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Personalized Electron Beam Therapy using Custom Treatment Devices

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AAPM Therapy Educational Course
July 31, 2017

Disclosures

- JAA has no conflicts to disclose
- KRH has had research agreements with .decimal, Inc.
- Several commercial products will be mentioned in this presentation.
  - Mention of specific products does not imply endorsement of the product

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Introduction and History

Introduction and History

History of Electron Therapy

Slides courtesy of Kenneth R. Hogstrom, Ph.D.

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Introduction and History

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-

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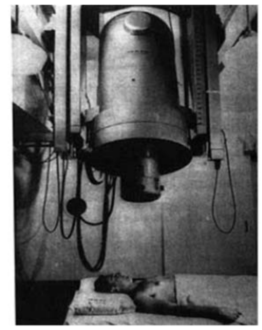
Introduction and History

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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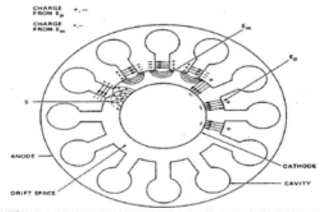
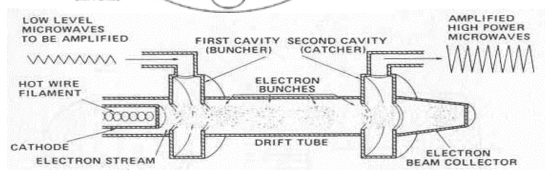
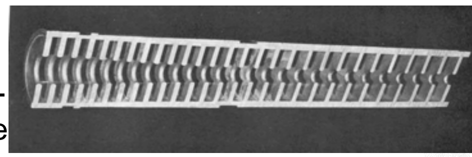
Introduction and History

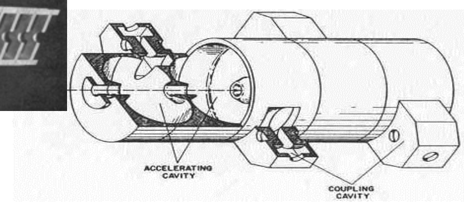
History of Electron Therapy Accelerator Technology

- 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

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Introduction and History

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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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Introduction and History

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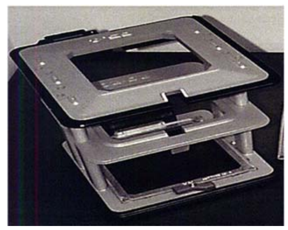
History of Electron Therapy
Accelerator Technology

- 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)

History of Electron Therapy
Dose Calculation & Measurement Technology

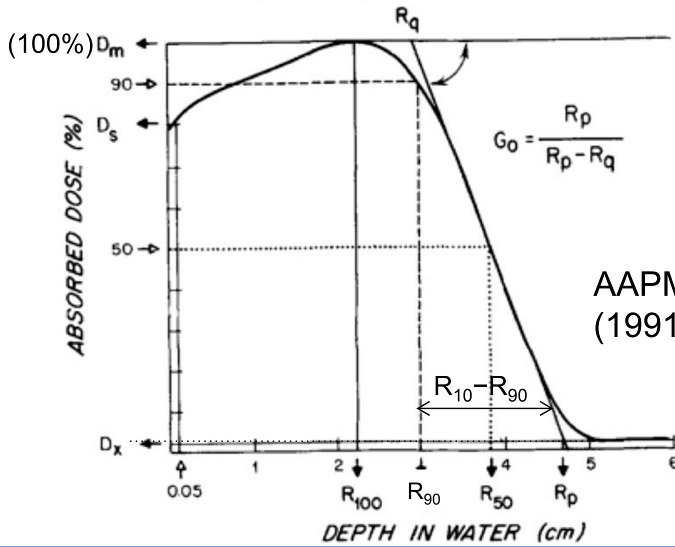
- Electron Transport and Dose Calculations
  - Analytical: Fermi-Eyges Theory (1980s) and ICRU 35 (1984)
  - Monte Carlo: EGS4, BEAM, DOSXYZ (1985-1995)
- Treatment Planning
  - CT-Based Planning: GE Target TPS (1981)
  - Pencil-beam Dose Calculations: GE Target TPS (1983)
  - 3D Treatment Planning Systems (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)

Review of Basic Electron Dosimetry

Primary Electron Interactions
5-25 MeV

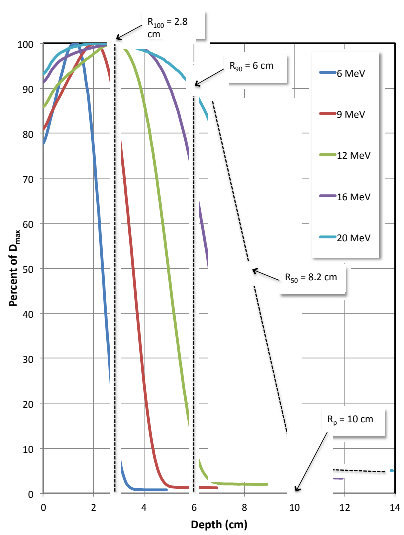
- Collisional energy loss
  - Electron - electron interactions
- Multiple Coulomb scattering
  - Electron - nuclear interactions

