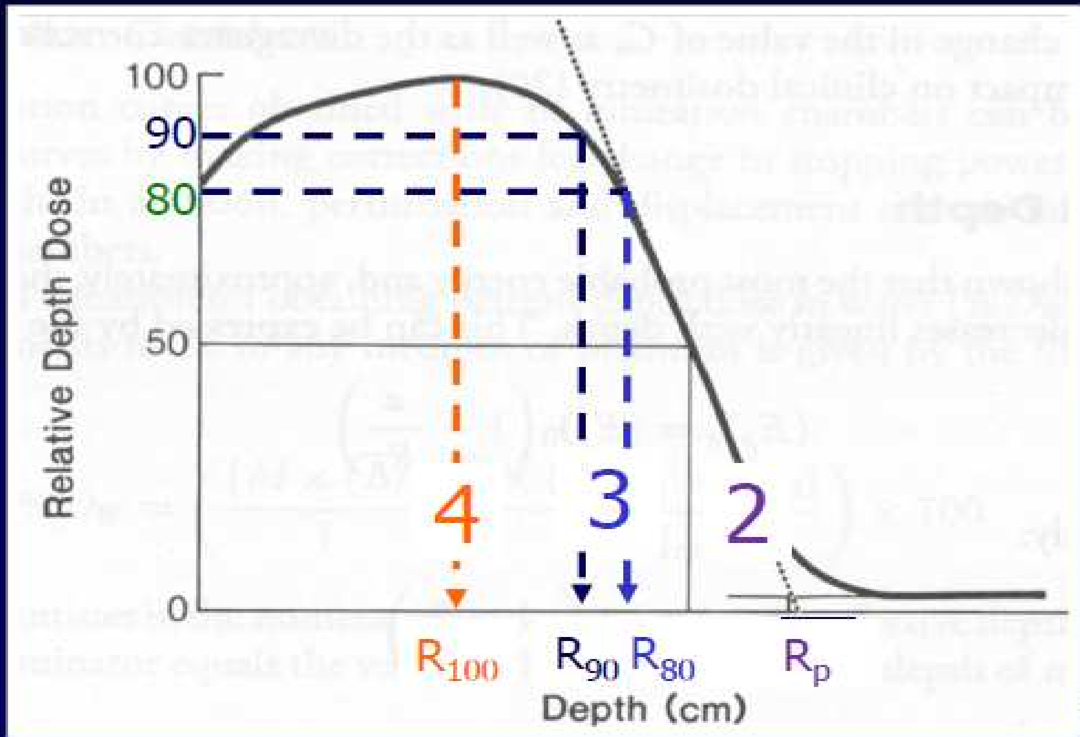
  For E<12MeV, R_{100} equal to approximately E/4
- **Practical Range is equal to approximately 1/2 nominal energy**

$E_{nominal}$	E_{nom} / 2	R_p
6	3.0	3.15
9	4.5	4.58
12	6.0	6.04
16	8.0	7.66
20	10.0	10.13

- **Energy loss is about 2 MeV / cm**

Electron Depth Dose Curves:
The *approximate* 4,3,2 rule of thumb

$$R_{100} \approx \frac{E_0}{4} \qquad R_{80-90} \approx \frac{E_0}{3} \qquad R_P \approx \frac{E_0}{2}$$



Entrance dose

- The percent surface dose increases with increasing energy
- At lower energies electrons are more easily scattered through larger angles.

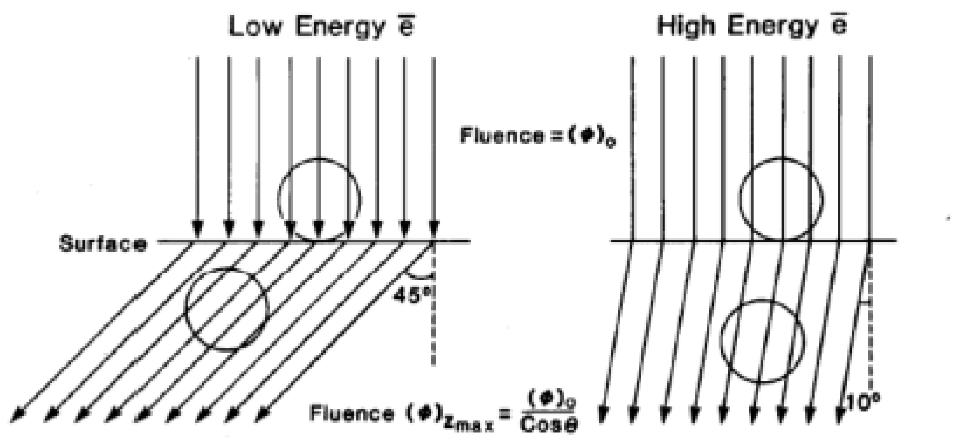


Figure 14.10. Schematic illustration showing the increase in percent surface dose with an increase in electron energy. From Khan FM. Clinical electron beam dosimetry. In: Keriakes JG, Elson HR, Born CG, eds. Radiation oncology physics—1986. AAPM Monograph No. 15. New York, American Institute of Physics, 1986:211.

