Session in Memory of Martin L. Rozenfeld, PhD:
Personalized Electron Beam Therapy Using Custom Treatment Devices
2018 AAPM Annual Meeting, August 1, 2018
John A. Antolak, PhD

Session in Memory of Martin L. Rozenfeld, PhD

John A. Antolak and James A. Kavanaugh

AAPM SAM Therapy Educational Course
August 1, 2018

Session in Memory of Martin L. Rozenfeld, PhD

FIG. 16. *Standing, left to right:* Dale Trout, Shirley Vickers, Colin Orton, Stewart Bushong, John Wright, Marty Rozenfeld, Mary Lou Merck, Ken Williams, N. Suntharalingam, Bengt Bjarngard. *Seated, left to right:* Fearghus O'Foghludha, Ben Galkin, Peter Almond, Jim Kereiakes, and Leonard Stanton.

Medical Physics, Vol. 25, No. 7, July 1998, Part 2

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Introduction

Memorial Tribute

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Session in Memory of Martin L. Rozenfeld, PhD

Department of Medical Physics
Rush-Presbyterian-St. Luke's Medical Center
October 1996

Session in Memory of Martin L. Rozenfeld, PhD

- Farrington Daniels Award, 1984
  - Jette D, Pagnamenta A, Lanzl LH, Rozenfeld M. The application of multiple scattering theory to therapeutic electron dosimetry. *Med Phys*. 1983;10(2):141-146. doi:10.1118/1.595235
- NCRP Report 088, 1986
  - Radiation Alarms and Access Controls Systems
- AAPM Task Group #25, 1991
  - Clinical Electron-Beam Dosimetry
- Fellow of the AAPM, 1997
- Calibration Laboratory Accreditation SC, 1996-2001

Memorial Tribute

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Disclosures

- JAA has no conflicts to disclose
- JAK has no conflicts to disclose
- Several commercial products will be mentioned in this presentation.
  - Mention of specific products does not imply endorsement of the product

History of Electron Therapy

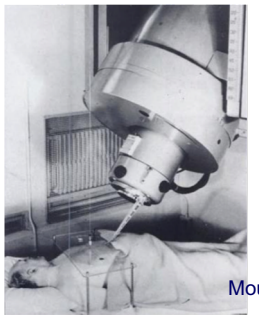
Slide content courtesy of Kenneth R. Hogstrom, Ph.D.

Clinical Utility

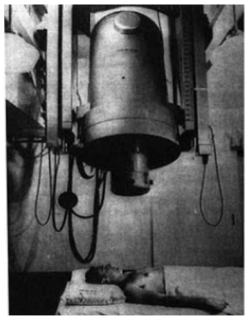
- Electron beams have been successfully used in numerous sites that are located within 6 cm of the surface:
  - Head (Scalp, Ear, Eye, Eyelid, Nose, Temple, Parotid, …)
  - Neck Node Boosts (Posterior Cervical Chain)
  - Craniospinal Irradiation for Medulloblastoma (Spinal Cord)
  - Posterior Chest Wall (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-

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 (1937)
  - 1st used for radiotherapy at Huntington Memorial Hospital in Boston (1937)
  - Van de Graaff and Trump founded High Voltage Engineering Corp. (1st company organized for express purpose of manufacturing particle accelerators, 1946)
  - Limited utilization for mycosis fungoides and other skin cancers--Trump et al (1940, 1953); Trump (1960)



Mould 1997



Suit 2011

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Introduction and History

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)

Siemens 15 MeV Betatron (1952)
www.siemens.com/history

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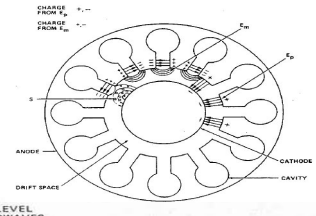
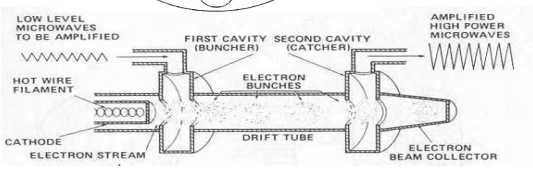
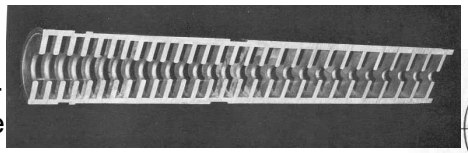
Introduction and History

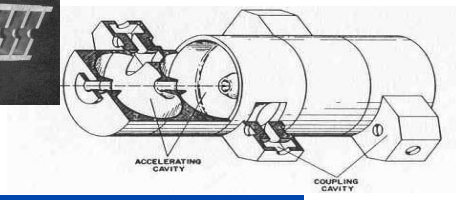
History of Electron Therapy Accelerator Technology

- Linear Accelerators (1960s)
  - Post WWII RF amplifiers (magnetron & klystrons)
    - Klystron invented in 1937 by Varian brothers
  - 1960s-present: Traveling wave & side-coupled standing wave
  - 1968: 137 betatrons/79 linacs (only few had e-)









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)

(www.dotmed.com)

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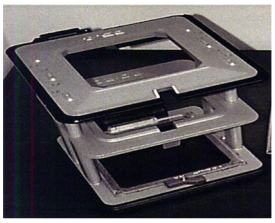
History of Electron Therapy Accelerator Technology

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

Elekta Infinity
(www.elekta.com)



Varian Trilogy
(www.varian.com)

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Introduction and History

History of Electron Therapy Dose Calculation & Measurement Technology

- Electron Transport and Dose Calculations
  - Analytical: Fermi-Eyges Theory (1980s) and ICRU 35 (1984)
  - Monte Carlo: EGS4, BEAM, DOSXYZ (1985-1995)
- 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)
- Dose Measurement Protocols
  - AAPM TG Reports 21, 39, & 51 (Dose Calibration)
  - AAPM TG Reports 25 & 70 (Relative Dose Measurements)

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Introduction and History

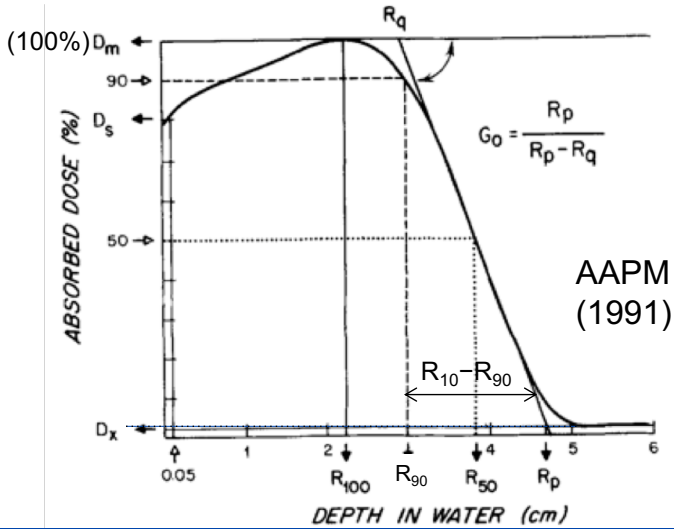
History of Electron Therapy

Review of Basic Electron Dosimetry

Primary Electron Interactions 5-25 MeV

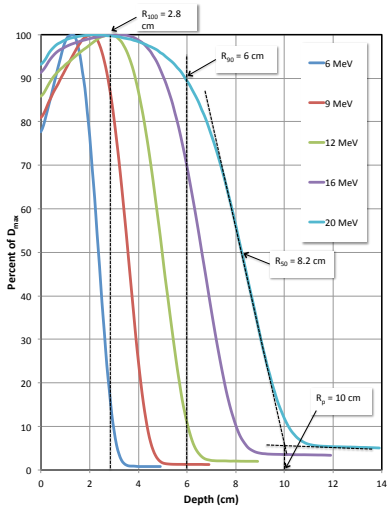
- Collisional energy loss
  - Electron - electron interactions
- Multiple Coulomb scattering
  - Electron - nuclear interactions

Percent Depth Dose (PDD)



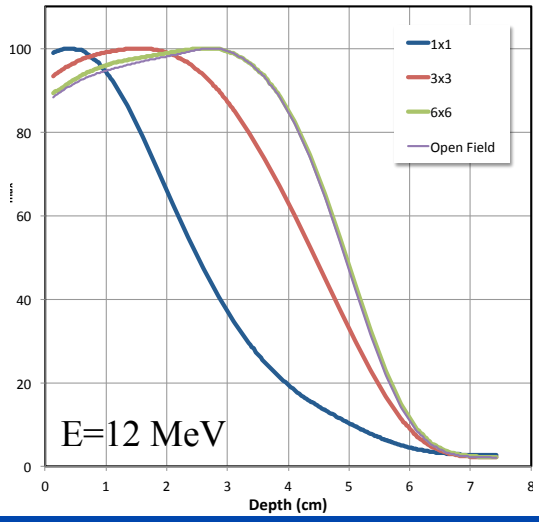
AAPM TG-25 Report (1991)

