Electron Radiotherapy Past, Present & Future

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Conflict of Interest Disclosure

- John A. Antolak
  - N/A
- Kenneth R. Hogstrom
  - Research funding from Elekta, Inc.
  - Research funding from .decimal, Inc.

Learning Objectives

1. Learn about the history of electron radiotherapy that is relevant to current practice.
2. Understand current technology for generating electron beams and measuring their dose distributions.
3. Understand general principles for planning electron radiotherapy
4. Be able to describe how electron beams can be used in special procedures such as total skin electron irradiation and intraoperative treatments.
5. Understand how treatment planning systems can accurately calculate dose distributions for electron beams.
6. Learn about new developments in electron radiotherapy that may be common in the near future.

Outline

- History, KRH
- Machines & Dosimetry, JAA
- Impact of heterogeneities, KRH
- Principles of electron planning, KRH
- Special Procedures, JAA
- Electron Dose Calculations, JAA
- Looking to the Future, JAA

History of Electron Therapy

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Clinical Utility

- Electron beams have been successfully used in numerous sites that are located within 6 cm of the surface:
  - Head (Scalp, Ear, Eye, Eyelid, Nose, Temple, Parotid, …)
  - Neck Node Boosts (Posterior Cervical Chain)
  - Craniospinal Irradiation for Medulloblastoma (Spinal Cord)
  - Posterior Chest Wall (Paraspinal Muscle Sarcomas)
  - Breast (IMC, Lumpectomy Boost & Postmastectomy CW)
  - Extremities (Arms & Legs)
  - Total Skin Electron Irradiation (Mycosis Fungoides)
  - Intraoperative (Abdominal Cavity) and Intraoral (Base of Tongue)
  - Haas et al (1954); Tapley (1976); Vaeth & Meyer (1991)

- Electron beam utilization peaked early 1990s
  - ≈15% of patients at MDACC received part of radiotherapy with e^-

History of Electron Therapy
Accelerator Technology

- Van de Graaff Accelerators (late 1930s)
  - E<3 MeV; mainly source of x-ray beams
  - Developed by MIT professors Van de Graaff and Trump in 1937
  - First used at Huntington Memorial Hospital in 1937
  - Limited utilization for mycosis fungoides and other skin cancers
    - Trump et al (1940, 1953); Trump (1960)

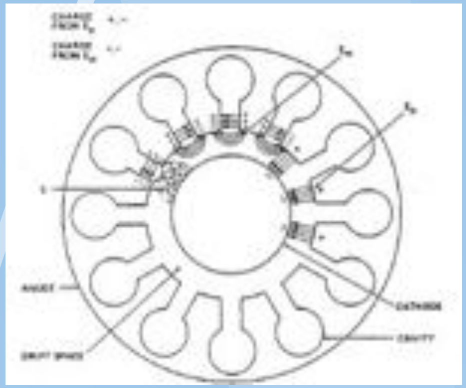
History of Electron Therapy
Accelerator Technology

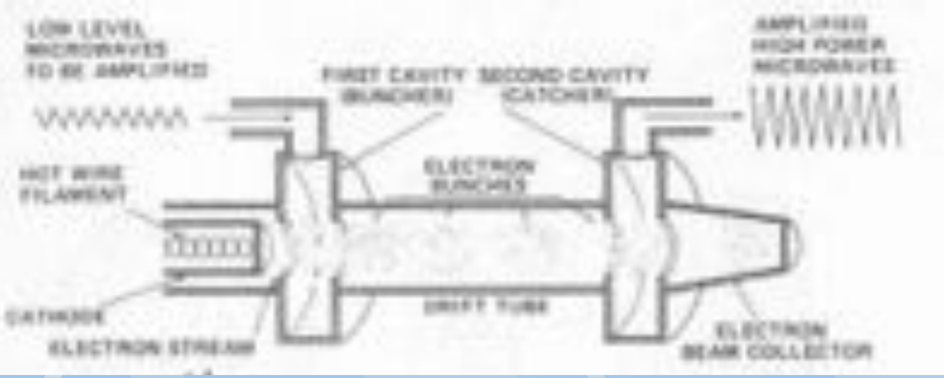
- Betatrons (late 1940s)
  - Developed in US (Kerst) and Germany (Glocker) (circa 1940)
  - Beam line and dosimetry development: 6<E<30 MeV (1943-1953)
    - Gund and Paul (1950); Laughlin et al (1953); Loevinger et al (1960)
  - Early clinical use (Haas et al 1954)
  - Clinical accelerators: Siemens, Brown Boveri, and Allis Chalmers

Siemens Betatron 42
(www.usask.ca)

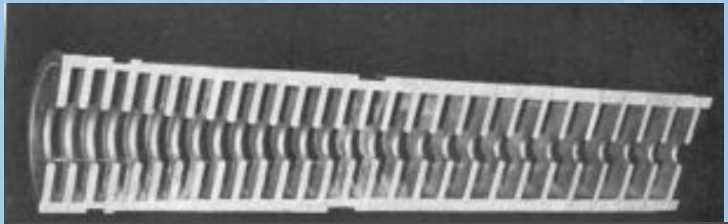
History of Electron Therapy
Accelerator Technology

- Linear Accelerators (1960s)
  - 1968: 137 betatrons/79 linacs (only few had e-)
  - Post WWII RF amplifiers (magnetron & klystrons)

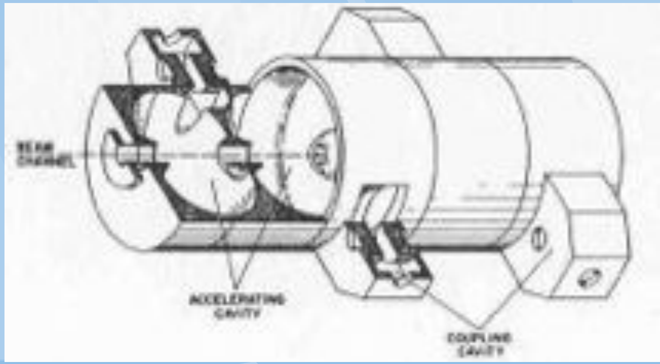




  - 1960s-present: Traveling wave & side-coupled standing wave



Karzmark & Morton 1989 & Karzmark et al 1993



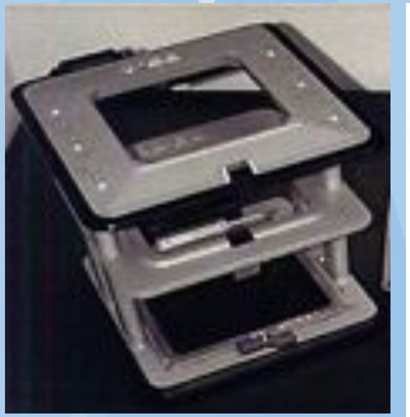
History of Electron Therapy
Accelerator Technology

- Phasing Out of Orthovoltage (kVp) X-ray Machines
  - Replaced by Cobalt-60 (late 1950-60s) & linacs (1970s)
  - Electrons became the replacement modality for skin cancers

- Loss of Scanned Beams (1985-1990)
  - %DD of scanned beams superior to scattered beams
  - AECL Therac 25 accidents (5 die; others injured)
  - GE repair of CGR Sagittaire in Zaragosa (18 die; 9 injured)
  - Scanditronix microtron accelerators failed in marketplace (1990s)

History of Electron Therapy
Accelerator Technology

- Manufacturers Offer Comparable Electron Beams
  - New units mostly Elekta and Varian; Siemens similar quality beams
  - Multiple electron beams: 7-8 in range 6-20 MeV
  - Special modalities: High dose rate TSEI & Electron arc therapy



Varian Trilogy
(www.varian.com)

Elekta Infinity
(www.elekta.com)

History of Electron Therapy
Dose Calculation & Measurement Technology

- Electron Transport and Dose Calculations
  - ICRU 35 (1984) and Use of Fermi-Eyges Theory (1980s)
  - Monte Carlo: EGS4, BEAM, DOSXYZ (1985-1995)
- Dose Measurement Protocols
  - AAPM TG Reports 21, 39, & 51 (Dose Calibration)
  - AAPM TG Reports 25 & 70 (Relative Dose Measurements)
- Treatment Planning
  - CT-Based Planning: GE Target TPS (1981)
  - Pencil-beam Dose Calculations: GE Target TPS (1983)
  - 3D Treatment Planning Systems (late 1990s)
  - Bolus Electron Conformal Therapy (2000s)

Electron Beam Therapy Impediments to Clinical Use

- Inadequate Education of Treatment Team
  - Administrators, Radiation Oncologists
  - Medical Physicists and Medical Dosimetrists
- Lack of Marketing by Vendors

Treatment Techniques

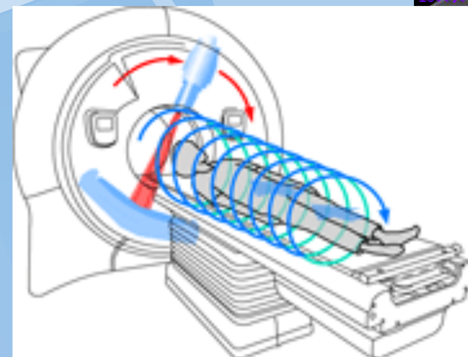
Varian offers the latest advanced treatment techniques in radiation therapy today:

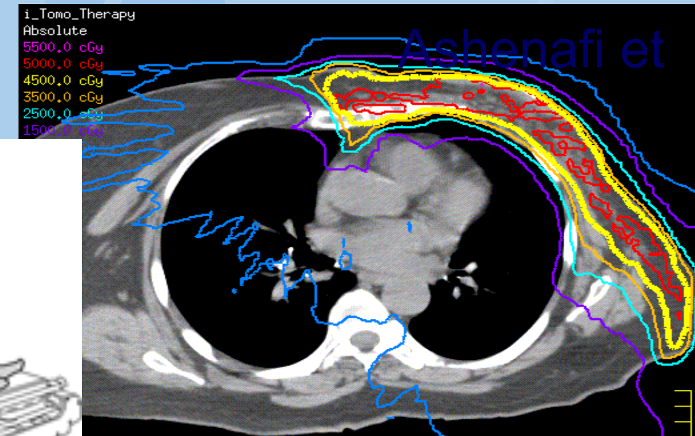
- **RapidArc**: RapidArc™ radiotherapy technology delivers uncompromised treatment in two minutes or less.
- **IGRT:** Image-guided radiation therapy pinpoints a moving target.
- **IMRT**: Intensity-modulated radiation therapy structures the dose to spare healthy tissue.
- **DART:** DART™ dynamic adaptive radiation therapy adapts treatment to changing needs.
- **IGBT:** Image-guided brachytherapy implants radiation quickly and precisely.
- **Proton Therapy**: Proton therapy focuses on tumor shape to avoid critical structures.

- Competing Technologies
- Lack of Commercially Available Technology

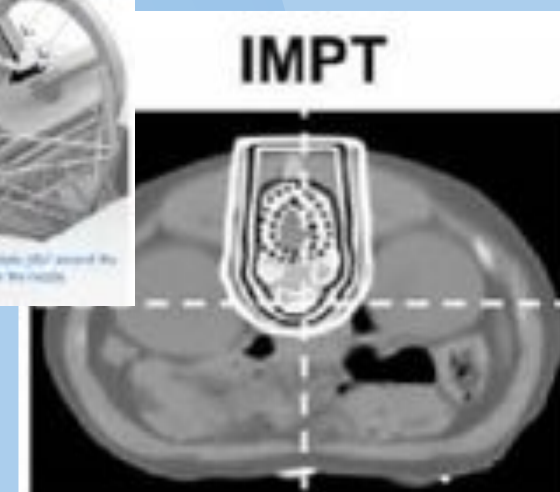
Competing Technology Examples

- Helical TomoTherapy
  - Chest Wall
  - Scalp
  - Craniospinal
  - Head and Neck
- Proton Therapy
  - Craniospinal, H&N
- HDR Brachytherapy
  - Lumpectomy Boost
  - Intraoperative Therapy





Ashenafi et al 2010



Mu et al 2005

Leveling the Playing Field
Missing Integrated Technologies

- Fixed Beam Therapy Lacks:
  - Treatment planning tools for segmented field e^- conformal therapy
  - Treatment planning tools for modeling treatment aids
  - Updated pencil beam (redefinition) algorithm
  - Integrated, retractable eMLC for treatment delivery
- Electron Arc Therapy Lacks:
  - Treatment planning tools (2º & 3º collimator design, energy segmentation, bolus design, dose & MU calculations)
  - Use of dynamic MLC for dose optimization
- Total Skin Electron Irradiation Lacks:
  - Configuration of beam delivery system
  - Treatment stand

Leveling the Playing Field: Missing Technologies- Treatment Planning Tools


Tapley et al 1976

(1) Bolus scatter plate not modeled

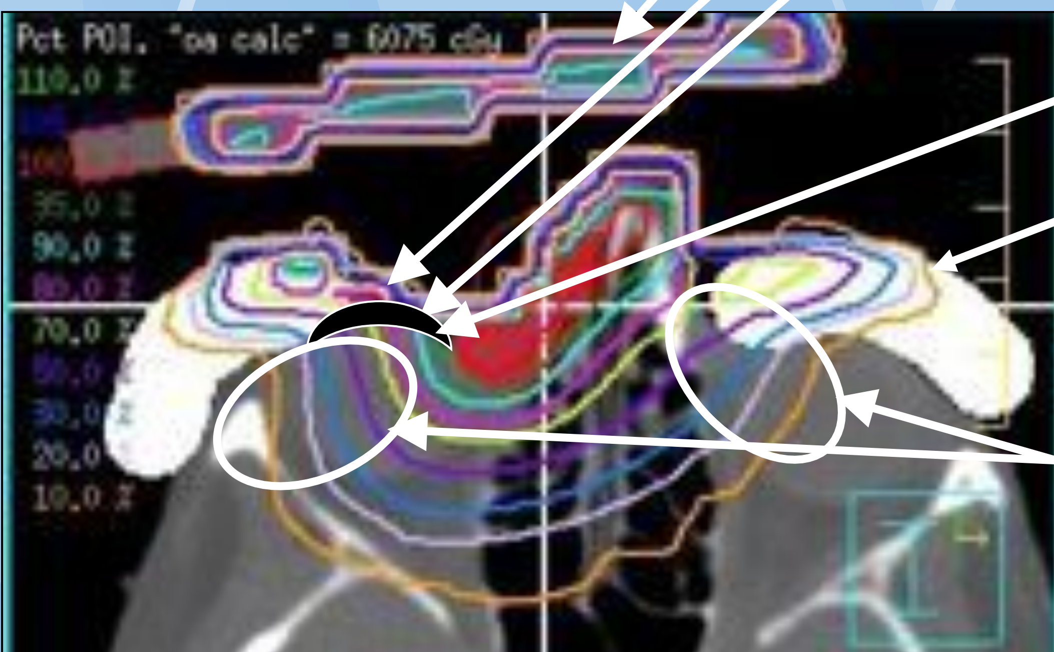
(2) Surface dose calculation inaccurate

(3) Backscatter dose calculation inaccurate

(4) Eyeshield not modeled

(5) Skin collimation not modeled

Squamous Cell Carcinoma
PTV=Red Volume



(6) Penumbra calculation inaccurate

Machines & Dosimetry

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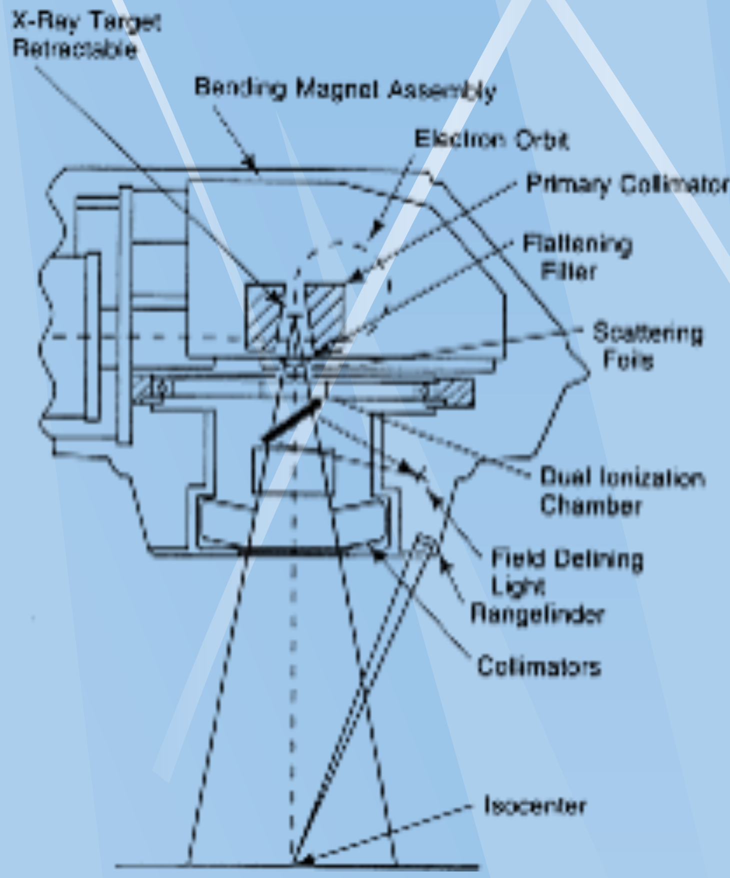
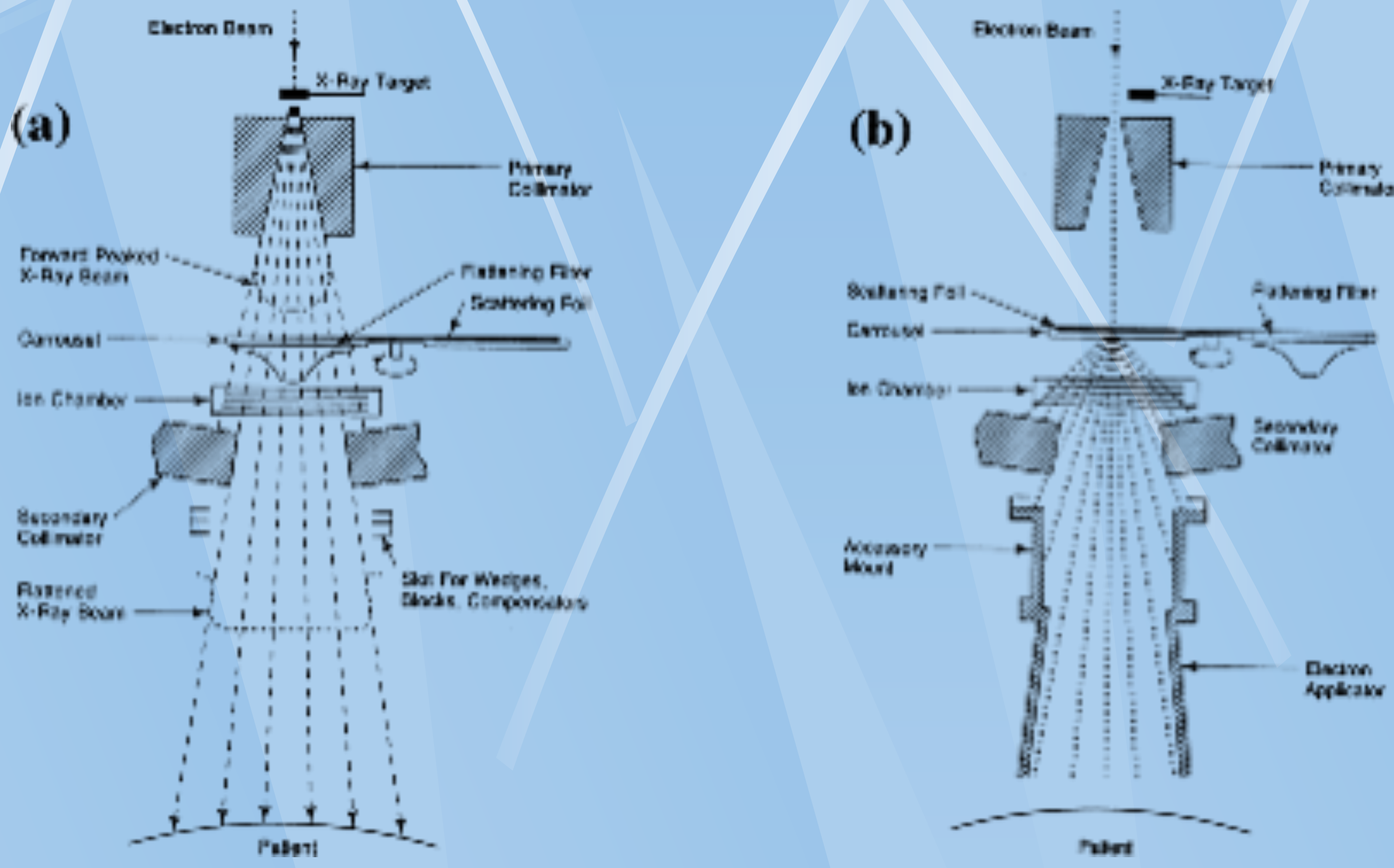
Linac Head



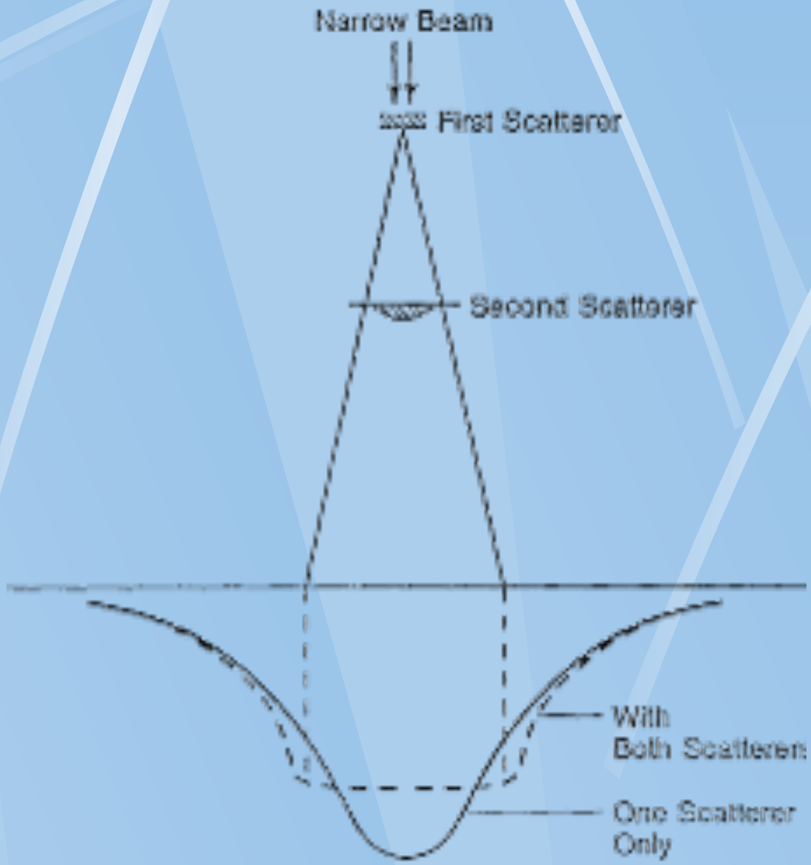
Karzmark, C. J., Nunan, C.S., Tanabe, E: Medical Electron Accelerators, McGraw Hill, 1992.

Electron Mode



Karzmark, C. J., Nunan, C.S., Tanabe, E: Medical Electron Accelerators, McGraw Hill, 1992.

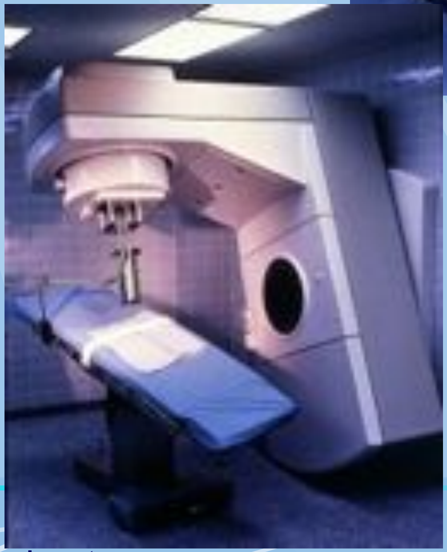
Dual Scattering Foils



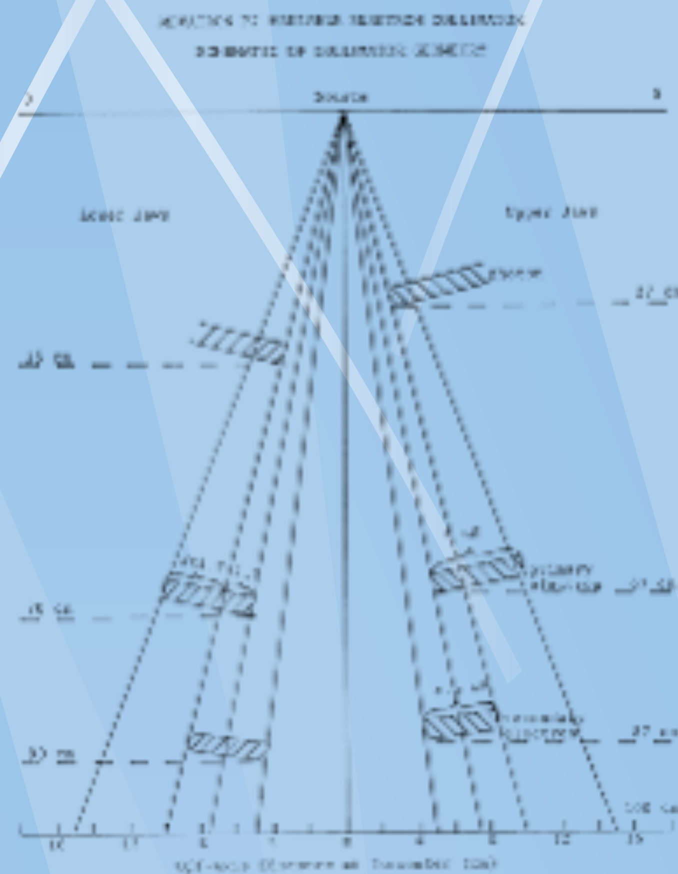
Karzmark, C. J., Nunan, C.S., Tanabe, E: Medical Electron Accelerators, McGraw Hill, 1992.

Electron Collimation Systems

- Applicators with Inserts
- Variable Trimmers
- Intracavitary Cones
  - Intraoperative radiotherapy cones
  - Intraoral Cones
  - Transvaginal cones



Applicators (Cones)



Hogstrom K.R., Meyer J.A, and Melson R. Variable electron collimator for the Mevatron 77: design and dosimetry. In: Proceedings of the 1985 Mevatron Users Conference, pp. 251-276, Iselin NJ; Siemens Medical Systems, 1985.

Dosimetry

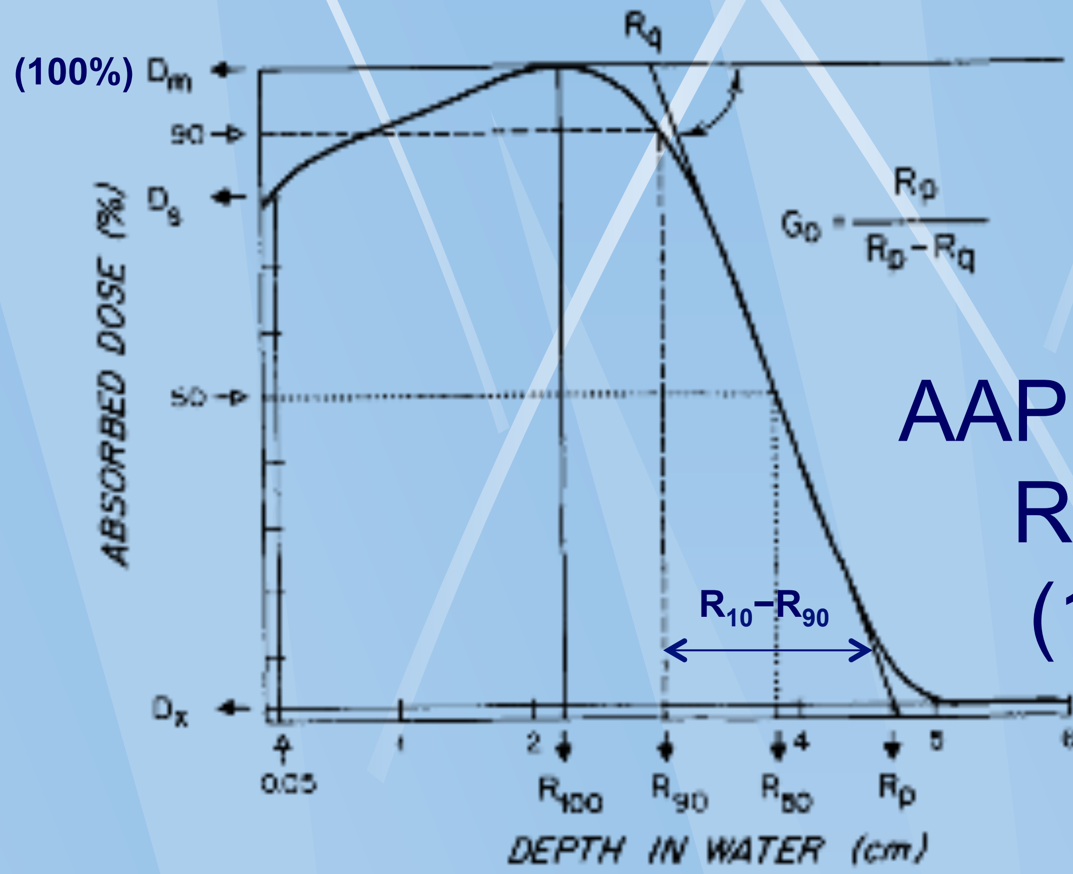
TG71: Ion Chamber Dosimetry

- Leakage < 0.1%
- Effective point of measurement
  - 0.5 r shift for cylindrical chambers
    - was 0.75 r in TG21
  - No shift (inside front electrode) for parallel plate
- Stopping power ratio
  - Burns equation (first used in TG51)
- Fluence correction (Table 1, same as TG21, TG25)
- P_{wall}, P_{ion} and P_{pol} "ignored"

TG71: Other Considerations

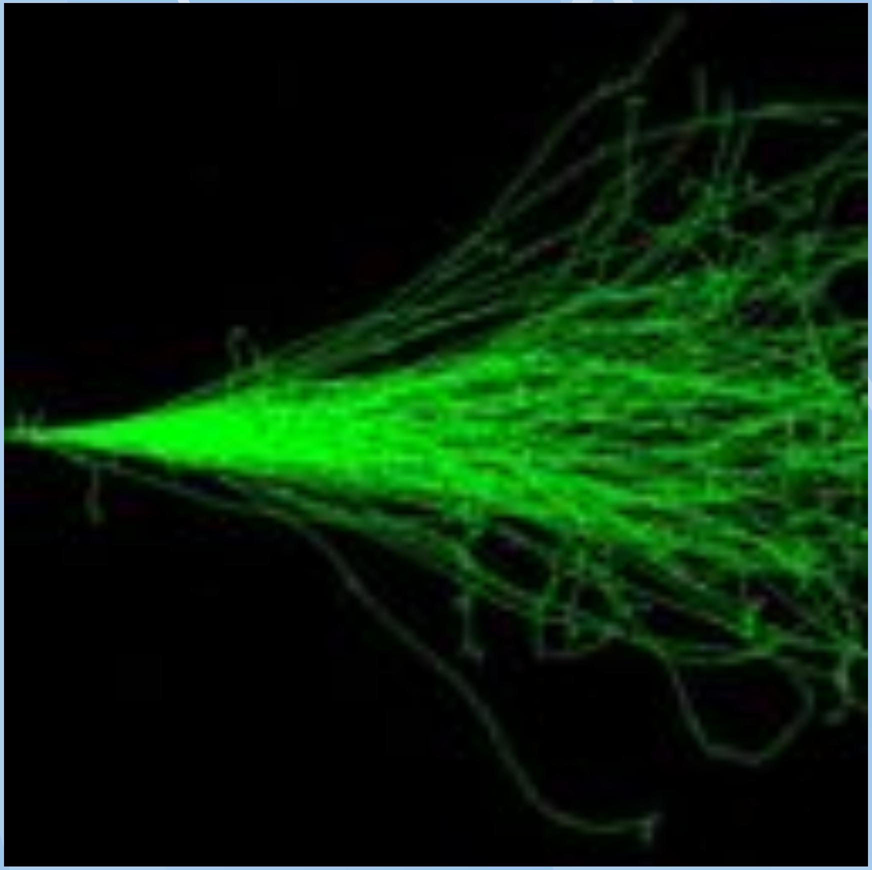
- Diodes
  - Directly gives dose, but should be checked versus correct ion chamber curves
- Scanning Water Phantoms
  - May not implement all recommended correction factors when converting ionization to dose
    - Need to verify

% Depth Dose

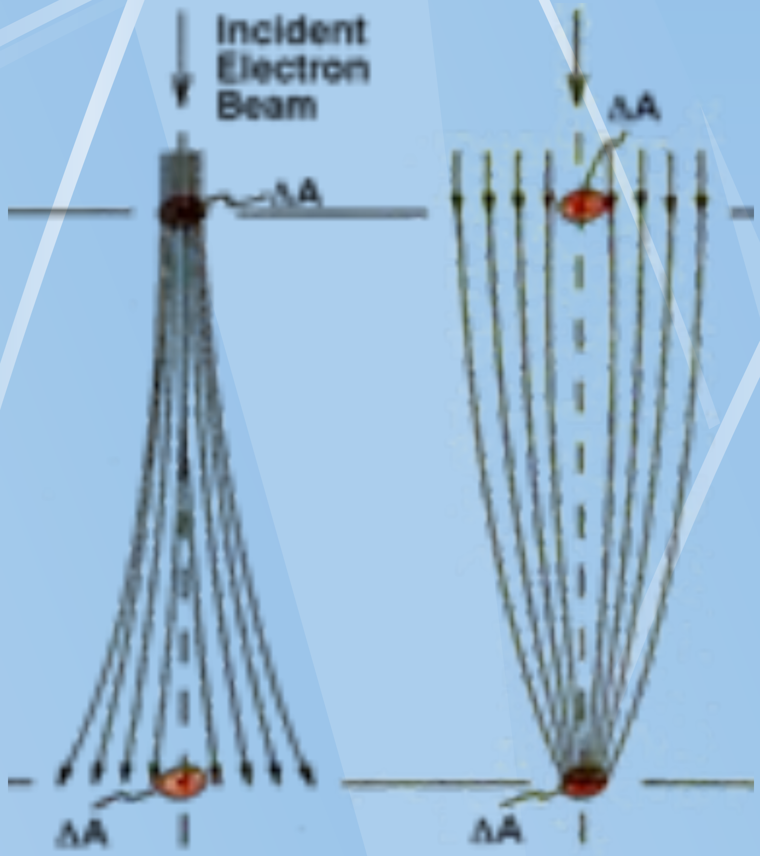


AAPM TG-25 Report (1991)

10-20 MeV Electrons in Water



Side-scatter Equilibrium



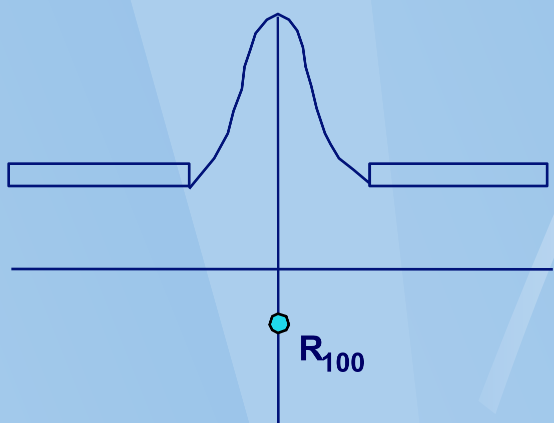
In-scatter Out-scatter

Side-scatter equilibrium exists if the electron fluence scattered away from a small area in the vicinity of a point is replaced by electrons scattering into that area.