Enom	Surface dose (%)
6	72
9	78
12	83
15	87
18	91

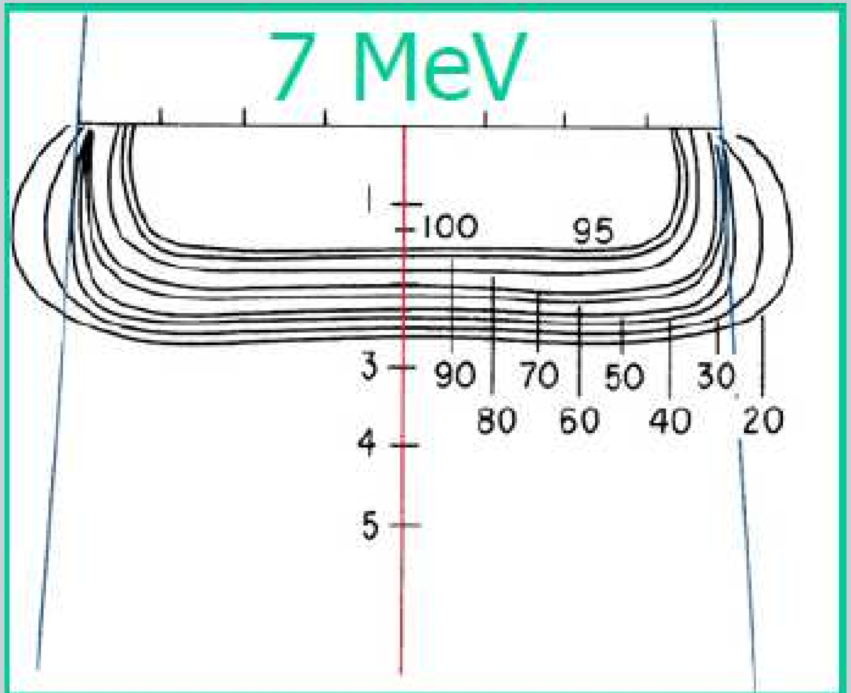
Electron Isodose Curves

- Isodose curves are lines connecting points of equal dose in the irradiated medium.
- Isodose curves are usually drawn at regular intervals of absorbed dose and are expressed as a percentage of the dose at a reference point, which is usually taken as the ***Dmax*** *point on* the beam central axis.
- Scattering of electrons very important factor in SHAPE of isodose curve.
- As the beam penetrates the medium, the beam expands rapidly below the surface due to scattering.
- Spread of isodose curve depends on:-
  - Isodose Level
  - Energy
  - Field Size
  - Collimation

Electron Isodose Curves

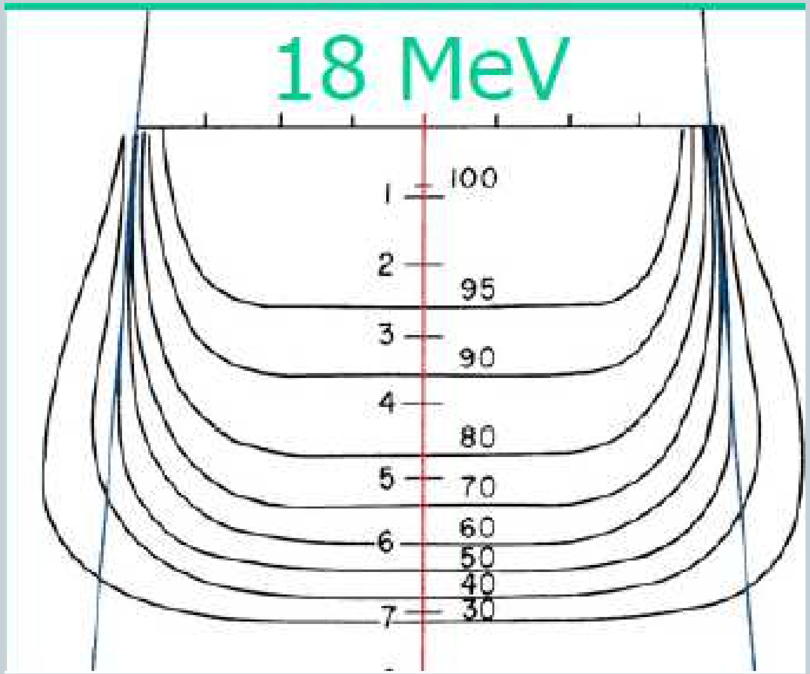
Low Energy Electron beams

- ALL isodose levels bulge out.



High Energy Electron Beams

- LOW isodose levels bulge out
- HIGH isodose levels show lateral constriction, which becomes worse with decreasing field size.



DOSE DISTRIBUTION IN PATIENT

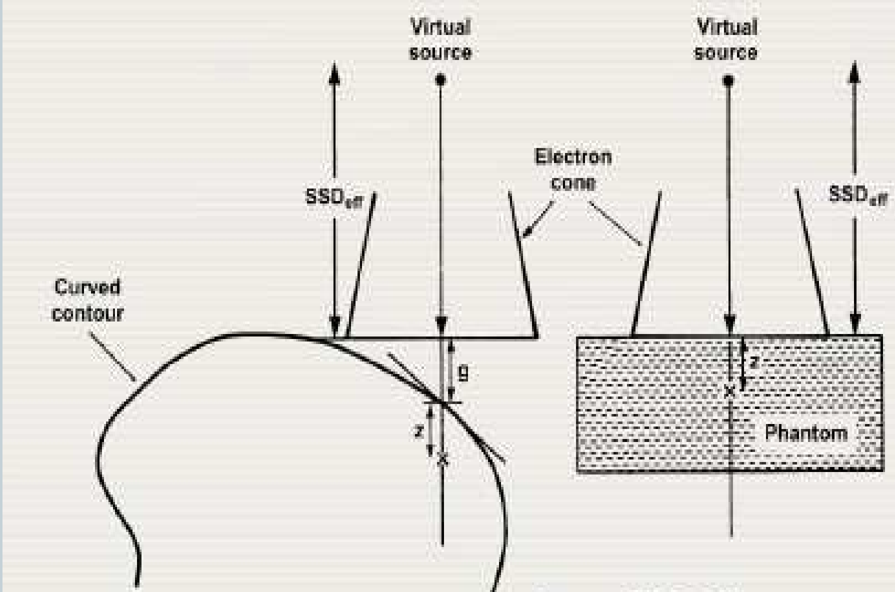
- The ideal irradiation condition is for electron beam to be incident normal to a flat surface with underlying homogeneous normal tissue.
- When the angle of incidence deviates from normal, surface becomes irregular.
- Internal heterogenous tissue present, the qualities of dose distribution deviates from that in phantom.
- Internal heterogenity can change depth of beam penetration.
- Both irregular surface and internal heterogenities create changes in side scatter equilibrium, producing volume of increased dose(***hot spot)*** *and* decreased dose(***cold spot)***

Air gap

- In electron beam therapy, the air gap is defined as the separation between the patient and the end of the applicator cone. The standard air gap is 5 cm.
- Due to Irregular skin surface extreme, curvature of the sloping surface the SSD has to increase.
- With increasing air gap:-
  - Low value isodose curves diverge.
  - High value isodose curves converge toward the central axis of the beam.
  - Physical penumbra increases.