Percent Depth Dose Energy Dependence 6-20 MeV



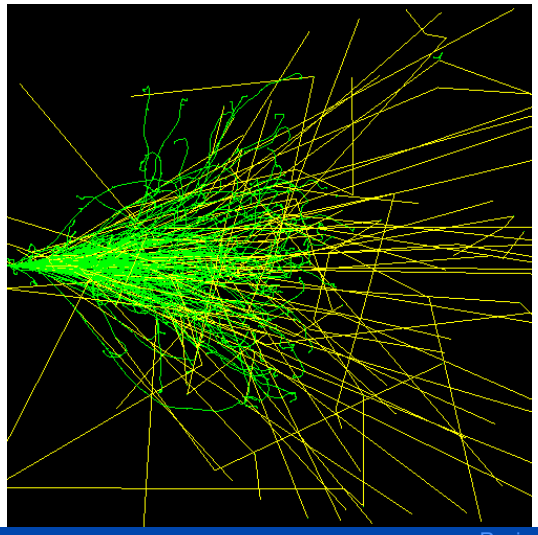
- As energy increases
  - Surface dose (D_s) increases (70%-90%)
  - Therapeutic depth (R_{90}) increases
  - Dose falloff (R_{10}-R_{90}) increases
  - Practical range (R_p) increases
  - Bremsstrahlung dose (D_x) increases
- Small variations due to method of beam flattening and collimation

Percent Depth Dose Field Size Dependence

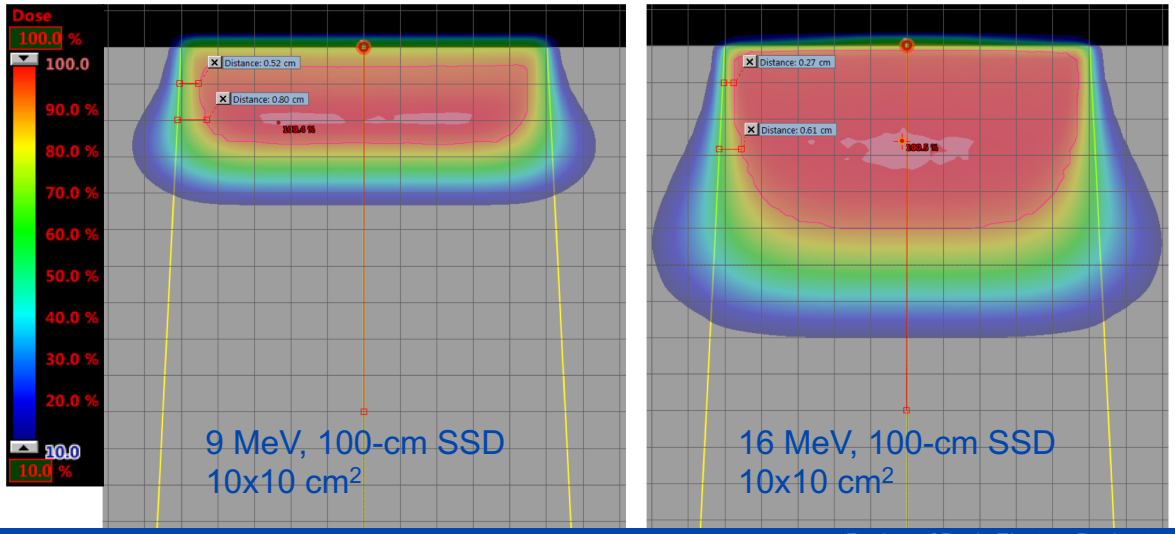


- As field size decreases
  - Therapeutic depth (R_{90}) decreases
  - Surface dose (D_S) increases
  - Practical range (R_p) remains constant
- Decrease in R_{90} less significant at lower energies
- Increase of D_S more significant at lower energies

10 MeV Electrons in Water



Electron Dose Distributions
Energy Dependence of Penumbra



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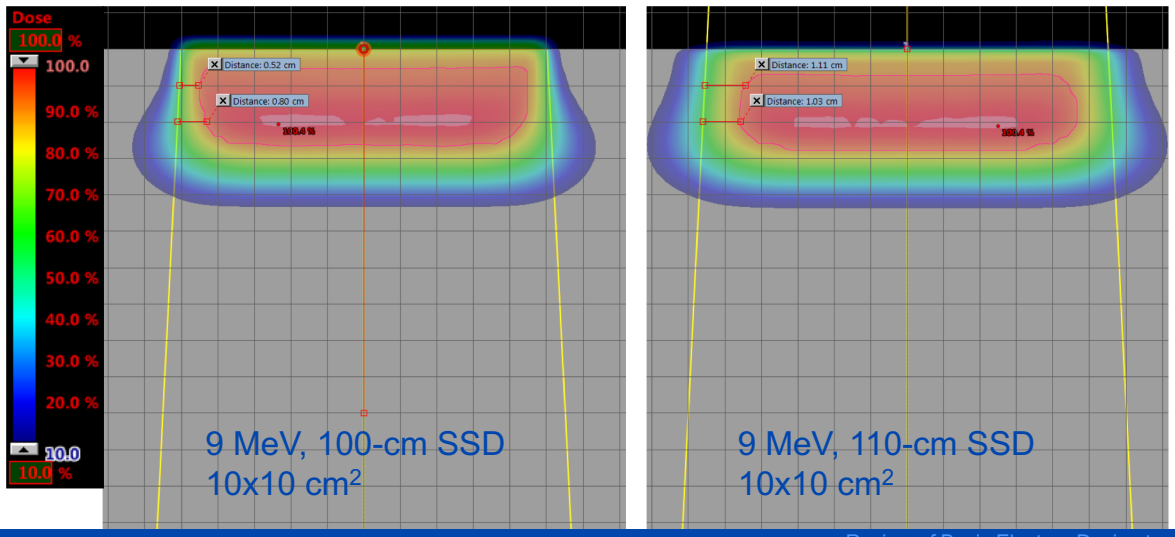
Review of Basic Electron Dosimetry

Electron Dose Distributions
SSD Dependence



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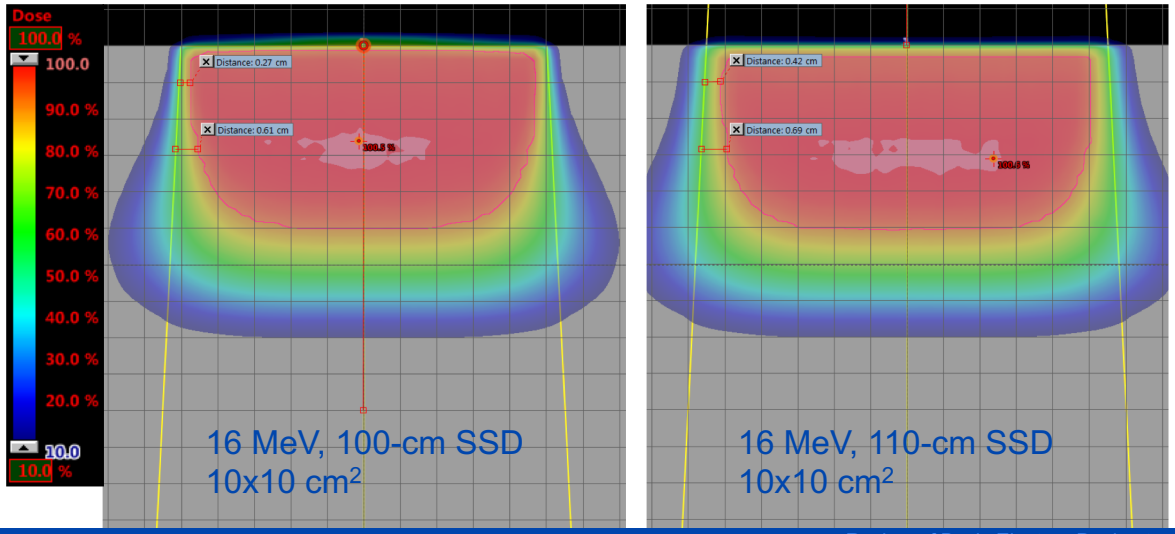
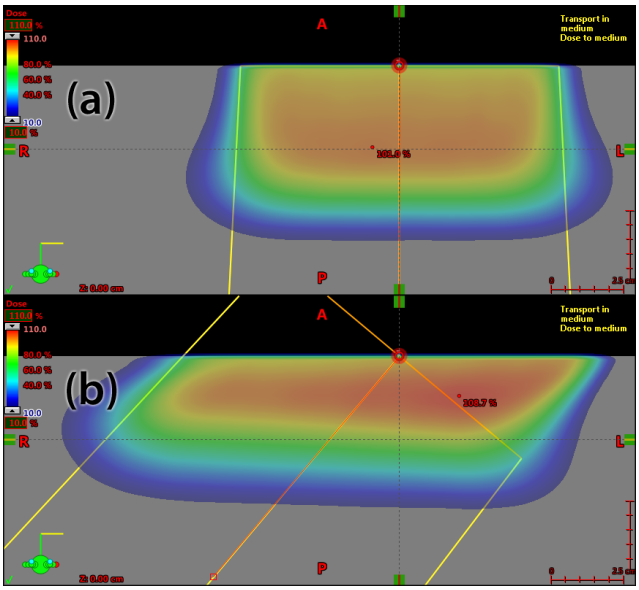
Review of Basic Electron Dosimetry