Side-Scatter Equilibrium (homogeneous phantom)

All of the electrons that can reach the point of interest are let through

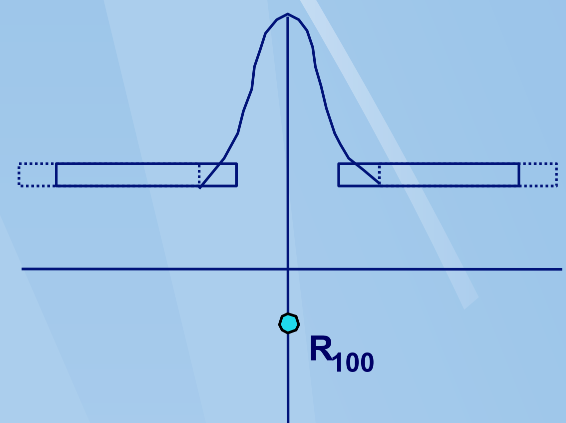
Side-scatter equilibrium exists!



Reference geometry

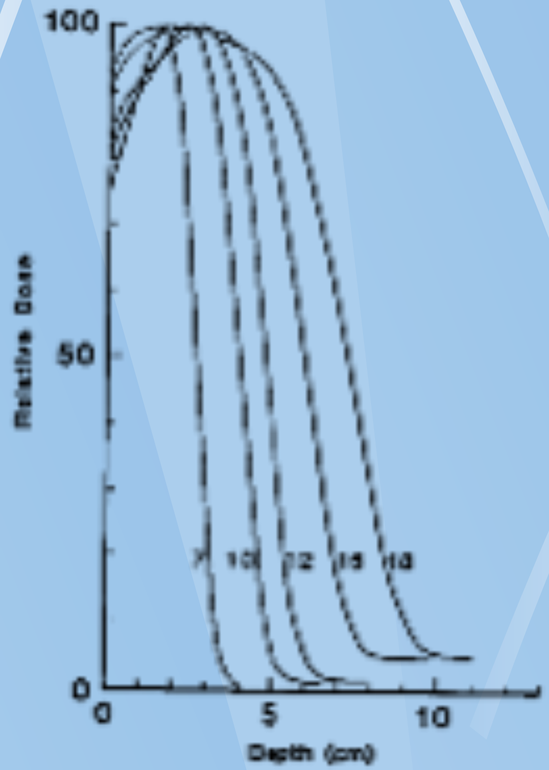
Some of the electrons that can reach the point of interest are blocked

Side-scatter equilibrium does not exist!



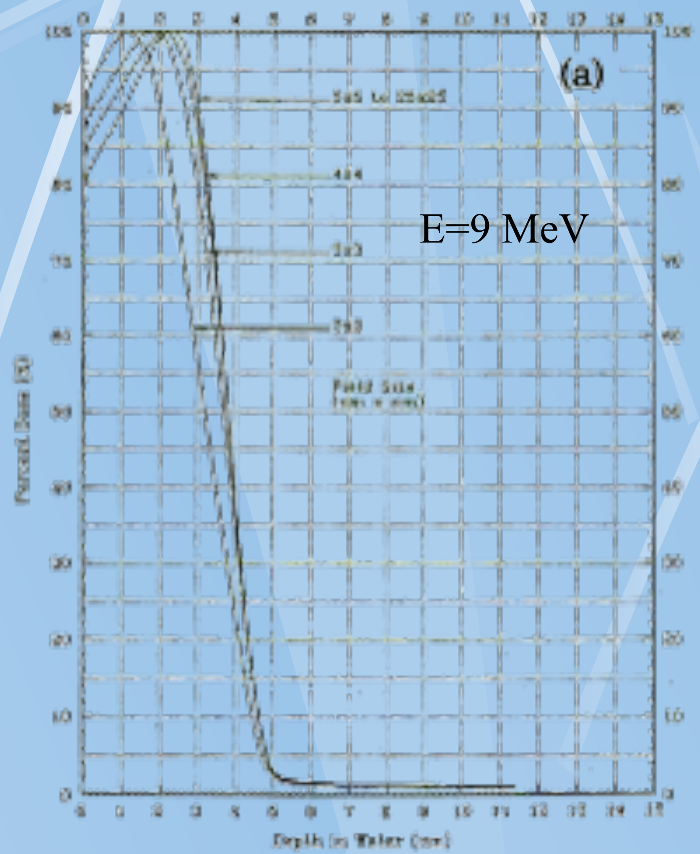
Reduced field size

Depth Dose Energy Dependence (6-20 MeV)



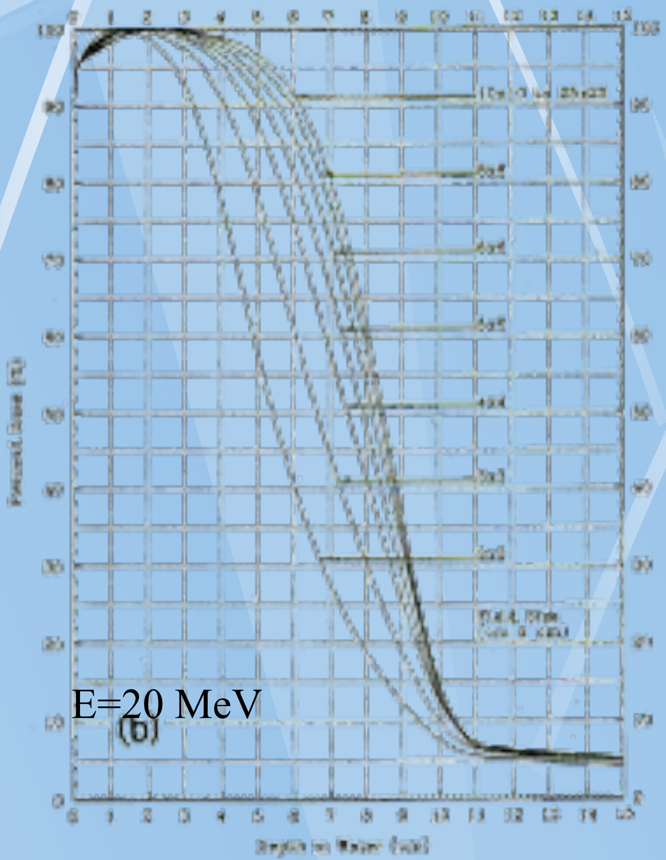
- As energy increases
  - Surface dose (D_s) increases (70%-90%)
  - Therapeutic depth (R_{90}) increases
  - Dose falloff (R_{10}-R_{90}) increases
  - Practical range (R_p) increases
  - Bremsstrahlung dose (D_x) increases
- Small variations due to method of beam flattening and collimation

% Depth Dose
Field Size Dependence



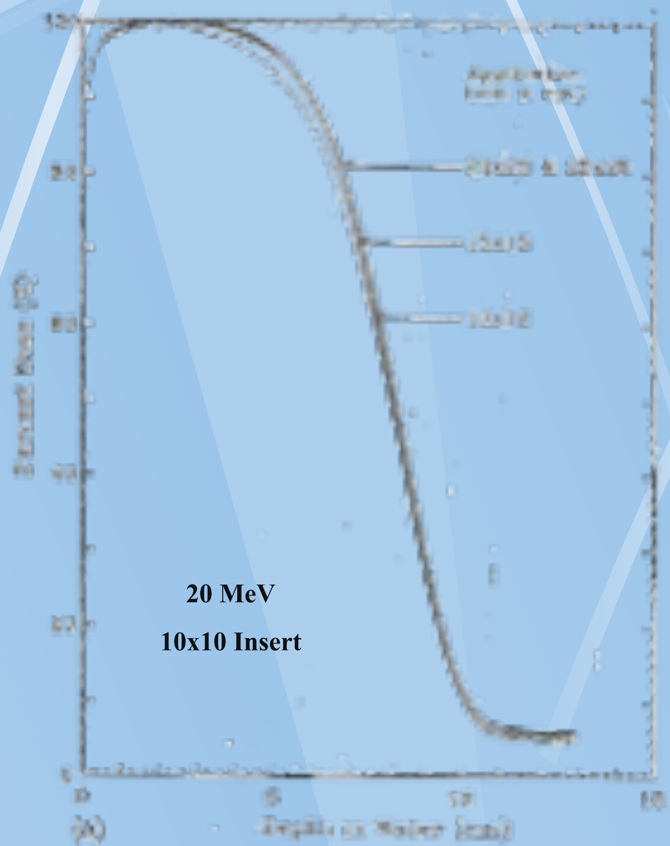
- As field size decreases
  - Therapeutic depth (R90) decreases
  - Surface dose (DS) increases
  - Practical range (Rp) remains constant
- Decrease in R90 less significant at lower energies
- Increase of DS more significant at lower energies

% Depth Dose
Field Size Dependence



- As field size decreases
  - Therapeutic depth (R90) decreases
  - Surface dose (DS) increases
  - Practical range (Rp) remains constant
- Decrease in R90 more significant at higher energies
- Increase of DS almost insignificant at higher energies

% Depth Dose Applicator Dependence



Square-Root Rule

% Depth Dose of Rectangular Field

$$\%DD^{L,W}(d) = \left[\%DD^{L,L}(d) \times \%DD^{W,W}(d)\right]^{1/2}$$

- $\%DD^{L,W}(d)$ is percent dose at depth d for rectangular field of dimensions L by W
- Note: the resultant %DD curve must be normalized such that its D_{max}=100%

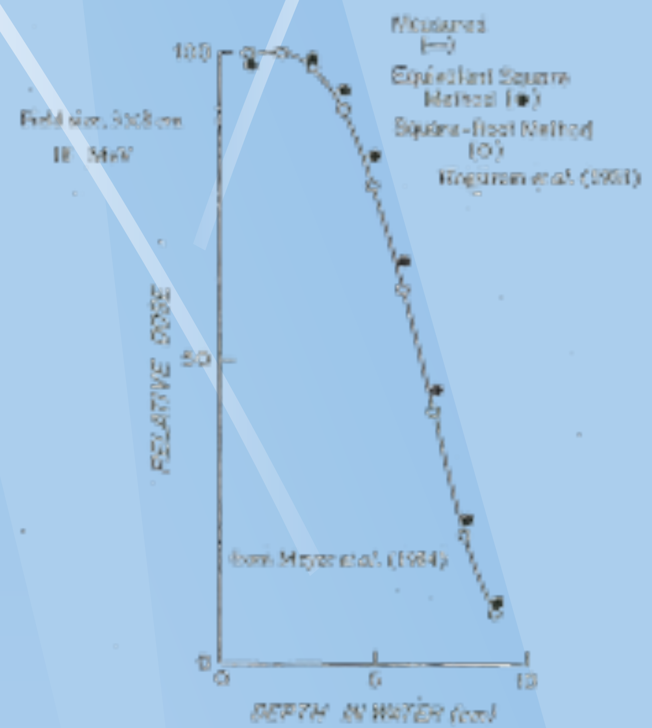
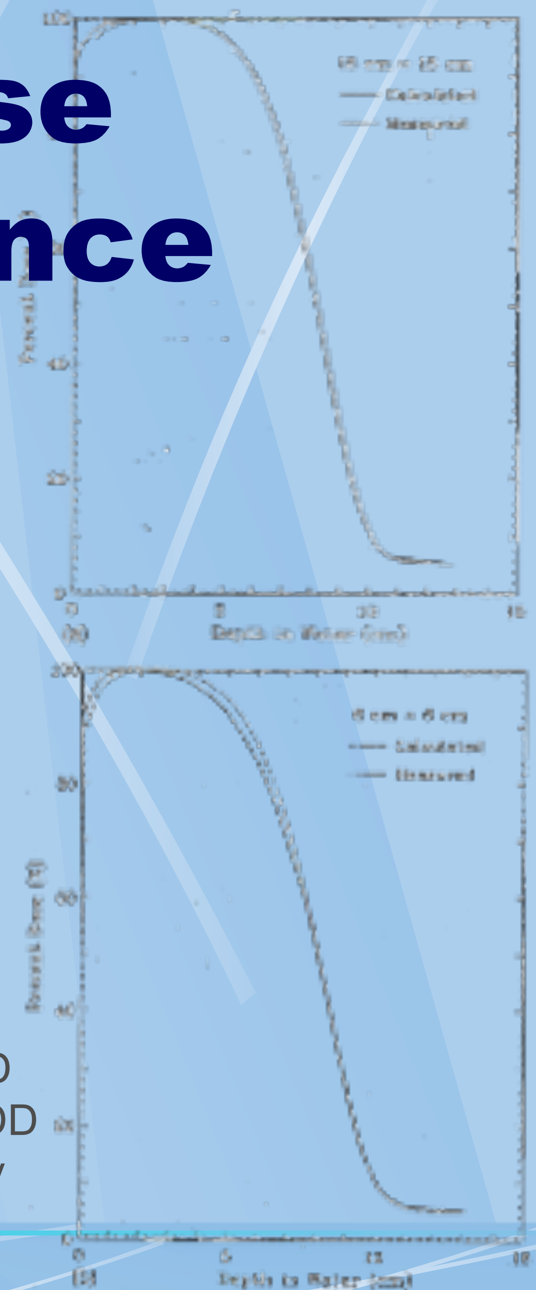


Fig. 13.

% Depth Dose SSD Dependence

- Inverse Square- small impact due to:
  - SSD>110 cm is seldom used
  - Dose is superficial (d<10 cm).
  - Ex: at R_{90} (d=6 cm)
    - %DD(110-cm SSD)≈%DD(100-cm SSD)*1.01
- Collimator Scatter- occasional impact due to:
  - Electrons scattered from collimating edges being at large angles and propagating out of field at extended SSD
  - Result is lowering of surface dose and deepening of R_{90}.

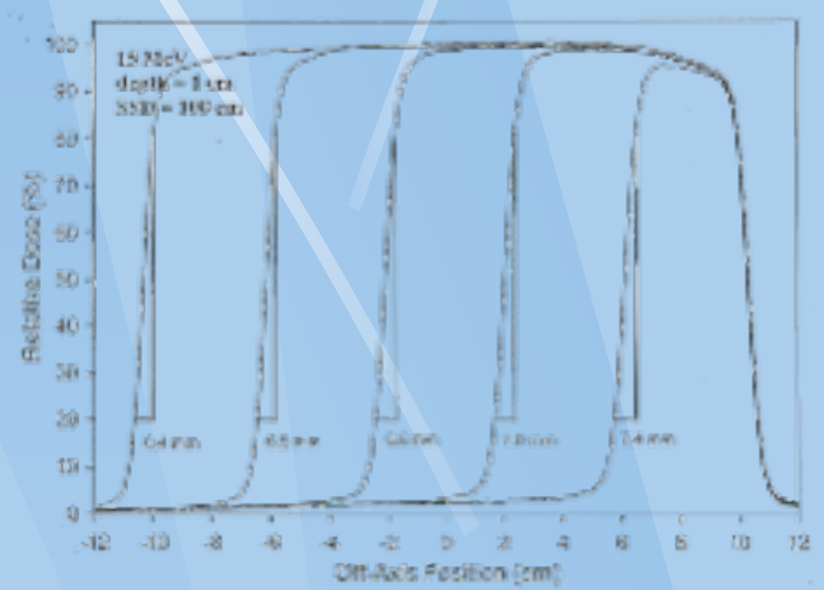


20 MeV

Measured %DD: 110-cm SSD (dashed) Calculated %DD: %DD at 100-cm SSD multiplied by inverse-square factor

Off-Axis Dose (Penumbra) Field Size Dependence

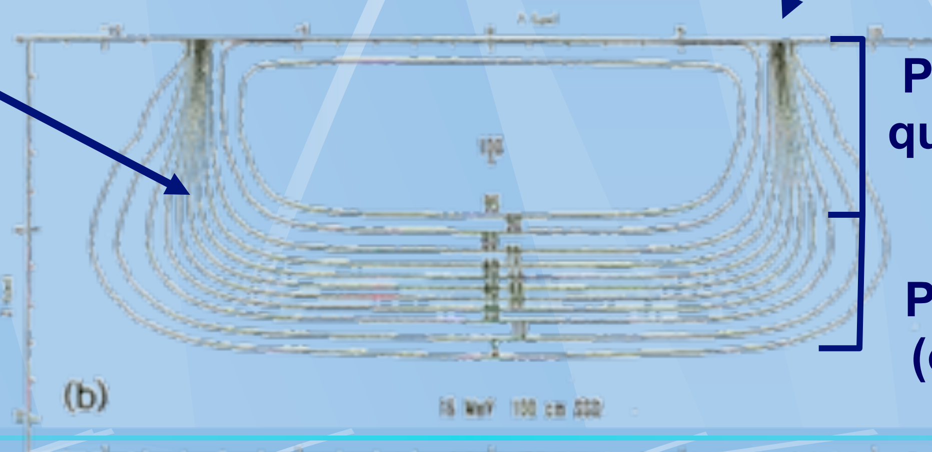
- Penumbra is the edge of the beam for which there is not side-scatter equilibrium
- Penumbra width is a measure of penumbra shape
  - P90-10=distance from 90% to 10% OAR
  - P80-20=distance from 80% to 20% OAR
- Penumbra width remains constant as field size increases once there is side-scatter equilibrium on central axis.



Off-Axis Dose
Energy & Depth Dependence

Penumbra at surface is sharper at higher energies

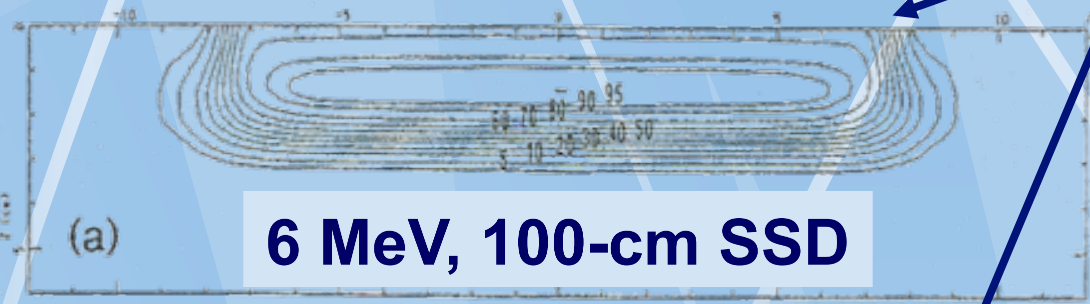
Penumbra width at depth of R_{90} increases with energy



Penumbra increases quickly for depth < R_{90}

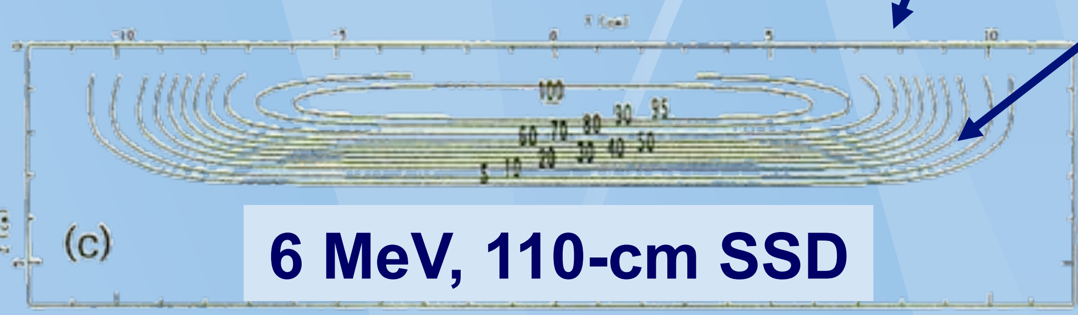
Penumbra constant (or getting smaller) for depth > R_{90}

Off-Axis Dose SSD Dependence



6 MeV, 100-cm SSD

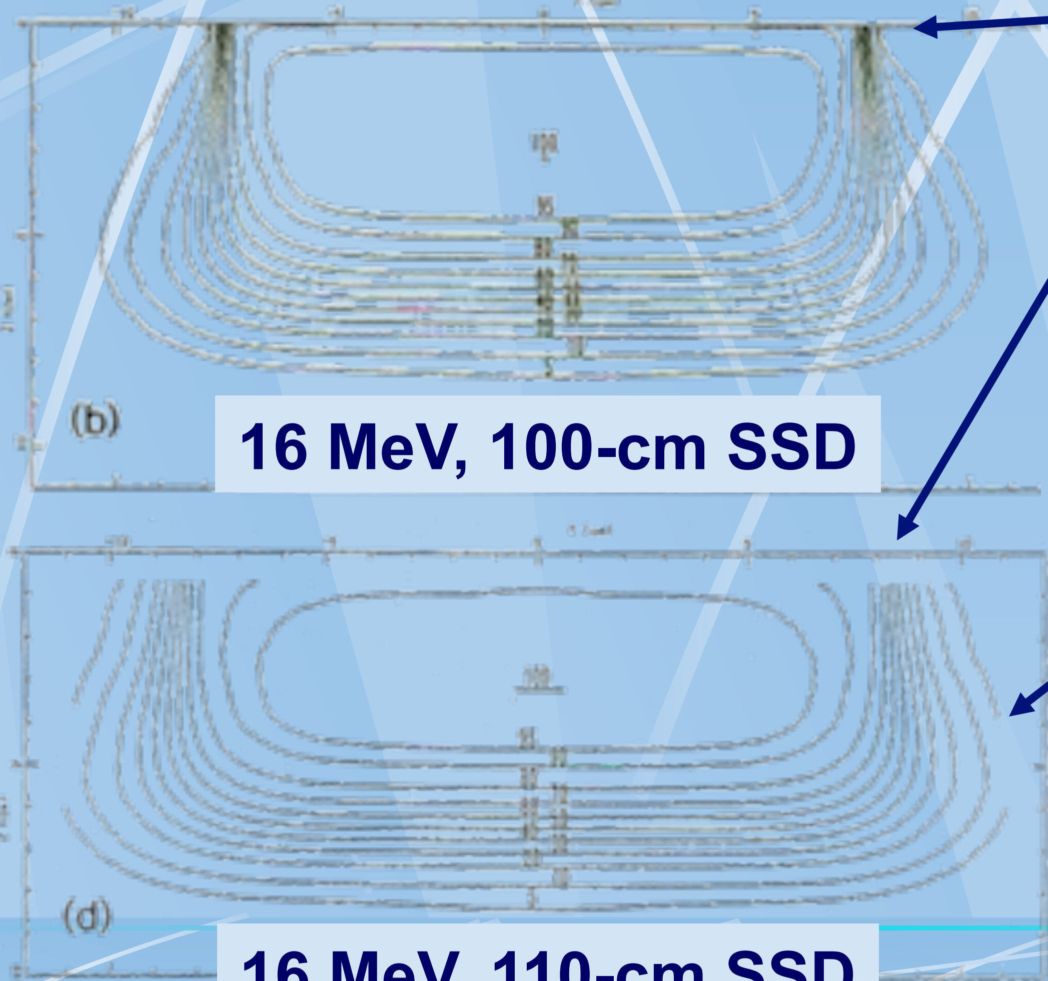
Penumbra width at surface increases in proportion to air gap (distance from final collimating device to patient, SSD-SCD)



6 MeV, 110-cm SSD

Penumbra width at depth of R_{90} increases significantly for lower electron energies

Off-Axis Dose SSD Dependence



16 MeV, 100-cm SSD

16 MeV, 110-cm SSD

Penumbra width at surface increases in proportion to air gap (distance from final collimating device to patient, SSD-SCD)

Penumbra width at depth of R_{90} increases little for higher electron energies

Impact of Patient Heterogeneity on Dose Distribution

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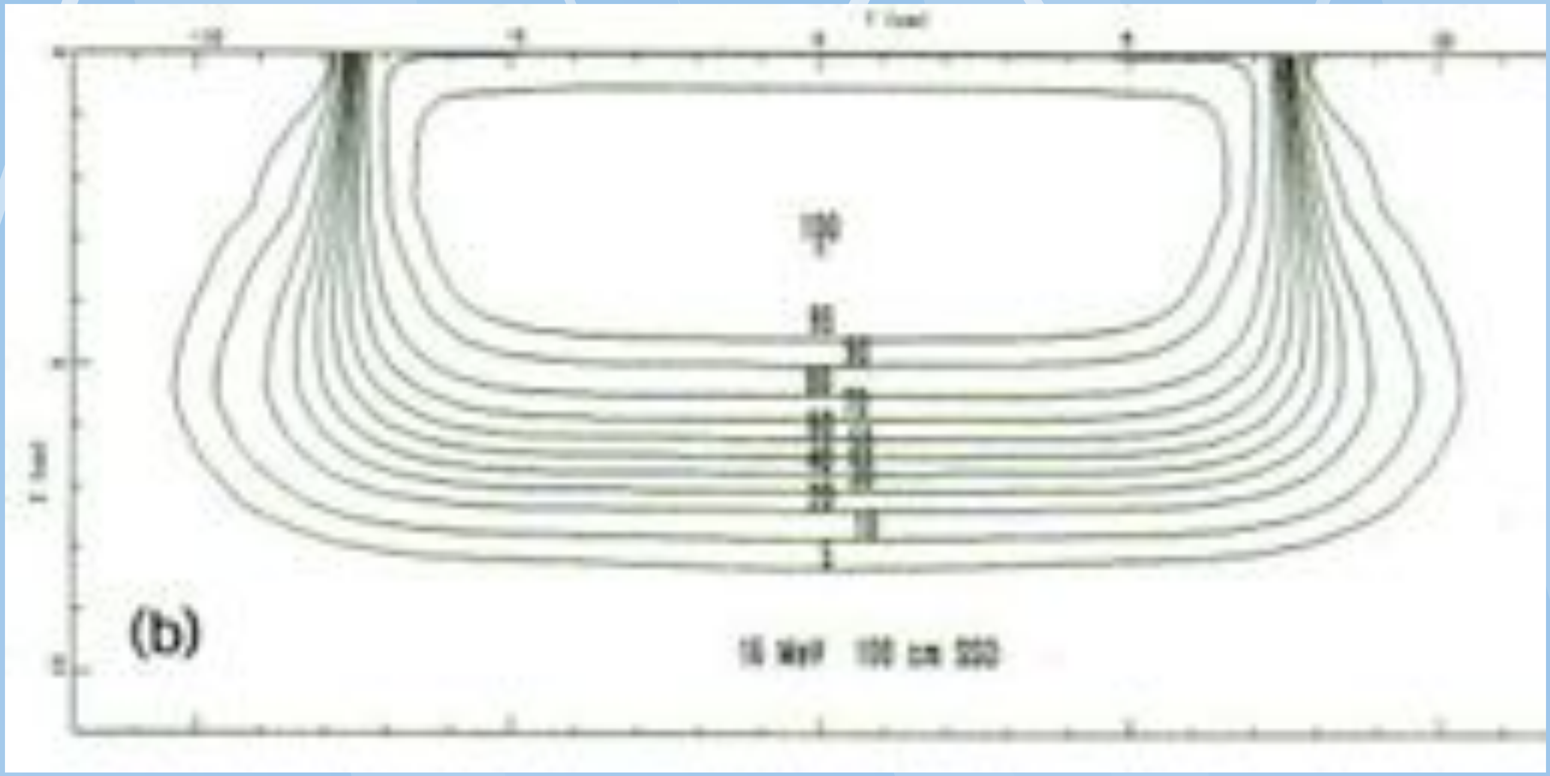
Influence of Patient Anatomy on Electron Dose Distributions

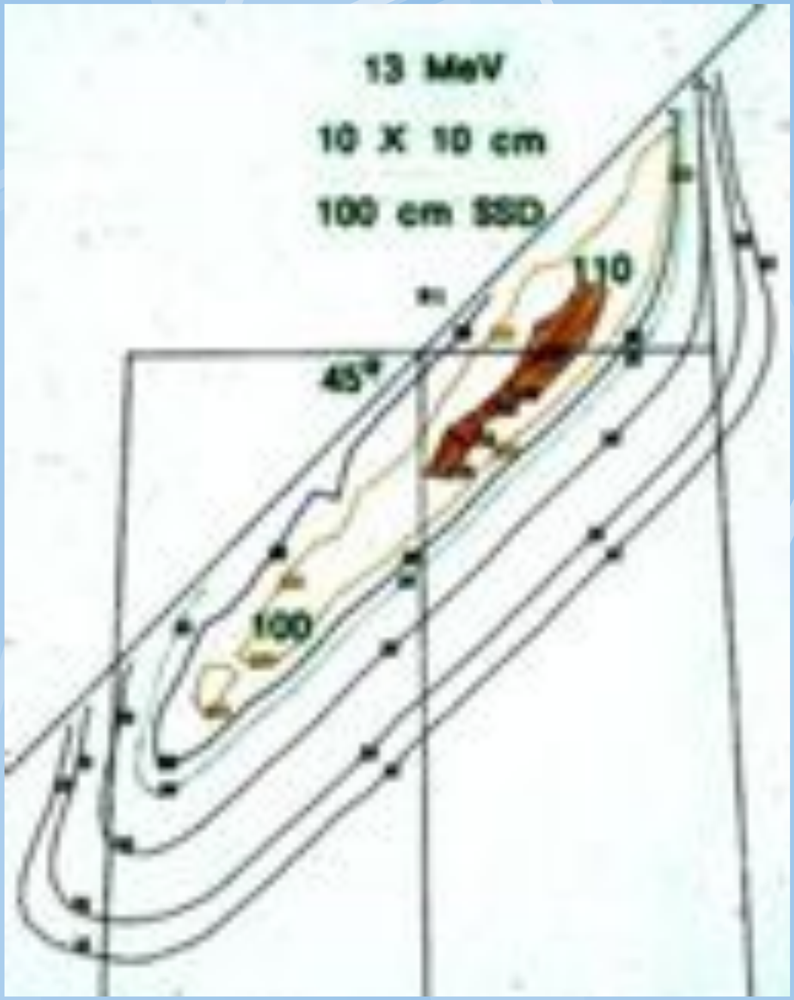
How do electron dose distributions in patients differ from those in water?



Influence of Patient Anatomy on Electron Dose Distributions

- Patient Surface
  - Oblique incidence
  - Irregular Surface
- Internal Heterogeneities
  - Bone
  - Air
  - Lung

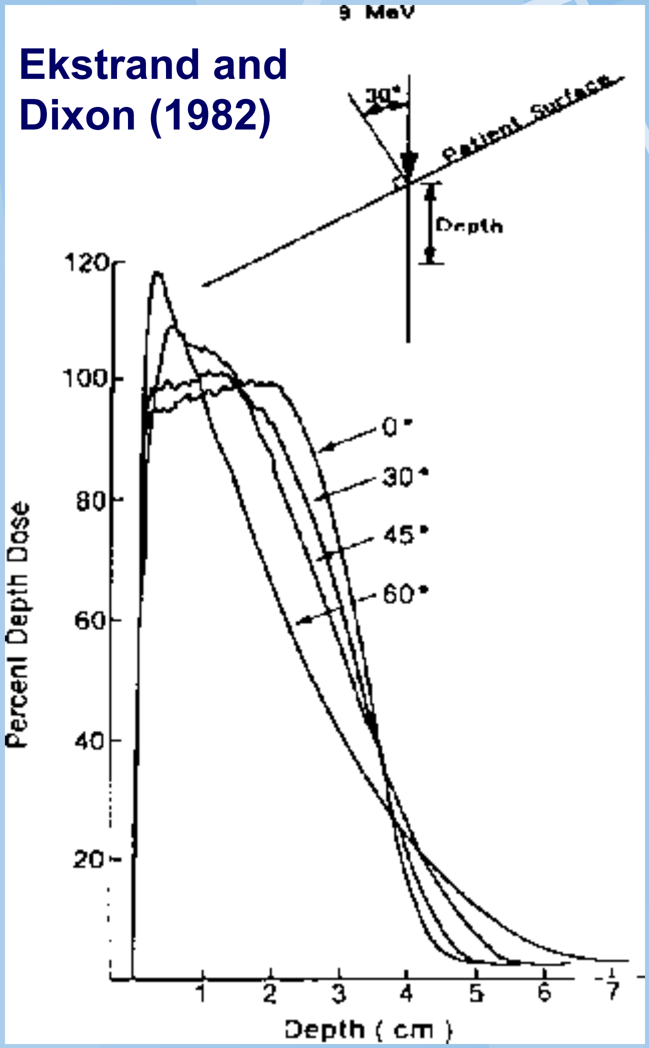
Effects of Oblique Incidence on Electron Dose Distribution



Penumbra

- decreases for surfaces closer to source
- increases for surface further from sources

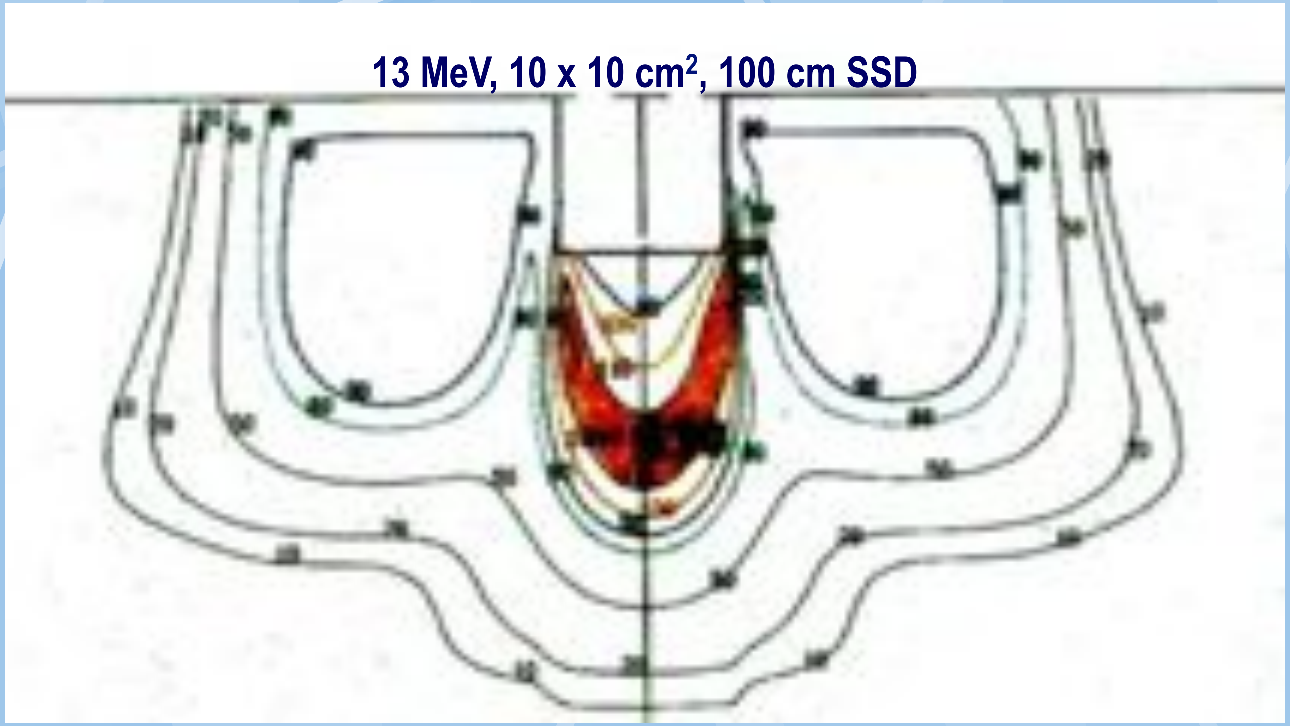
Effect of Oblique Incidence on Electron Dose Distribution