Air gap

- Output for extended SSD cannot be accurately predicted by using ISL from the nominal source position (x-ray target) due to electron scattering.
- The distance from this effective source position to the patient surface (at isocentre) is called the "***Effective SSD***". The dose at a gap is given by:-

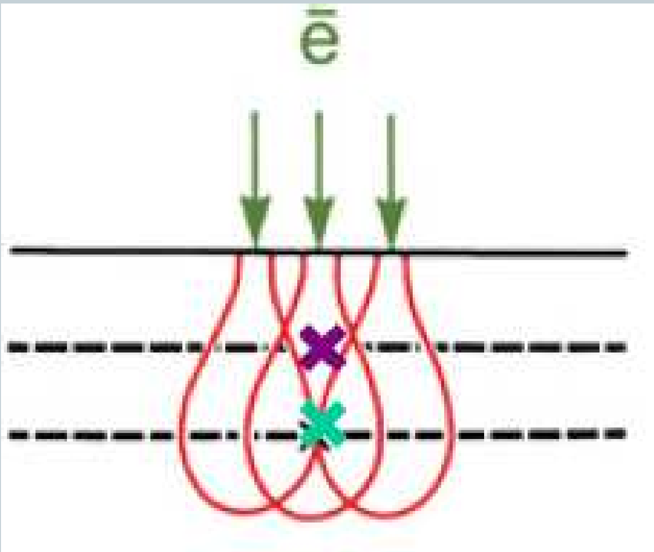


From F.M. Khan: "The Physics of Radiation Therapy"

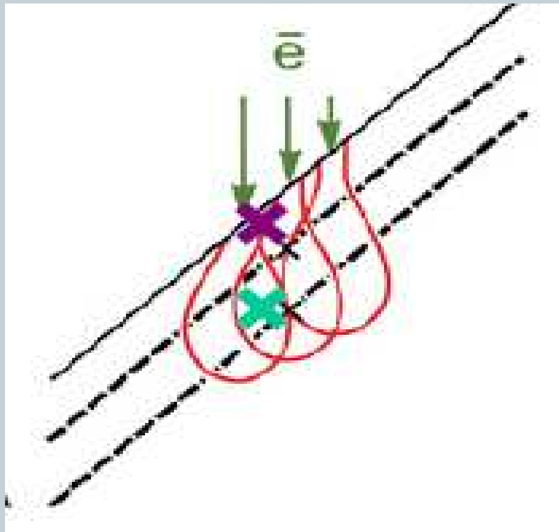
$$D\,(d_{max},\, SSD + g) = D\,(d_{max},\, SSD_{eff}) \cdot \frac{(SSD_{eff} + d_{max})^2}{(SSD_{eff} + d_{max} + g)^2}$$

Effect of Oblique Incidence on Dose Distribution

- The broad electron beam can be represented as a large number of pencil beams placed adjacent to each other.



- When a beam is obliquely incident on the patient's surface:
  - Points at shallow depths receive greater side scatter from adjacent pencil beams, which have traversed a greater amount of the material.
  - Points at greater depths receive less scatter.



Effect of Oblique Incidence on Dose Distribution

- Increased dose at shallow depths.
- Decreased dose at deeper depths.
- In reality as obliquity increases, the air gap between the skin surface and the cone end increases.
- The depth dose at a point in an obliquely incident beam is effected by both “pencil scatter effect” and “beam divergence”.

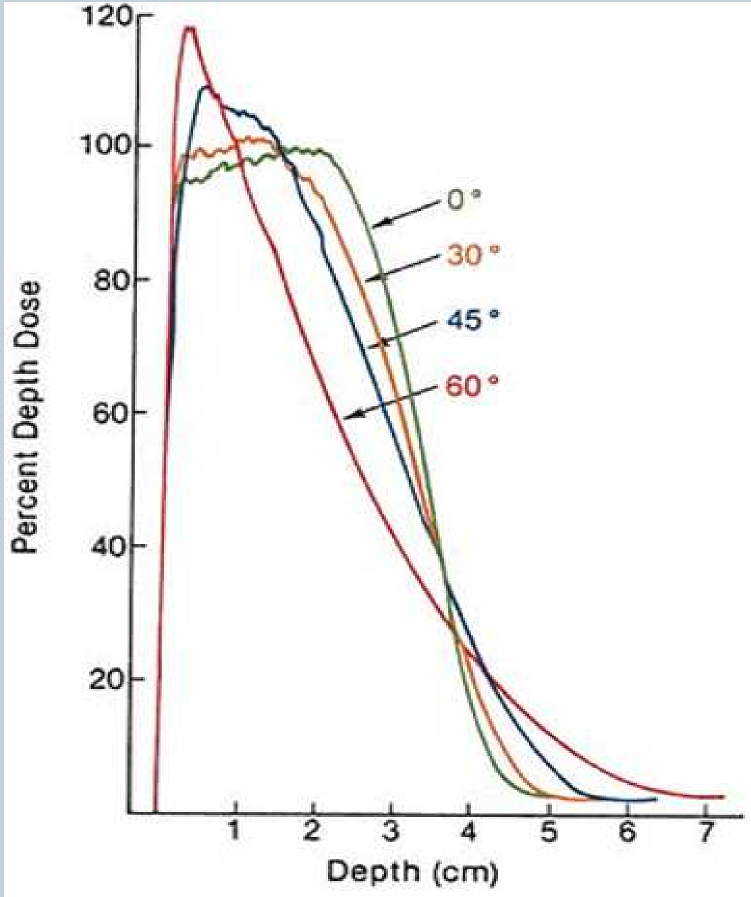


Fig. Change in depth dose with angle of obliquity for 9 MeV electron beam.

Effect of Oblique Incidence on Dose Distribution

- The obliquity factor becomes significant for angles of incidence approaching 45 degrees or higher.
- For example:-
- A 60-degree angle of obliquity for a 9-MeV electron beam
  - gives rise to OF = 1.18 at the d_{max},
  - a shift of the d_{max} to about 0.5 cm,
  - a shift of the 80% depth to about 1.5 cm.

Inhomogeneity corrections

- The dose distribution from an electron beam can be greatly affected by the presence of tissue inhomogeneities (heterogeneities) such as lung or bone.
- The dose inside an inhomogeneity is difficult to calculate or measure, but the effect of an inhomogeneity on the dose beyond the inhomogeneity is relatively simple to measure and quantify.
- The simplest correction for a tissue inhomogeneity involves the scaling of the inhomogeneity thickness by its electron density relative to that of water and the determination of the coefficient of equivalent thickness (CET).
- Electron density of an inhomogeneity is essentially equivalent to the mass density of the inhomogeneity.