Electron Dose Distributions
SSD Dependence



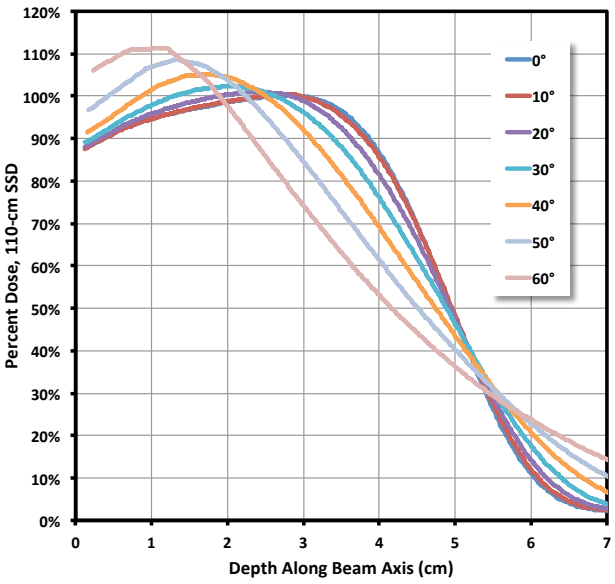
Electron Dose Distributions
Oblique Incidence

- 12-MeV, 10x10 cm^2, 110-cm SSD
- Penumbra sharper for surfaces closer to source
- Penetration decreases relative to the surface normal



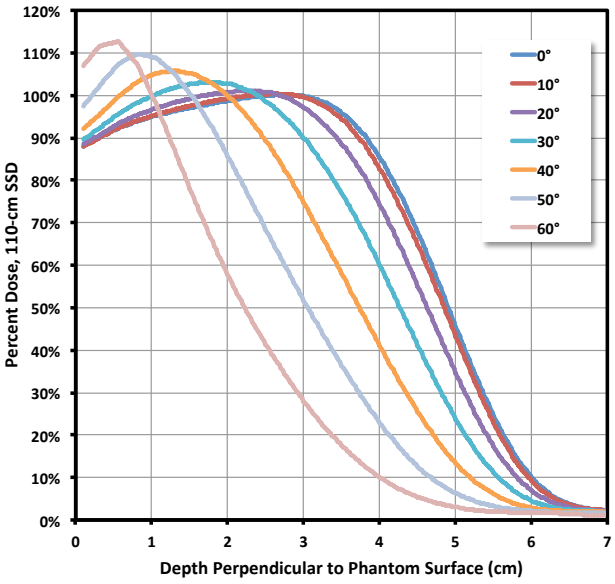
Electron Dose Distributions Oblique Incidence

- 12-MeV, 10x10 cm^2, 110-cm SSD
- Penetration increases relative to the beam direction



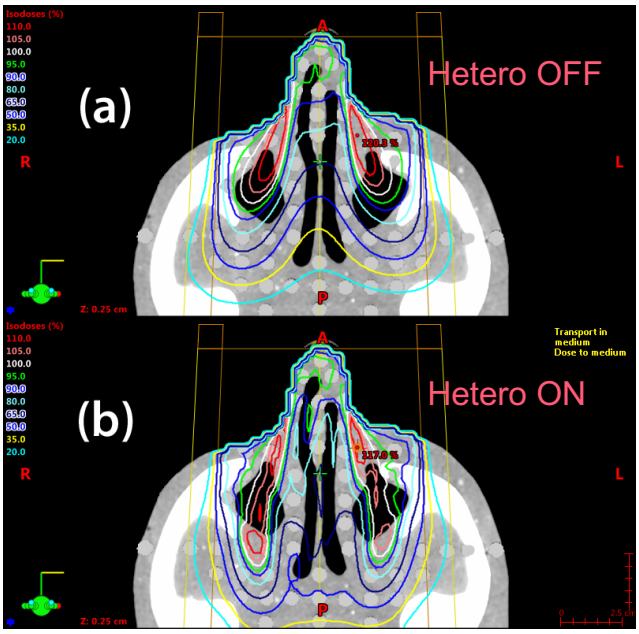
Electron Dose Distributions Oblique Incidence

- 12-MeV, 10x10 cm^2, 110-cm SSD
- Penetration decreases relative to the surface normal



Electron Dose Distributions Heterogeneities

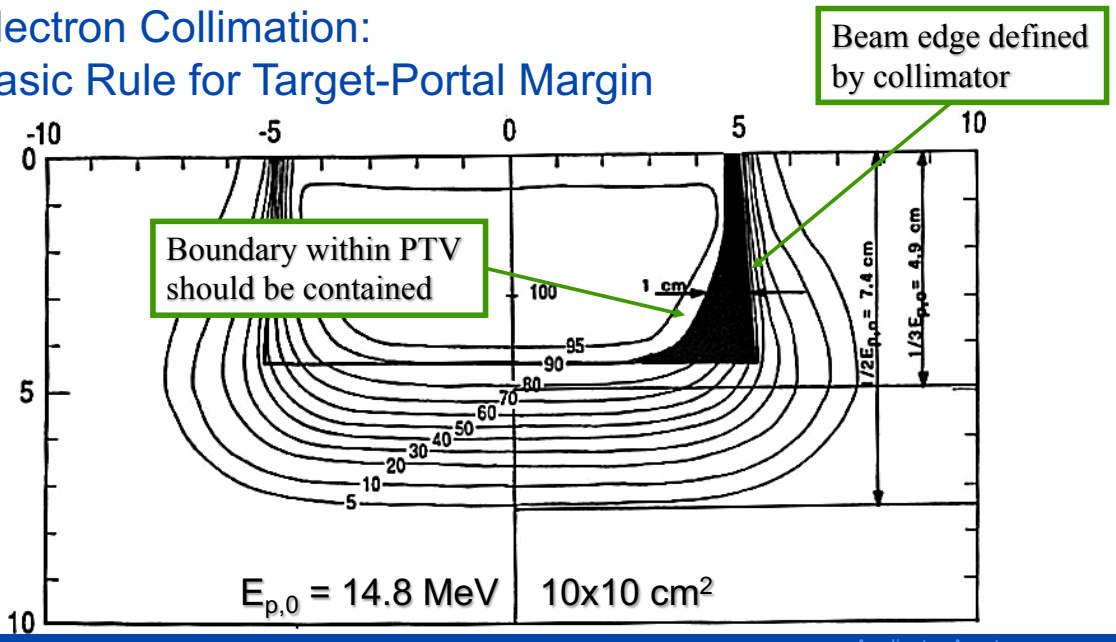
- 16-MeV 8×8 cm^2 field at 100-cm SSD
- Significant dose effects due to surface irregularities
- Internal heterogeneities make things even more complicated
- Important to know if your planning system can handle these effects



Custom Electron Treatment Devices

- Applicator Aperture
- Skin Collimation
- Eye blocks and Eye shields
- Bolus Electron Conformal Therapy

Electron Collimation: Basic Rule for Target-Portal Margin



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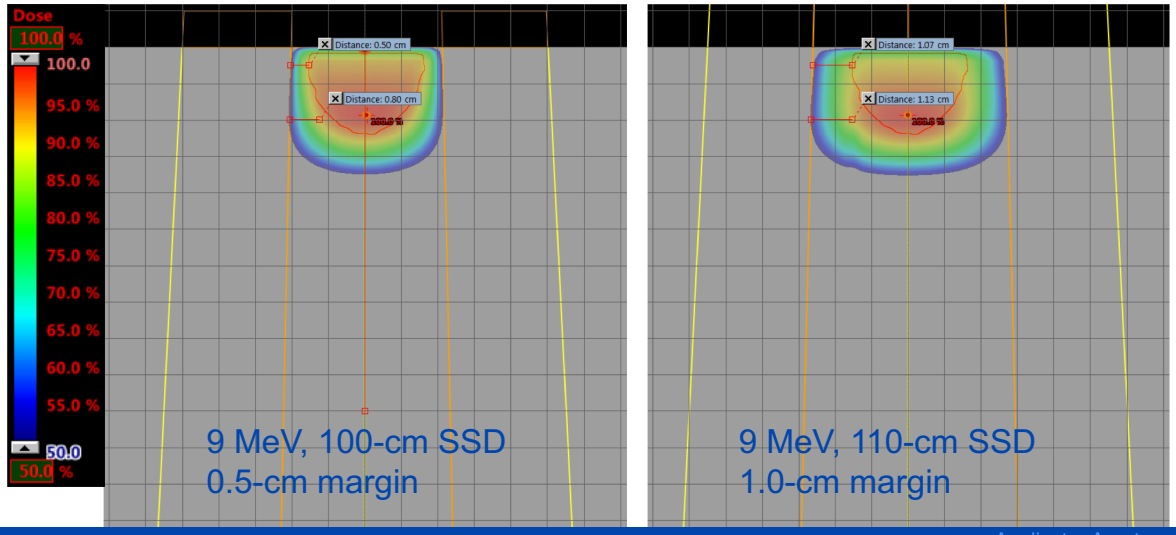
Applicator Aperture