<u>Depth Dose</u>

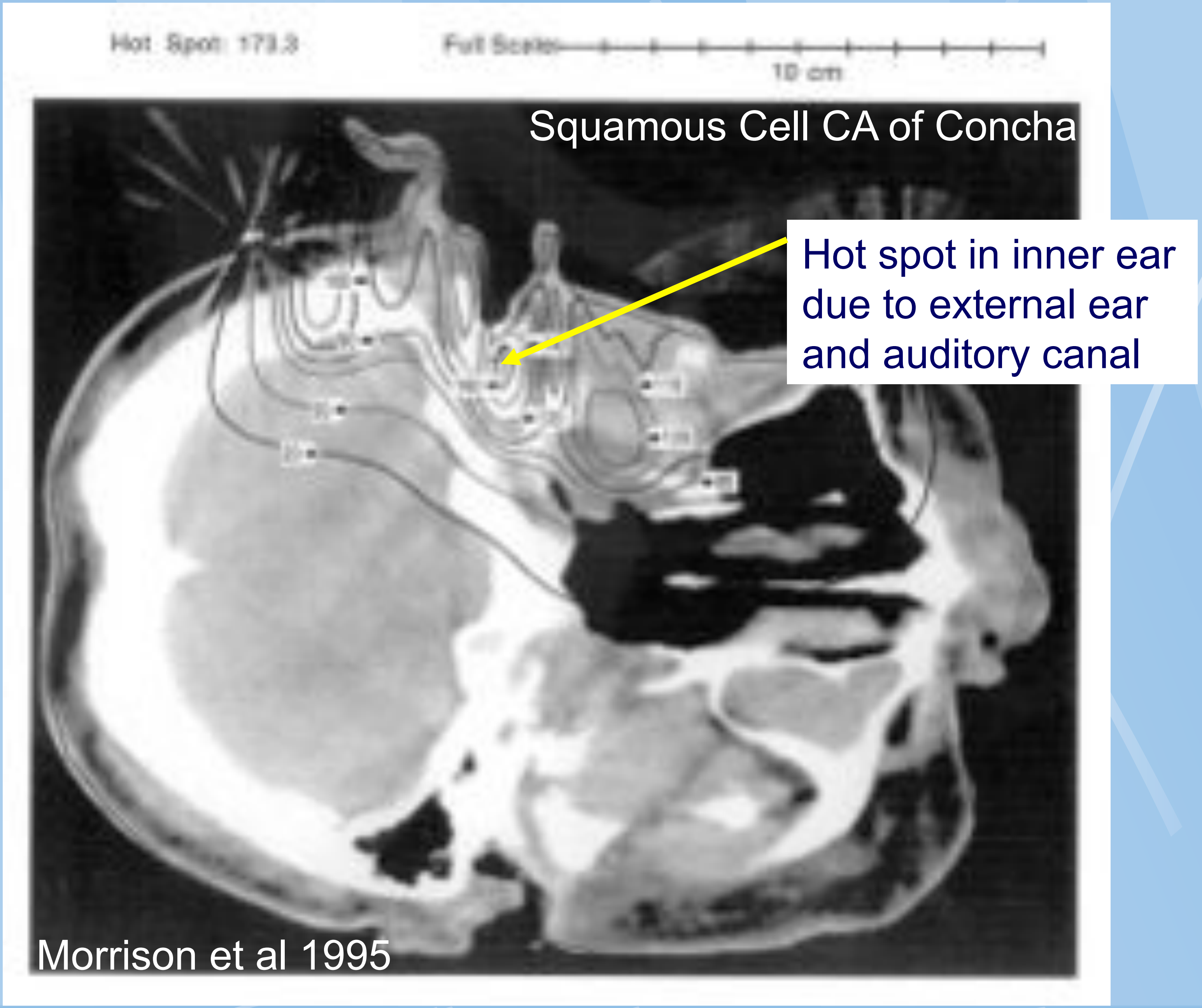
- Surface dose (D_s) increases
- Depth of maximum dose (R_{100}) decreases
- Maximum dose (D_{max}) increases
- Therapeutic depth (R_{90}) decreases
- Depth of maximum penetration (R_p) increases
- Effects become more severe as angle from ⊥ increases

Effect of Irregular Surface on Electron Dose Distribution



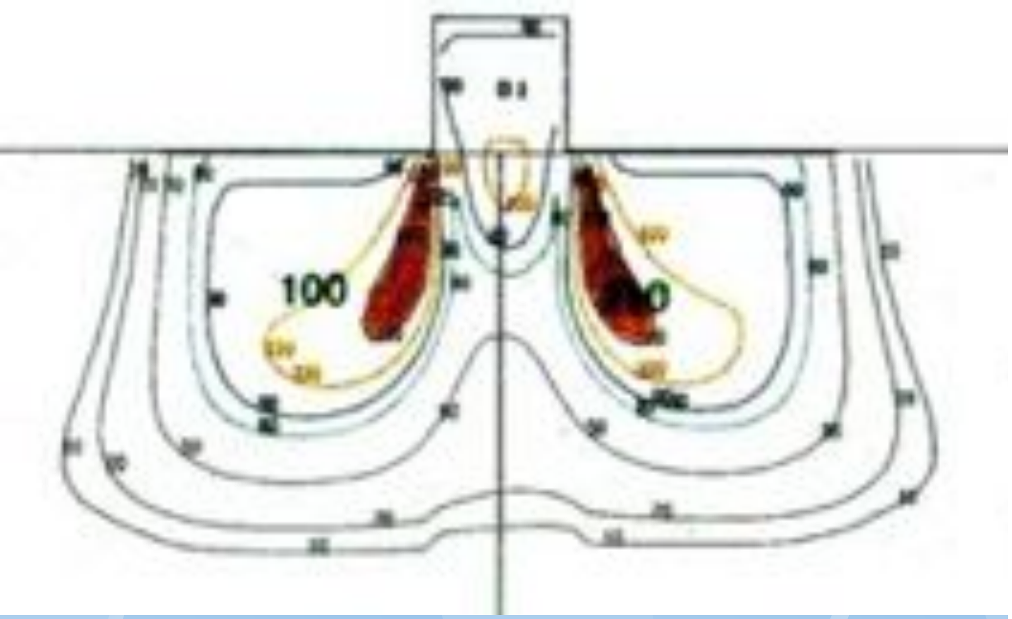
<u>Depression (e.g. ear canal, surgical defect)</u>

- Increased dose in shadow of depression
- Decreased dose around its periphery

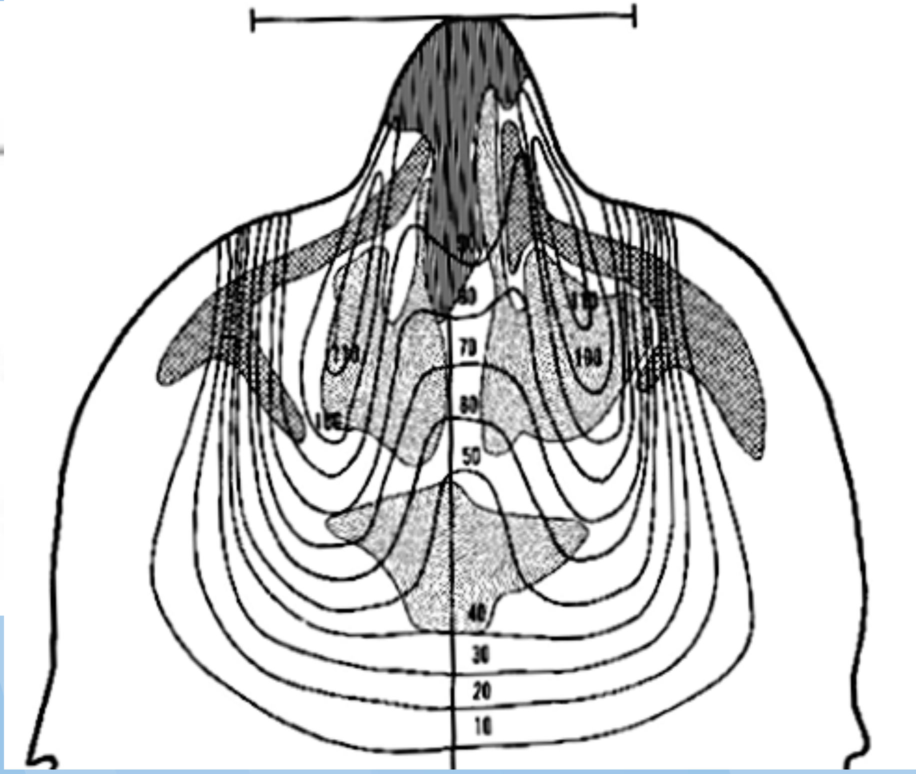

Hot Spot: 173.3
Full Scale
10 cm
Squamous Cell CA of Concha
Hot spot in inner ear due to external ear and auditory canal
Morrison et al 1995

Effect of Irregular Surface on Electron Dose Distribution

13 MeV, 10 x 10 cm^2, 100 cm SSD



17 MeV, 7.3 x 6.8 cm^2,100 cm SSD

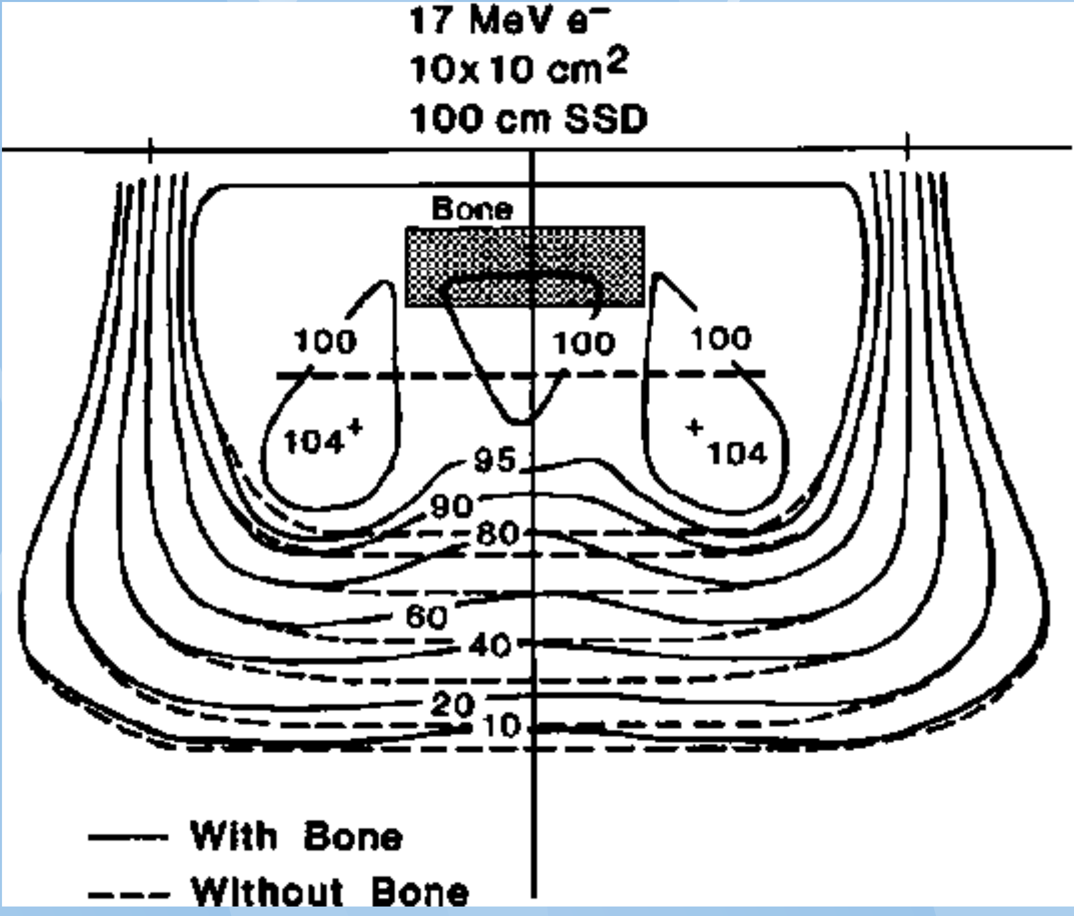


Protrusion (e.g. nose, ear)

- Decreased dose in shadow of protrusion
- Increased dose around its periphery

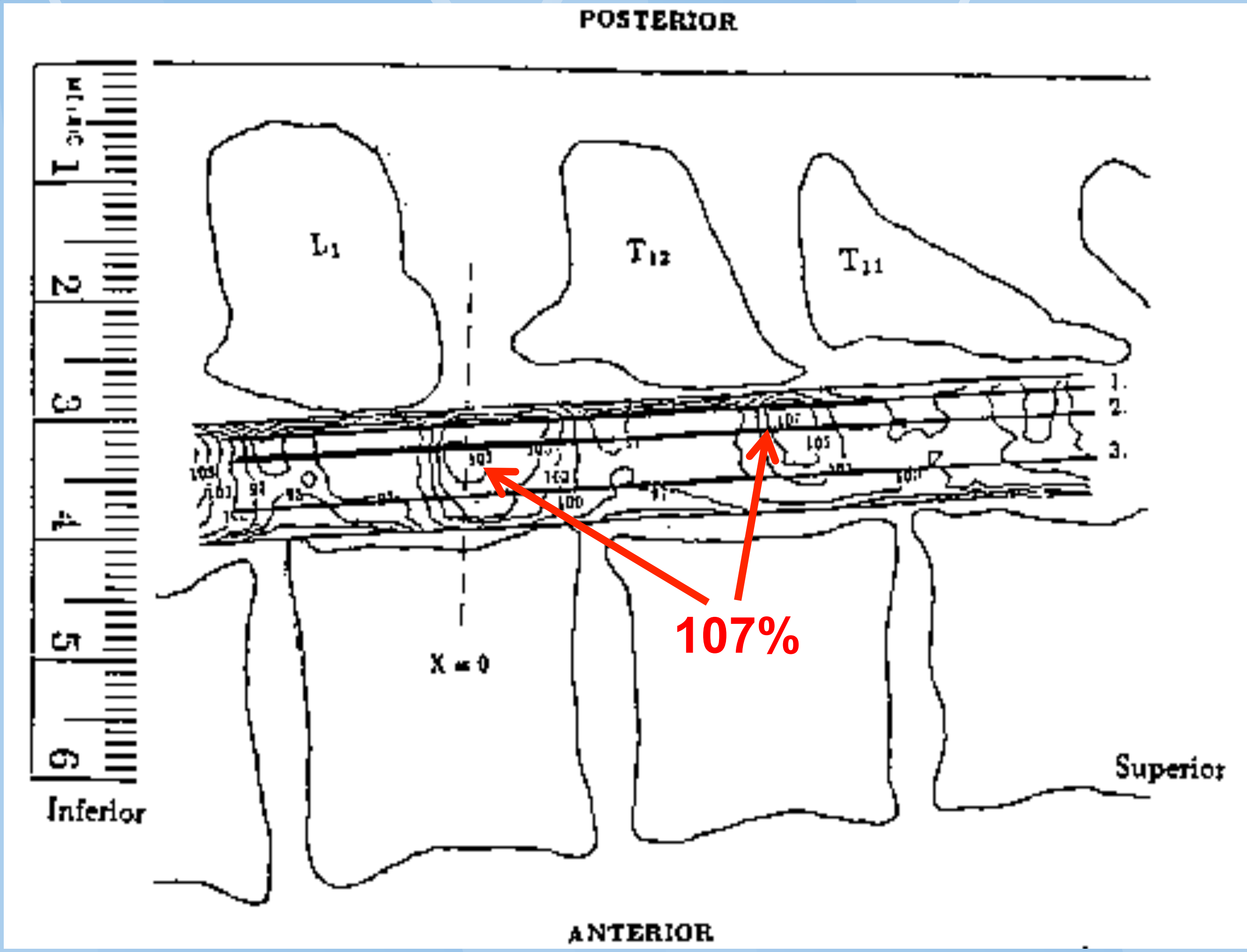
Effects of Bone on Electron Dose Distribution

- Therapeutic dose contours (80%-90%) shift toward the surface due to increased stopping power of bone.
- Hot spots lateral to bone and cold spots under bone have small effect (< 5%).

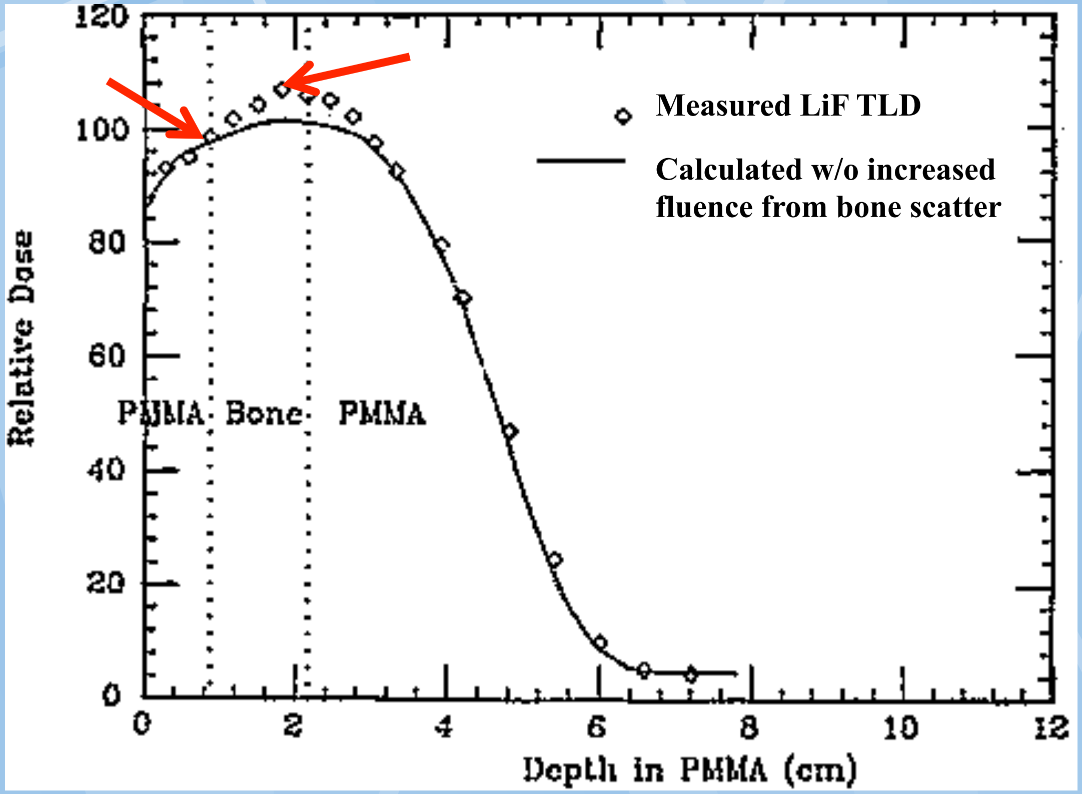


Effects of Bone on Electron Dose Distribution

- Hot spots between spinous process; cold spots under spinous process

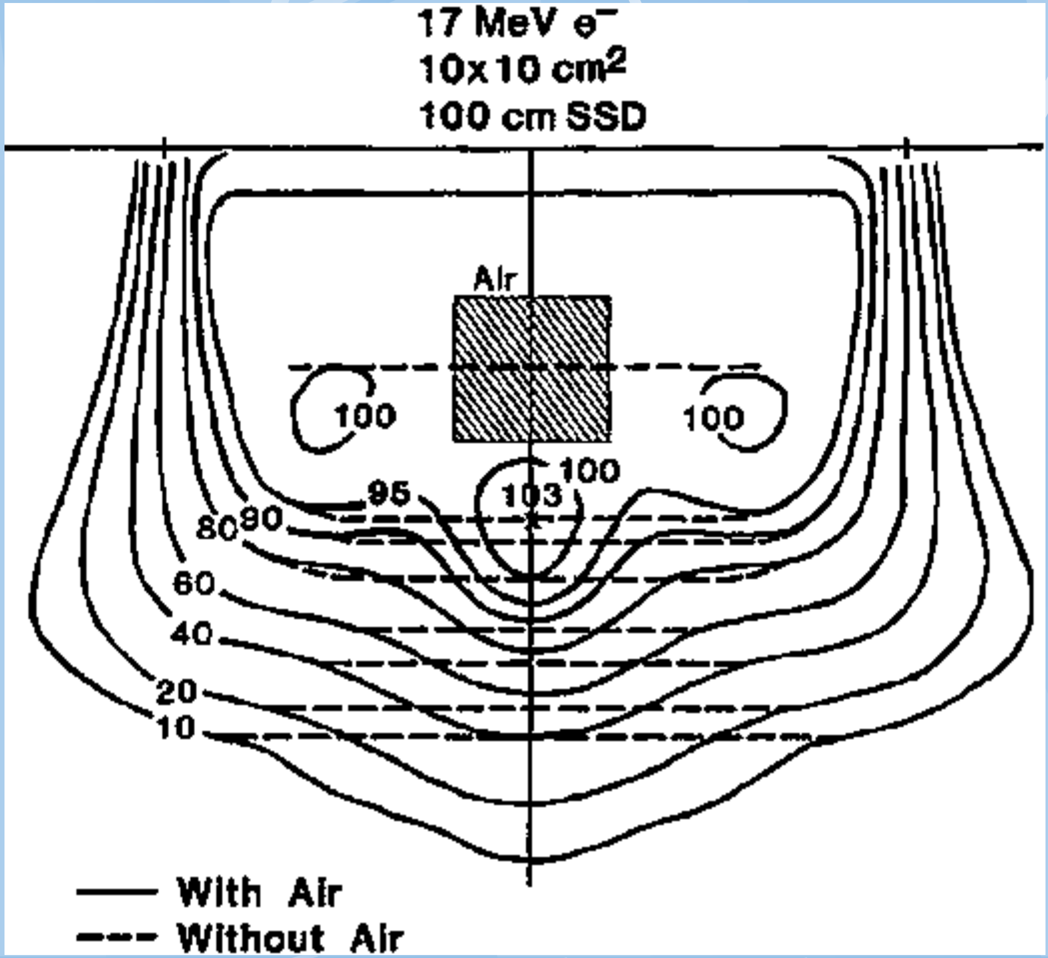


Effects of Bone on Electron Dose Distribution



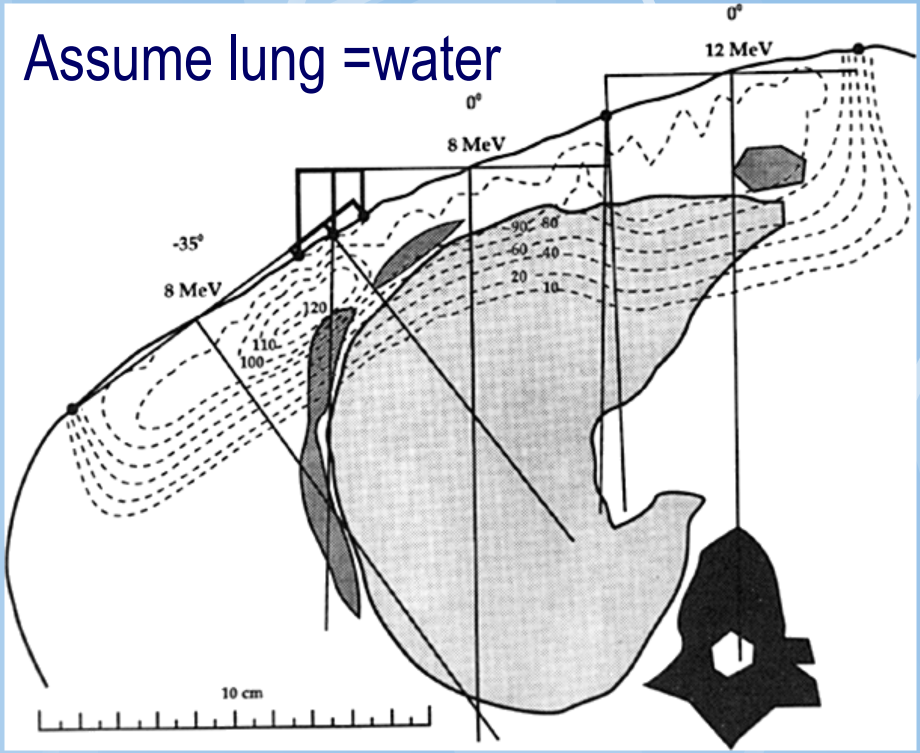
- Small increase in dose to upstream tissue due to backscatter (< 4%)
- Small increase in dose in bone due to multiple Coulomb scattering (< 7%)

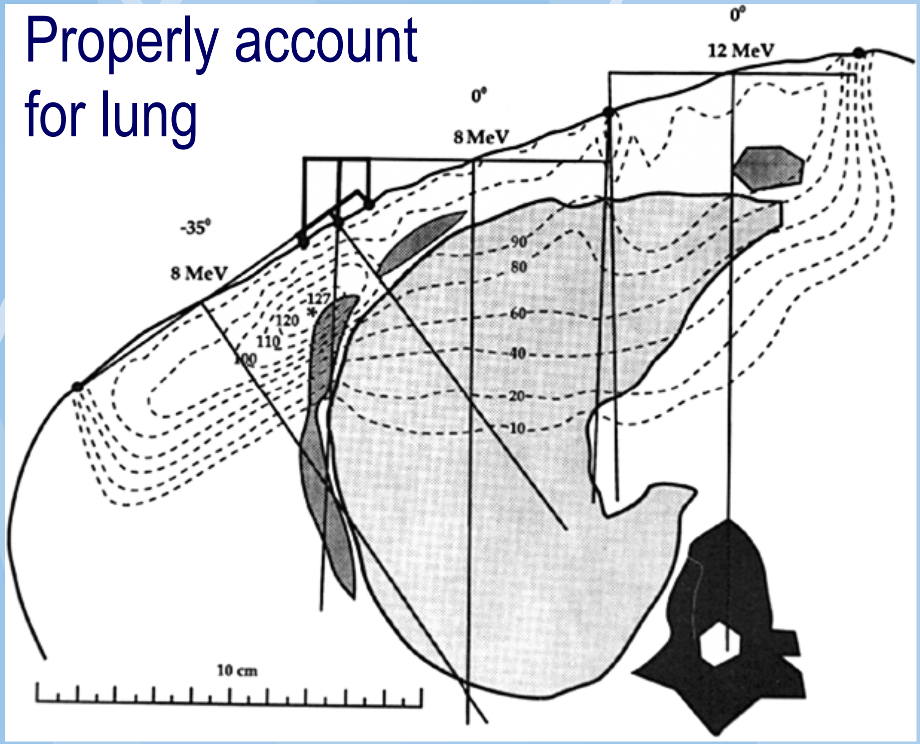
Effects of Air on Electron Dose Distribution



- Influence of Air Cavities
  - Dose falloff region penetrates deeper
  - Hot/cold spots can become significant (as much as 20%)

Effects of Lung on Electron Dose Distribution





Dose penetration in lung can be 3-4 times that of unit density tissue.

Summary
Impact of Patient Heterogeneity on Dose Distribution

- Key effects of patient anatomy (heterogeneity) on the dose distribution include
  - Isodose shifting due to bone, air, & lung
  - Hot/cold spots due to loss of side-scatter equilibrium resulting from irregular surfaces and edges of internal air cavities

- Effect of patient anatomy (heterogeneity) must be accounted for in electron beam planning to ensure:
  - Adequate electron energy, i.e. no geographical miss of PTV in depth
  - Adequate dose homogeneity in PTV, i.e. minimal hot/cold spots
  - Minimal dose to critical structures underlying PTV

Principles of Electron Beam Treatment Planning

Kenneth R. Hogstrom, Ph.D.

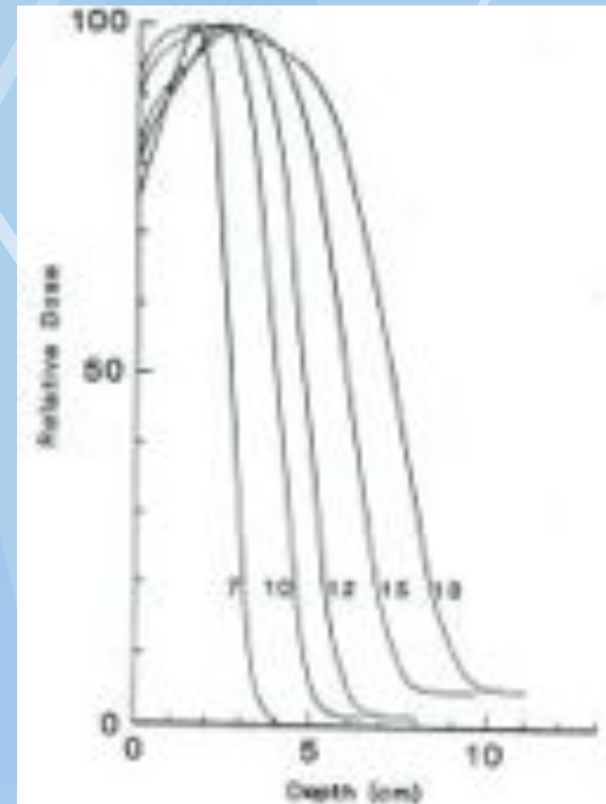
Principles of Electron Beam Treatment Planning

- Selection of Beam Energy
- Selection of Beam Direction
- Collimating Techniques
- Field Abutment Techniques
- Bolus Techniques

Reference: Hogstrom KR 2004 Electron beam therapy: dosimetry, planning, and techniques *Principles and Practice of Radiation Oncology* ed C Perez *et al* (Baltimore, MD: Lippincott, Williams, & Wilkins) pp 252-282

Selection of Beam Energy

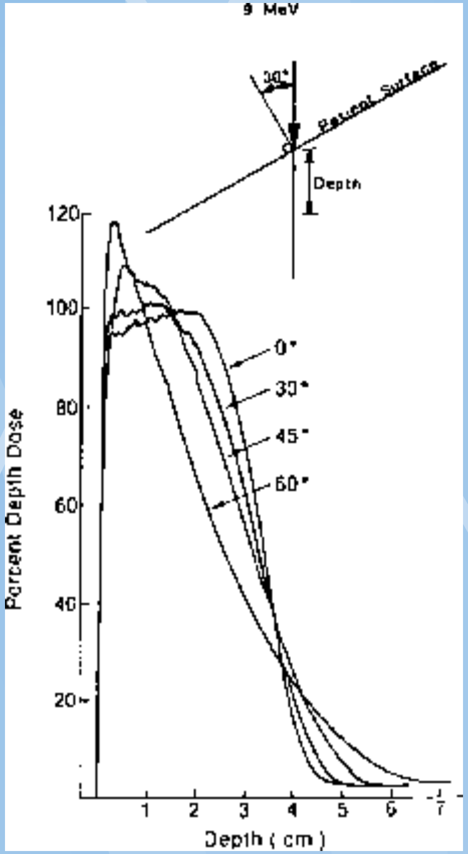
- Beam energy should be selected to ensure that:
  - R_{90}>maximum depth of PTV
  - R_p<minimum depth of critical structures
- Rules of thumb (in water)
  - $E_{p,o}(\text{MeV}) \approx 3.3 \times R_{90}(\text{cm})$
  - $E_{p,o}(\text{MeV}) \approx 2.0 \times R_p(\text{cm})$
- Therefore, to estimate beam energy:
  - $E_{p,o}$(MeV)>3.3 x maximum depth in cm of PTV
  - $E_{p,o}$(MeV)<2.0 x minimum depth in cm of CS
- Actual beam energy may differ due to:
  - Field-size dependence of %DD
  - Patient heterogeneity

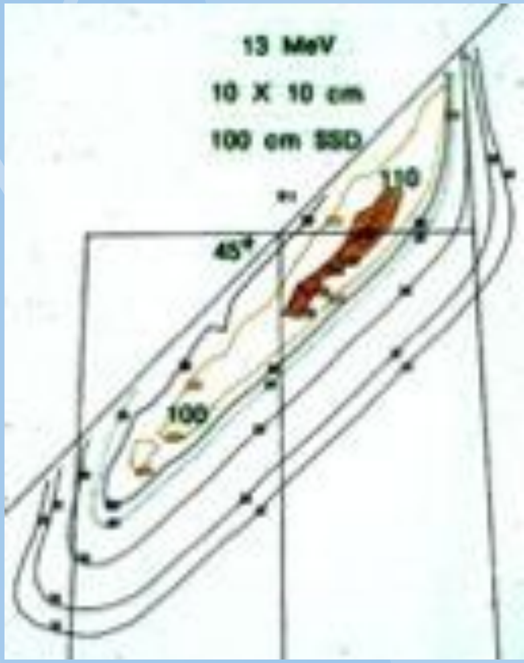


<u>Example</u>: max depth of PTV=3 cm; min depth of cord =6 cm)
$\Rightarrow$9.9 MeV<$E_{p,o}$<12.0 MeV $\Rightarrow$10 MeV

Selection of Beam Direction

- Generally, electron beam should be incident ⊥ to skin (or bolus) surface to ensure:
  - Maximum penetration of therapeutic depth
  - Most uniform penumbra width

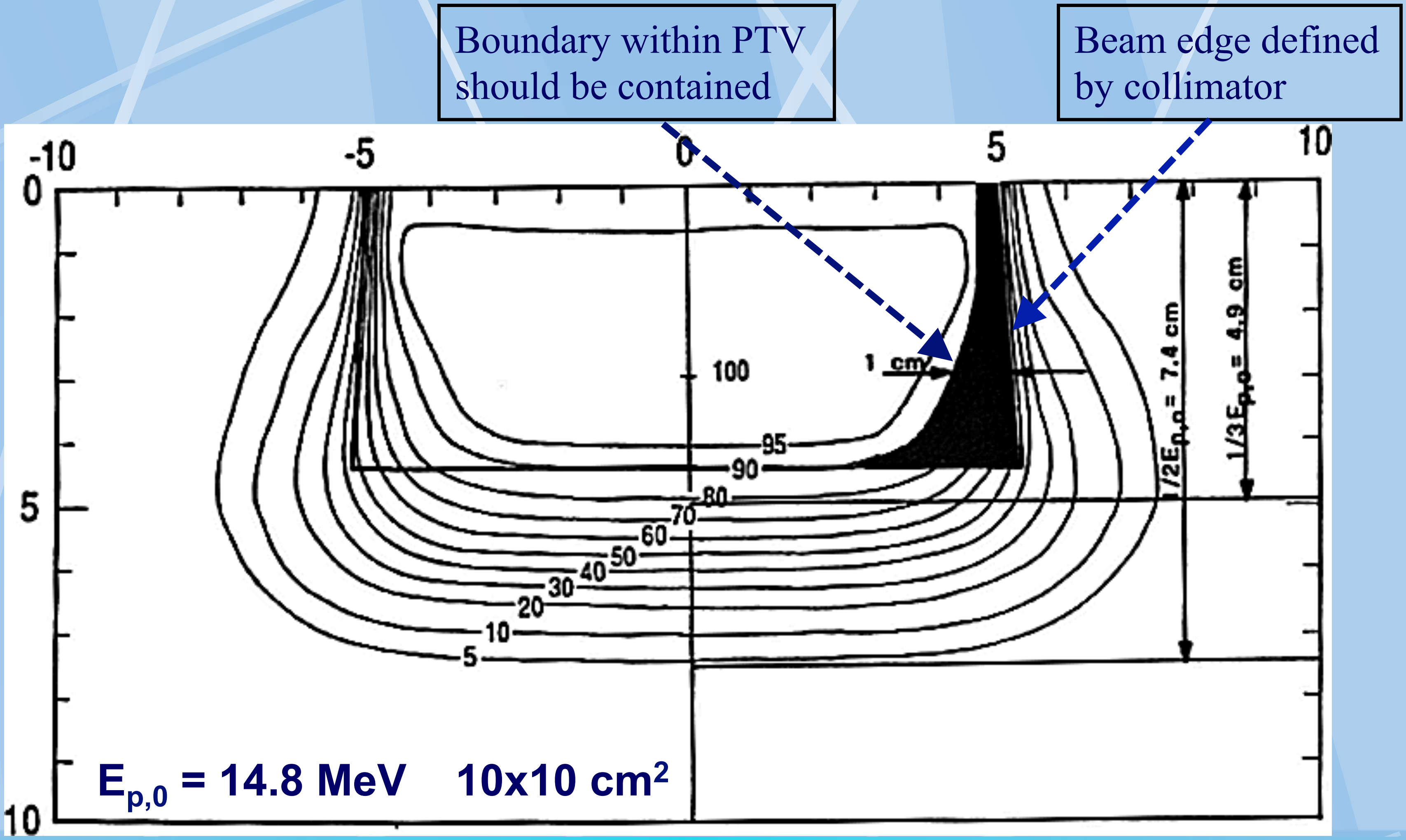




Collimating Techniques

- Collimator Thickness
- Design of Aperture (PTV-Portal Margin)
- Skin Collimation
- Utility of Small Blocks
- Internal Collimation