Inhomogeneity corrections

- CET is used to determine the effective depth in water equivalent tissue Z_{eff} *through the following expression:-*

$$\boxed{Z_{eff} = Z - t(1 - CET)}$$

z = actual depth of the point of interest in the patient

t = thickness of the inhomogeneity

For example:

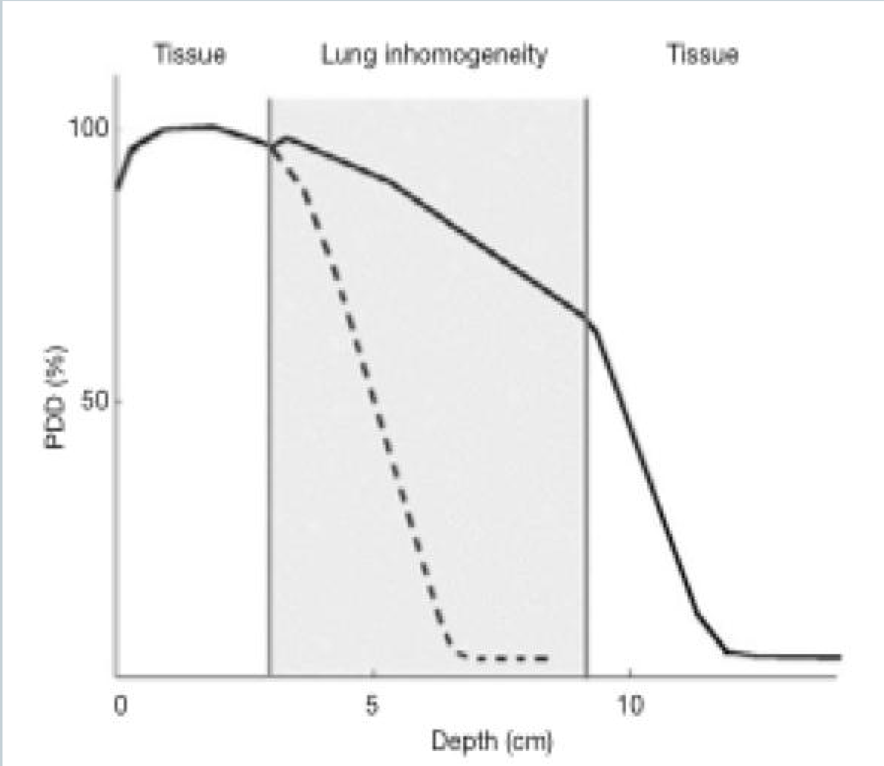
- Lung has approximate density of 0.25 g/cm3 and a CET of 0.25.
- A thickness of 1 cm of lung is equivalent to 0.25 cm of tissue.
- Solid bone has approximate density of 1.6 g/cm3 and a CET of 1.6.
- A thickness of 1 cm of bone is equivalent to 1.6 cm of tissue.

Effect of lung inhomogeneity on the PDD distribution of an electron beam

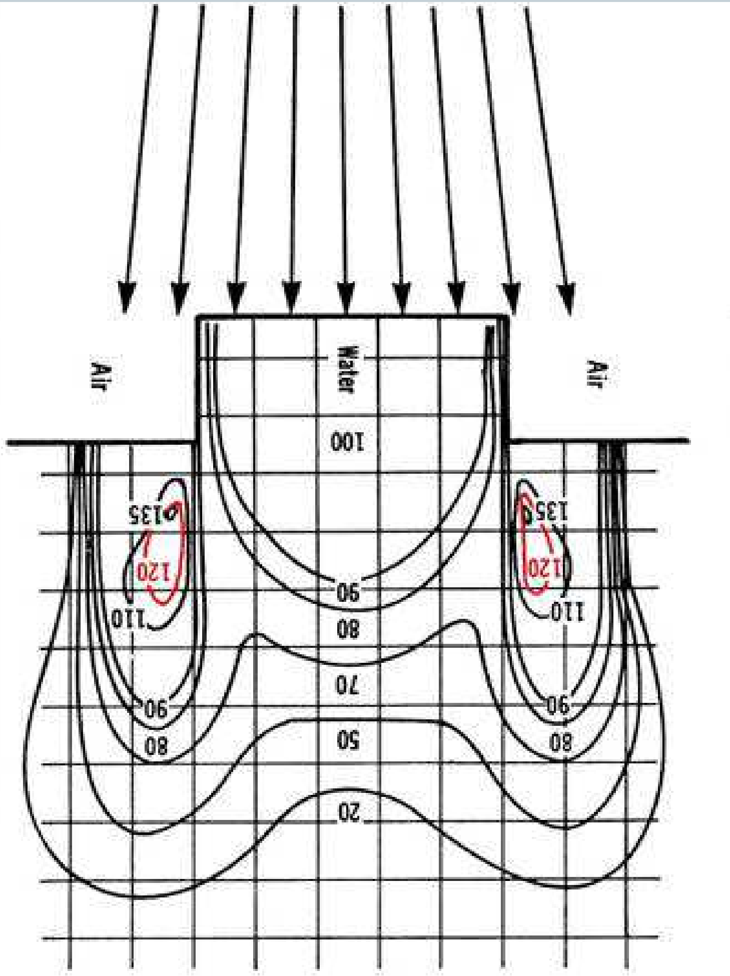
(energy: 15 MeV, field: 10×10 cm²).