Electron Dose Distributions SSD Dependence



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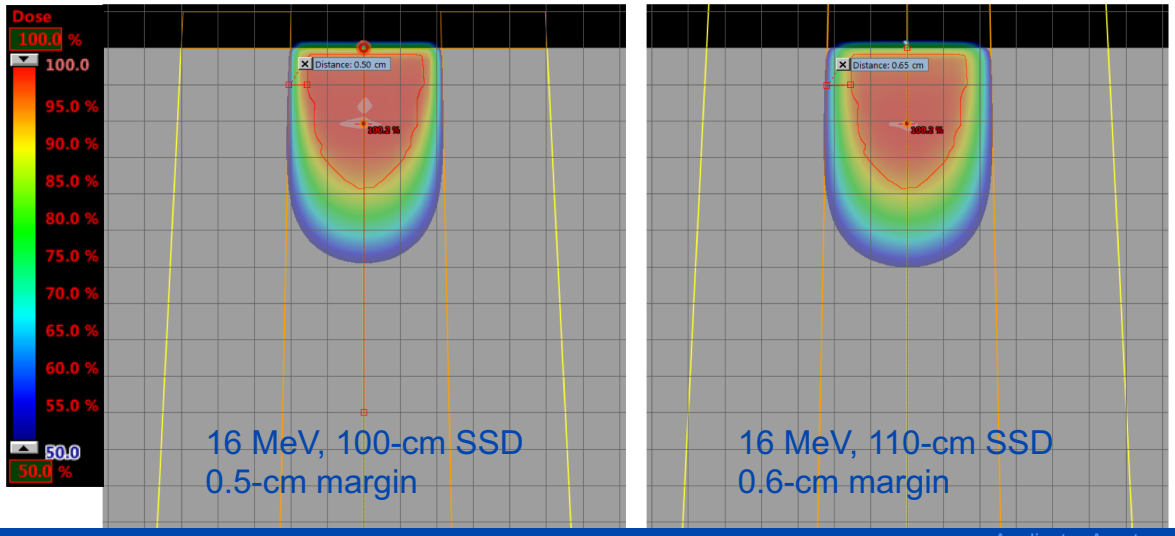
Applicator Aperture

Electron Dose Distributions
SSD Dependence



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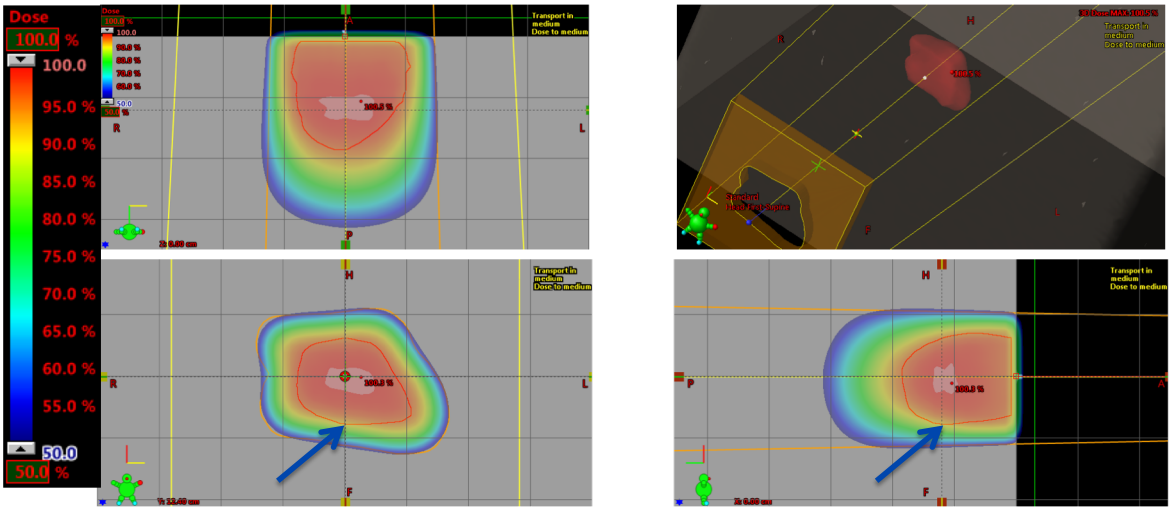
Applicator Aperture

Limitations of Uniform Margin Expansion



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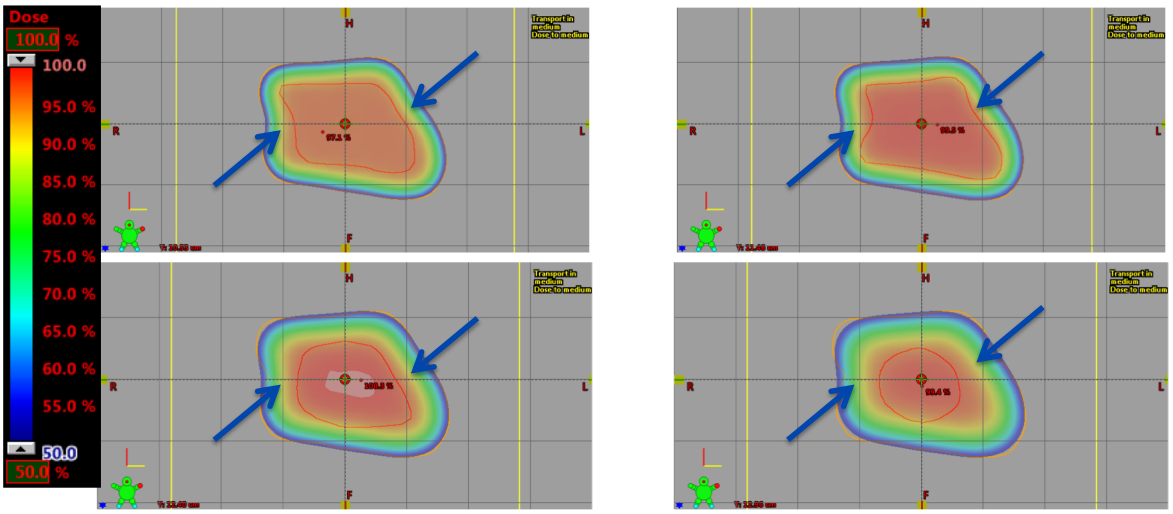
Applicator Aperture

Limitations of Uniform Margin Expansion



Electron Collimation
Basic Rules for Collimator Thickness

- t_{Pb} (mm) = 1/2 $E_{p,0}$ (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

Copper Inserts Commercially Available

- Density is 8.96
- Cost
  - Fabrication cost: $100-200
    - 6x6 – 25x25 cm2 applicator
  - Shipping cost: depends on location
  - Recyclable locally (scrap value ≈ shipping cost)
  - Cost neutral (fabrication cost ≈ allowed billing)
  - Costs shift from insourcing to outsourcing
- Users
  - ≈ 175 active sites
  - Average annual site usage: ≈ $4,000
- http://dotdecimal.com/products/electrons/apertures/

.decimal

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Applicator Aperture

Copper Inserts Commercially Available

- Process (commissioning)
  - Completion of site survey
  - Download free p.d software onto PC
- Process (patient)
  - Transfer field size parameters (shape & applicator) to p.d and order
  - Factory machining, QA, and mailing performed at factory
  - Received 1-2 days after ordered

.decimal

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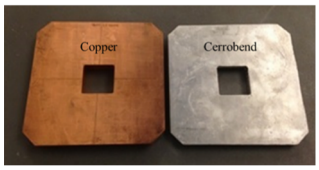
Applicator Aperture

Copper Applicator Inserts
Pros and Cons

- Pros
  - Space savings: allows elimination of block room
  - Safety: eliminates Cerrobend toxicity concerns
  - Accuracy: more accurate, machined apertures provide:
    - More accurate abutment dosimetry for abutted fields
    - More accurate commissioning data, if used
  - Durability: Copper less likely to break if dropped
  - Dosimetry: Less out-of-field leakage dose to patient
- Cons
  - Modifications: Post fabrication changes (filing) more difficult

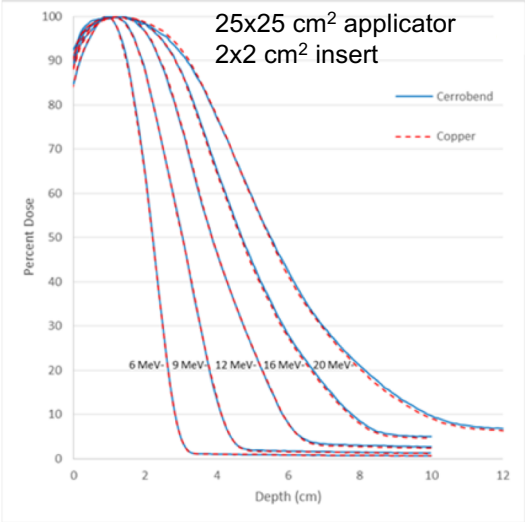
Dosimetry Study, Copper vs Cerrobend
Measurement Conditions

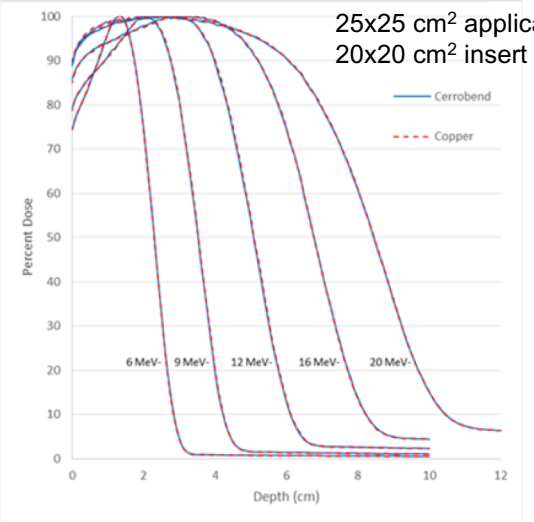
Machine	Varian Clinac 21EX 4/10				
Energy	6, 9, 12, 16, 20 MeV				
SSD	100 and 110 cm				
Field Size (cm^2)	Applicator Size (cm^2)				
	6x6	10x10	15x15	20x20	25x25
2x2	X	X	X	X	X
3x3	X	X	X	X	X
4x4	X	X	X	X	X
6x6		X	X	X	X
8x8		X	X	X	X
10x10			X	X	X
12x12			X	X	X
15x15				X	X
20x20					X