Design of Aperture:
Basic Rule for Target-Portal Margin



Skin Collimation:
Basic Rules for Collimator Thickness

t_{Pb} (mm) = 1/2 $E_{p,o}$ (MeV) + 1

$t_{Cerrobend} = 1.2\ t_{Pb}$

Examples:

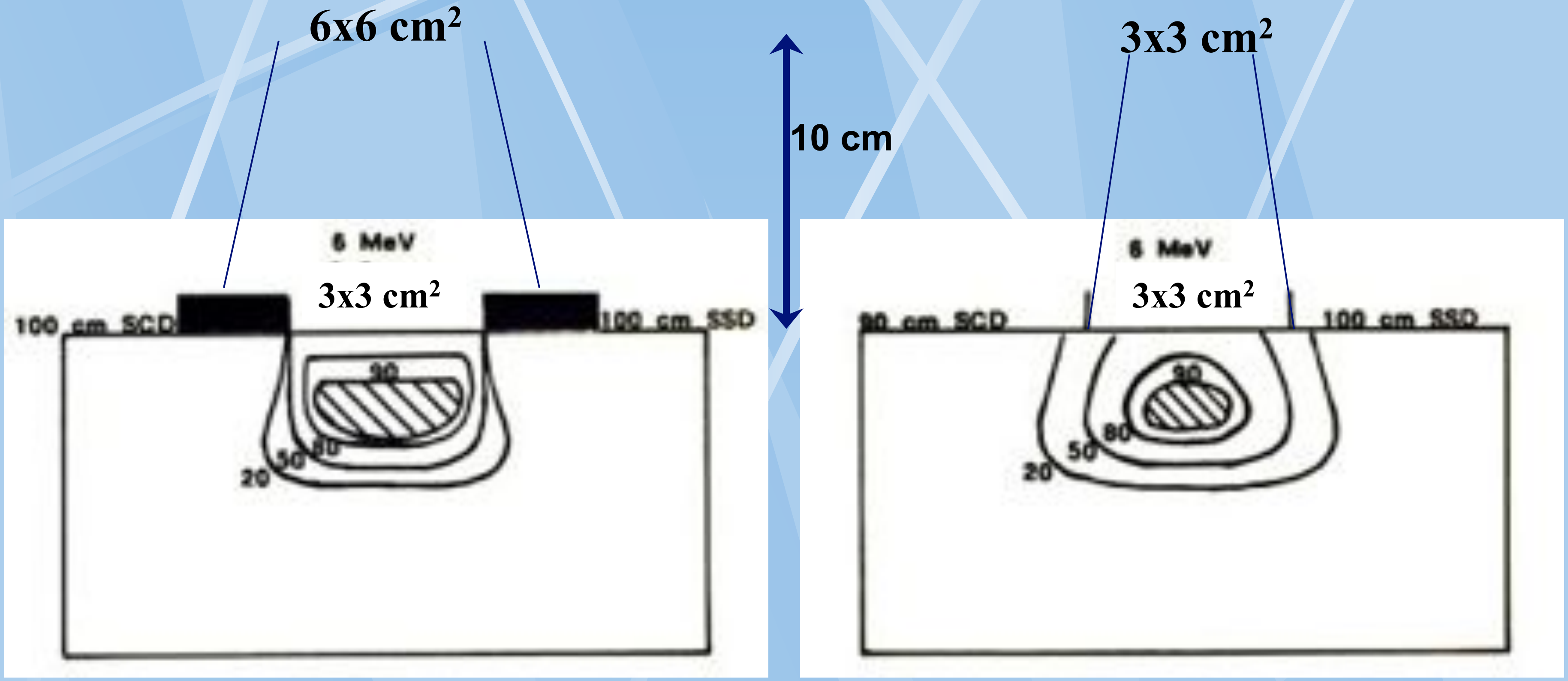
8 MeV → 5 mm Pb → 6 mm Cerrobend

20 MeV → 11 mm Pb → 13 mm Cerrobend

Utility of Skin Collimation Clinical Indications

- Small Fields
- Protection of Critical Structures
- Under Bolus
- Electron Arc Therapy

Utility of Skin Collimation: Small Fields



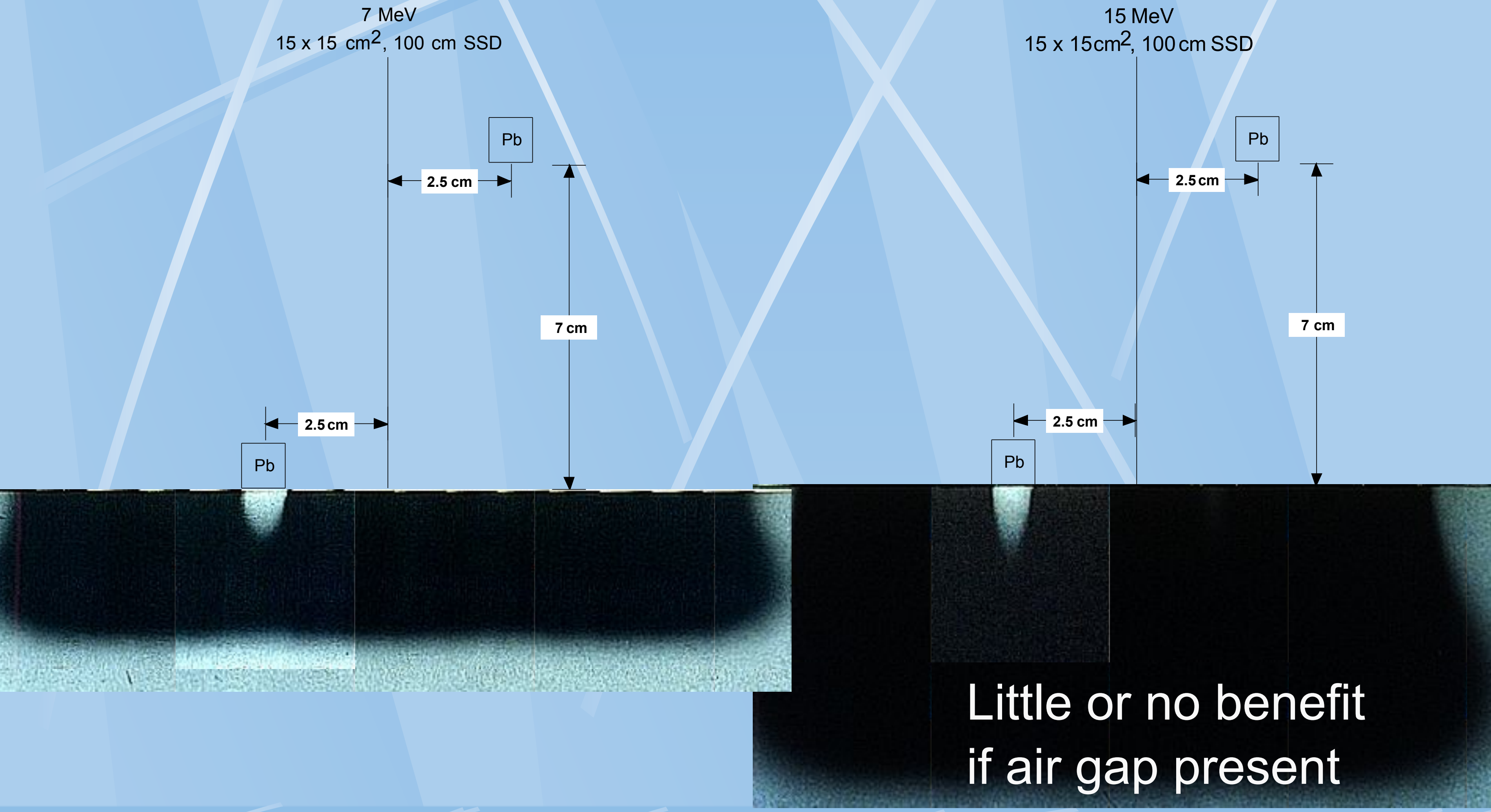
- Restores penumbra enlarged by air gap.
- This is particularly important for small fields.

Utility of Skin Collimation (Large Blocks): Protection of Critical Structures

Nose CA: Maximum protection of eyes

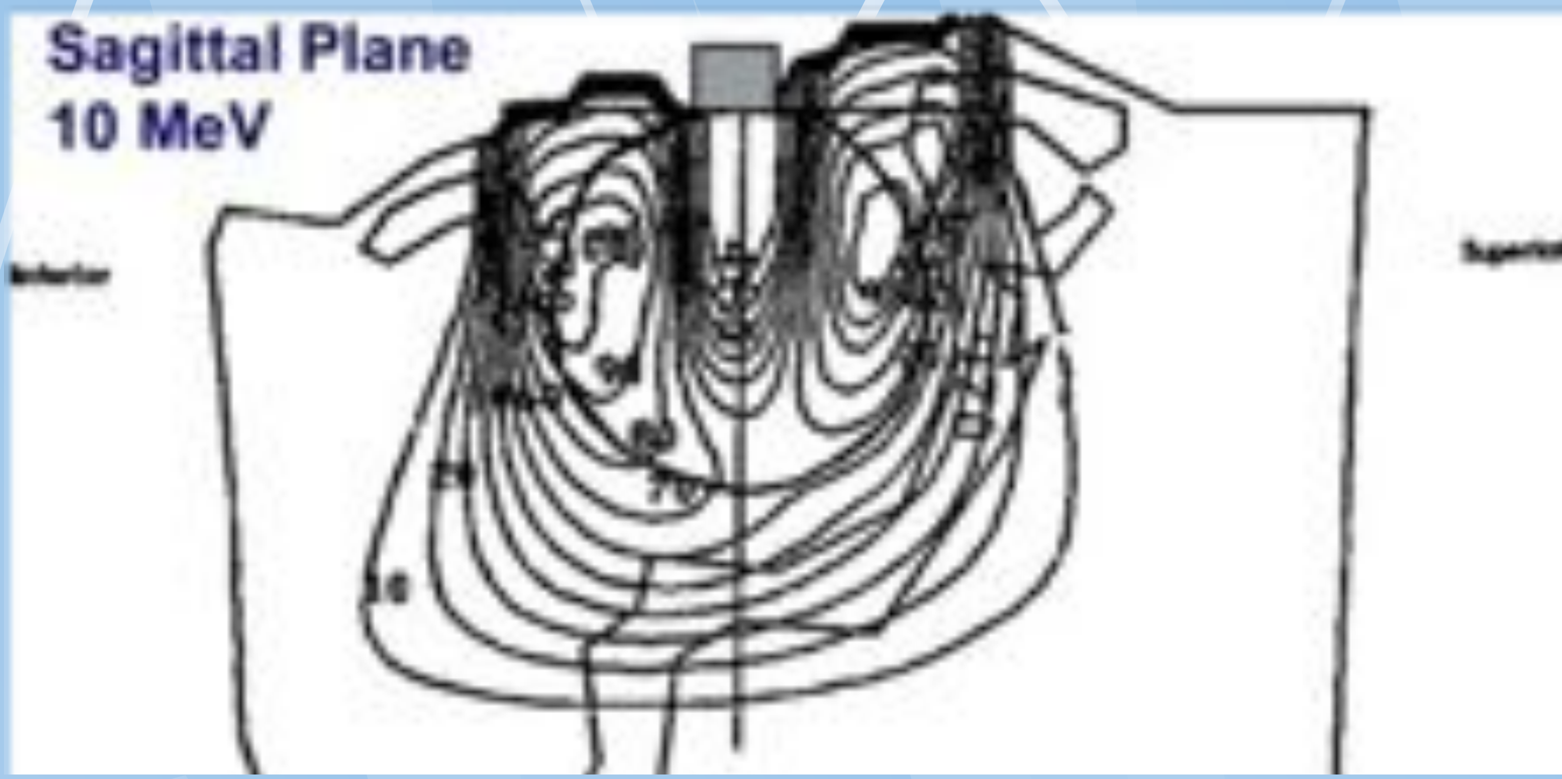
CA of Inner Canthus: Protection of eye

Electron Collimation: Utility/Futility of Small Blocks

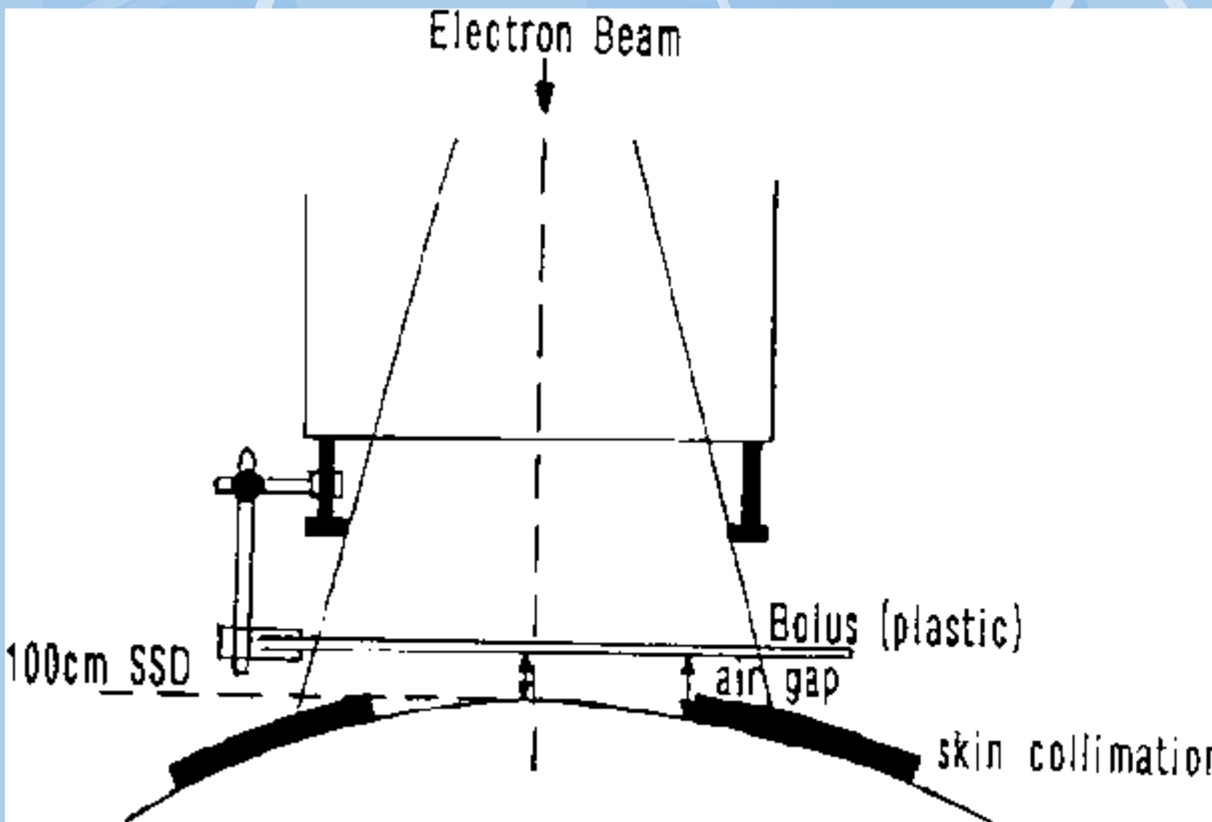


Utility of Skin Collimation(Small Blocks)
Protection of Critical Structures

- Useful for protecting superficial structures
- Ex: lens, cornea in treatment of retinoblastoma)

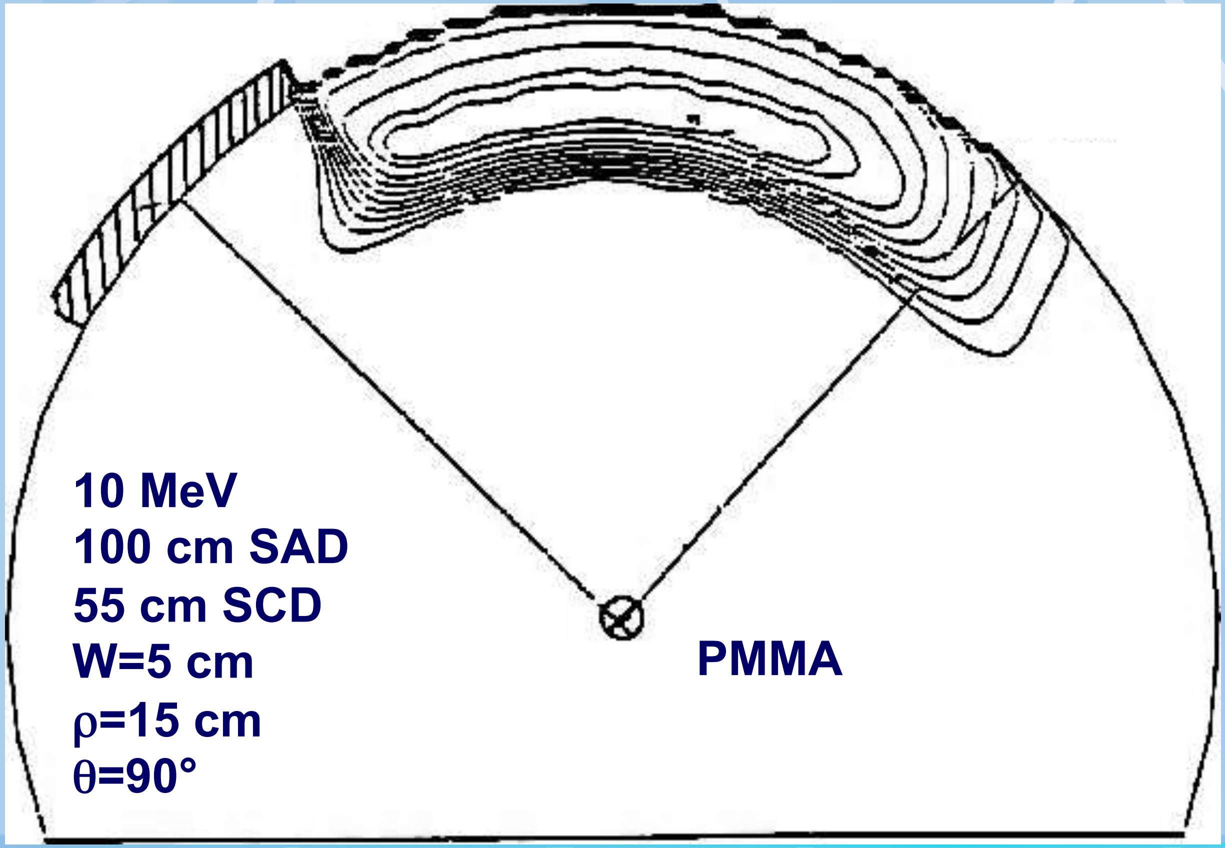


Utility of Skin Collimation: Under Bolus



- Restores penumbra under bolus

Utility of Skin Collimation: Arc Electron Therapy

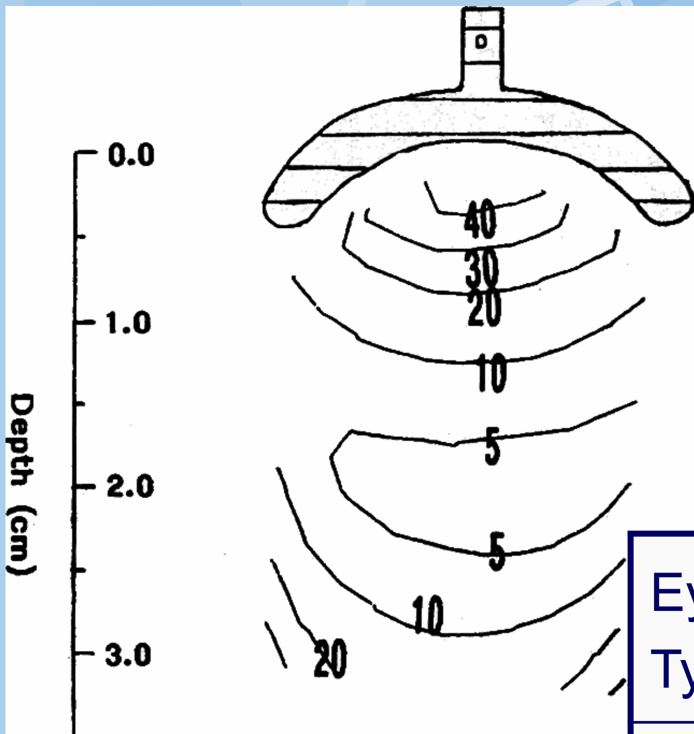


- Restores penumbra for electron arc treatments

Electron Collimation: Internal Collimation

- Used for:
  - Protection of eye in treatment of eyelid tumors
  - Intraoral stents in head and neck treatments
- Problems with:
  - Penetration due to insufficient thickness
  - Increased dose due to backscattered electrons

Eye Shields:
“X-ray” Lead Eye Shield Unsuitable

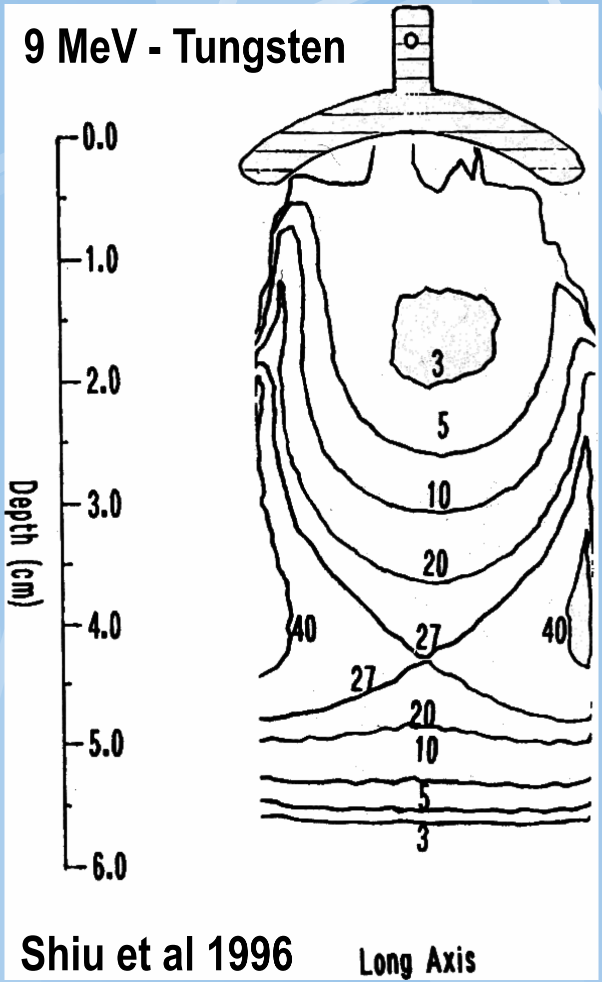


Eye Shield Type	Incident Energy	%Transmission	
		Surface	6 mm
Medium*	5.7 MeV	35%	22%
	7.1 MeV	60%	37%
	125 kVp x-rays	5%	4%
Gold (Large)**	5.7 MeV	50%	36%

***”black” plastic coated lead eyeshields from Ace Medical Supply**
****gold-plated lead eyeshields**

Electron Collimation: Tungsten "Electron" Eye Shield

9 MeV - Tungsten

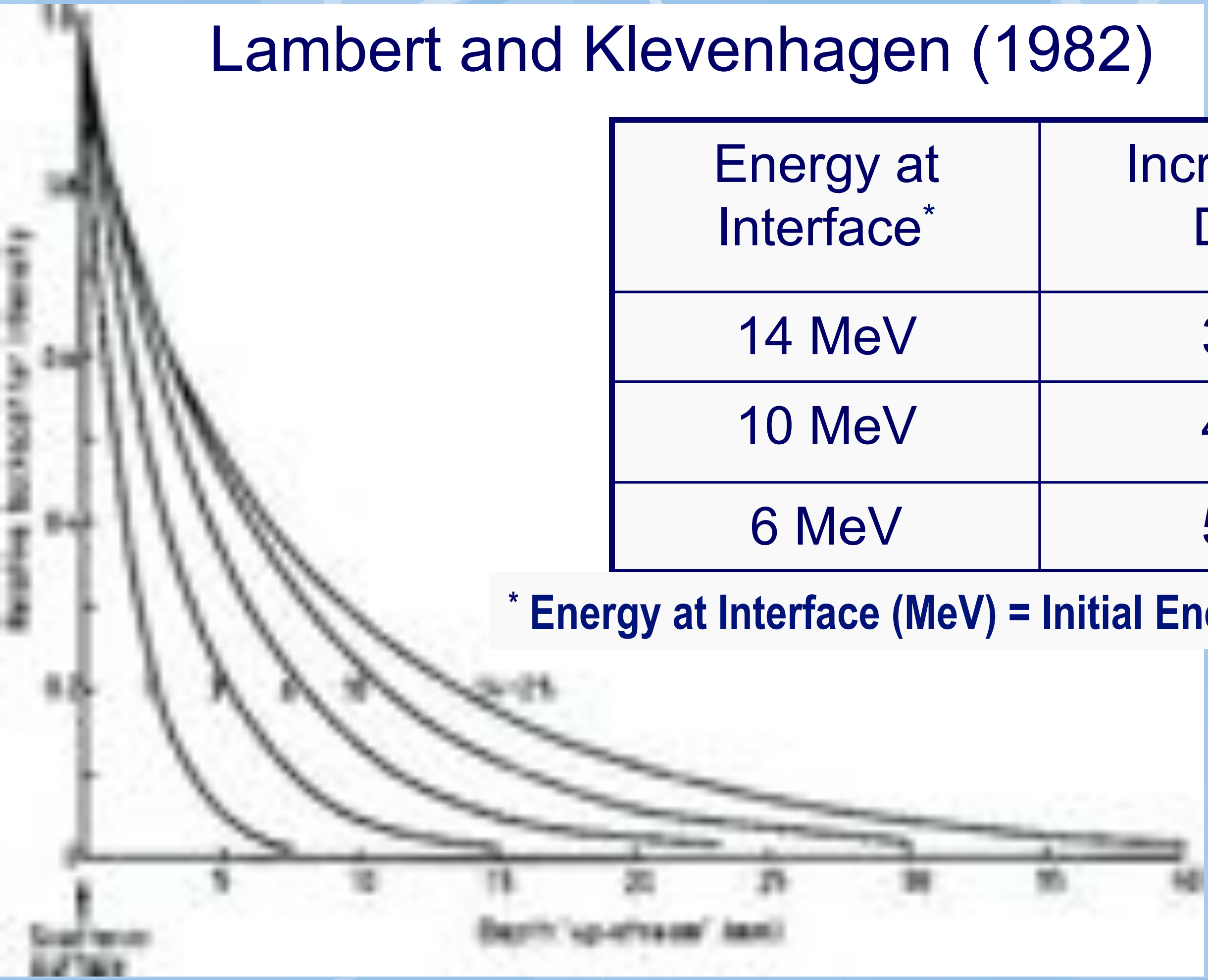


Shiu et al 1996

Tungsten rather than lead eye shields should be used for 6-9 MeV electrons.

Internal Electron Collimation:
Attenuation of Back-scattered Electron Dose

Lambert and Klevenhagen (1982)



Energy at Interface*	Increase in Dose	HVL of Back-scattered Dose
14 MeV	35%	6 mm
10 MeV	45%	5 mm
6 MeV	55%	4 mm

* **Energy at Interface (MeV) = Initial Energy (MeV) - Depth (cm) * 2 MeV/cm**

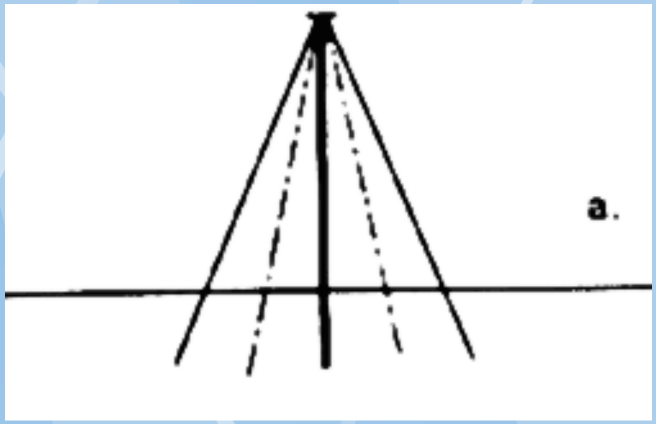
Field Abutment: Ideal Criteria

- Broad penumbra
- Matched penumbra
- Overlap at 50% dose ratios
  - usually, but not always, edge of light fields
- Virtual source in same position for both fields.

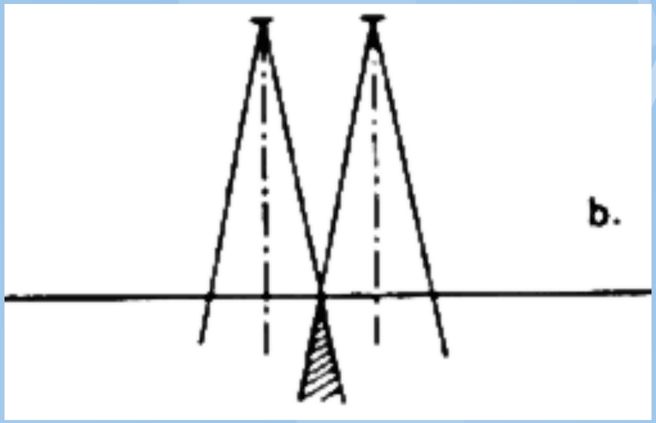
Field Abutment Classification Scheme

Three possible beam configurations of adjacent radiation beams in order of increasing overlapping problems.