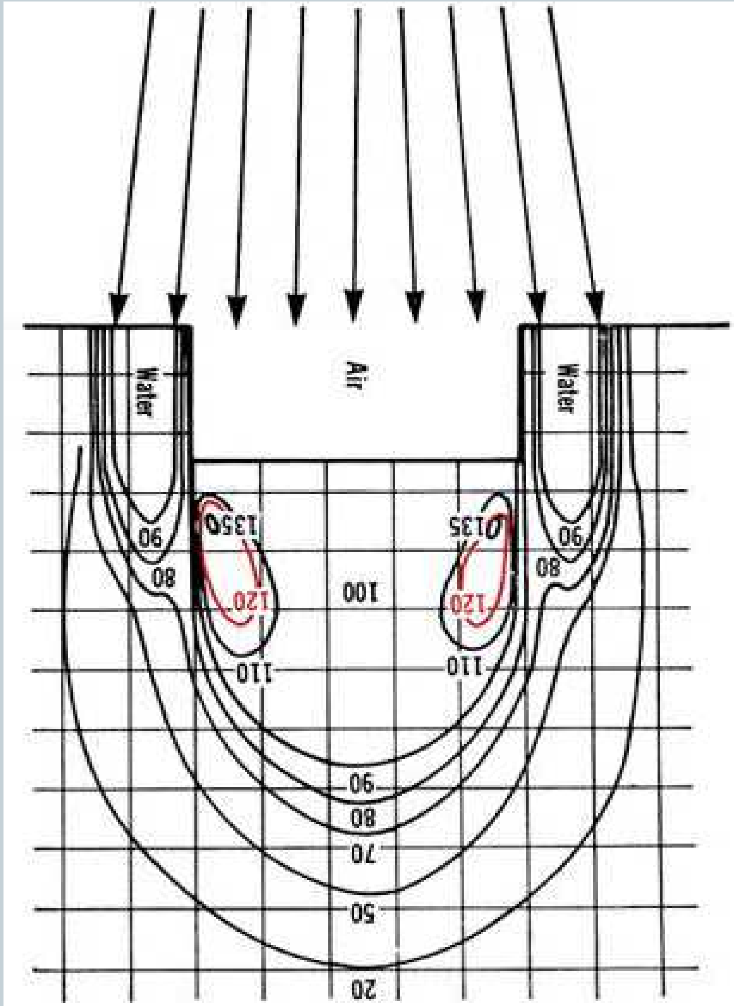
Thickness *t of lung* inhomogeneity: 6 cm

Tissue equivalent thickness: $z_{eff} = 1.5\ cm$



Surface Irregularities





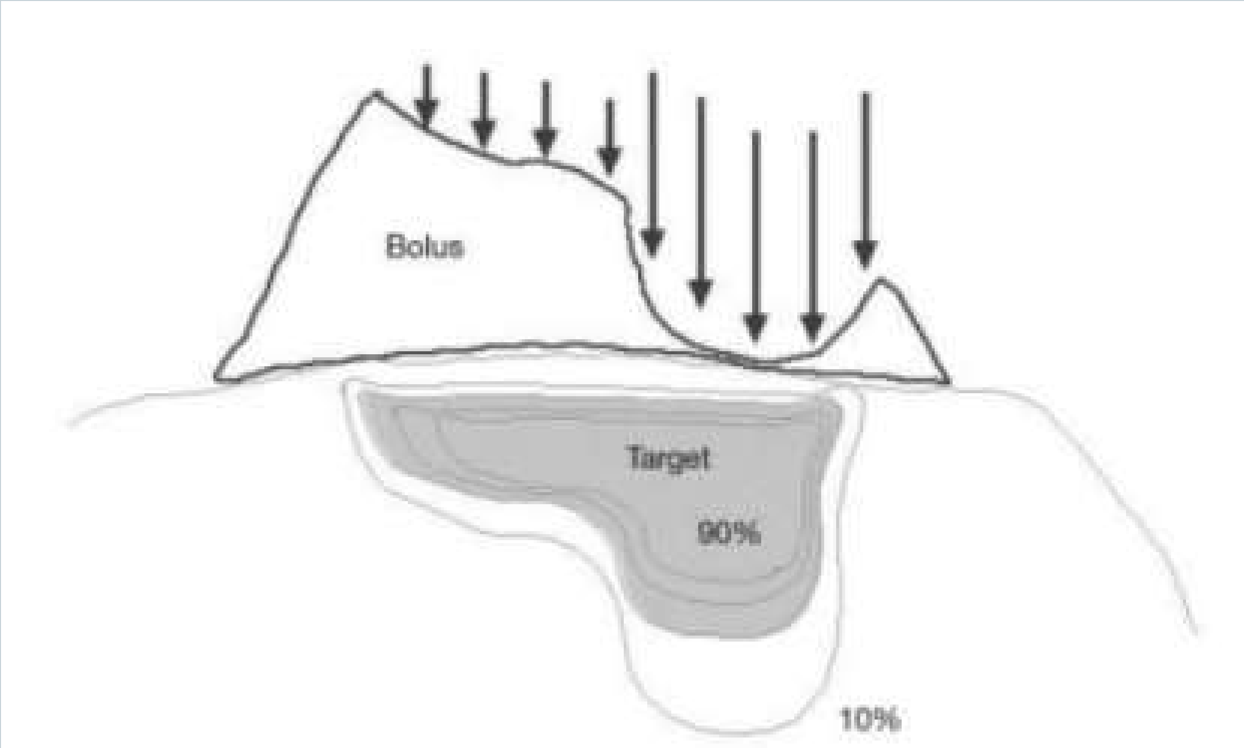
Use of Bolus and Absorbers

- Bolus is tissue equivalent material often used in electron beam therapy to (a) flatten out an irregular surface, (b) reduce the penetration of the electrons in parts of the field, and (c) increase the surface dose.
- Ideally, the bolus material should be equivalent to tissue in stopping power and scattering power. A given bolus material should be checked by comparing depth dose distribution in the bolus with that in the water.
- A number of commercially available materials can be used as bolus e.g.,

  -Paraffin wax, polystyrene, Lucite, Superstuff, and Superflab

Bolus

- Construction of a custom bolus to comform isodose lines to the shape of the target



Bolus

- Sharp surface irregularities, where the electron beam may be incident tangentially, give rise to a complex dose distribution with hot and cold spots.
- Bolus around the irregularity may be used to smooth out the surface and reduce the dose inhomogeneity.
- The use of bolus for electron beam treatments is very practical, since treatment planning software for electron beams is limited and empirical data are normally collected only for standard beam geometries.

External electron shielding

- To achieve a more customized electron field shape, a lead or metal alloy cut-out may be constructed and placed on the applicator as close to the patient as possible.
- Field shapes may be determined from conventional or virtual simulation, but are most often prescribed clinically by a physician prior to the first treatment.
- Thickness of shielding should give < 5% transmission.