B. D. Rusk MSc thesis, LSU

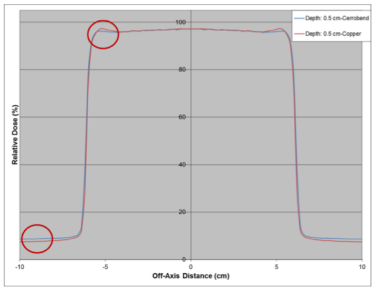
Percent Depth Dose Results: Copper vs Cerrobend

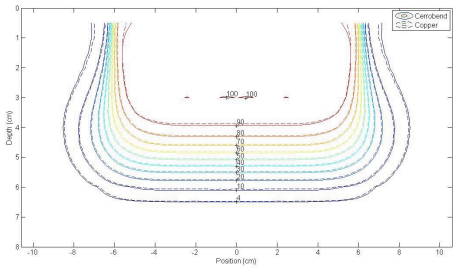




B. D. Rusk *et al*, J. Appl. Clin. Med. Phys. 17 (5), 245-261 (2016).

Off-axis Dose Results: Copper vs Cerrobend





- Greatest Difference
  - 20 MeV, 100-cm SSD, d=0.5 cm
  - 12x12-cm² field
  - 20x20-cm² applicator
- Typical Results
  - 12 MeV, 100-cm SSD
  - 12x12-cm² field
  - 15x15-cm² applicator

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Dose Output (R_{100} cGy/MU) Copper vs Cerrobend

- 100-cm SSD: Agree within □ 2%; 110-cm SSD: Agree within □ 1%
- Cerrobend output higher for higher energies, smaller fields, and larger applicators
  - Difference is likely due to differences in bremsstrahlung generation in collimating inserts

OCF	6 MeV			12 MeV			20 MeV		
Field Size (cm^2)	Applicator (cm^2)			Applicator (cm^2)			Applicator (cm^2)		
	6x6	15x15	25x25	6x6	15x15	25x25	6x6	15x15	25x25
2x2	1.000	0.993	0.992	1.005	0.998	1.000	1.003	0.991	0.991
3x3	1.007	1.002	0.995	1.005	1.000	0.988	1.007	0.995	0.986
4x4	1.004	1.008	0.999	1.004	1.003	0.994	1.007	0.997	0.988
6x6	–	1.002	0.997	–	1.001	0.995	–	1.003	0.994
10x10	–	0.998	0.998	–	0.999	0.995	–	1.001	0.996
15x15	–	N/A	0.995	–	N/A	0.994	–	N/A	0.995
20x20	–	N/A	0.996	–	N/A	0.995	–	N/A	0.995

B. D. Rusk MSc thesis, LSU

Conclusions Copper vs Cerrobend Inserts

- All field size-applicator size-energy combinations passed 3%/1 mm criteria for 100% of points
  - Therefore, it should be possible to use dosimetry commissioning data measured for Cerrobend with Copper inserts
- Copper inserts have slightly less leakage dose than Cerrobend under the inserts
  - Less bremsstrahlung creation in the insert material

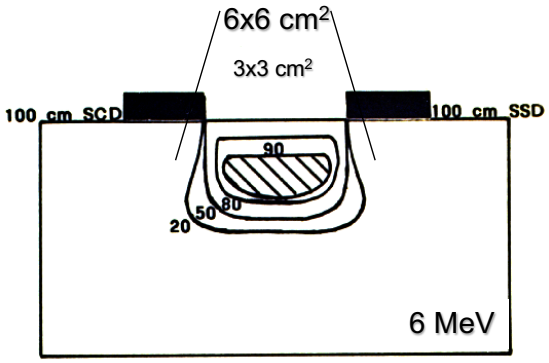
Custom Electron Treatment Devices

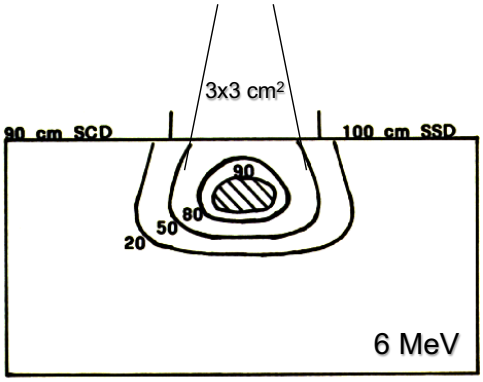
- Applicator Aperture
- Skin Collimation
- Eye blocks and Eye shields
- Bolus Electron Conformal Therapy

Utility of Skin Collimation

- 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
Protection of Critical Structures

- Example: Maximum protection of eyes

Skin Collimation Clinical Examples

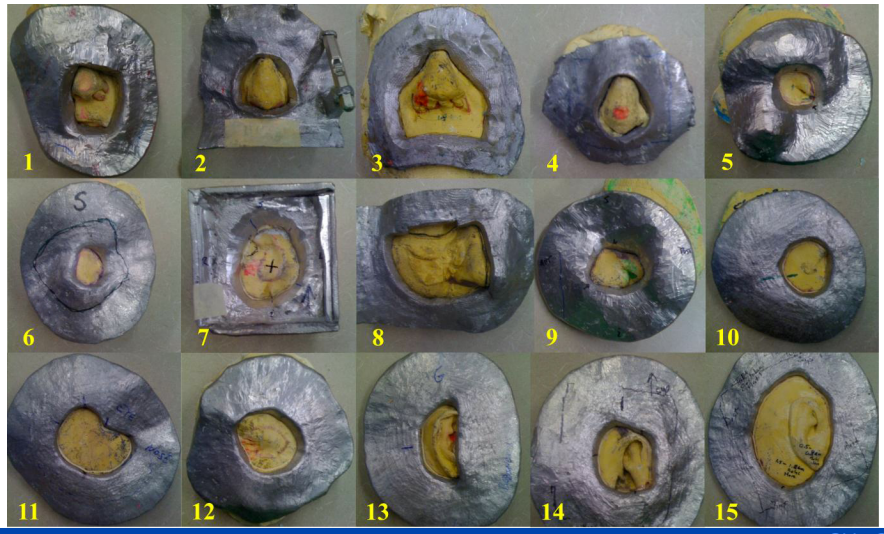


Figure 3.1 from RK Posey MSc thesis, LSU

Skin Collimation Design in Pinnacle

- Bolus tool used to create constant thickness
- Bolus structure converted to normal structure by editing plan files
- Desired cutout manually contoured using BEV margin beam edges
- Cutout contour subtracted from bolus to create skin collimation structure

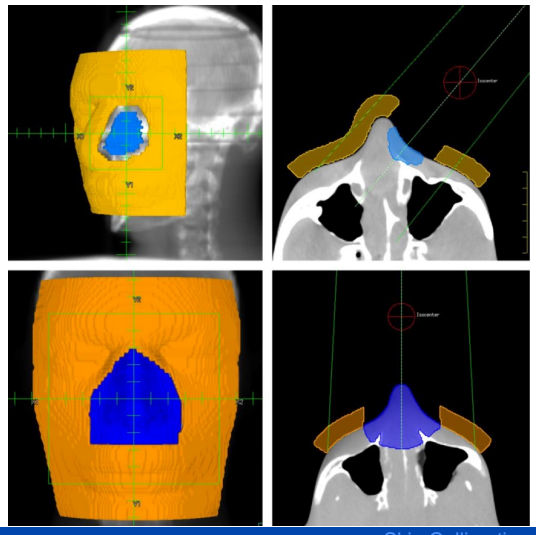


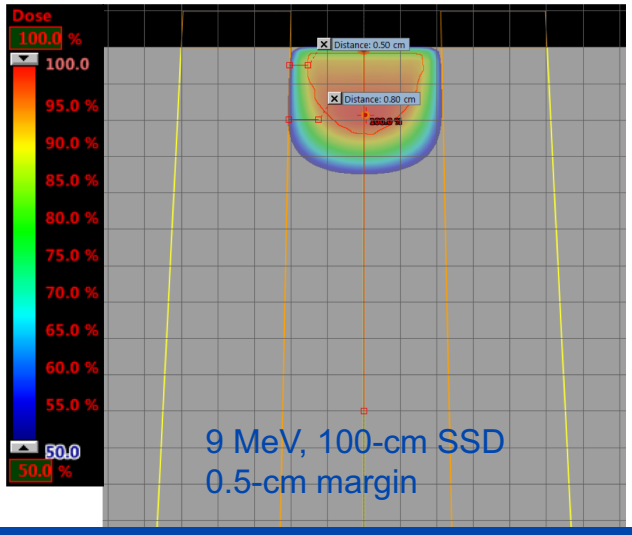
Figure 4.4 from RK Posey MSc thesis, LSU