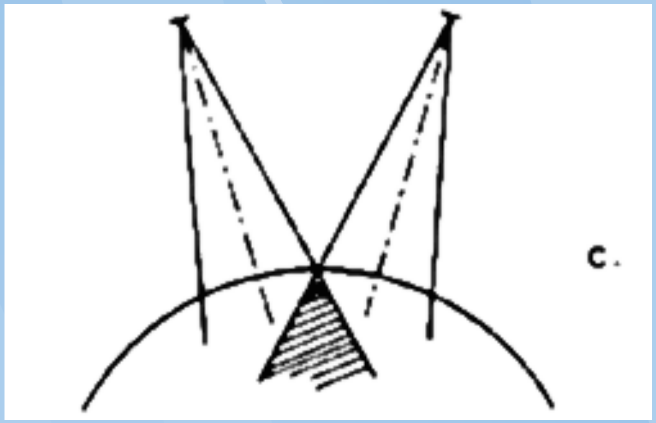
Figure 7.3, ICRU-35.



a. Common virtual source position

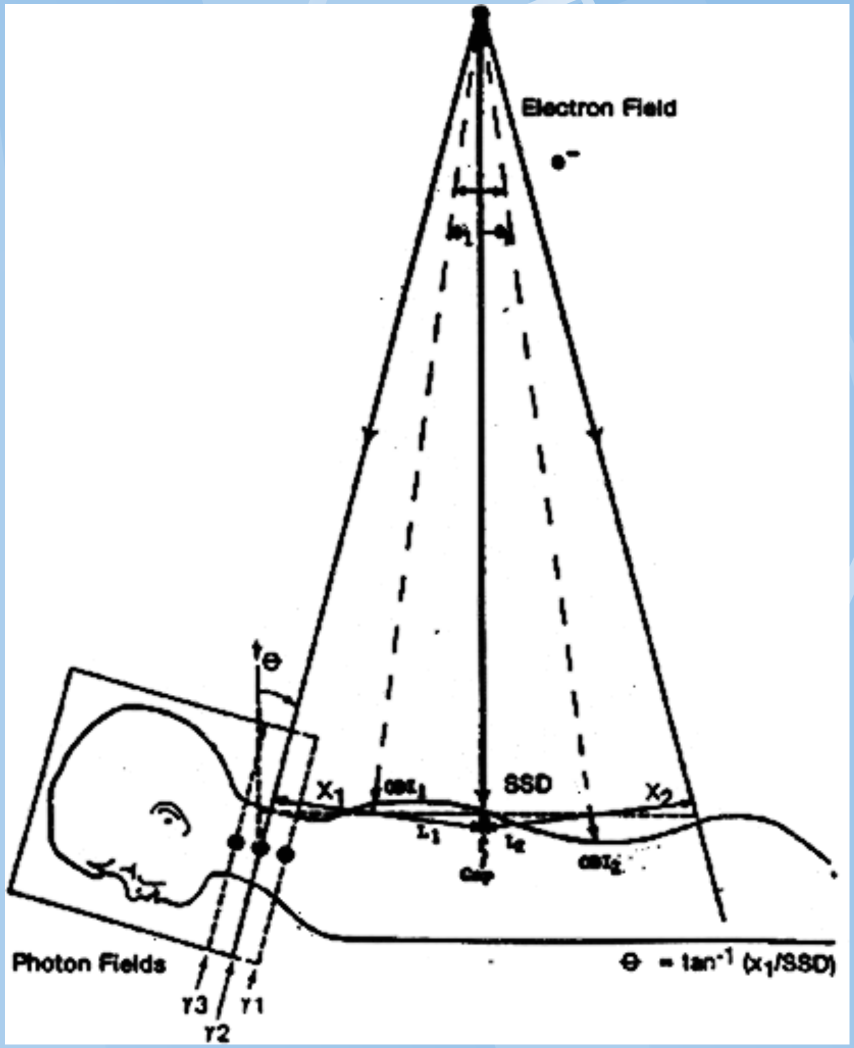


b. Parallel central axes



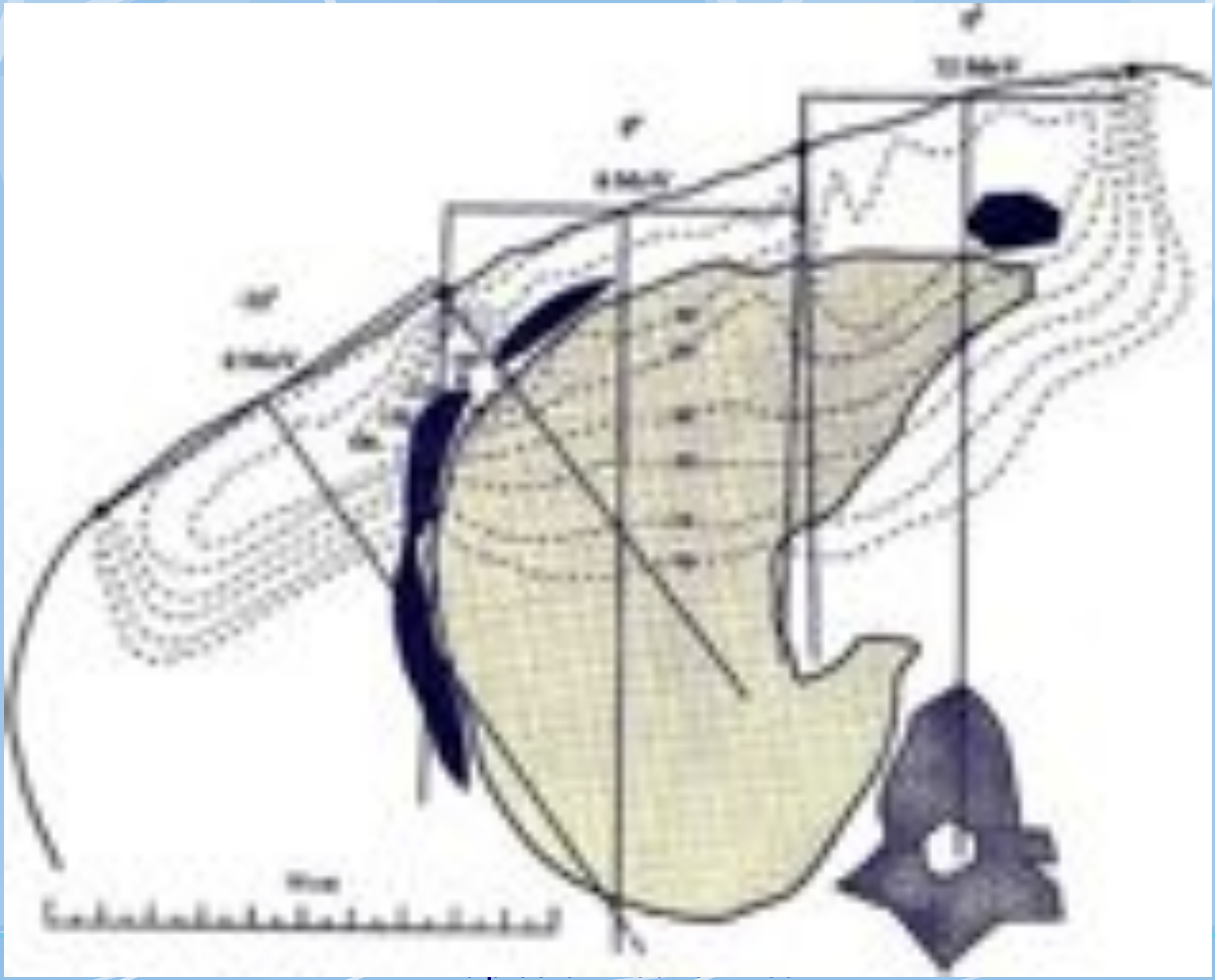
c. Converging central axes

Field Abutment
Craniospinal Irradiation Technique

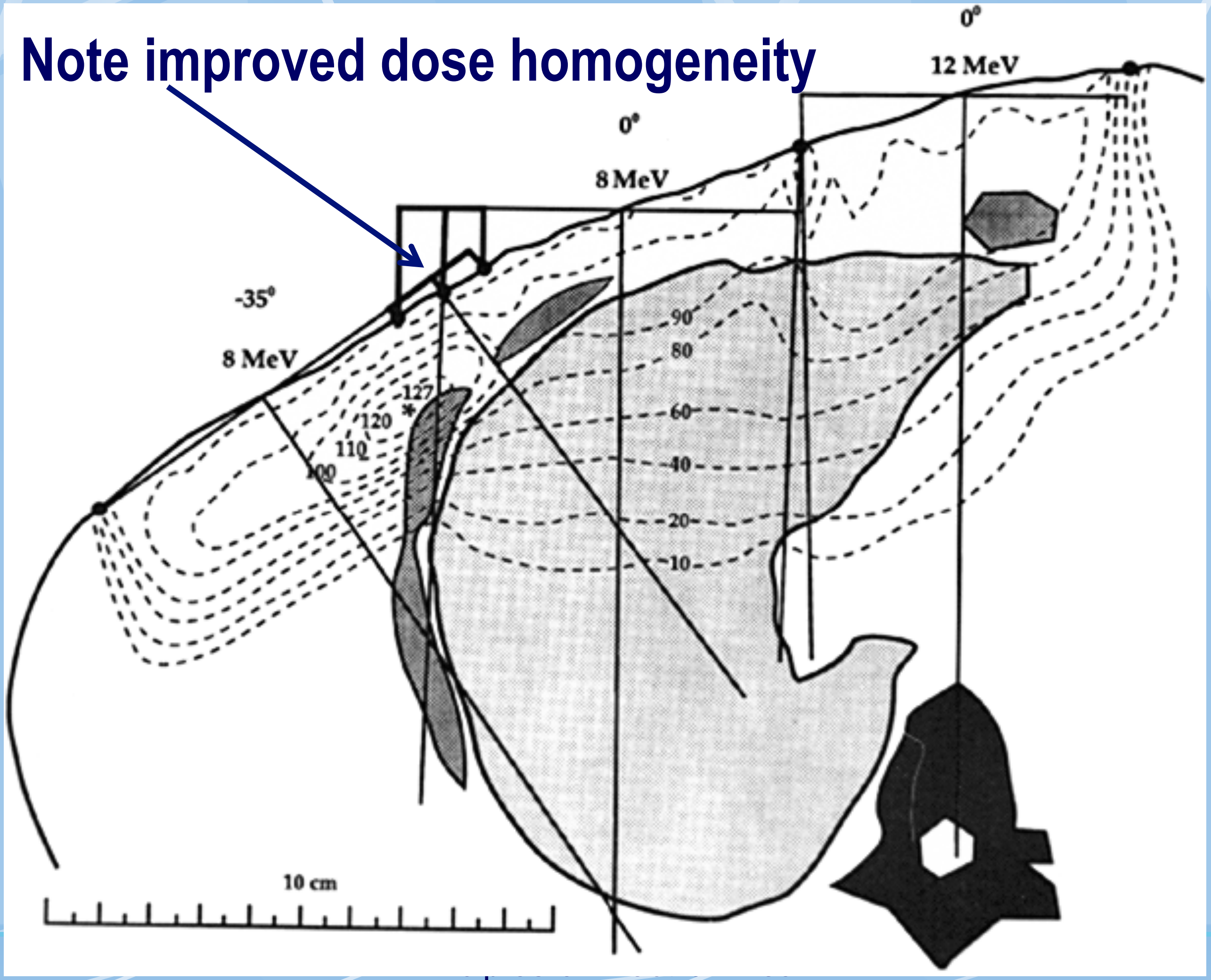


- X-ray field edge feathered to match electron penumbra.
- Extended SSD used to broaden electron beam penumbra.
- Two posterior electron fields abutted along common edge to give uniform dose.

Field Abutment
Chest Wall: Junction Hot Spot



Field Abutment
Chest Wall: Junction Shift

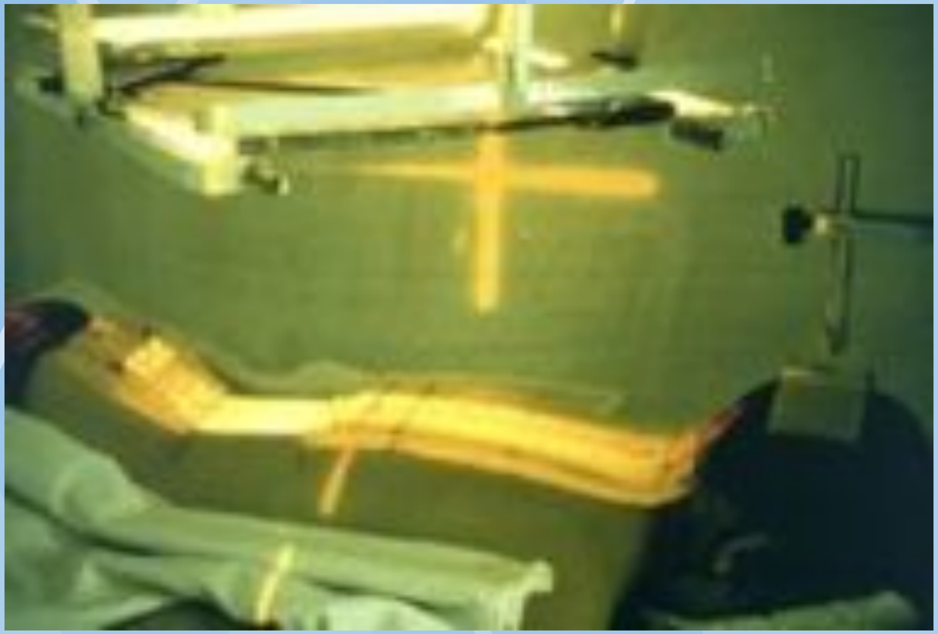


Electron Bolus: Definition

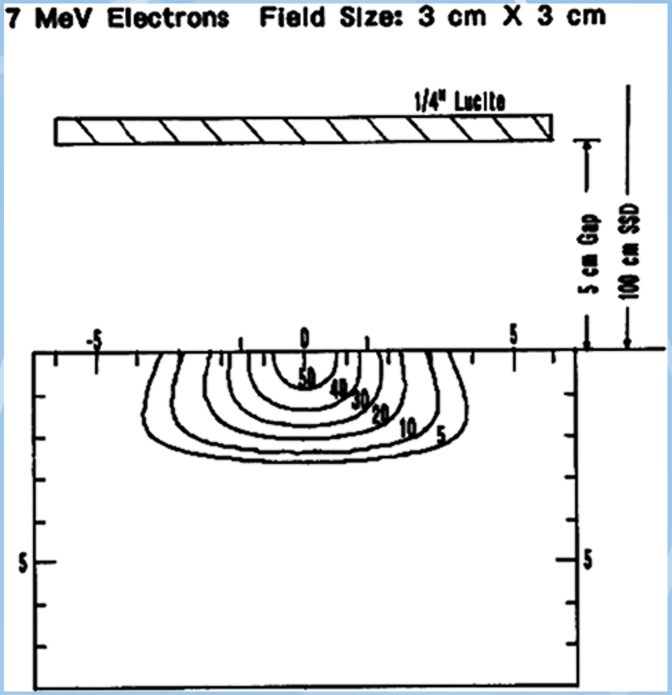
- A specifically shaped material, which is usually tissue equivalent and which is normally placed either in direct contact with the patient’s surface, close to the patient’s surface, or inside a body cavity.
- The material is designed to provide extra scattering or energy degradation of the electron beam.
- Its purpose is usually to shape the dose distribution to conform to the target volume and/or to provide a more uniform dose inside the target volume.

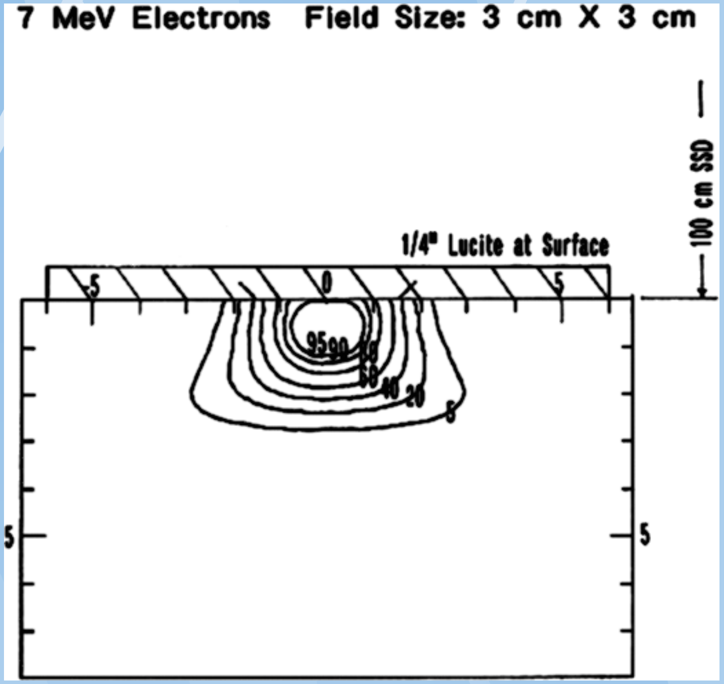
Electron Bolus: Basic Rules for Clinical Use

- Tissue-like Material
  - Wax, water, SuperFlab, plastic sheets, ...
- Close to the Skin Surface
- No Sharp Edges in Field
  - Extend sharp edges outside field
- Verify Intent
  - In-vivo dosimetry (TLD)
  - CT-based dose calculation with bolus



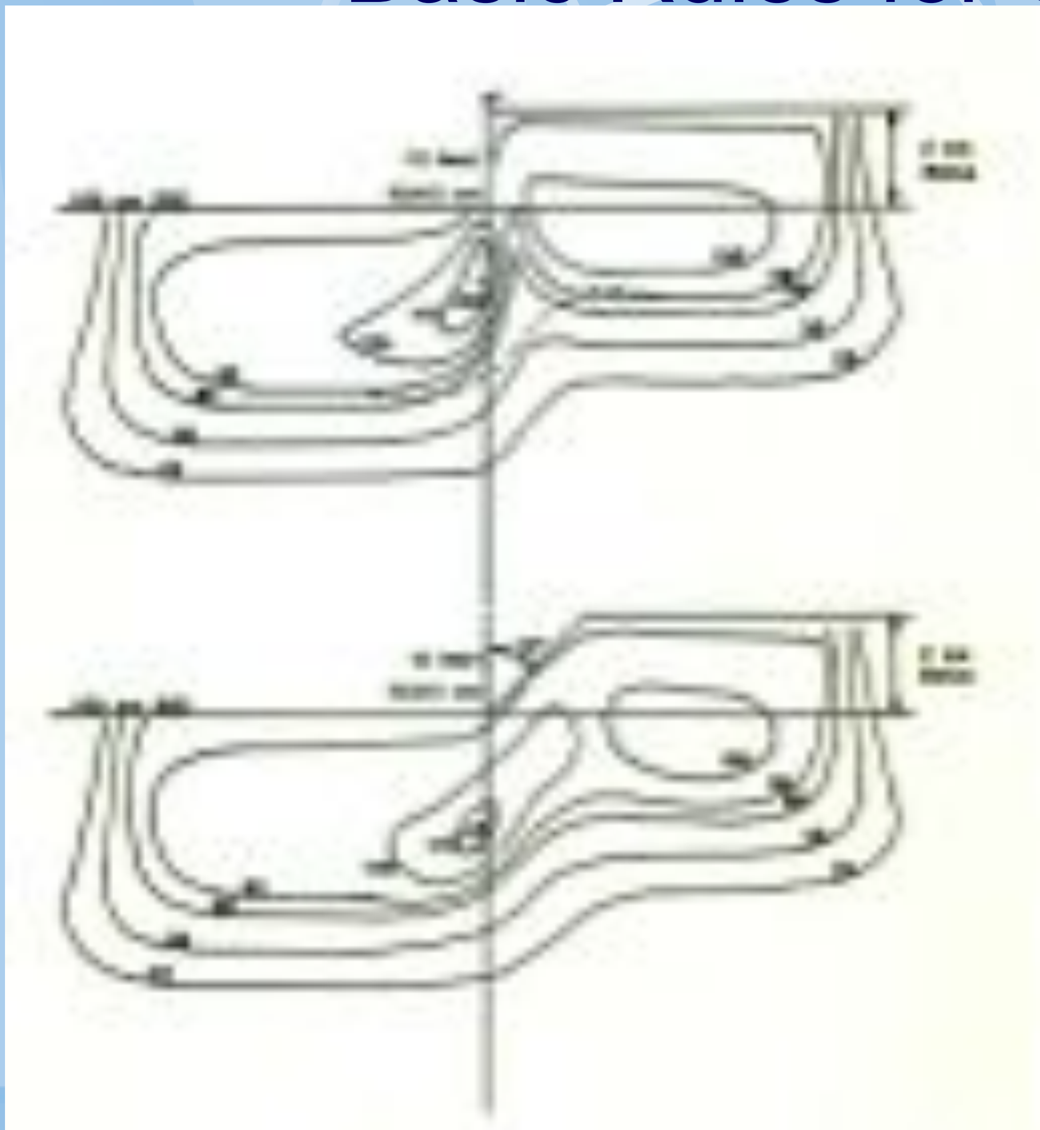
Electron Bolus:
Basic Rule for Clinical Use:
Place Bolus Close to Skin Surface.





If bolus is placed too far from surface, scattered electrons can increase penumbra and decrease maximum dose.

Electron Bolus: Basic Rules for Clinical Use

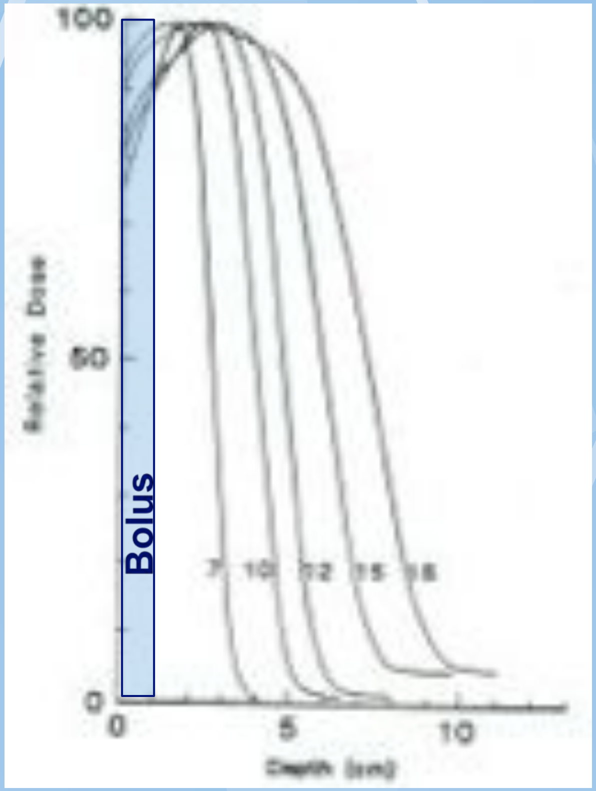


- No Sharp Edges in Field

Electron Bolus: Clinical Indications

- Increased Surface Dose
  - Low energy electron beams
  - electron arc beams
- Homogenize Dose Distribution
  - Irregular surface anatomy
  - Surgical defects
- Sparing of Distal Structures
  - Critical structures
  - Normal tissue

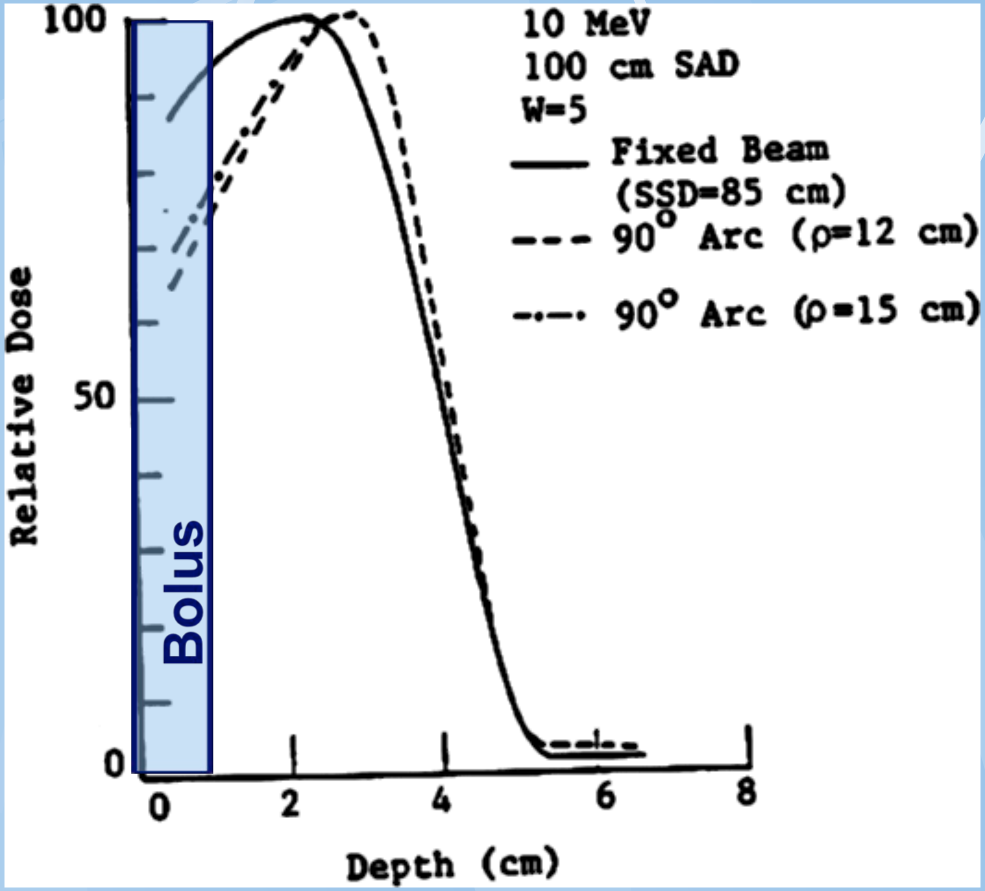
Clinical Indications for Electron Bolus: Low Energy Electron Beams



D_s decreases with decreasing energy.

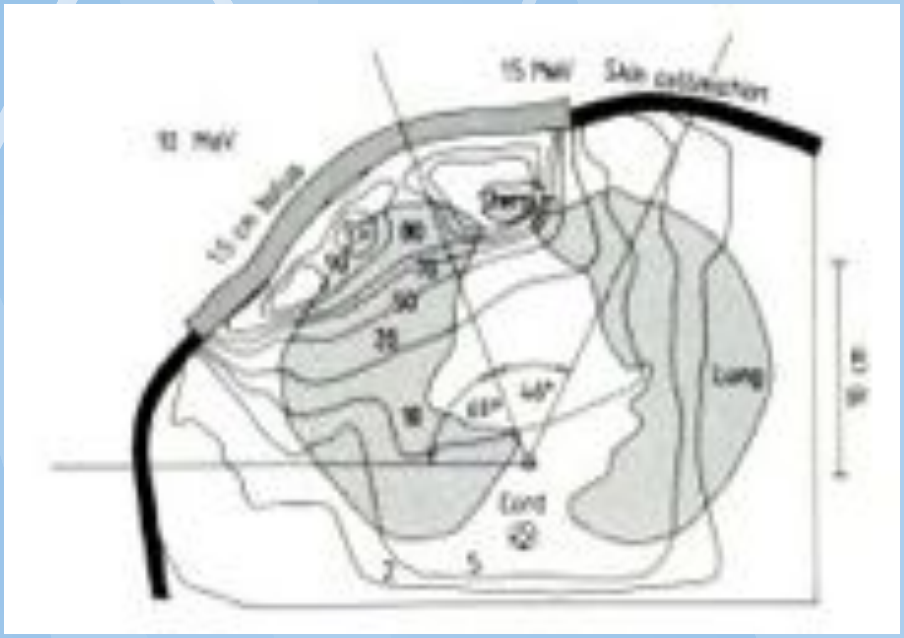
Bolus for total scalp irradiation

Clinical Indications for Electron Bolus: Electron Arc Therapy



- Electron arc therapy lowers surface dose relative to that of a fixed beam
- Surface dose can be increased by using surface bolus

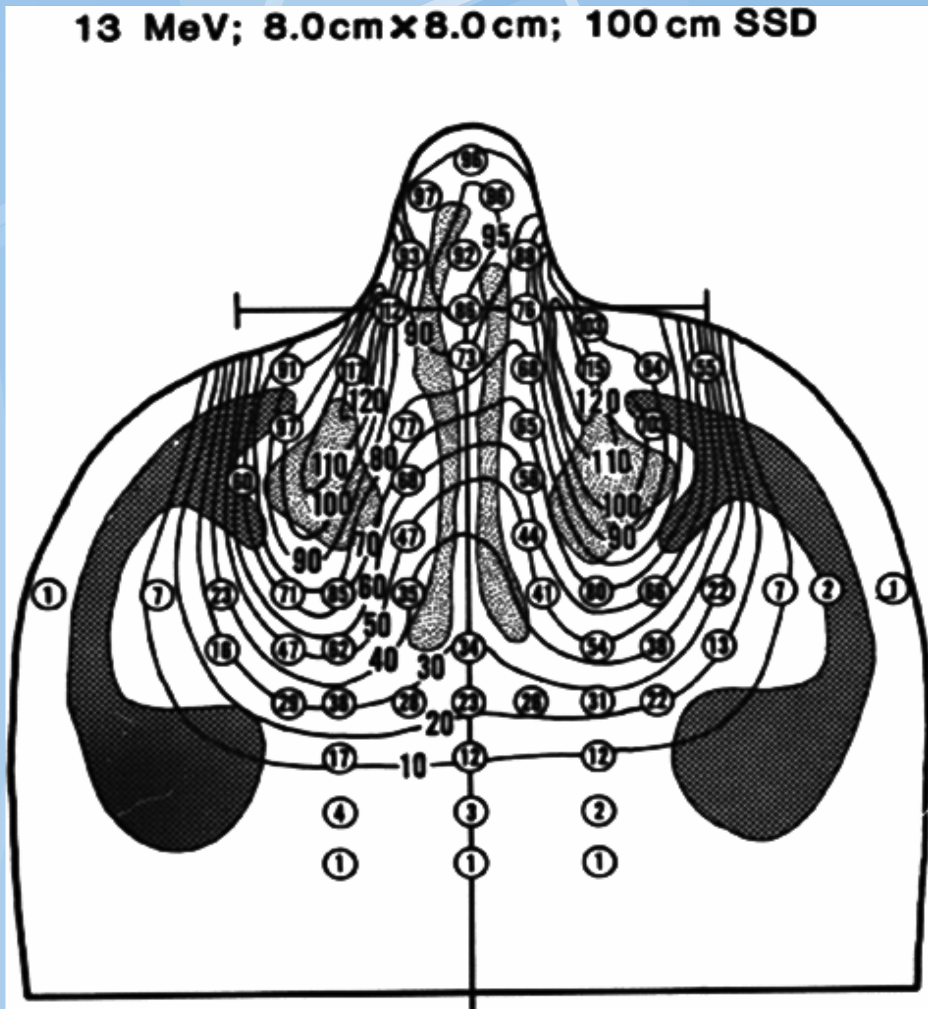
Clinical Indications for Electron Bolus: Electron Arc Therapy



Clinical Indications for Electron Bolus: Irregular Patient Surface (Ear)

Water bolus in ear canal (R) reduces dose to inner ear from 160% to 110% (Morrison et al. 1995)

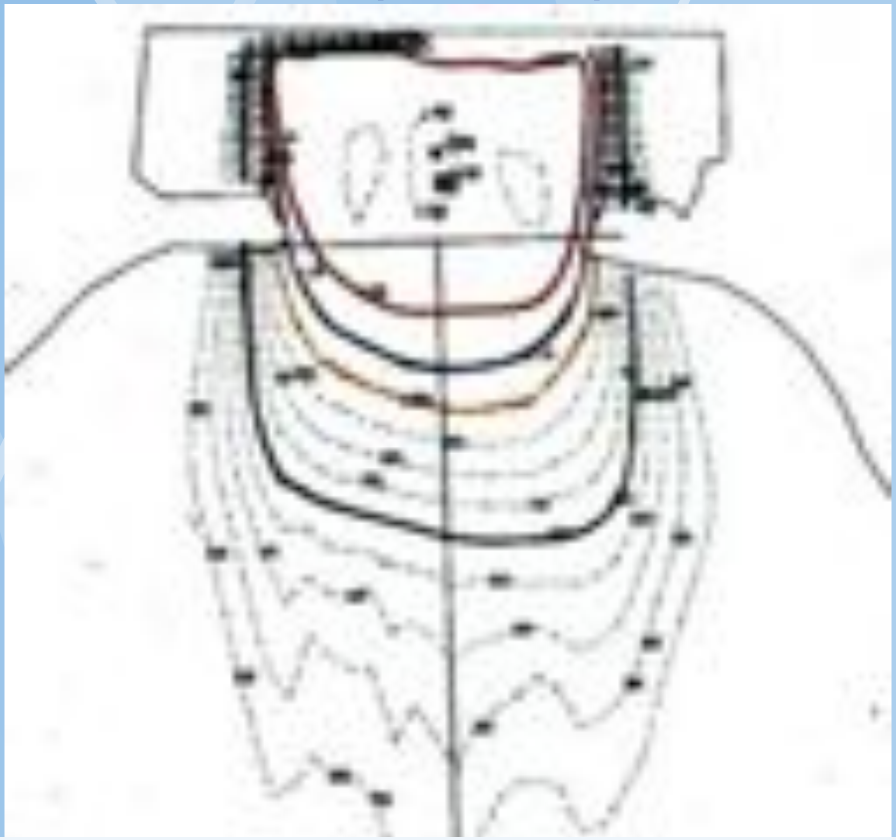
Clinical Indications for Electron Bolus: Irregular Patient Surface (Nose)



- Nose creates hot spots lateral to nose and a cold spot under nose.
- Nasal passages creates a cold spot in septum, location of cancer.

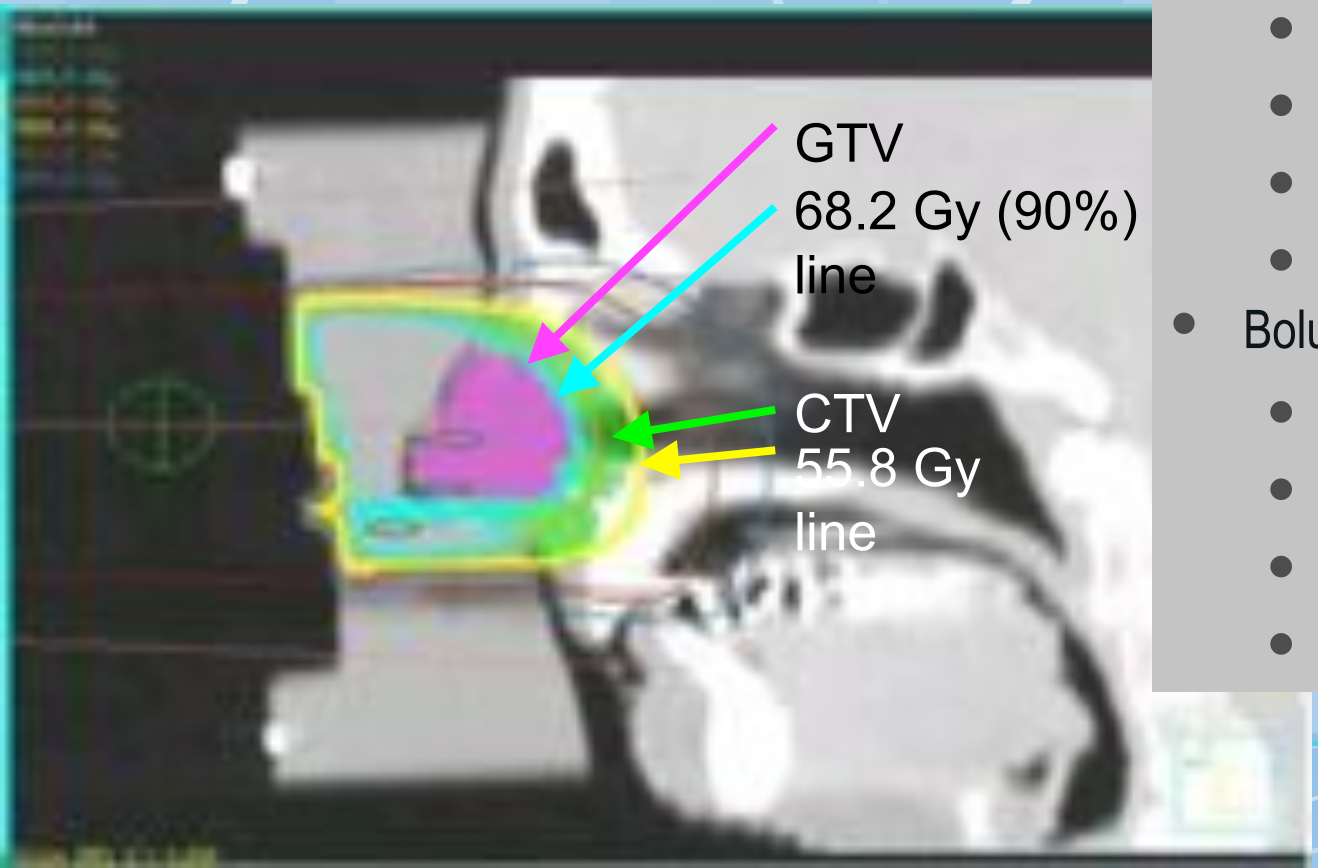
Clinical Indications for Electron Bolus: Irregular Patient Surface (Nose)

Clinical Indications for Electron Bolus: Irregular Patient Surface (Nose)



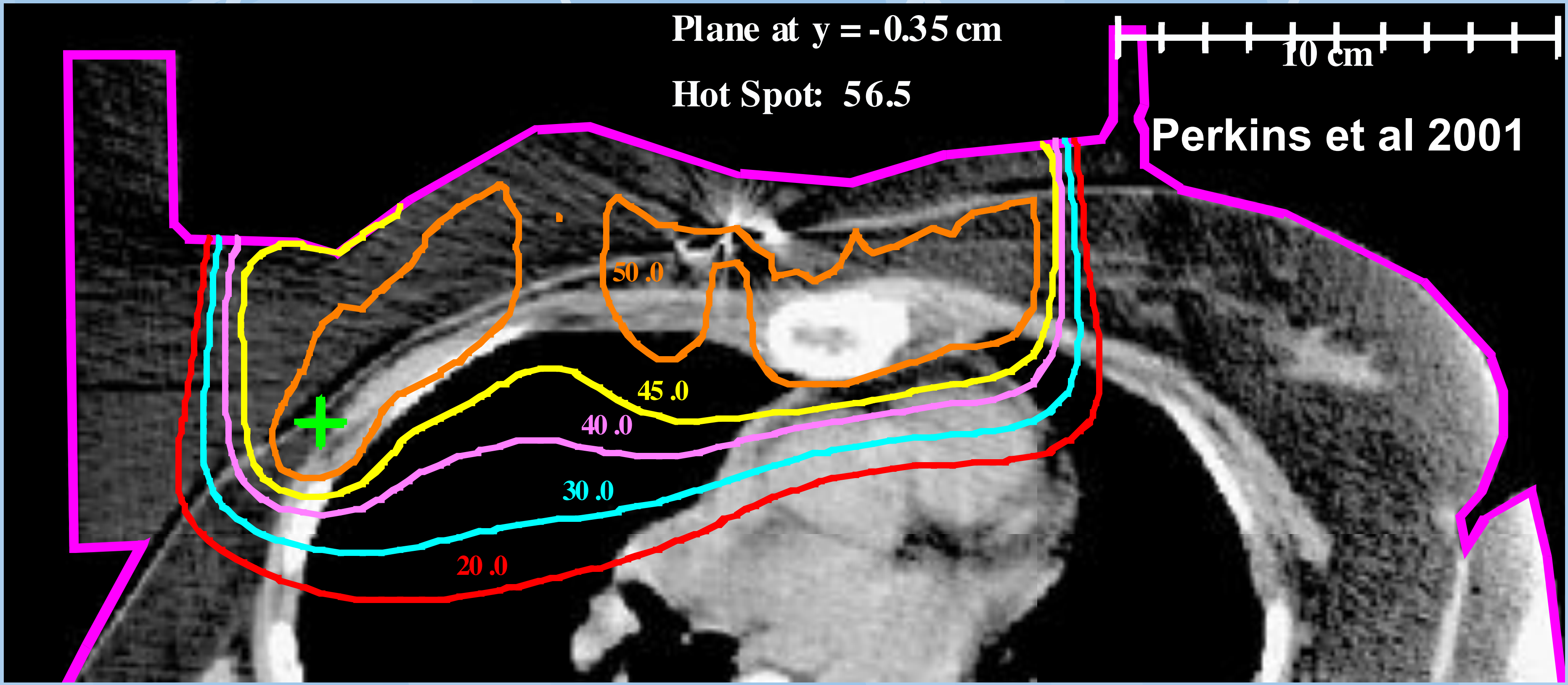
<u>Rule of Thumb</u>: Make the patient as much like a bucket of water as possible.