Rule of Thumb: Minimum thickness of Pb for blocking electrons in mm is given by electron energy INCIDENT in the lead divided by 2.

$$mm_{pb} = \frac{E_0(MeV)}{2}$$

Internal Shielding

- Internal shielding can be useful to protect structures beyond target volume.
- Commonly used for:
  - Buccal mucosa, lip, eye lid lesions.
- Electron backscatter from the lead can enhance dose near the shield.
  - Magnitude of the Increase: 30-70% in the range of 1 to 20 MeV, having higher value for lower energies
- Internal shields are usually coated with low atomic number materials to minimize the electron backscattering into healthy tissue above the shield.

Internal Shielding

- Electron back scatter Factor (EBF) -

The quotient of dose at interface with lead in place to that with homogeneous polystyrene phantom at the same point

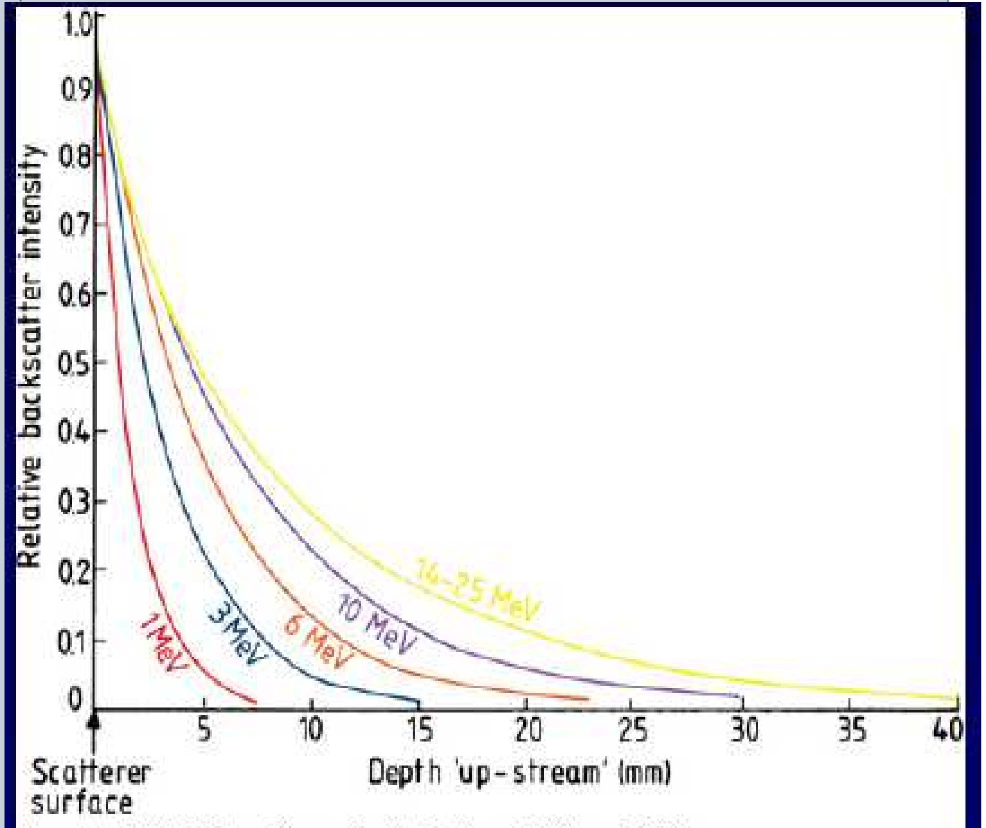
$$EBF = 1 + 0.735e^{(-0.052\overline{E}_z)}$$

Where

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

Internal Shielding

- To dissipate the effect of elect of electron backscatter from Pb shield, place suitable amount of low Z absorber between lead shield and preceding tissue interface.
- Typically want to reduce transmission of the backscattered electron intensity to ≤10%.
- Thickness of Low Z (ρ=1) material required to absorb the backscattered electrons is determined using the data in the figure



Internal Shielding Example

- A buccal mucosa lesion is treated with a 9MeV electron beam incident externally on the cheek.
- Assuming the thickness of the lesion is 2cm, calculate:

a) The thickness of lead required to shield the oral structures beyond the cheek.

b) Thickness of bolus to absorb the backscattered electrons.

Internal Shielding Example

- The thickness of lead required to shield the oral structures beyond the cheek.
- Incident Energy = 9MeV
- Need to calculate energy at depth = 2cm

$$\bar{E}_z = \bar{E}_0\left(1 - \frac{z}{R_p}\right) = 9\left(1 - \frac{2}{4.5}\right) = 5MeV \qquad mm_{Pb} = \frac{5}{2} = 2.5$$

Recall: Rule of Thumb: Minimum thickness of Pb for blocking electrons in mm is given by electron energy INCIDENT in the lead divided by 2.

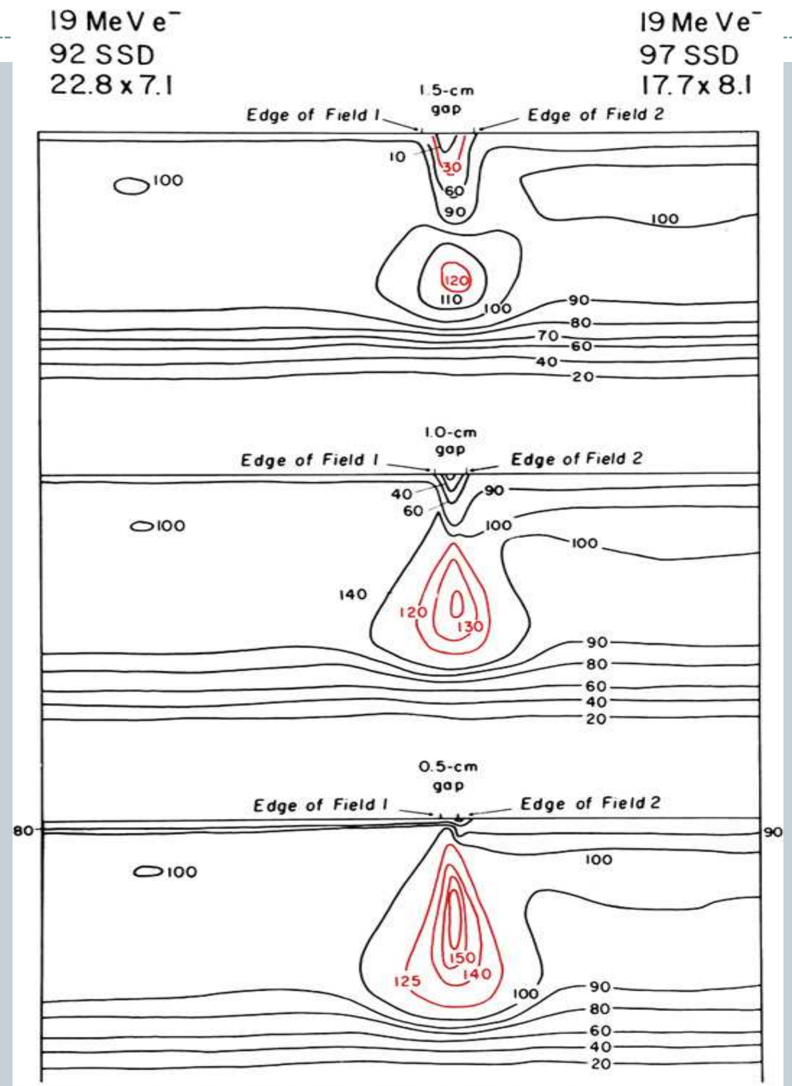
- From Figure a 5 MeV beam **10mm of polystyrene or bolus** required to reduce the transmission of backscattered electrons to 10% transmission.