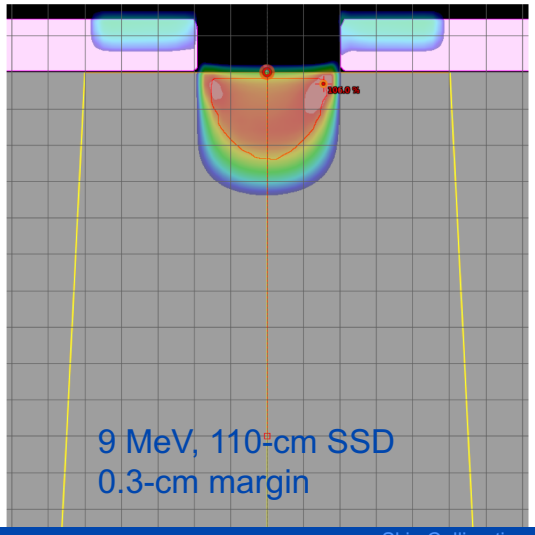
Skin Collimators Fabricated for Research Study

- First column shows brass skin collimators machined by .decimal from Pinnacle design
- Second column is same beam portal, but manually constructed using Cerrobend
- Third column is manually constructed using lead
- Final column is wax dummy machined by .decimal from Pinnacle design

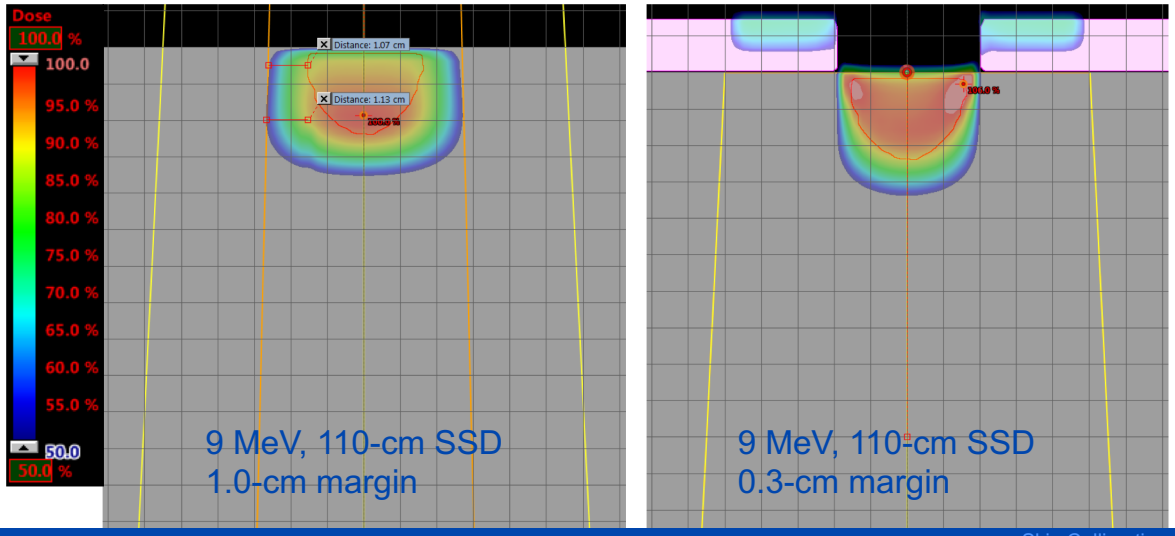
Figure 4.5 from RK Posey MSc thesis, LSU

Skin Collimation Treatment Planning Example





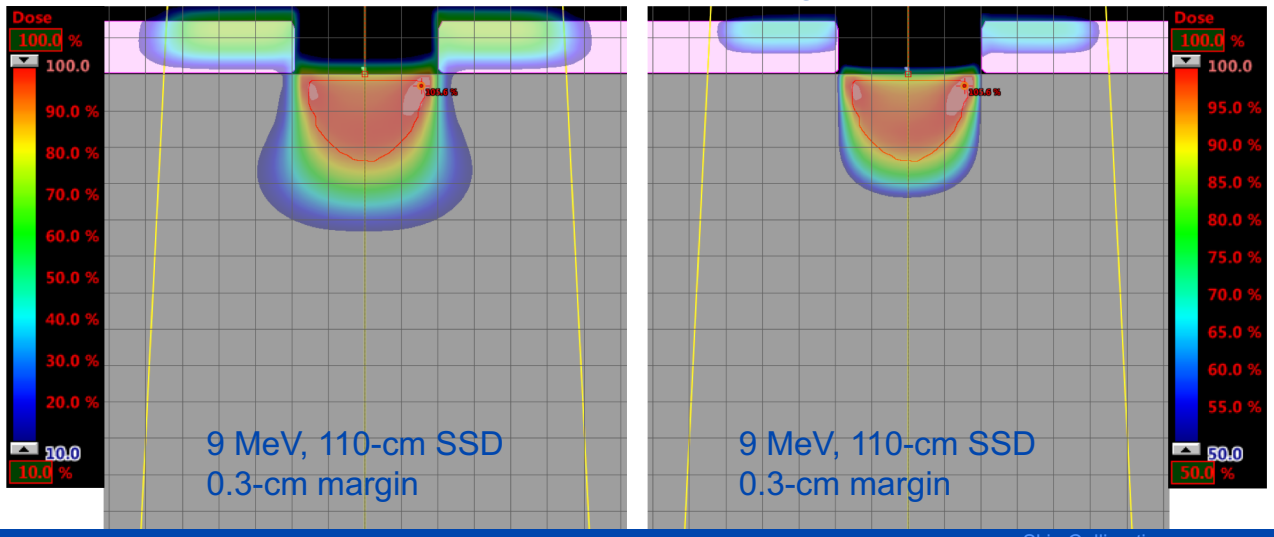
Skin Collimation Treatment Planning Example



MAYO CLINIC

Skin Collimation

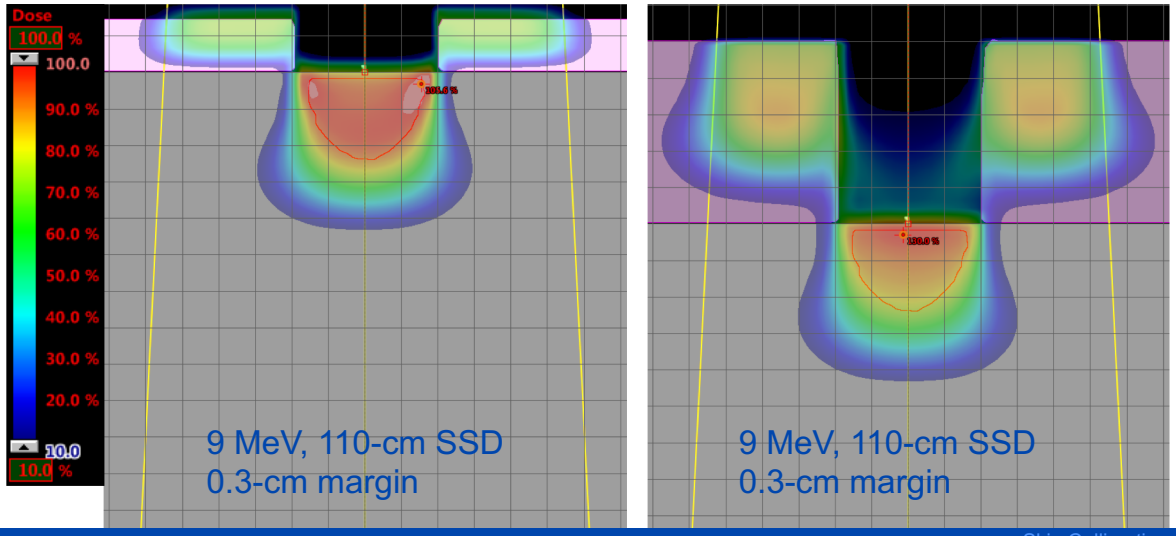
Skin Collimation Treatment Planning Example



MAYO CLINIC

Skin Collimation

Skin Collimation Treatment Planning Example



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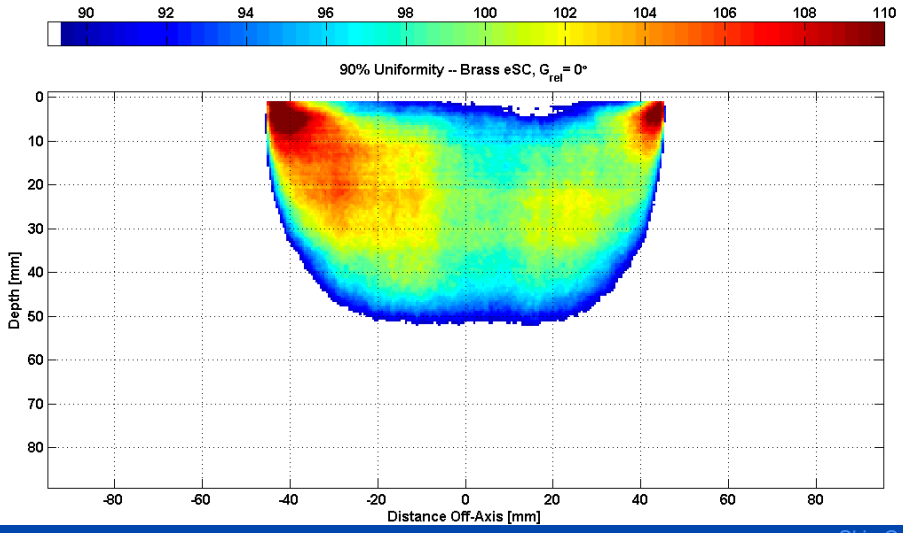
Skin Collimation