Clinical Indications for Bolus Electron Conformal Therapy (ECT): Variable Depth of PTV



- Variable Depth of PTV
  - Post mastectomy chest wall
  - Paraspinal muscles
  - Parotid
  - Nose
  - Ear
  - Temple
- Bolus Spares Distal Structures
  - Lung
  - Salivary glands
  - Brain
  - Spinal Cord

Clinical Indications for Bolus ECT: Variable Depth of Target Volume (Chest Wall) Recurrence at CW-IMC Junction

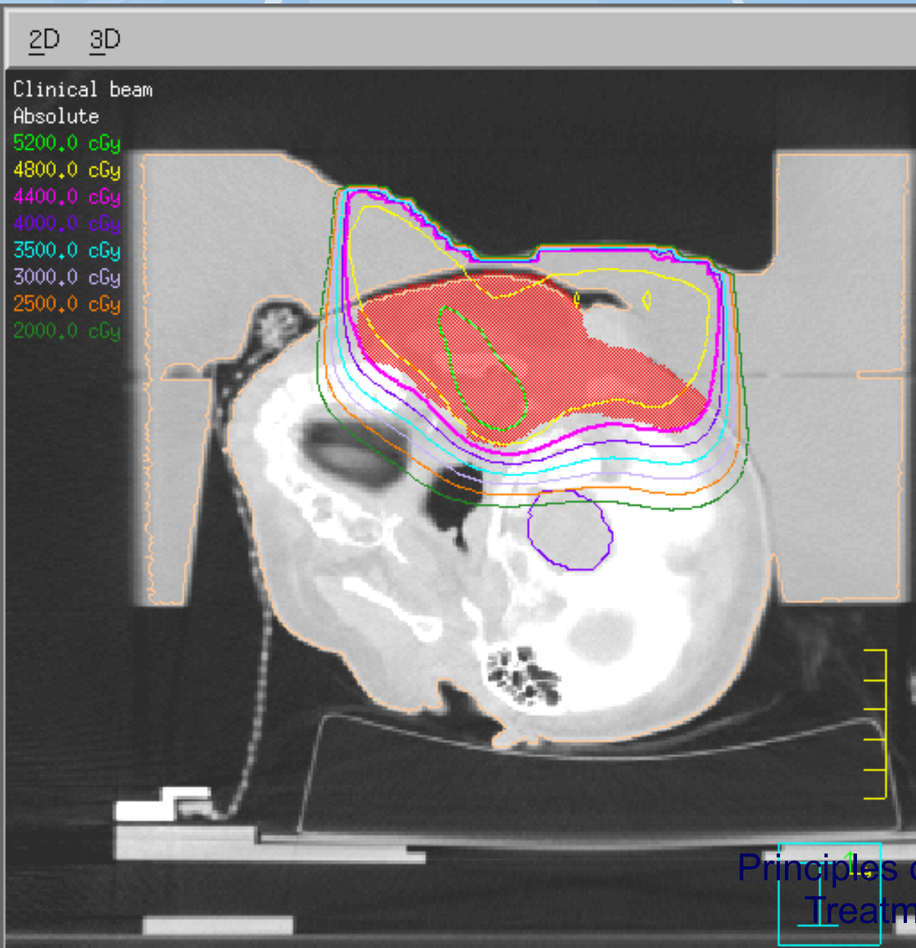


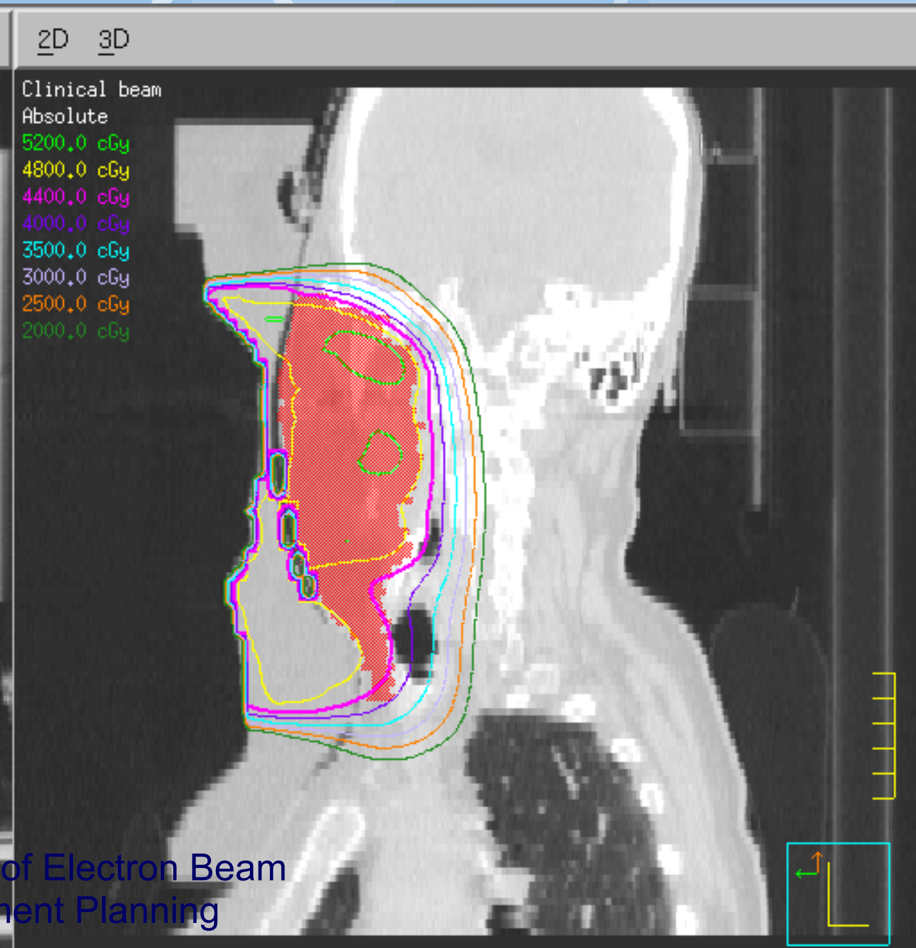
Prescription: 50 Gy @ 100% or 45 Gy @ 90%

Clinical Indications for Bolus ECT: Head & Neck (Parotid Gland)

Distal Surface

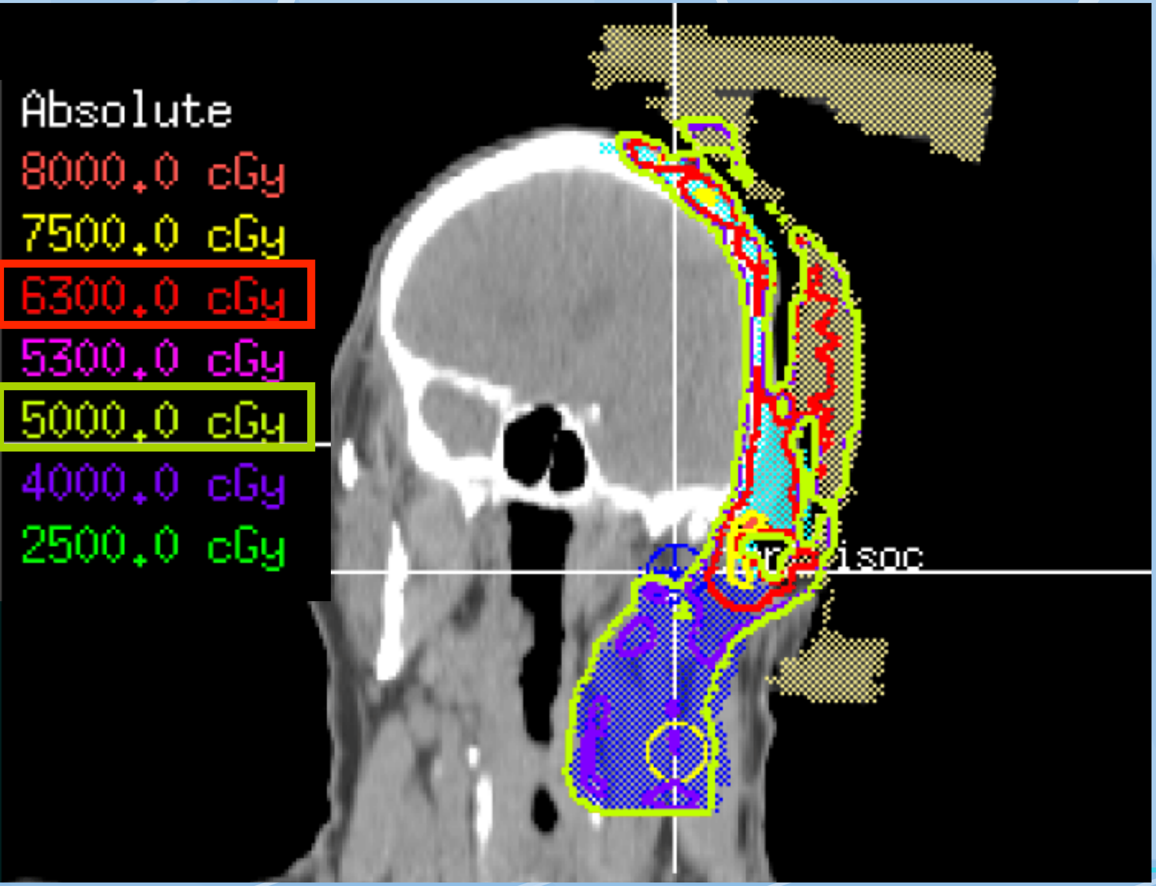
Proximal Surface

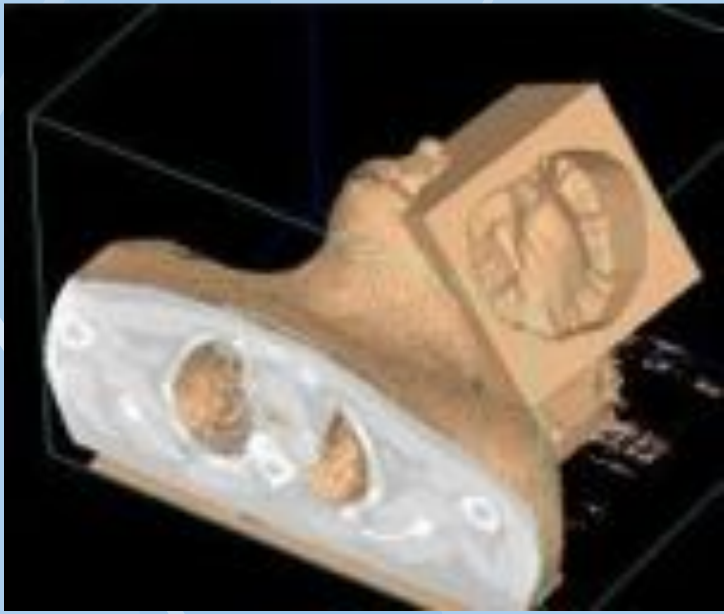




Clinical Indications for Bolus ECT: L Temple & Upper Neck (Mixed Beam Plan)

9 MeV Bolus ECT + 6 MV IMRT





Summary: Electron Beam Treatment Planning

- For optimal electron therapy, consider:
  - Properties of dose distributions
  - Effects of patient anatomy
    - Utilization of 3D treatment planning system
  - Proper utilization of collimation
  - Proper utilization of field abutment methods
  - Proper utilization of electron bolus

Electron Special Procedures

John A Antolak, Ph.D.

Electron Special Procedures

- TSEI
- Total Limb
- Intraoperative electrons
- Total scalp
- Craniospinal
- Electron arc

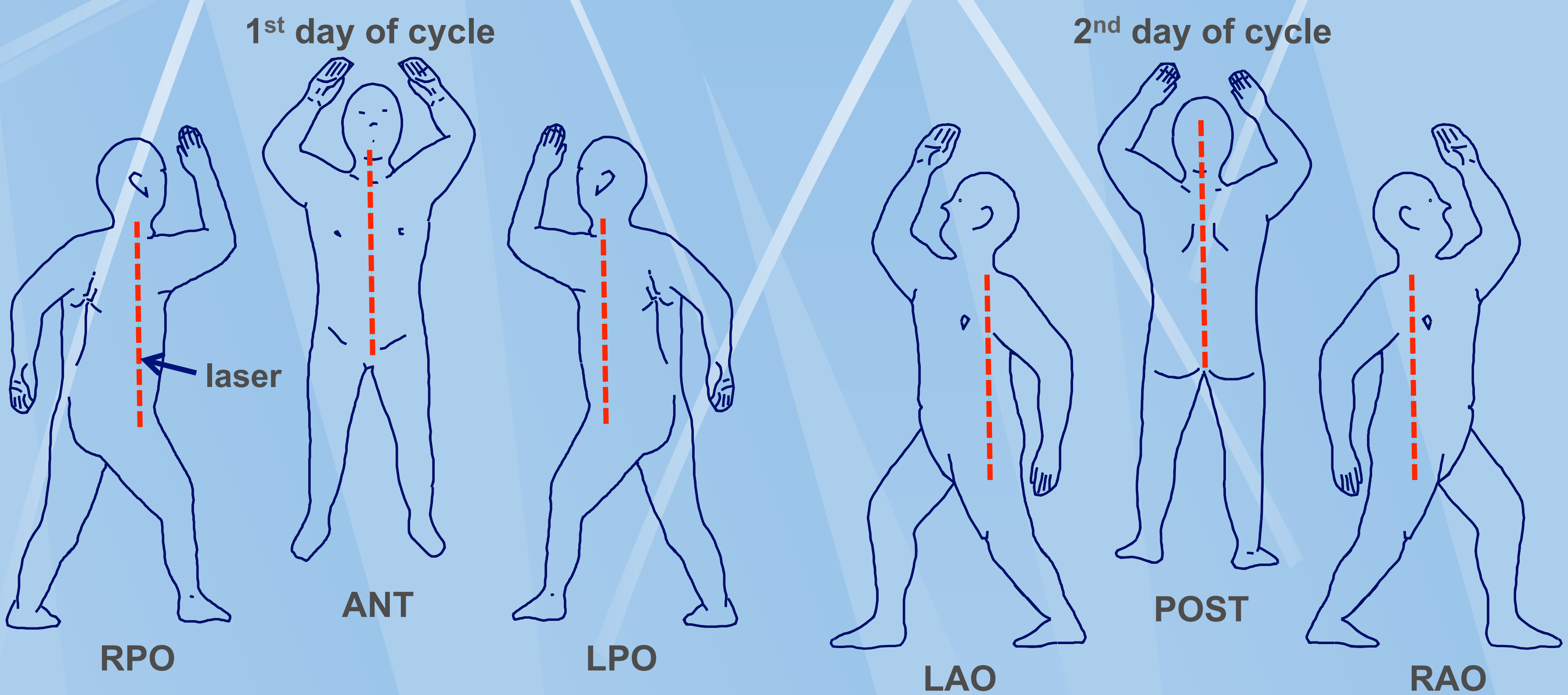
Treatment of Mycosis Fungoides (cutaneous T-cell lymphomas)

- First described and named by Alibert (Paris, 1806)
- First x-ray treatments by Sholtz (Berlin, 1902), but there were severe side effects
- First electron treatment by Trump (Boston, 1952) with Van de Graaff generator @ 2.5 MeV
- Stanford University Medical Linear Accelerator adapted in 1957

Total Skin Electron Irradiation

- AAPM Report #23, Total Skin Electron Therapy: Technique and Dosimetry (1988)
- Antolak, J. A. and K. R. Hogstrom (1998). “Multiple scattering theory for total skin electron beam design." Medical Physics **25**(6): 851-859.
- Antolak, J. A., J. H. Cundiff, et al. (1998). "Utilization of thermoluminescent dosimetry in total skin electron beam radiotherapy of mycosis fungoides." International Journal of Radiation Oncology, Biology, Physics **40**(1): 101-108.

TSEI Stanford Technique

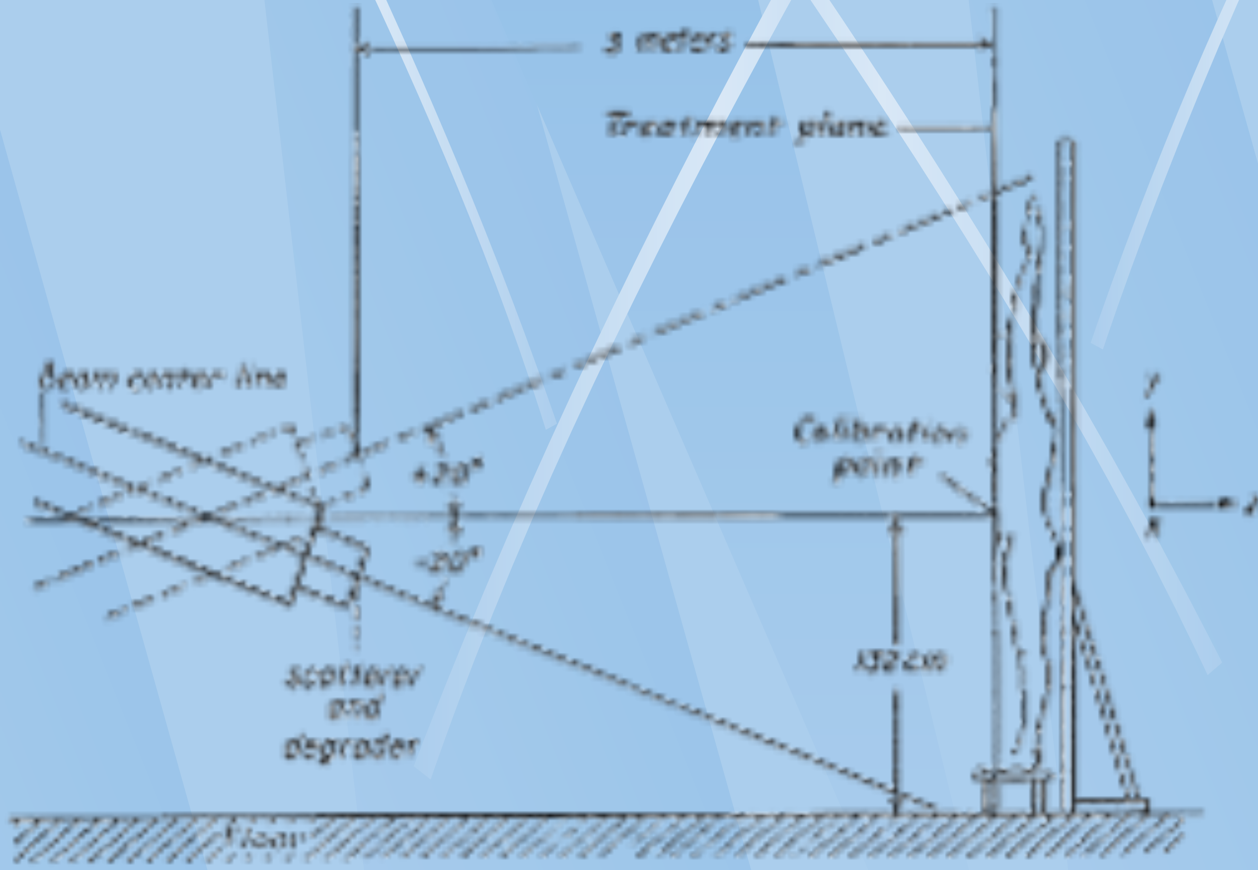


TSEI Treatment Positions

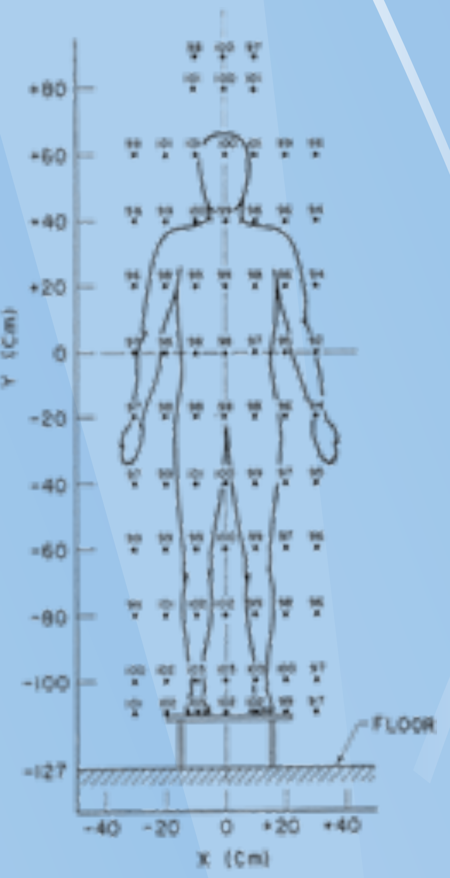
(note: disposable paper gown, thickness < 0.005 g cm^{-2}, acceptable)

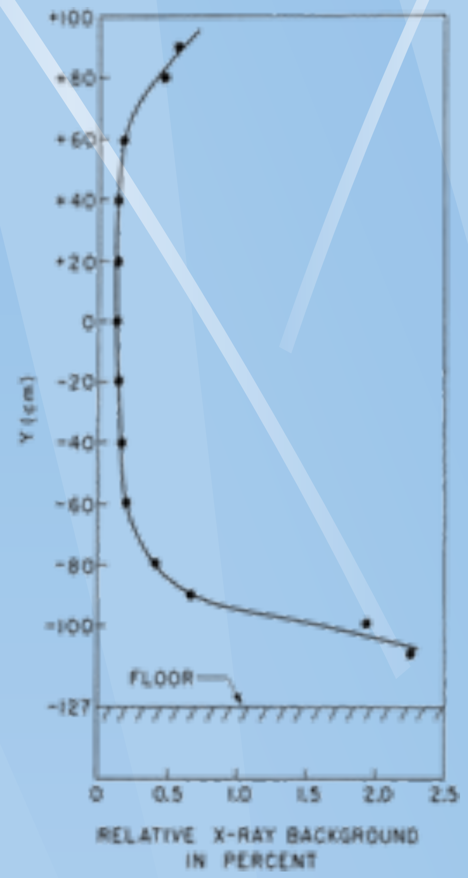
MD Anderson Technique

Stanford Dual-Beam Technique



Stanford Dual-Beam Dosimetry Karzmark CJ, et al. Radiology 74:633-644(1960)





Monitor unit calculation

50% of dose delivered with beam up/down

$$\text{Prescribed Skin Dose per Treatment Cycle} = \frac{\text{Total Prescribed Dose}}{\text{Number of Cycles}}$$

$$\text{Dose per Field per Treatment Cycle} = \frac{\text{Prescribed Skin Dose per Treatment Cycle}}{2.8} \times 0.5$$

$$\frac{\text{cGy}}{\text{MU}} = \text{current TSEI Calibration Factor}$$

$$\text{MU} = \frac{\text{Dose per Field per Treatment Cycle}}{\text{cGy}/\text{MU}}$$

measured quantity:
ratio of average skin dose for all 6 positions (12 fields, equal weights) to the given dose to the calibration point for one patient position (2 fields, up/down)

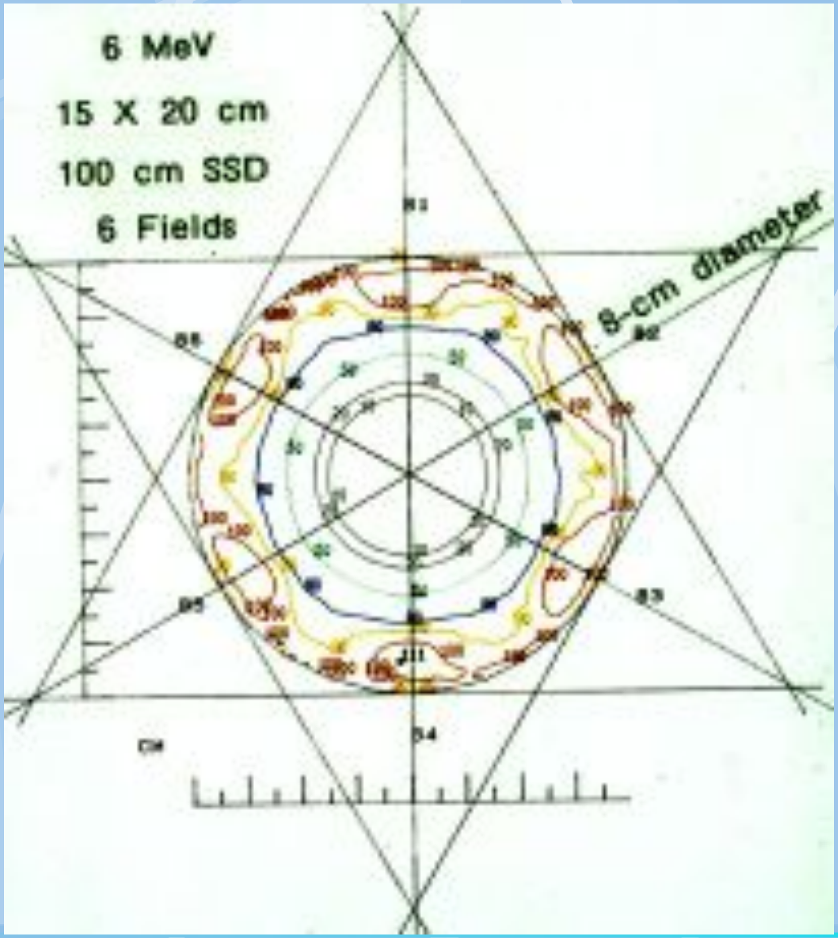
TSEI Desirable Beam Characteristics

- $E_{p,0} \approx 4-5$ MeV (at patient plane)
- 90% width ≈ 60−65 cm
  - Narrower beams make uniform coverage difficult
  - Wider beams give slightly better uniformity, but at the expense of lower dose rate and higher bremsstrahlung dose
- Angular spread > 0.3 rad
  - Less shadowing and more uniform coverage
  - Easily achieved with a scatter plate

Total Limb Electron Irradiation Diagnoses

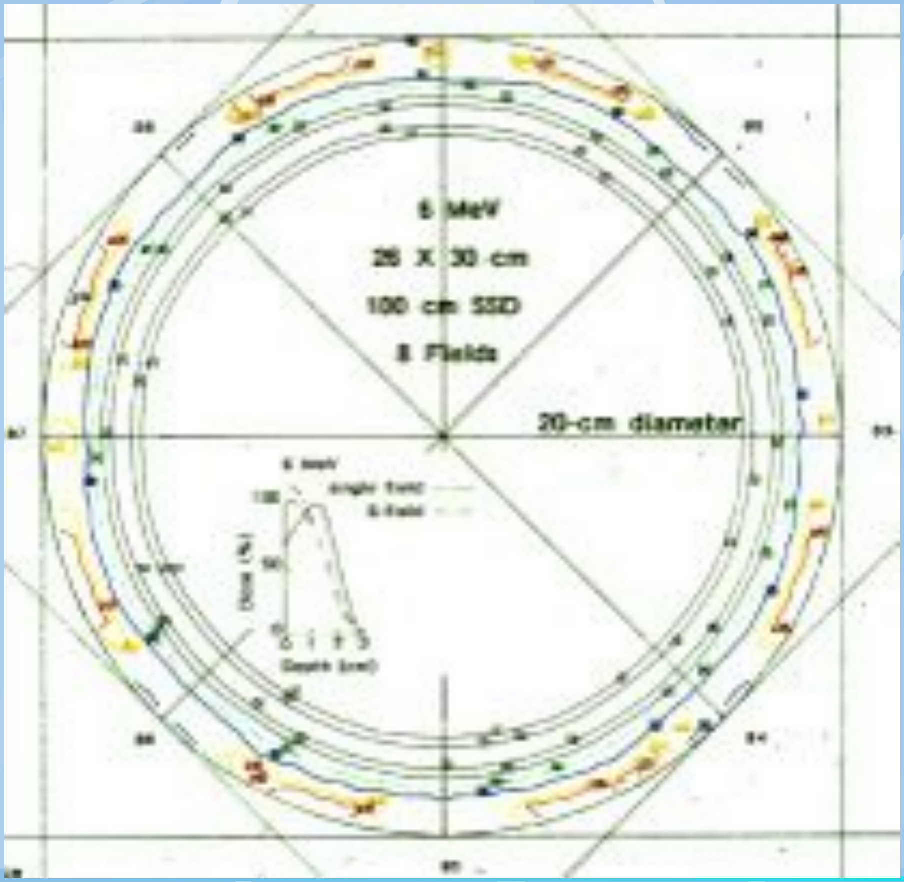
- Diffuse Large Cell Lymphoma
  - Right lower leg
- Kaposi’s sarcoma
  - Right lower leg
- Recurrent malignant melanoma
  - Right arm
- Malignant melanoma
  - Right upper leg

6-Field Extremity Technique

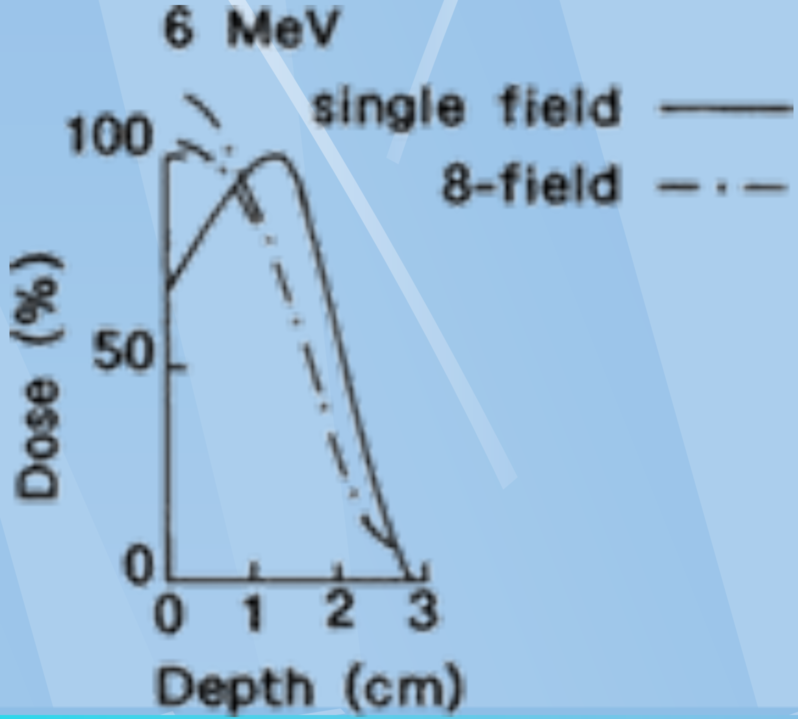


- 6 large fields with "flash"
- Wooden, K. K., K. R. Hogstrom, et al. (1996). "Whole-limb irradiation of the lower calf using a six-field electron technique." Medical Dosimetry **21**(4): 211-218.

8-Field Extremity Technique



- 8 large fields with "flash"

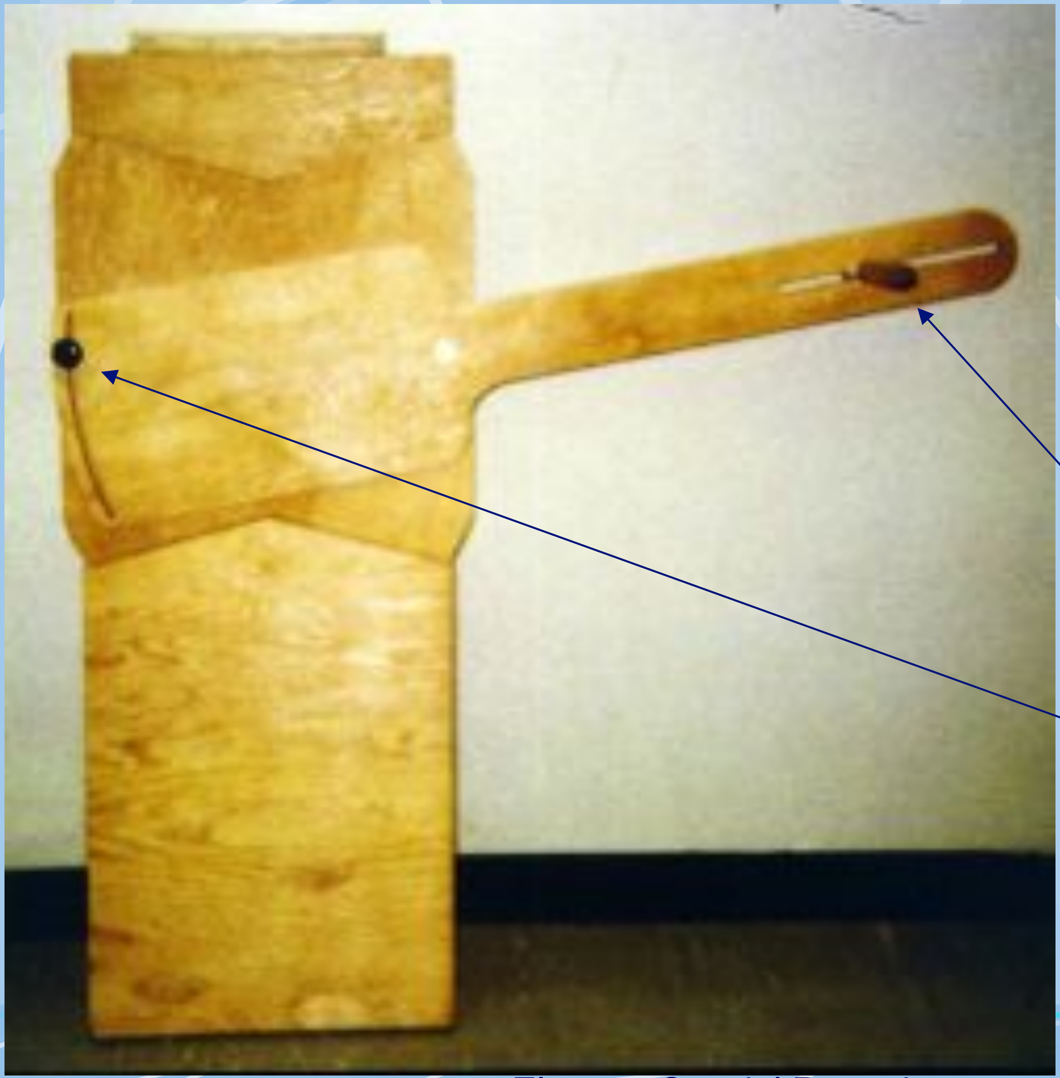


Example Treatment Setup Positions R Arm/ Melanoma

Supine: Ventral field

Prone: Dorsal field

Total Arm Couch Top



Adjust to length of arm: Note position of thumb)

Rotate for arm to be parallel to isocentric axis

Intraoperative Electron Radiotherapy Advantages and Disadvantages (Owens and Graves, 1991)

Advantages

- Spares skin, subcutaneous tissues, and abdominal wall.
- Allows confinement of dose to disease sparing nearby tissues.
- Does not preclude postop radiotherapy.
- Does not interfere with chemotherapy

Disadvantages

- Requires surgical procedures: anesthesia, postop pain, potential surgical complications.
- Only single irradiation dose possible.
- Puts some normal tissue at risk of injury.
- Is expensive in personnel, scheduling, and equipment.