Electron beam combinations

- When two adjacent electron fields are overlapping or abutting, there is a danger of delivering excessively high doses in the junction region. On the other hand, separating the fields may seriously under dose parts of the tumor.
- the tumors treated with electrons are mostly superficial, the electron fields are usually abutted on the surface.
- The hot spots can be accepted, depending on their magnitude, extent, and location. Similar considerations apply to electron fields adjacent to x-ray fields.

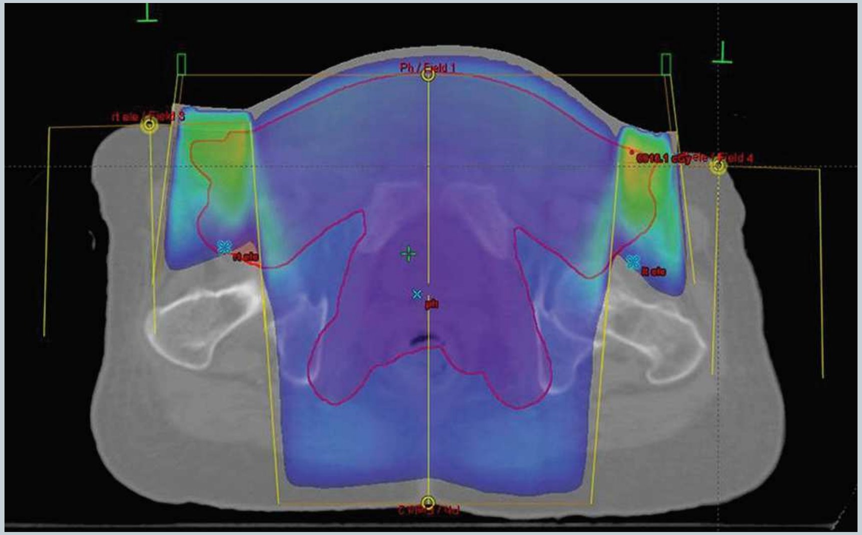
Electron beam combinations

- In general, it is best to avoid using adjacent electron fields.
- If the use of abutting fields is absolutely necessary, the following conditions apply:-
  - Contiguous electron beams should be parallel to one another in order to avoid significant overlapping of the high value isodose curves at depth in the patient.
  - Some basic film dosimetry should be carried out at the junction of the fields to ensure that no significant hot or cold spots in dose occur.



Electron beam combinations

- Electron - photon field matching is easier than electron -electron field matching.
  - A distribution for photon fields is readily available from a treatment planning system (TPS) and the location of the electron beam treatment field as well as the associated hot and cold spots can be determined relative to the photon field treatment plan.
  - Matching of electron and photon fields on the skin will produce a hot spot on the photon side of the treatment.



Combination of electron and photon beam in carcinoma vulva

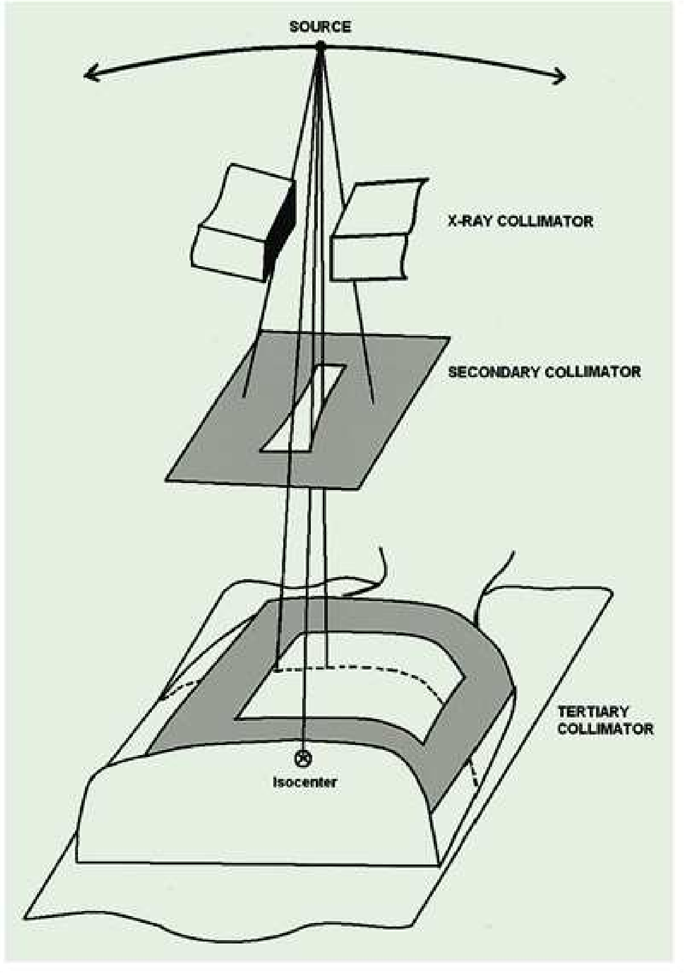
Electron therapy treatment planning

- Complexity of electron-tissue interactions makes treatment planning for electron beam therapy difficult and look up table type algorithms do not predict well the dose distribution for oblique incidence and tissue inhomogeneities.
- Early methods in electron beam treatment planning were empirical and based on
  - Water phantom measurements of PDDs,
  - Beam profiles for various field sizes.
  - Tissue inhomogeneities the CET approximation
- Fermi-Eyges multiple scattering theory considers a broad electron beam as being made up of many individual pencil beams that spread out laterally in tissue following a Gaussian function.