Skin Collimation Edge Scatter



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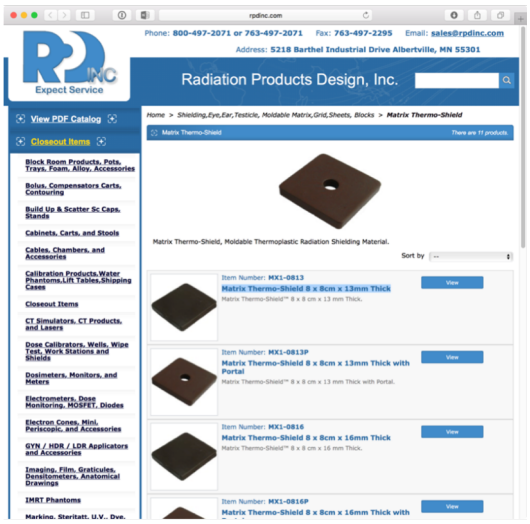
Skin Collimation

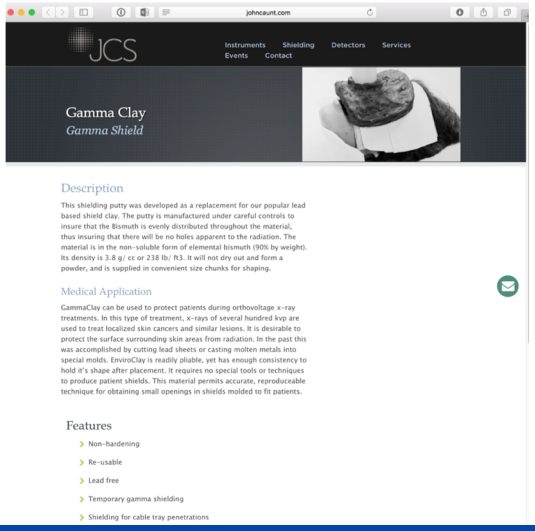
Figure 5.3 from RK Posey MSc thesis, LSU

Moldable shielding material: Matrix Thermo-Shield NOT Recommended for Electrons



- Moldable thermoplastic
- Density of 1.7
  - 2.2 cm water equivalent for nominal 1.3 thick material
  - Not thick enough to stop even 6-MeV electrons

Moldable shielding material: Gamma Clay NOT Recommended for Electrons



- Moldable clay or putty mixed with bismuth
  - Less toxic than lead that was previously used
- Primary uses
  - Shielding for cable penetrations
  - Temporary use during reactor maintenance
  - Industrial radiograph masking
  - They do claim medical uses for Orthovoltage treatments
- Bismuth formulation density is 3.8

Moldable shielding material: Gamma Putty NOT Recommended for Electrons

- Moldable clay or putty mixed with iron
  - Formulations with bismuth or tungsten available
- Primary uses
  - Shielding for cable penetrations
  - Temporary use during reactor maintenance
  - Industrial radiograph masking
  - They do not claim medical uses
- Iron putty density of 2.5

Skin Collimation Treatment Planning Improvements Needed

- Most treatment planning systems can generate uniform thickness bolus
  - Eclipse maximum density is 5
  - Tools for cutting out the beam shape are primitive
- No commercially available manufacturing yet.

Custom Electron Treatment Devices

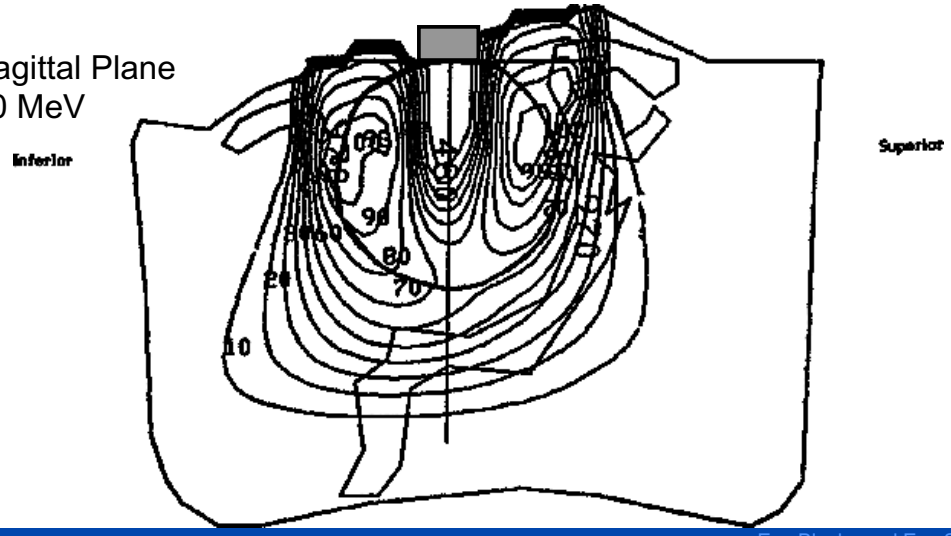
- Applicator Aperture
- Skin Collimation
- Eye blocks and eye shields
- Bolus Electron Conformal Therapy

Utility of Small Blocks

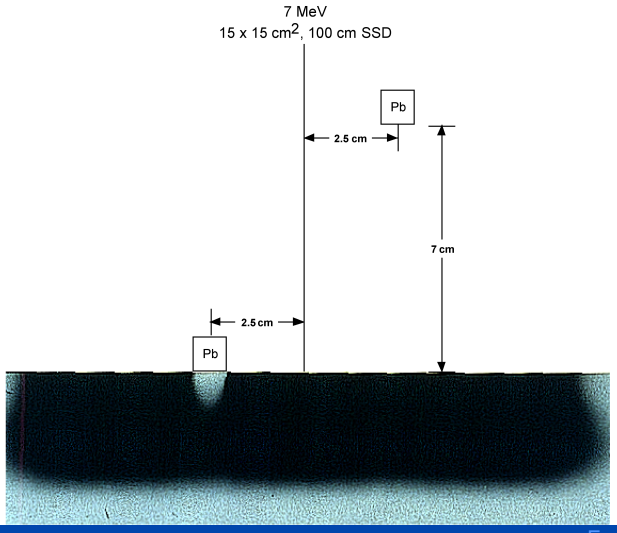
- Useful for protecting superficial structures only (e.g. lens, cornea in treatment of retinoblastoma)
  - Place on patient surface
- Futility of Small Blocks
  - Little or no benefit if air gap present

Utility of Small Blocks
1-cm Block on Eye to Protect Lens

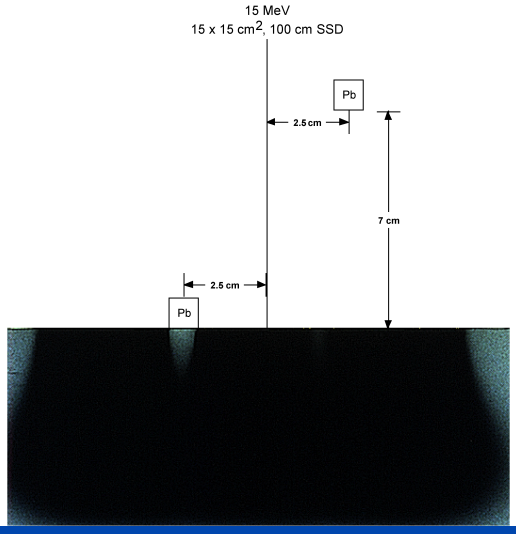
Sagittal Plane
10 MeV



Electron Collimation
Utility/Futility of Small Blocks



Electron Collimation
Utility/Futility of Small Blocks



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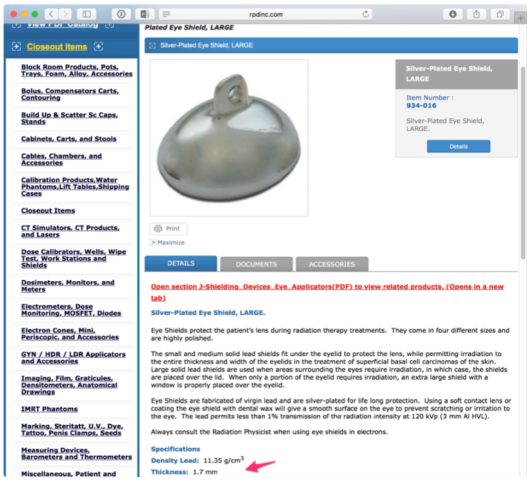
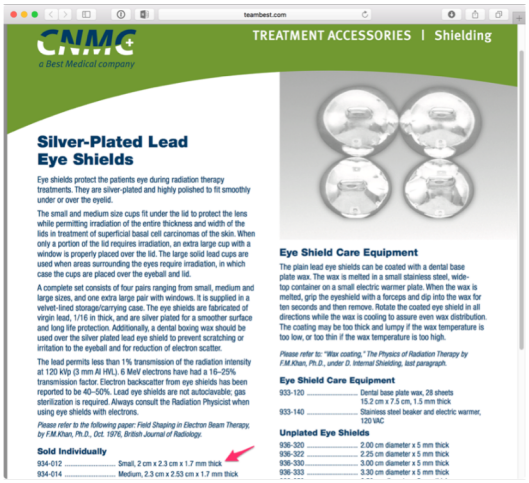
Eye Blocks and Eye Shields