Intraoperative Radiotherapy Modalities

- Treatment modalities used for IORT include
  - Electron beams
  - kVp x-ray beams
  - Brachytherapy using HDR or implants
- Electron dose distal to tumor can be eliminated using lead sheets to stop electrons, protecting distal and adjacent structures.
- Thus, electron beams can offer the advantage of very small exit dose (x-ray contamination)

Room Requirements for IORT

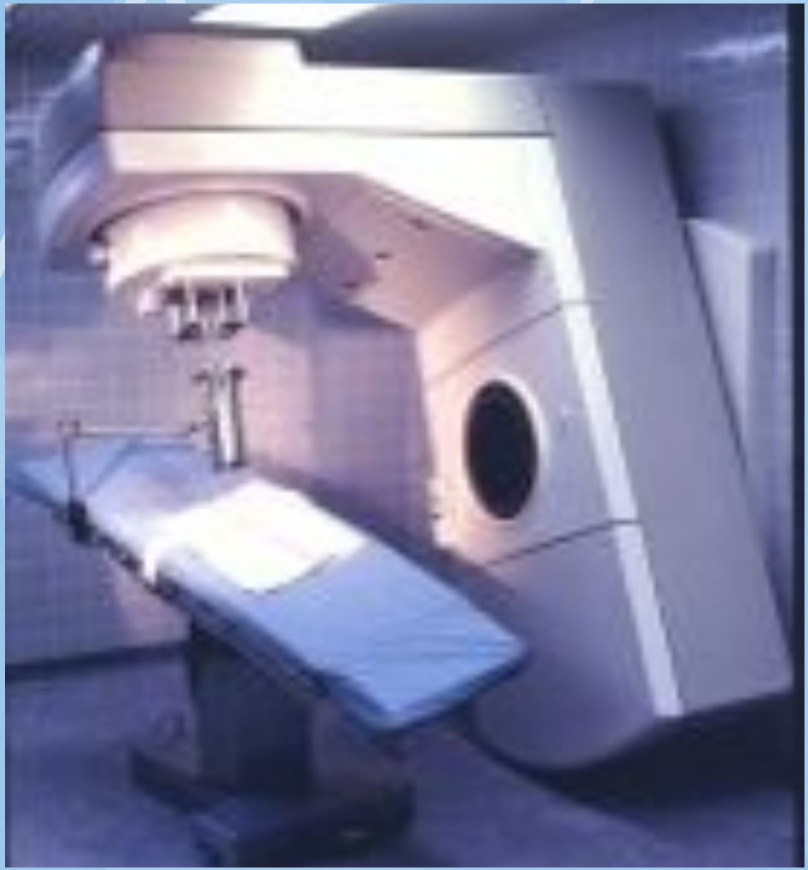
- Operating room for initial surgical procedure
- Sterile irradiation facility that can accommodate needs of IORT irradiation
- Post irradiation operating room for closing of wound

Options for IORT Facilities

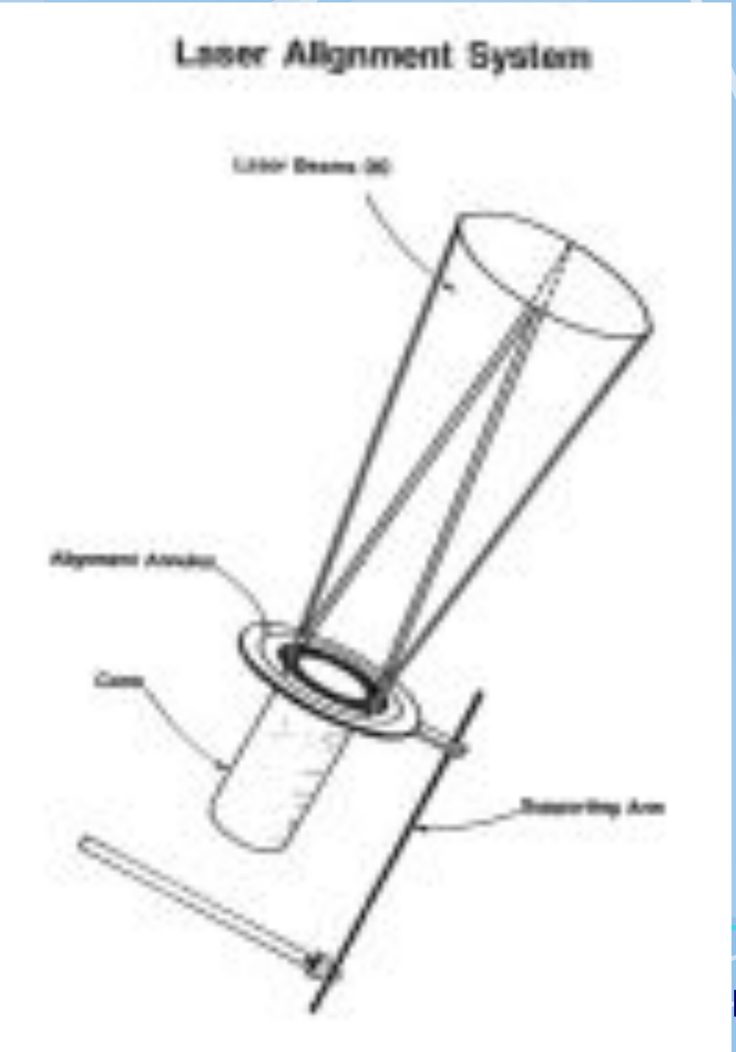
- Dedicated IORT/OR Suite (M D Anderson, Mayo)
  - Patient operated in room housing linac
  - Patient moved from surgical area to linac for IORT
- Mobile IORT Linac in OR (Univ Louisville)
  - Patient operated in surgical OR
  - Mobile linac in surgical area rolled into OR
- OR adjacent to RT Treatment Room (Mass General, Med College of Ohio)
  - Patient operated in surgical OR
  - Patient transported to sterile linac in adjacent room
- Totally separate OR and IORT facilities
  - Patient operated in surgical OR
  - Patient transported from OR to RT clinic to sterile treatment room

M D Anderson Cancer Center IORT Suite

- 6-15 MeV

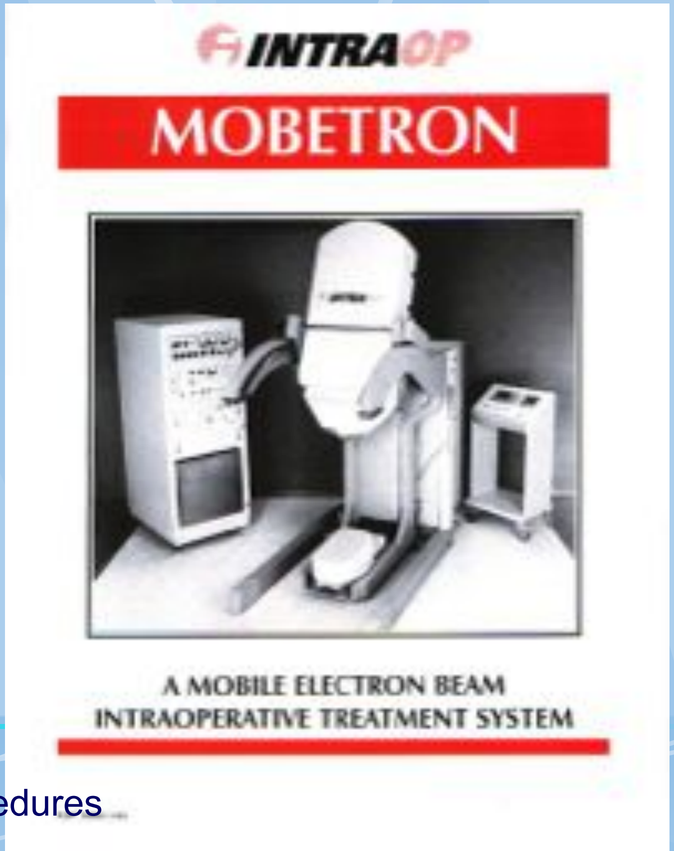


Example of Soft Docking System: Laser Guided (Hogstrom et al. 1990)



Beam
IORT System-Mobetron

4-12 MeV



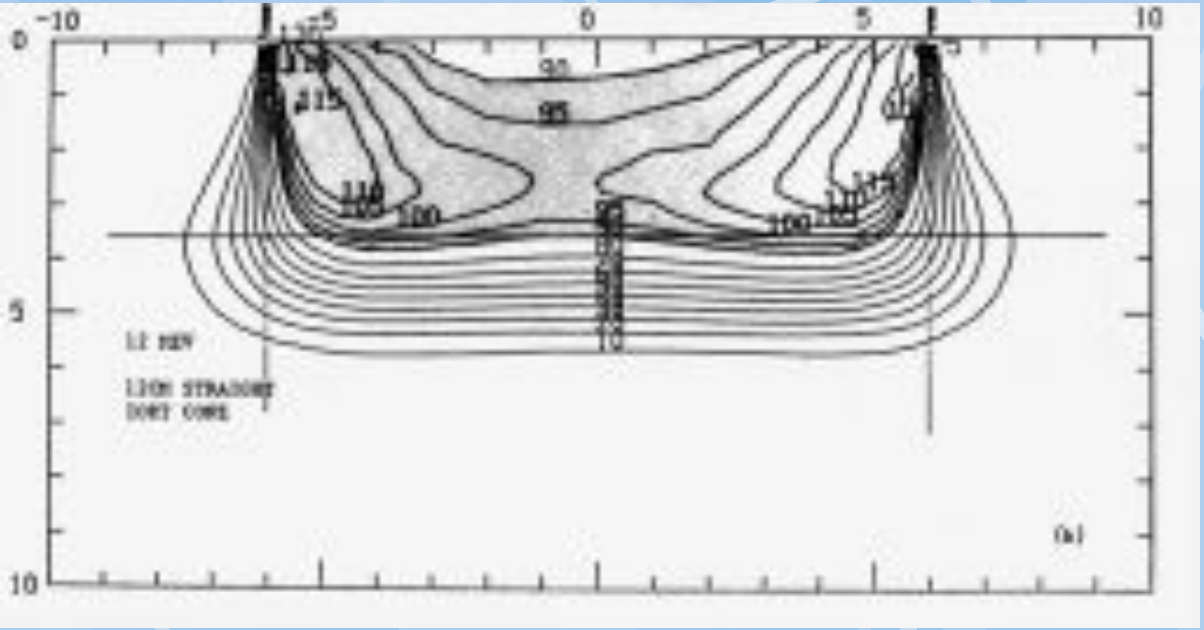
Properties of IORT Electron Cones

- Shapes
  - Circular
  - Rectangular
  - Squircle (half square-half circle)
- Ends
  - 0º-30º bevel
- Material
  - Able to be sterilized
  - Able to shield surrounding material from scattered electrons
  - Thin as possible to allow minimal tumor-normal tissue clearance

Properties of IORT Electron Cones

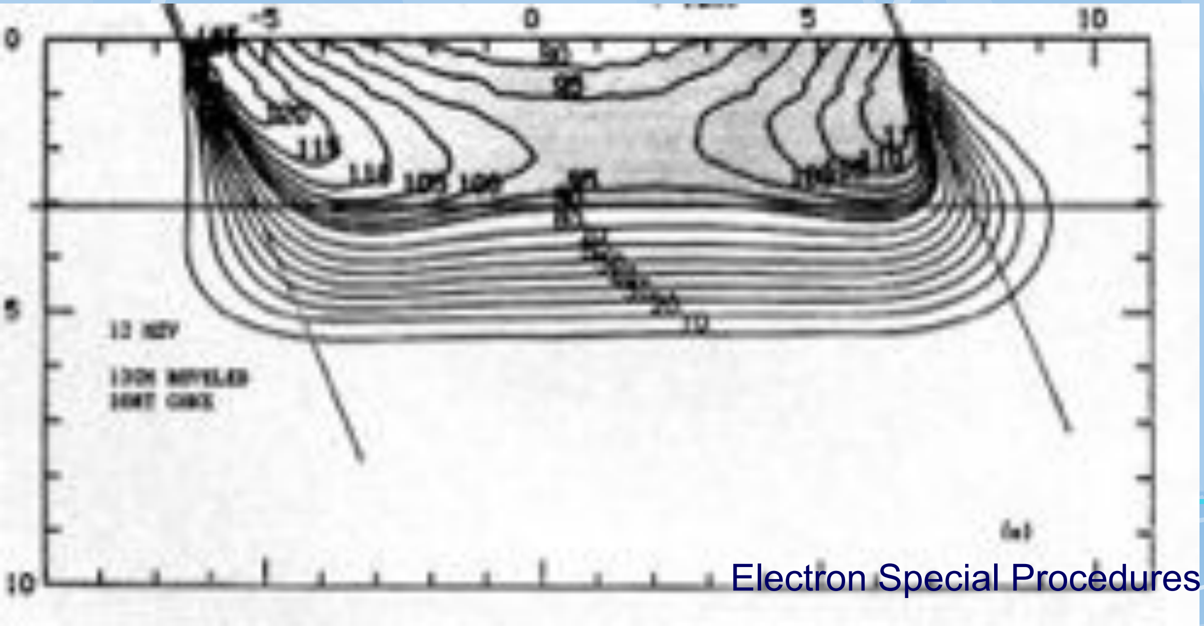
- Typical materials
  - Lucite, stainless steel, chrome-plated brass
- Able to view irradiated volume
  - Direct visual viewing
  - Mirror reflector
  - Camera
- Cones have differing alignment templates to allow manual docking

IORT Electron Dose Distributions



12 MeV

12-cm ∅, 0º
cone



12 MeV

12-cm ∅, 30º
beveled cone

Treatment Delivery (continued)

- Visual verification of treatment field
  - Target volume in field of view
  - Critical structures avoided
  - Treatment field free of blood
- All personnel evacuated from room
- Deliver radiation as rapidly as possible
  - High dose rate option useful (e.g. 600-1000 MU/min)
- Patient monitoring
  - Visual monitoring of patient
  - Blood pressure and pulse
  - Pulse and breathing using esophageal stethoscope

Treatment Results Stomach (Abe et al. 1991)

- 228 Patients
  - No distant metastasis
  - Surgical resection vs. IORT (28-35 Gy)
- Results
  - 5-y survival rates based on serosal invasion (+/-)
    - Surgery: 89% for s(−) vs 51% for s(+)
    - IORT: 94% for s(−) vs 60% for s(+)
  - 5-y survival rates based on lymph node metastasis
    - Surgery: 97% for n0; 67% for n1; 32% for n2,n3
    - IORT: 100% for n0; 64% for n1; 51% for n2,n3
- Conclusion
  - IORT is able to improve survival of patients with serosal invasion or with n2 or n3 lymph node metastases

Treatment Results Pancreas (Abe et al. 1991)

- 103 Patients
  - Inoperable tumor due to vessel involvement or retroperitoneal invasion
  - No liver involvement or distant metastases
- Arms
  - Control (41 patients), Operation alone
  - IORT (25-40 Gy)
  - Operation +EBRT (55-60Gy in 1.6-1.8Gy fractions)
  - IORT(10-25Gy)+EBRT(35-50Gy in 1.6-1.8Gy fractions)
- Results (median survival time)
  - Operation alone: 5.5 months
  - IORT alone: 5.5 months
  - Operation + EBRT: 9 months
  - IORT +EBRT: 12 months

Total Scalp Irradiation Electron + X-ray Technique

- Clinical Indications
- Treatment Objectives
- Electron + X-ray Technique
  - Treatment Planning
  - Dose Distribution
  - Treatment Setup
  - Treatment Verification

Total Scalp Irradiation Clinical Indications

- Cutaneous tumors with widespread involvement of scalp and forehead:
  - Lymphoma
  - Melanoma
  - Angiosarcoma

Total Scalp Irradiation Treatment Objectives

- To provide a uniform dose distribution ($\pm10\%$) to the entire scalp and target volume.
- To keep brain dose as low as possible.
- To provide a simple and reproducible treatment.

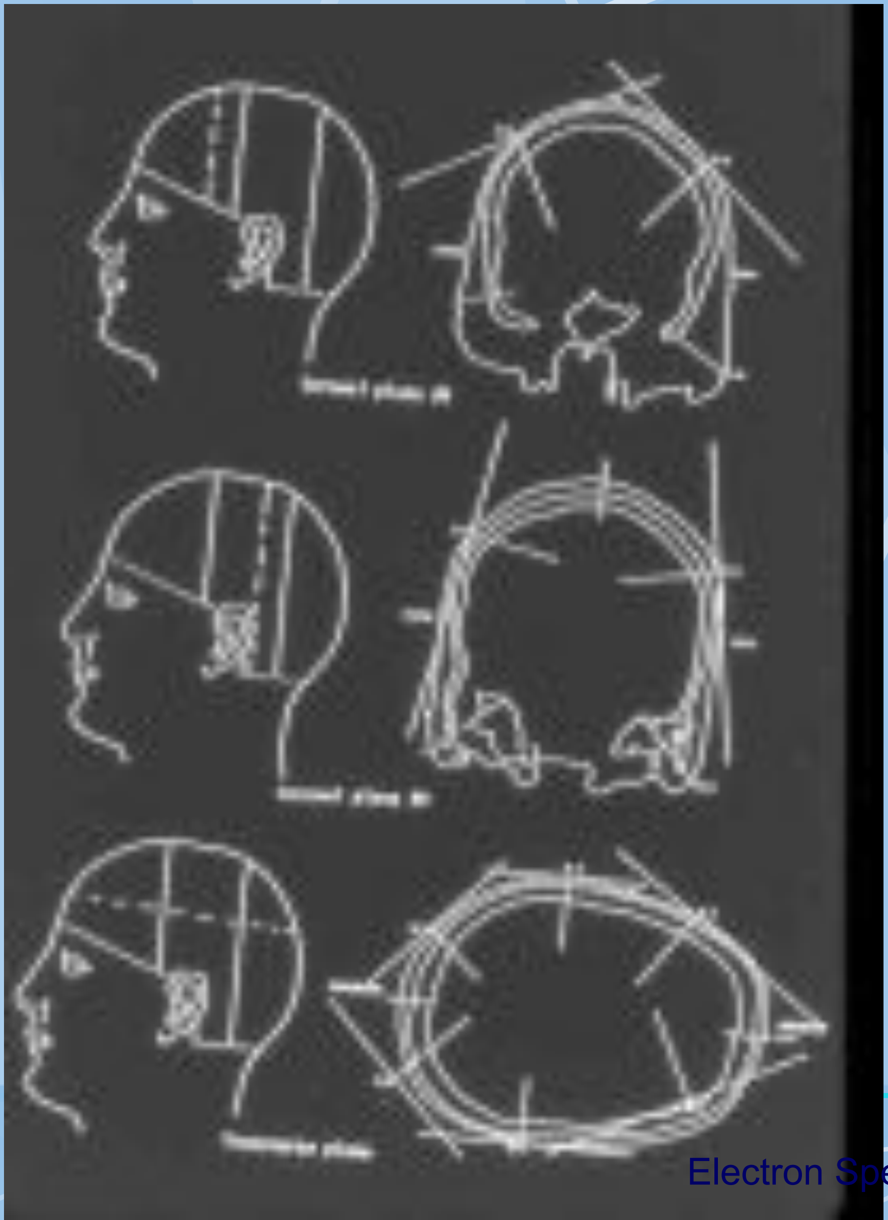
Total Scalp Irradiation Treatment Planning Challenges

- Topology of the head
- Depth variation of the target volume
- Close proximity of brain to the scalp
- Impact of bone on dose distribution

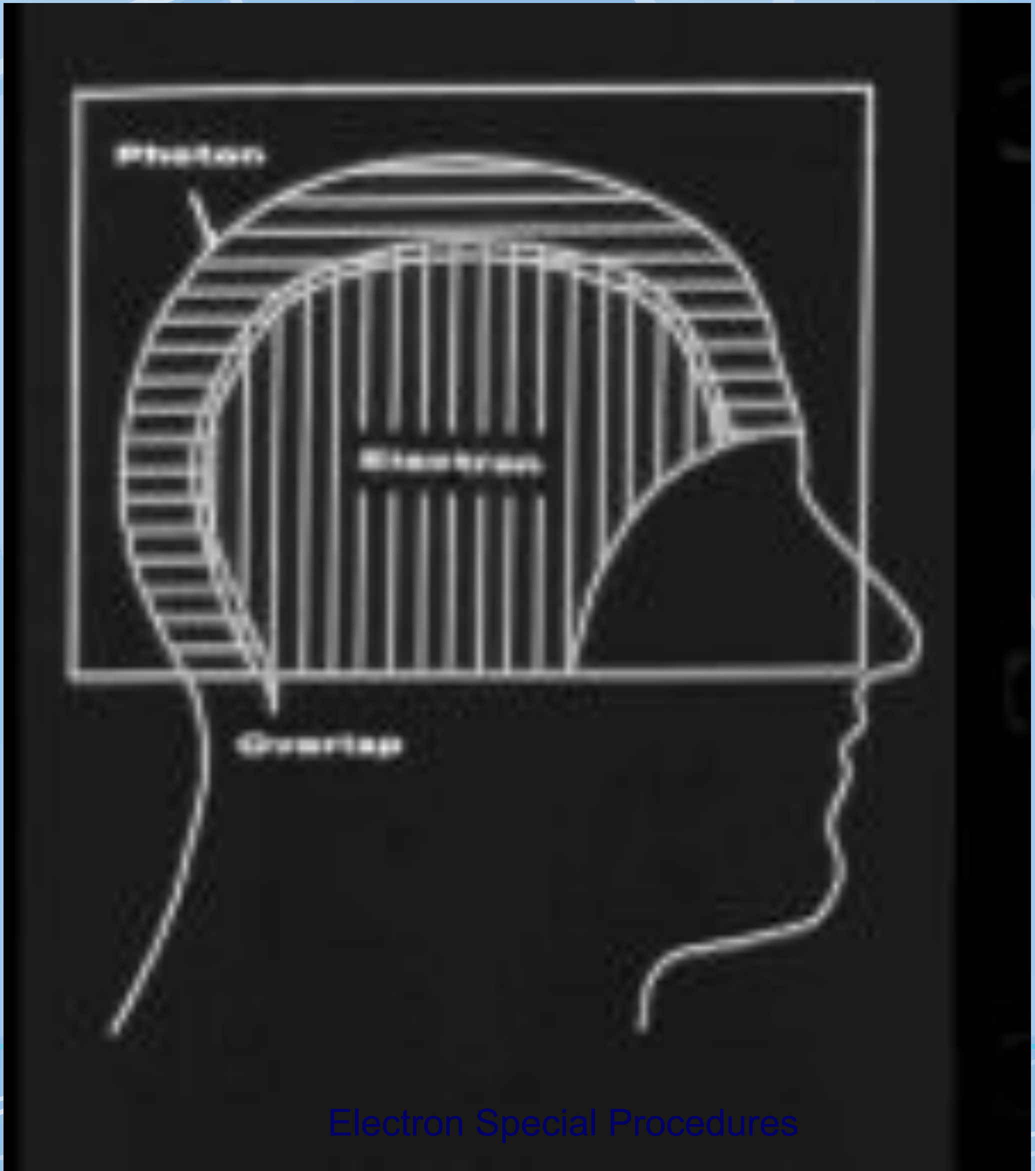
Total Scalp Irradiation Treatment Options

- 6-field electron beam technique (Able et al 1991)
- Electron + 6MV x-ray technique (Akazawa et al 1989; Tung et al 1993)
- Tomotherapy
  - Nomos (Locke et al 2002)
  - TomoTherapy HI-ART II (Orton et al 2005)

Total Scalp Irradiation
6-Field Electron Technique (Able et al.)



Total Scalp Irradiation
Electron + X-ray Technique (Tung et al.)



Total Scalp: Electron + X-ray Technique
Beam Arrangements

- Beams 2,4
  - Electron beams
  - 6-9 MeV
  - 100-cm SSD
  - Beam weight=100%
- Beams 1,3
  - 6 MV X-ray beams
  - 100-cm SSD
  - Beam weight = 60%

Total Scalp: Electron + X-ray Technique Custom Bolus (6-mm thick)

Wax Bolus Fabrication

Patient Prone with Bolus

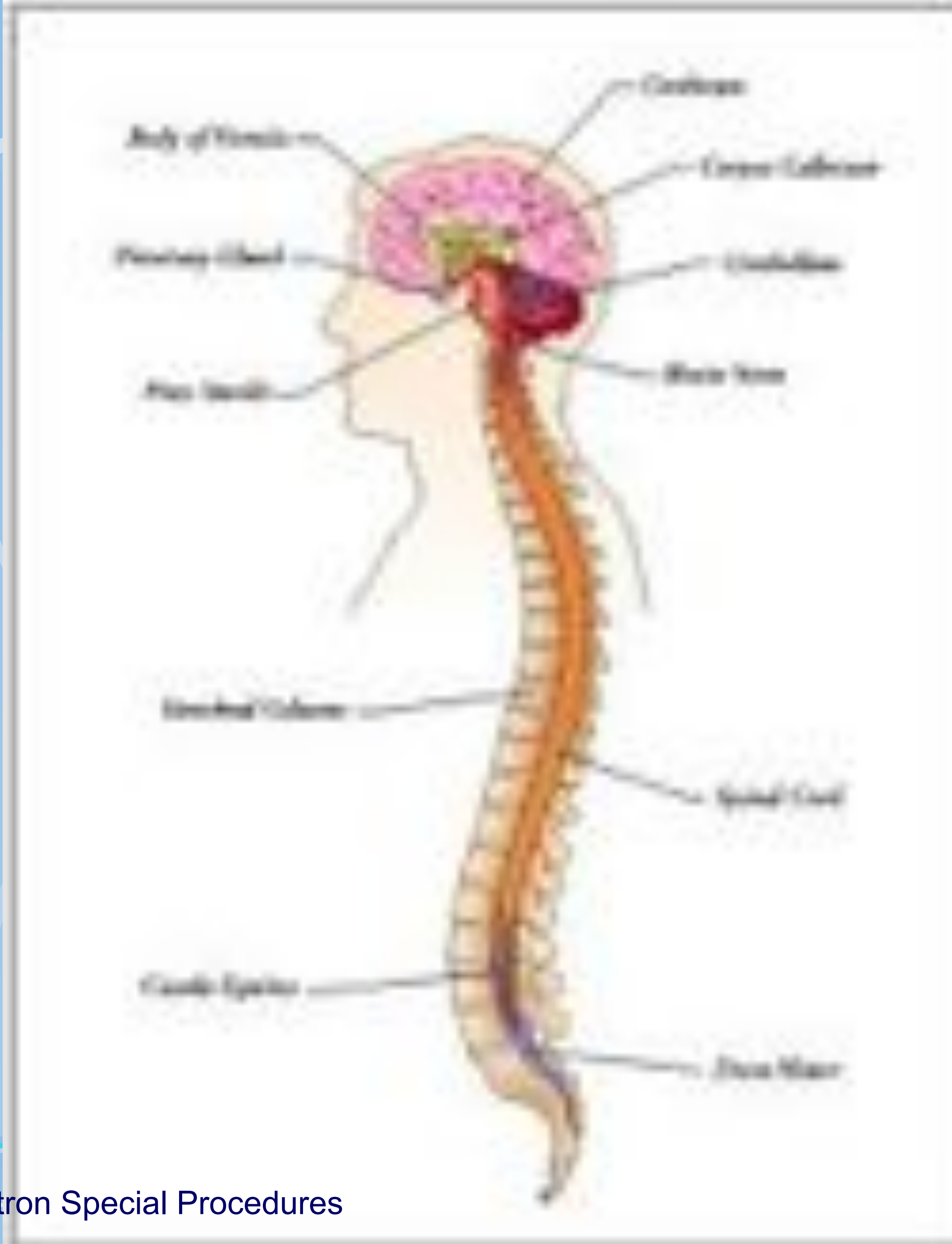
Craniospinal Irradiation Clinical Indications

- Pediatric brain tumors that have a tendency to seed along the pathways of cerebrospinal fluid:
  - Medulloblastoma
  - Malignant ependymoma
  - Germinoma
  - Infratenrotial glioblastoma

(Maor et al. 1985)

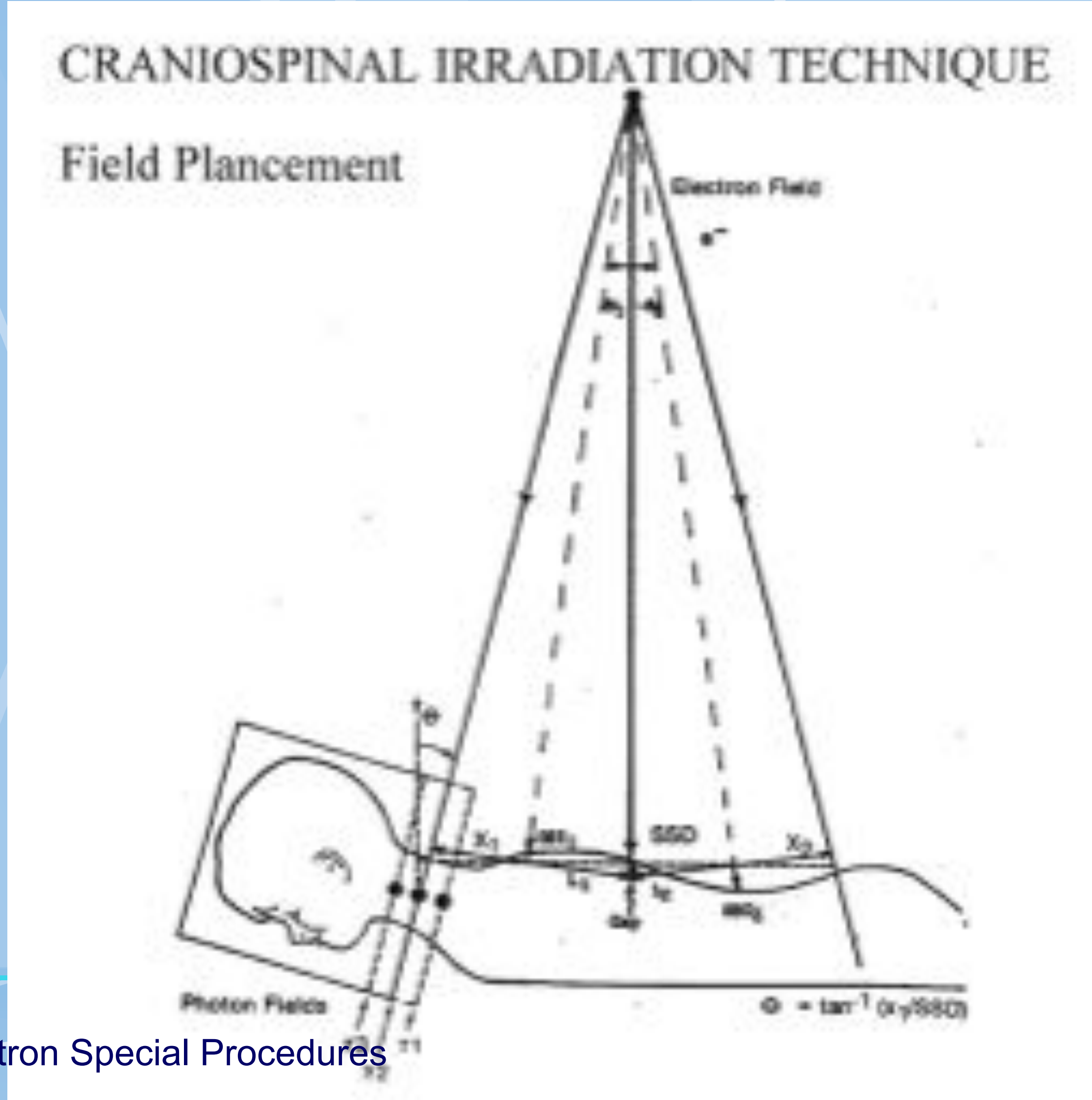
Treatment Volumes

- Whole Brain
- Base of Brain
- Spinal Theca



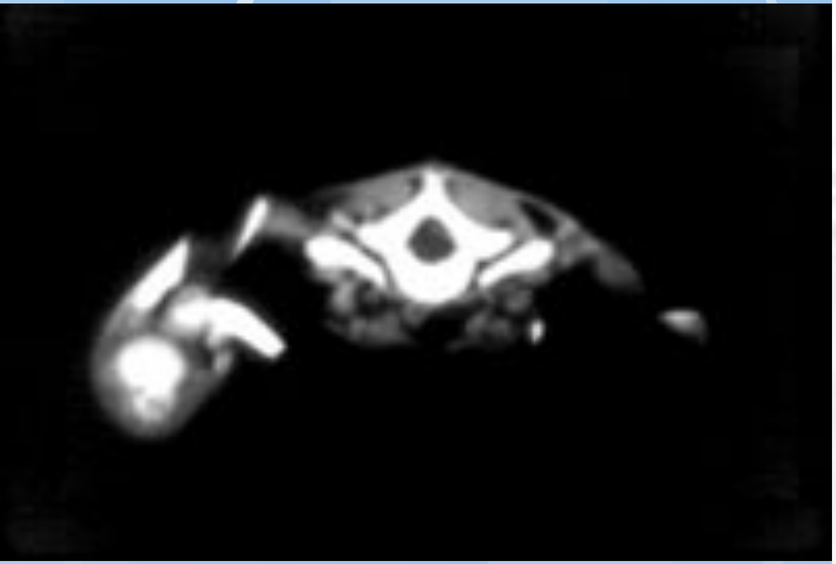
Craniospinal
Electron & Photon Beam Technique

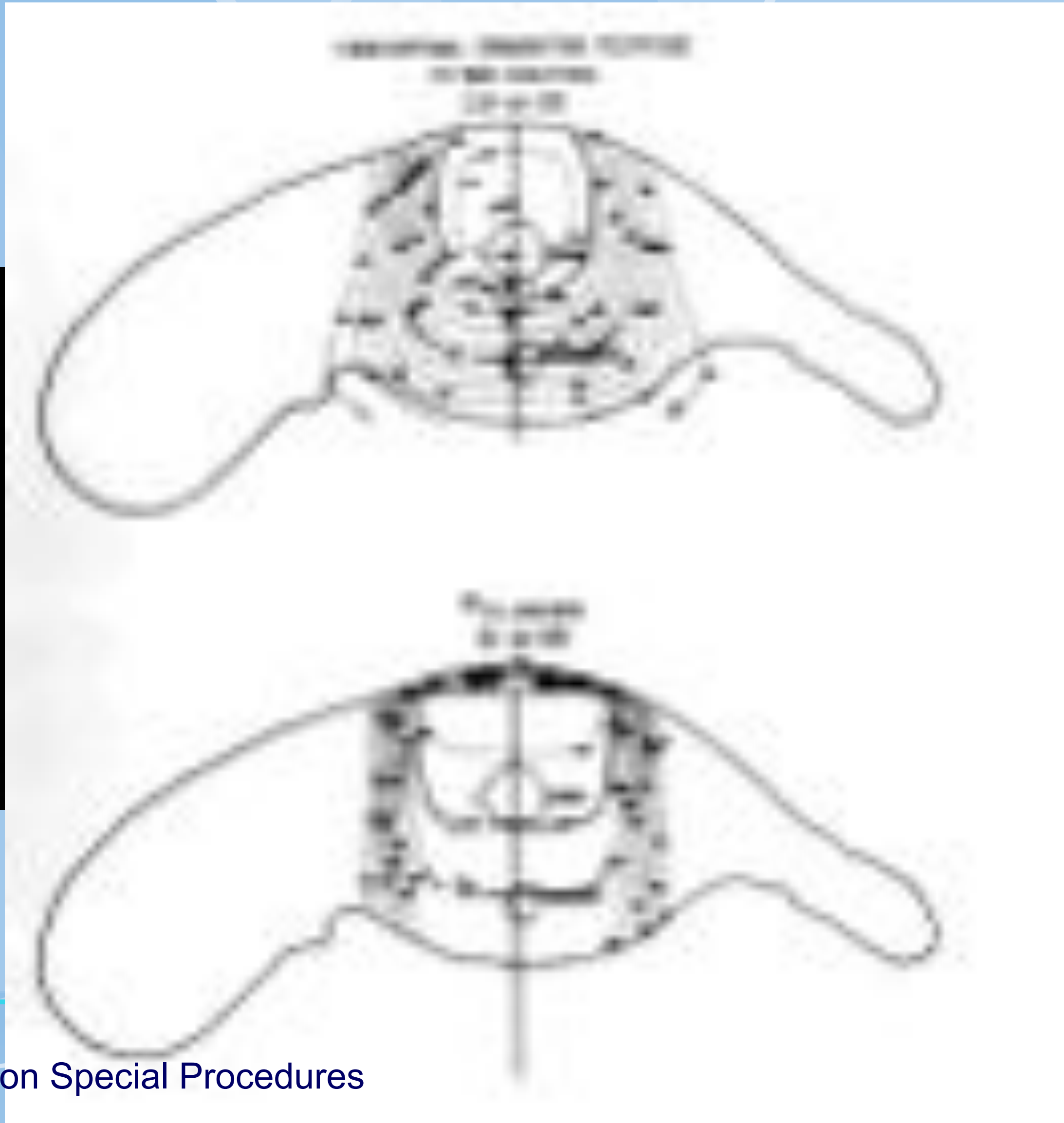
- Brain: Parallel-opposed lateral photon beams
- Spine/Electrons: True posterior electron beam consisting of 1 or 2 fields
- Spine/Photons: 6 MV x-rays from posterior fields:
  - 1 field (180°)
  - 2 fields (180°±30°)
  - 3 fields (180°, 180°±30°).