Electron therapy treatment planning

- Pencil beam algorithm can account for tissue inhomogeneity, patient curvature and irregular field shape.
- Despite applying both the stopping powers and scattering powers, the modern refined pencil beam, multiple scattering algorithms generally fail to provide accurate dose distributions for most general clinical conditions.
- The most accurate and reliable way to calculate electron beam dose distributions is through Monte Carlo techniques.

Electron Arc Therapy



- Electron beam arc technique gives excellent dose distribution for treating superficial tumors along curved surfaces.
- On the basis of isodose distribution, electron arc therapy is most suited for treating superficial volumes that follow curved surfaces such as the chest wall, postmastectomy, ribs, and entire limbs.
- This technique is mostly useful in cases for which the tumor involves a large chest wall span and extends posteriorly beyond the midaxillary line.

INTRAOPERATIVE ELECTRON BEAM RADIATION THERAPY(IOERT)

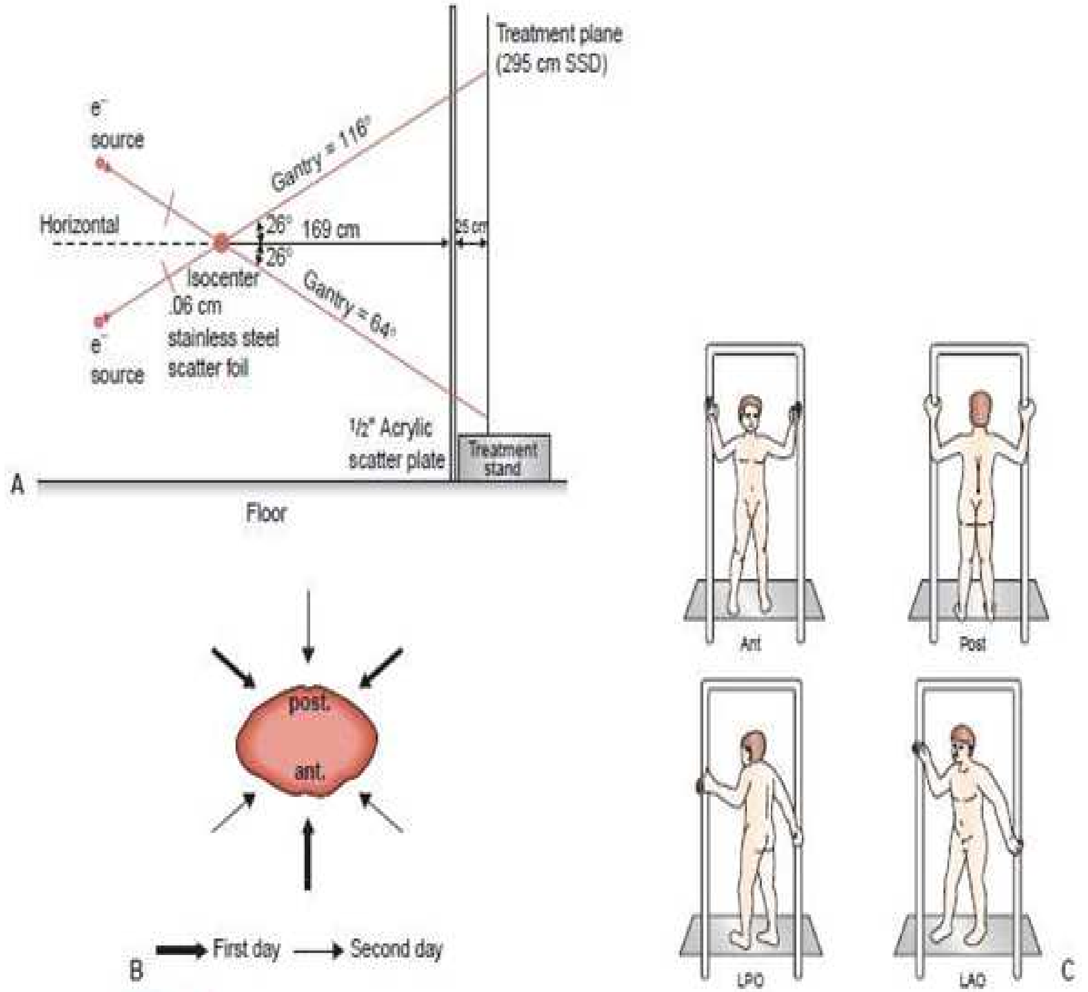
- IOERT is a treatment option that delivers a concentrated, precise dose of radiation during surgery, immediately after a tumor is removed.
- Intraoperative treatments are performed completely in the operating room.
- Benefits
  - One to two minutes IOERT can reduce the likelyhood of tumor recurrence and increase cure rates.
  - It also lessen the need for post operative external radiotherapy

TOTAL SKIN IRRADIATION

- Total-skin electron irradiation is a modality designed for management of diseases that require irradiation of the entire skin surface or a significant portion of it.
- The technique is used most frequently for treatment of
  - mycosis fungoides
  - kaposi's sarcoma.
- Multiple techniques for total-skin electron therapy have been reviewed.
- The underlying principles of the various techniques are similar, which are exemplified by the ***modified stanford technique.***

TOTAL SKIN IRRADIATION

- Schematic of **modified Stanford technique.**
- Side view of setup shows the relative position of patient plane, scatter plate, isocenter, and gantry angles (A).
- Six beam directions (B) are achieved by placing the patient in six patient positions (C).



SUMMARY

- Electron beam therapy is used for treating superficial tumor with minimum dose to the deeper tissue.
- Proper electron applicators, cut outs (standard/custom) should be used in Linac for electron beam therapy.
- Accurate dose calculation using PDD curve is required make sure that the target volume is well within the specified isodose curve.
- Oblique incidence, irregular surface and tissue heterogeneity must be consider while planning for electron beam therapy.
- Water or other water equivalent phantoms are used to study properties of electron beam therapy.

Thank you