Orthovoltage Eye Shields
Do NOT use for Electron Beams





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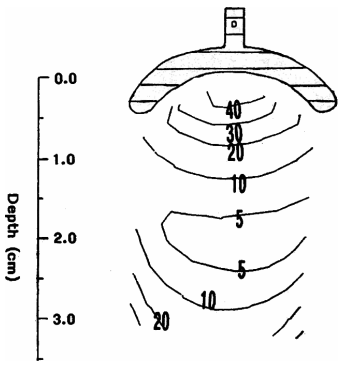
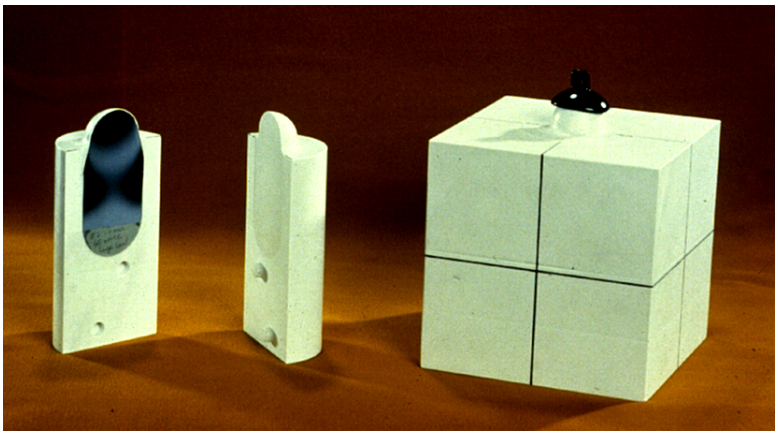
Eye Blocks and Eye Shields

Orthovoltage Eye Shields
Do NOT use for Electron Beams

Shiu et al



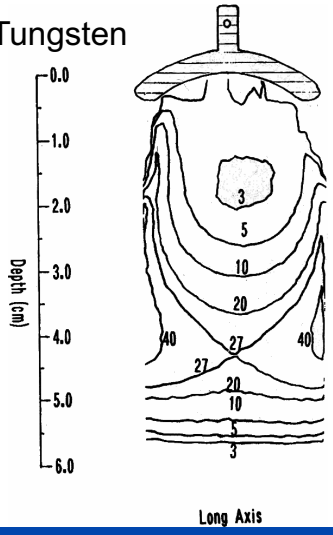


1.7 mm Pb equivalent to 1.9 cm water!

Shiu *et al*, Int. J. Radiat. Oncol. Biol. Phys. **35** (3), 599-604 (1996).

Electron Collimation
Tungsten "Electron" Eye Shield

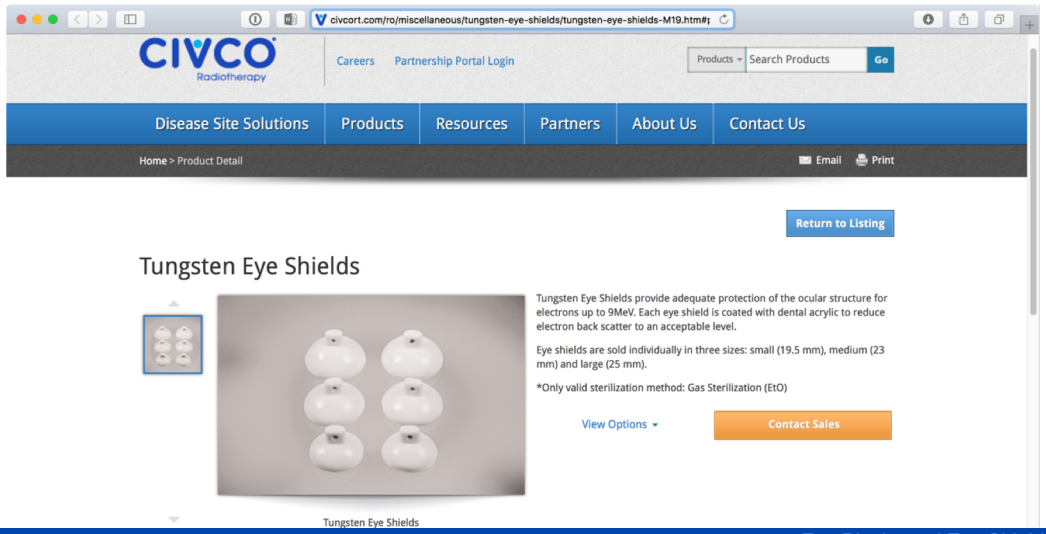
9 MeV - Tungsten



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

Shiu *et al*, Int. J. Radiat. Oncol. Biol. Phys. **35** (3), 599-604 (1996).

Commercial Electron Eye Shields



Eye Blocks and Eye Shields

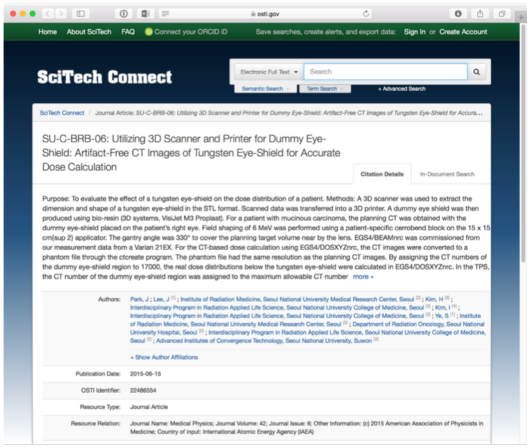
Shiu *et al*, Int. J. Radiat. Oncol. Biol. Phys. **35** (3), 599-604 (1996).

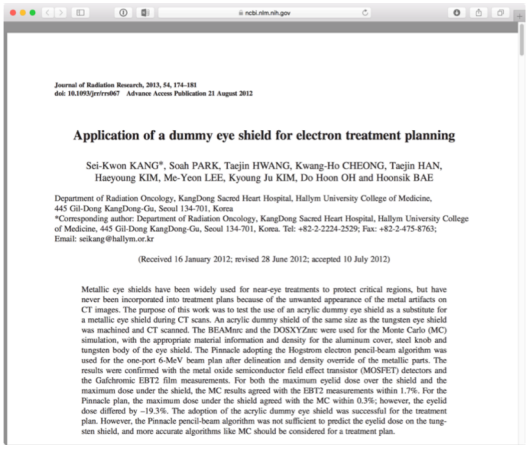
Commercial Electron Eye Shields

Eye Blocks and Eye Shields

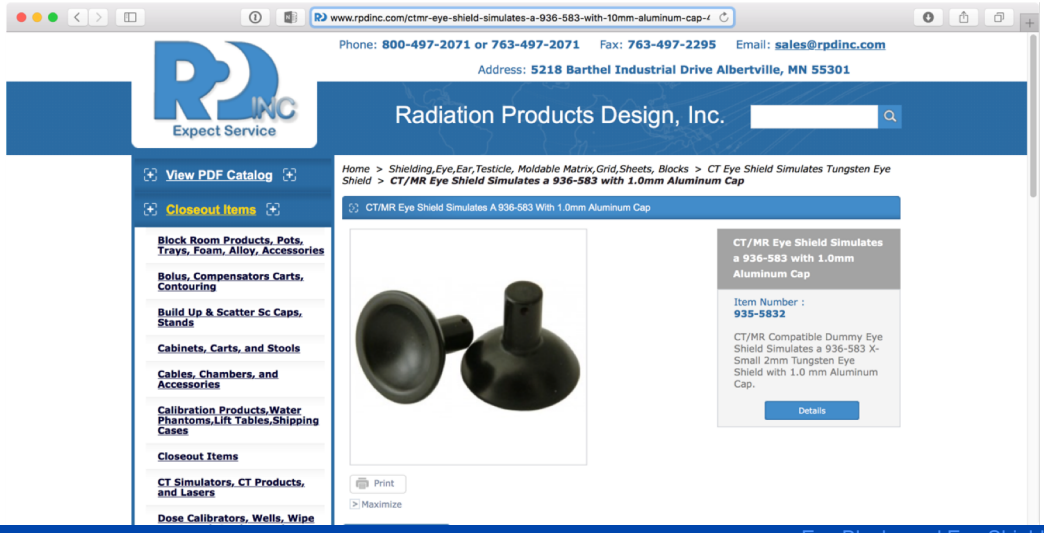
Weaver *et al*, Int. J. Radiat. Oncol. Biol. Phys. **41** (1), 233-237 (1998).

Dummy Eye Shields for Treatment Planning





Dummy Eye Shields for Treatment Planning



Electron Eye Shields: Summary

- Orthovoltage eye shields are NOT suitable for electron beam radiotherapy
- Tungsten eye shields capable of shielding 9-MeV electrons are commercially available
  - Higher energies require very thick custom blocks
- Dummy eye shields can be used to aid treatment planning

Custom Electron Treatment Devices

- Applicator Aperture
- Skin Collimation
- Eye blocks and Eye shields
- Bolus Electron Conformal Therapy