Comparison of Spinal-field Dose Distributions Photon & Electron Beams

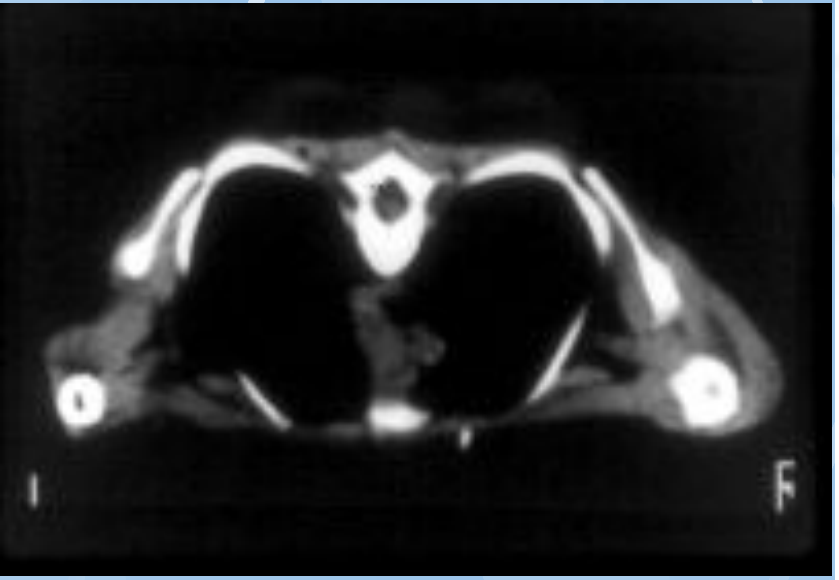
- CT Lower Neck

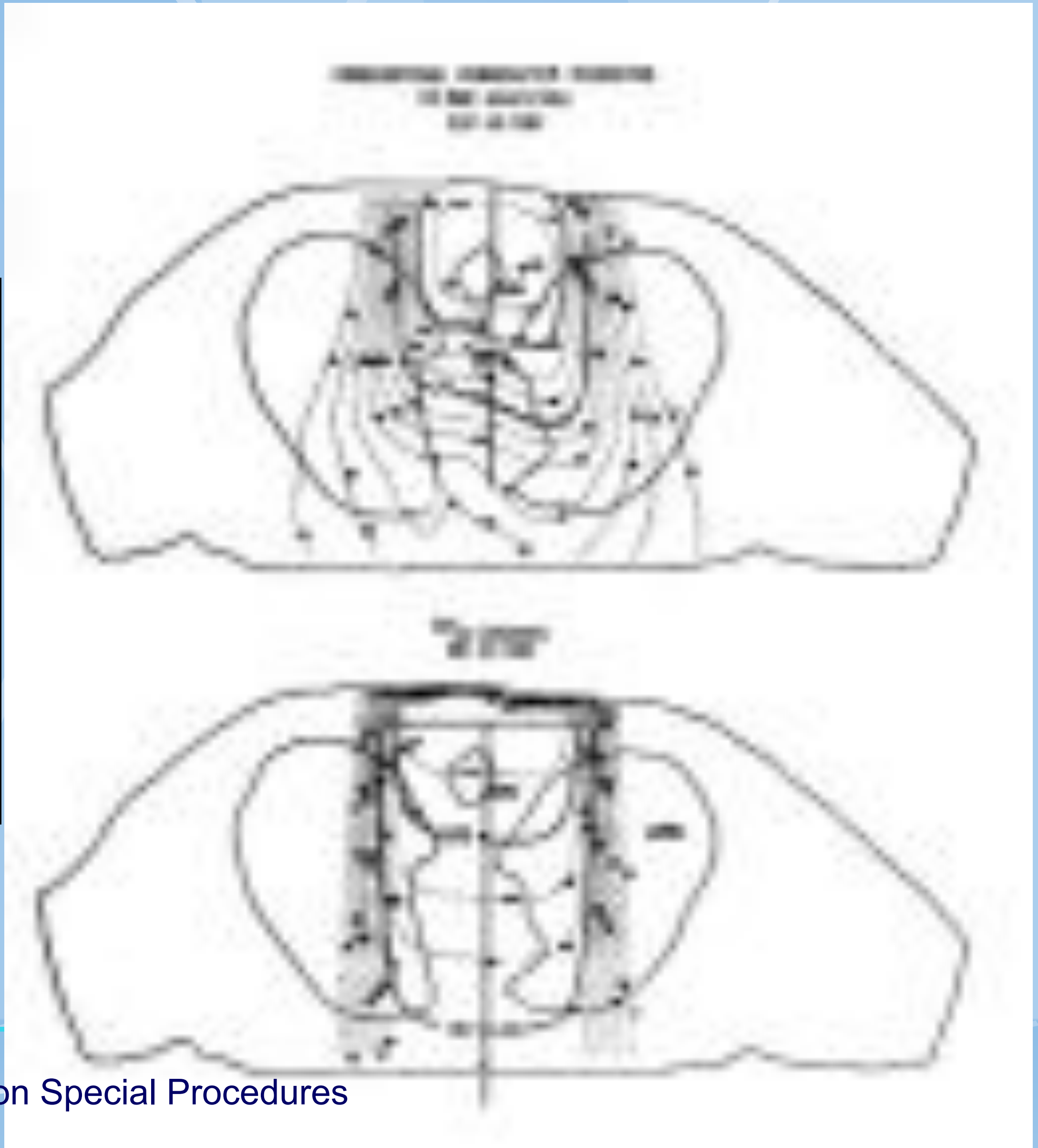




Comparison of Spinal-field Dose Distributions Photon & Electron Beams

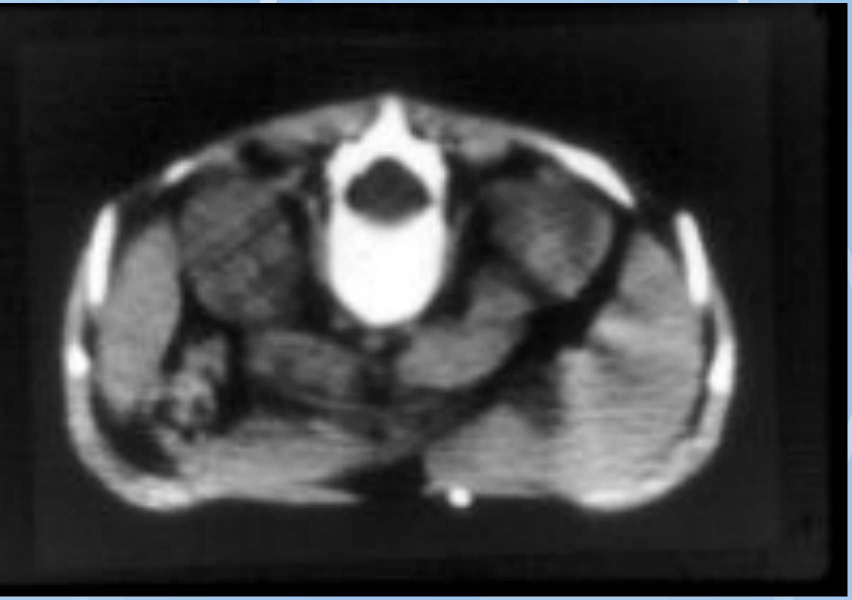
- CT Thorax

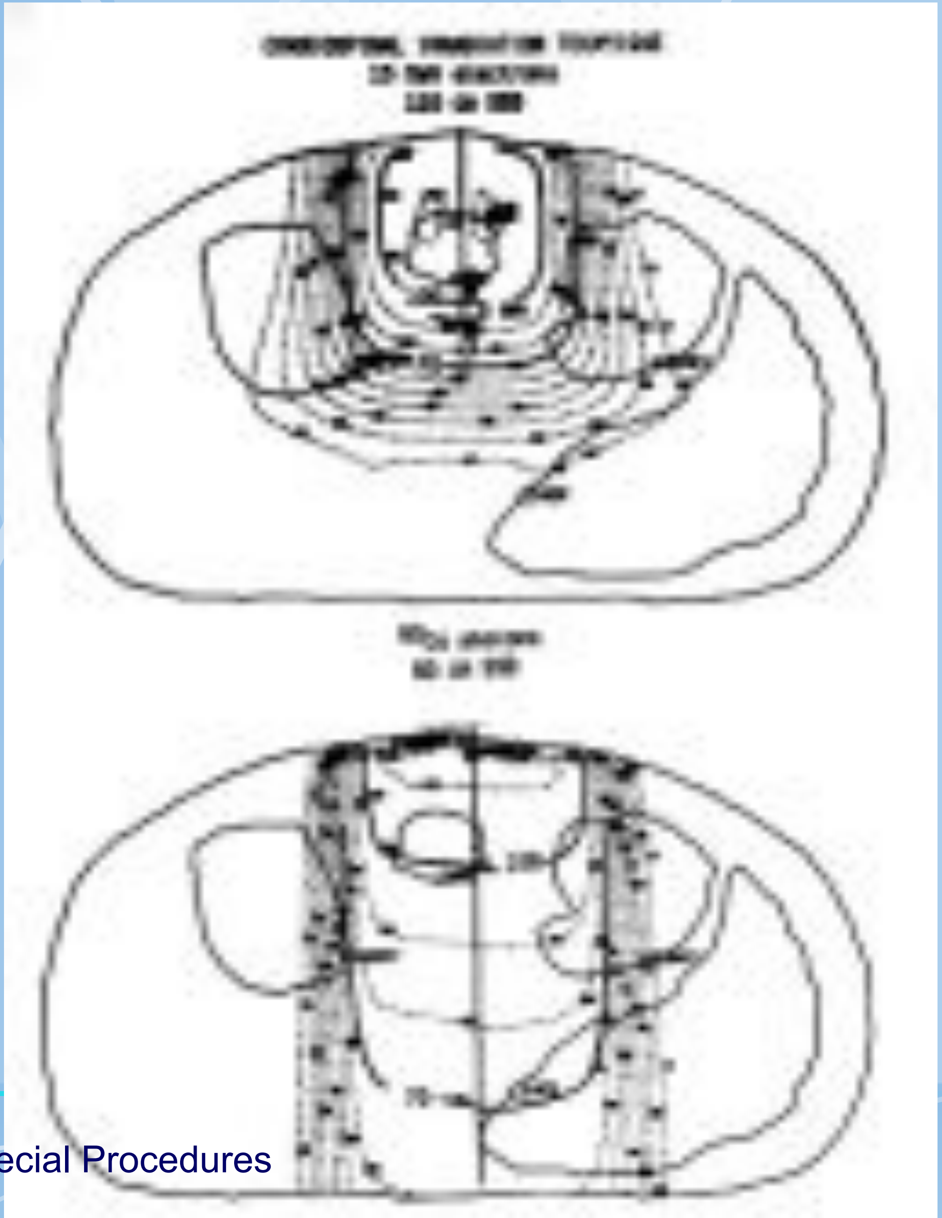




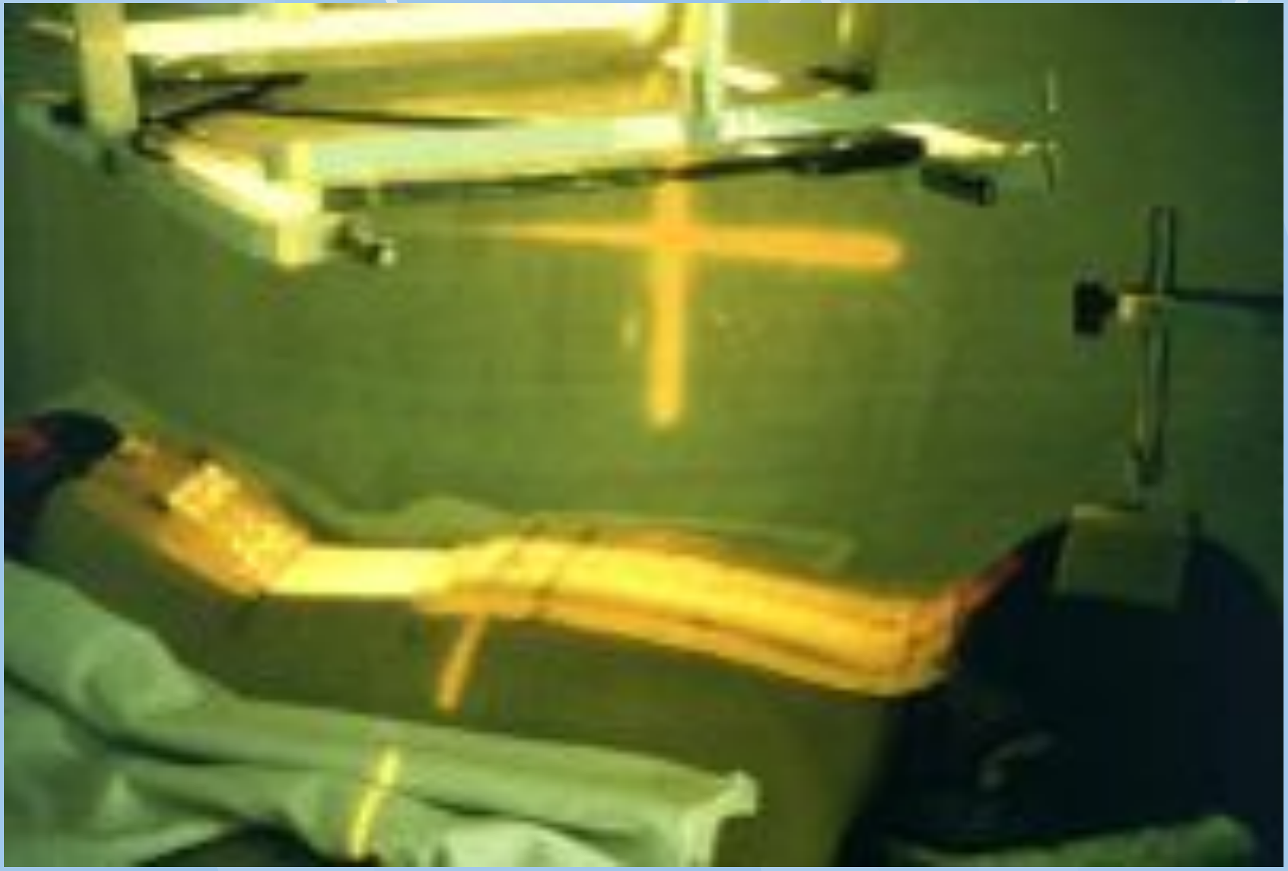
Comparison of Spinal-field Dose Distributions Photon & Electron Beams

- CT Abdomen





Electron Bolus for Craniospinal Irradiation



Electron Dose Calculations

John A. Antolak, Ph.D.

Before Pencil Beams

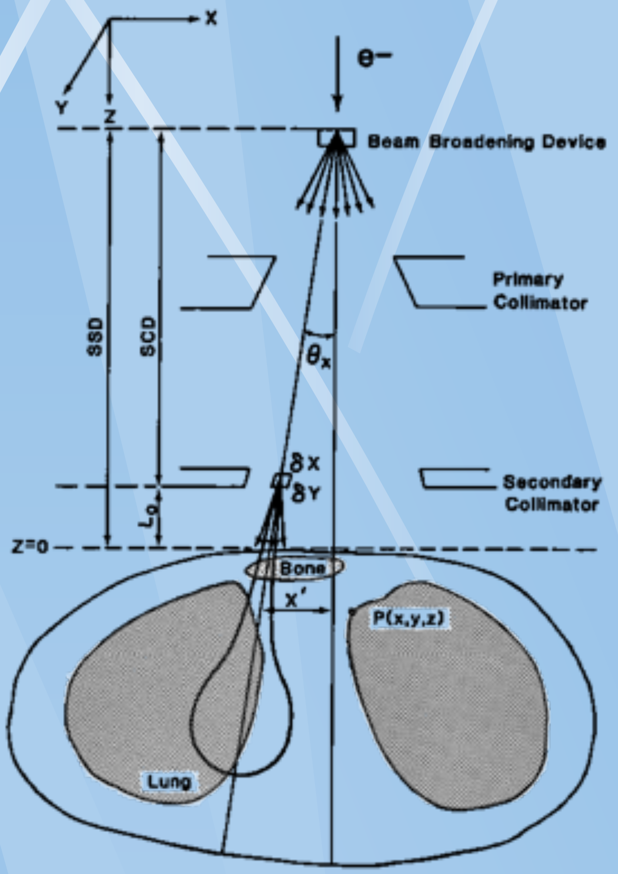
- Milan & Bentley method implemented into the RAD-8 and GE RT/Plan
- Kawachi (1975) used diffusion theory to calculate broad beam dose distributions using a diffusion approximation
  - Approach not amenable to calculating dose distributions in the presence of heterogeneities
  - Steben (1979) implemented into AECL TP-11
- Mohan et al (1981) implemented a method at MSKCC based on measured data
- All methods inaccurate due to lack of physics

Pencil-Beam Algorithms

- Lillicrap et al (1975) showed that broad beam doses could be predicted by summing up measured doses from small (pencil) beams
- Ayyangar (1983) extended Steben (1979) to implement pencil beam based on diffusion in AECL Theraplan

Hogstrom PBA

- Fermi-Eyges thick slab multiple scattering
- Calculate dose for any fields size
- CT-based heterogeneity correction
- Accurately modeled air gap and irregular surface by redefining pencil beams at the surface
- Used in GE RT/Plan, Pinnacle^3 and Focus planning systems



Hogstrom PBA Limitations

- Central-axis (CAX) approximation
  - Heterogeneity effects underestimated in the second half of the range
- Large angle scattering not included
- Assumed that all electrons reached the practical range

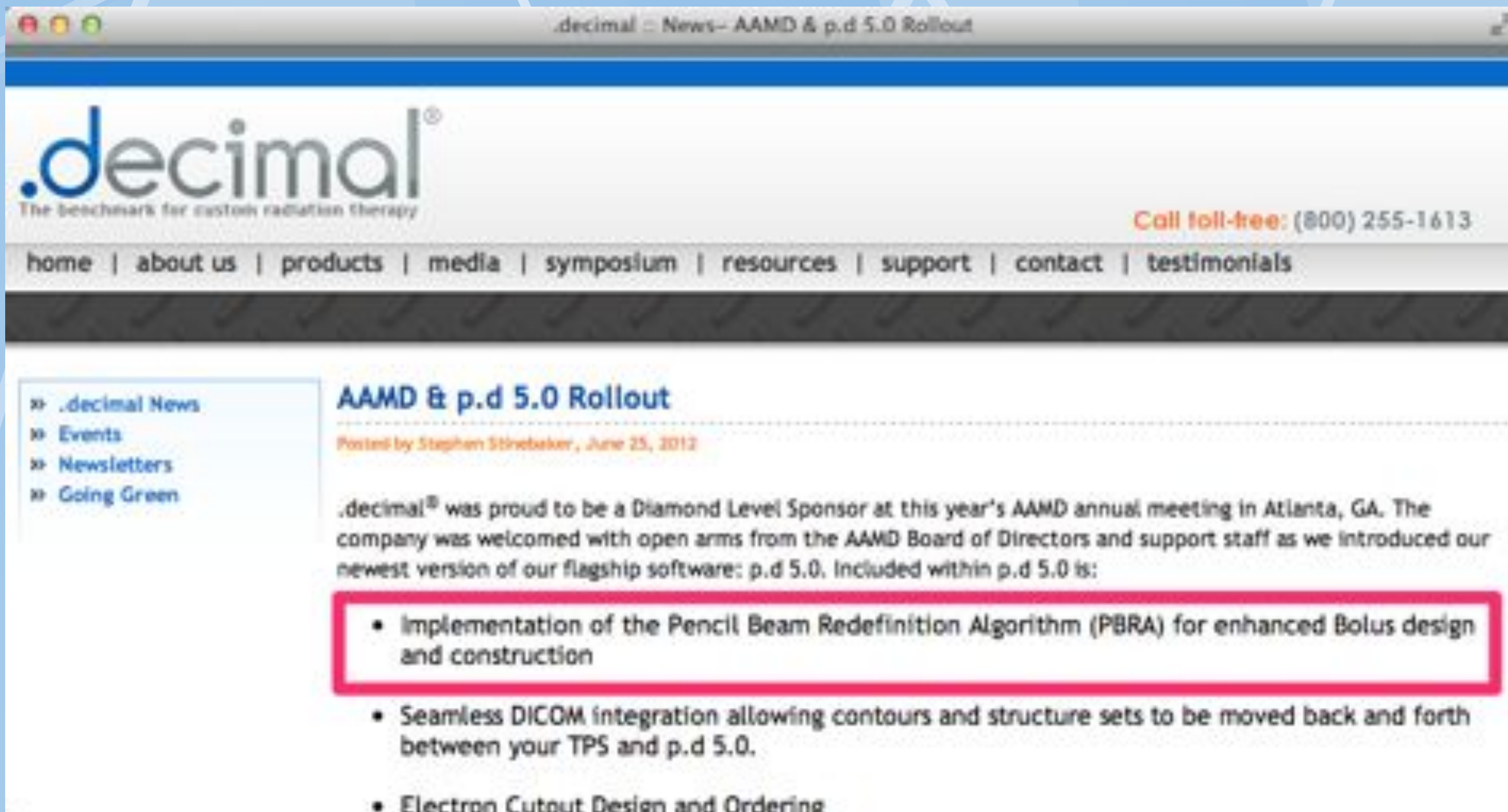
Lax & Brahme PBA

- Similar to Hogstrom PBA
- Used 3 Gaussians to better model large angle scattering
- Still subject to CAX approximation
- Used in Varian CadPlan (Eclipse)

Improved Analytical Algorithms

- Phase Space Evolution
  - Huizenga and Storchi 1989
- PB Redefinition Algorithm (PBRA)
  - Shiu and Hogstrom 1991; Boyd et al 1998
  - Plug-in upgrade to PBA (same input data), but redefined pencil beams every 5 mm to overcome CAX approximation
  - Benchmarked against Boyd dataset (2001), and shown to be equivalent to Monte Carlo for patients
- Jette & Walker extension to Jette PBA (1992)
- None implemented in commercial planning systems

PBRA

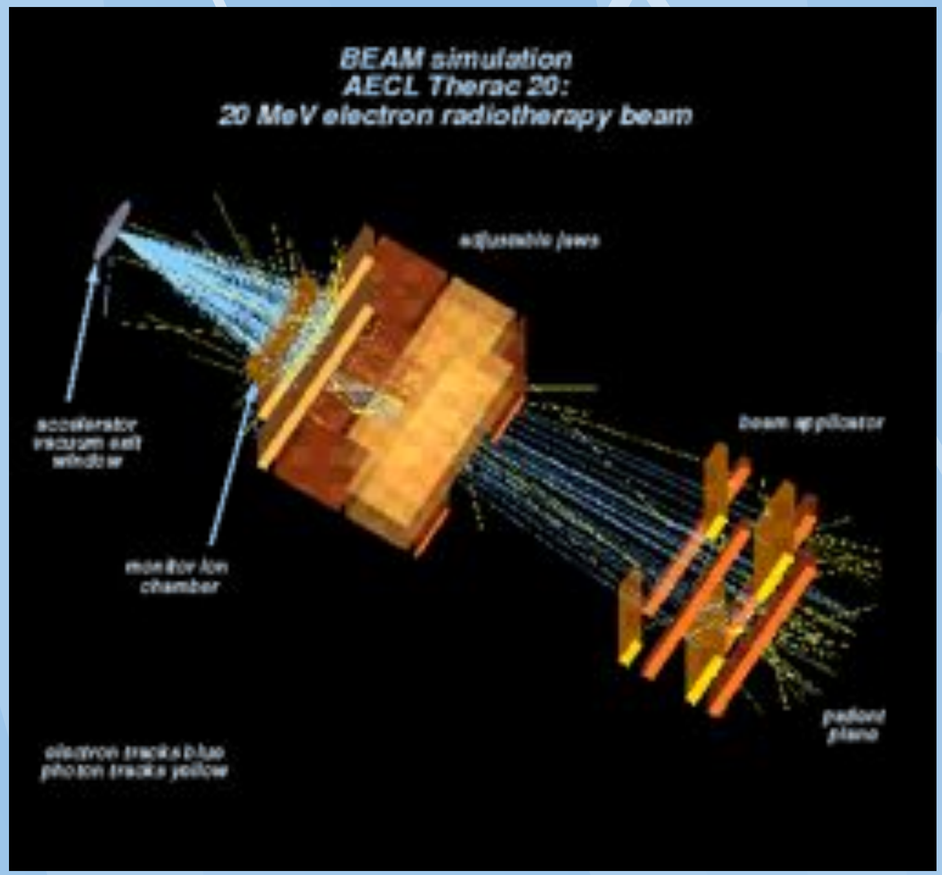


http://www.dotdecimal.com/news/eventjun2512, accessed Jul 25, 2012

Monte Carlo Algorithms

- EGS (EGS4, EGSnrc, EGS5)
  - Accurate, generally too slow for clinical use
  - Users must develop their own geometry & dose scoring code
- Ottawa-Madison Electron Gamma Algorithm (OMEGA) collaboration developed BEAM
  - Calculating transport through accelerators
  - DOSXYZ code for patient geometry
- MCDOSE (Ma et al 2002)
  - Alternative to BEAM, similar capabilities
- MCNP
  - No programming needed, but not as widely used as EGS in therapy

BEAMnrc



http://irs.inms.nrc.ca/software/beamnrc/documentation/pirs0509/img1.png, accessed Jul 25, 2012

General Characteristics Monte Carlo Algorithms

- Stochastic
  - Uncertainty proportional to square root of number of histories
- Electron boundary crossings are tricky
  - Simulating every interaction impractical, so a condensed history approach is used

Calculation Times Monte Carlo Algorithms

- For a given stochastic uncertainty, calculation time is
  - Proportional to
    - Field area
    - Energy
  - Inversely proportional to
    - Volume of dose elements

Faster Monte Carlo

- Mackie & Battista (1984) suggested using EGS4 pre-calculated kernels
  - Impractical at the time due to computer memory constraints
- MMC (Neuenschwander 1992) used pre-calculated kernels in spherical geometry
- Super Monte Carlo (Keall & Hoban 1996) used pre-calculated electron tracks
- VMC (Kawrakow et al 1996) used analytical methods to approximate the Monte Carlo transport in a voxel geometry

Macro Monte Carlo

- Neuenschwander et al (1995)
- Commercially implemented in Eclipse
- Uses pre-calculated EGS4 data
- Benchmarked against Boyd (2001) dataset
  - Popple et al (2006)
- Calculation times from several seconds to a few minutes on current hardware
  - Takes advantage of multiple cores and multiple computers
- Choice of smoothing algorithms and levels
  - Be careful not to over-smooth

Voxel Monte Carlo

- Commercially implemented in Oncentra
- Does not use pre-calculated data
- Optimized for tissue-like materials and voxel geometries

Monte Carlo techniques should replace analytical methods for estimating dose distributions in radiotherapy treatment planning

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William R. Hendee, Moderator

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OVERVIEW

Analytical models have traditionally been used to estimate dose distributions for treatment planning in radiation therapy. Recently, some physicists have suggested that Monte Carlo techniques yield more accurate computations of dose distributions, and a few vendors of treatment planning systems have incorporated Monte Carlo methods into their software. Other physicists argue that, for a number of reasons, analytical methods should be preserved. This controversy is the topic of this Point/Counterpoint article. Thanks are extended to Paul Nizin, Ph.D. of Baylor College of Medicine for suggesting the topic.

Arguing for the Proposition is Radhe Mohan, Ph.D. Dr. Mohan received his Ph.D. from Duke University and is currently Professor and Director of Radiation Physics at the Medical College of Virginia (MCV) Hospitals, Virginia Commonwealth University. Dr. Mohan has been actively engaged in research and clinical implementation of ad-

Arguing against the proposition is John Antolak, Ph.D. Dr. Antolak received his Ph.D. in Medical Physics from the University of Alberta (Canada) in 1992. He then joined the Department of Radiation Physics at The University of Texas M. D. Anderson Cancer, where he is currently an Assistant Professor. He is certified by the American Board of Radiology and licensed to practice Medical Physics in Texas. He is active in the education of graduate students, dosimetrists, and other physicists, and his research interests center around the use of electron beams for conformal radiotherapy. In his spare time, he enjoys playing ice hockey and coaching his son's ice hockey team.

FOR THE PROPOSITION: Radhe Mohan, Ph.D.

Opening Statement

Monte Carlo techniques produce more accurate estimates of dose than other computational methods currently used for planning radiation treatments. Were it not for limitations of computer speed, Monte Carlo methods probably would have

Looking to the Future

http://www.flickr.com/photos/pasukaru76/3998273279/, accessed Jul 25, 2012

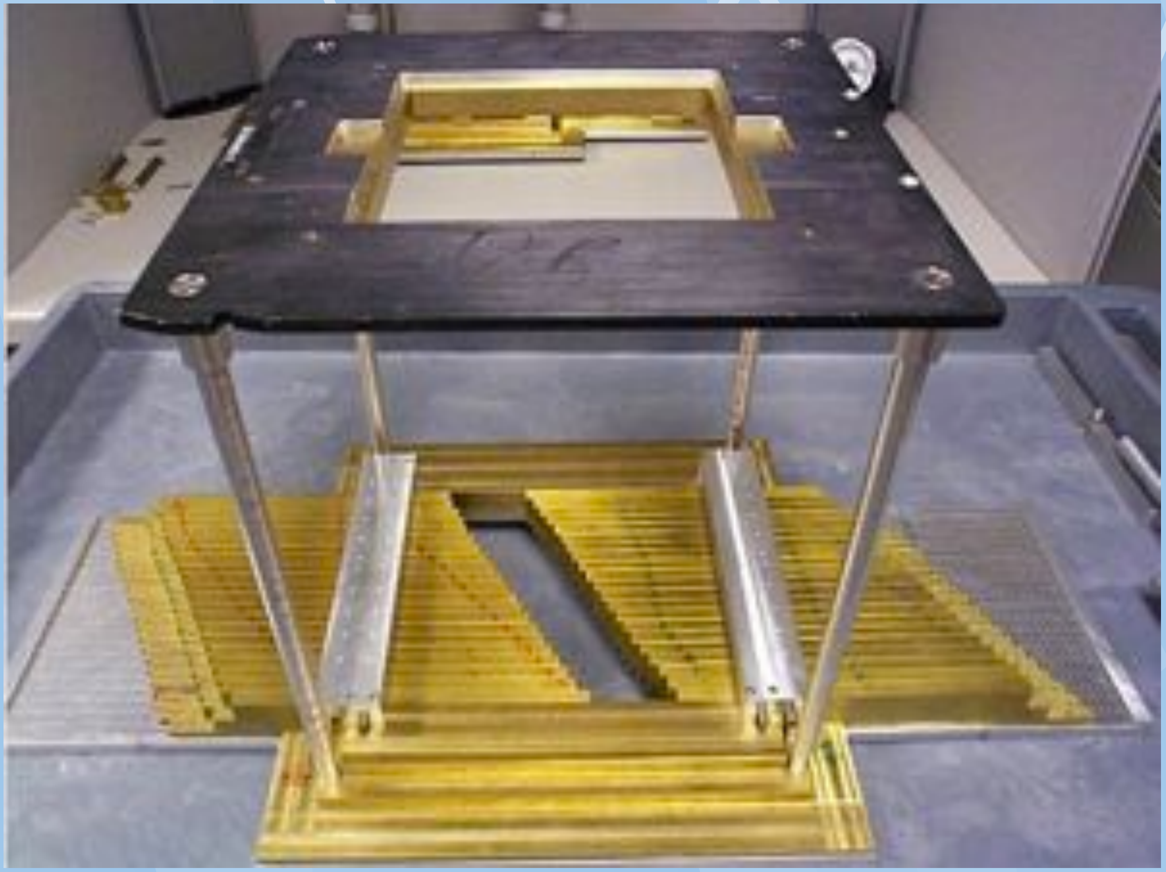
Challenges

- Planning systems unable to model
  - Skin collimation
  - Internal collimation
  - Variable thickness bolus (except through .decimal)
  - Modulated electron therapy
  - Arc therapy
- New technologies competing with traditional electron techniques
  - Tomotherapy, IMRT
    - Increased non-target dose
  - Proton therapy
    - Increased treatment cost
  - HDR brachytherapy

Possible Future Tech for Electron Radiotherapy

- eMLC for arc therapy
  - Short SCD
  - Use x-ray MLC?
- eMLC for fixed-beams
  - Modulated electron RT (MERT, Ma et al 2000, 2003)
  - Intensity-modulated electrons improve bolus ECT dose uniformity (Kudchadker et al 2002)
  - IMRT + electrons (mixed-beam therapy) potentially better than IMRT alone

Prototype eMLC



Hogstrom, K. R., R. A. Boyd, et al. (2004). "Dosimetry of a prototype retractable eMLC for fixed-beam electron therapy." Medical Physics 31(3): 443-462

Commercial eMLC

Gauer, T., D. Albers, et al. (2006). "Design of a computer-controlled multileaf collimator for advanced electron radiotherapy." Physics in medicine and biology 51(23): 5987-6003.
http://euromechanics.com/e_emlc.html

Education is Key

- Learn how to use electrons well
  - Make the most of what you have now
  - Learn new technology (e.g., bolus ECT)
- Teach other members of your treatment team to do the same
- Encourage your treatment planning vendor to add and improve electron planning tools
- Encourage your linear accelerator vendor to add and improve electron delivery tools

Getting Started

- AAPM Report #32
  - Khan, F. M., K. P. Doppke, et al. (1991). "Clinical electron-beam dosimetry: report of AAPM Radiation Therapy Committee Task Group No. 25." Medical Physics **18**(1): 73-109.
- AAPM Report #99
  - Gerbi, B. J., J. A. Antolak, et al. (2009). "Recommendations for clinical electron beam dosimetry: Supplement to the recommendations of Task Group 25." Medical Physics **36**(7): 3239-3279.
  - Gerbi, B. J., J. A. Antolak, et al. (2011). "Erratum: "Recommendations for clinical electron beam dosimetry: Supplement to the recommendations of Task Group 25" [Med. Phys. 36, 3239-3279 (2009)]." Medical Physics **38**(1): 548-548.
- Hogstrom, K. R. (2004). Electron-beam therapy: Dosimetry, planning, and techniques. Principles and Practice of Radiation Oncology. C. A. Perez, L. W. Brady, E. C. Halperin and R. K. Schmidt-Ullrich. Philadelphia, PA, Lippincott Williams & Wilkins: 252-282.

Getting Started

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REVIEW

Review of electron beam therapy physics

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Thank You