Percent Depth Dose (PDD)



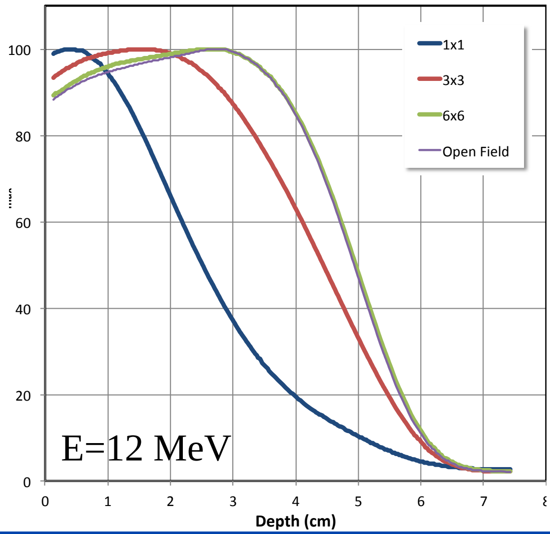
AAPM TG-25 Report (1991)

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

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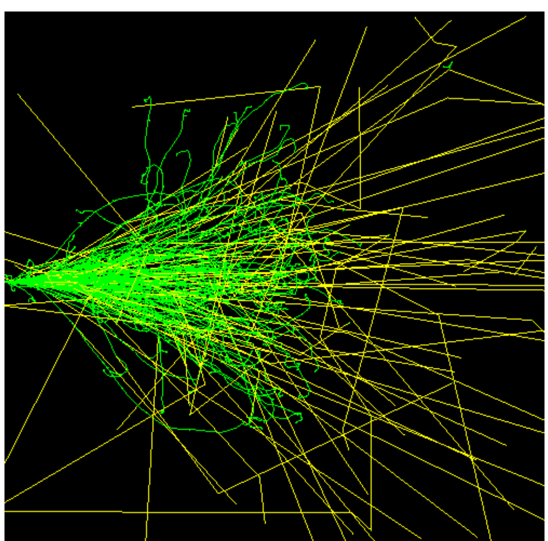
Review of Basic Electron Dosimetry

10 MeV Electrons in Water



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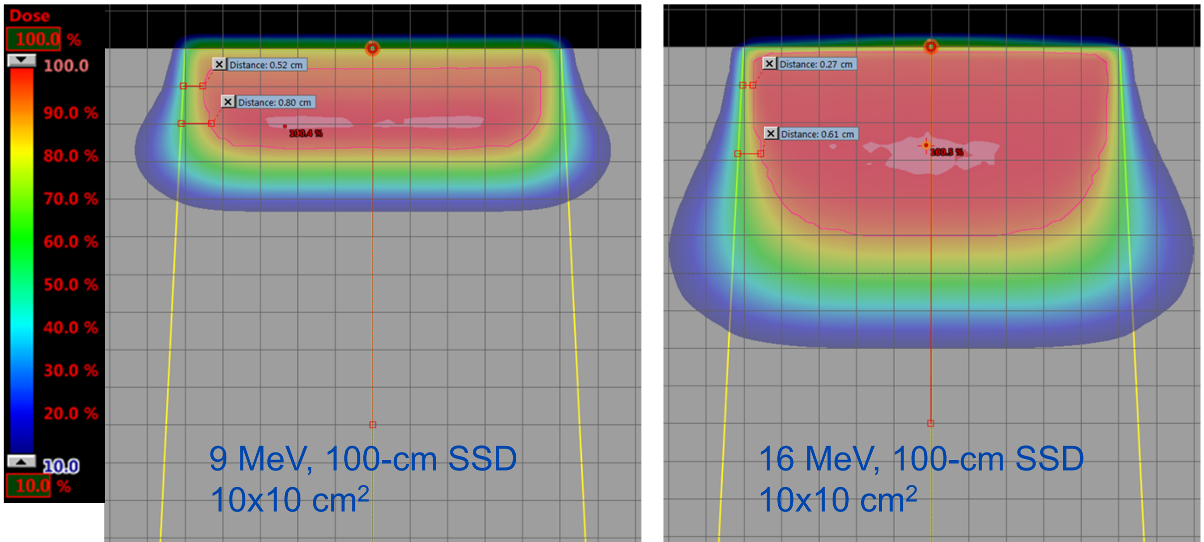
Review of Basic Electron Dosimetry

Electron Dose Distributions
Energy Dependence of Penumbra



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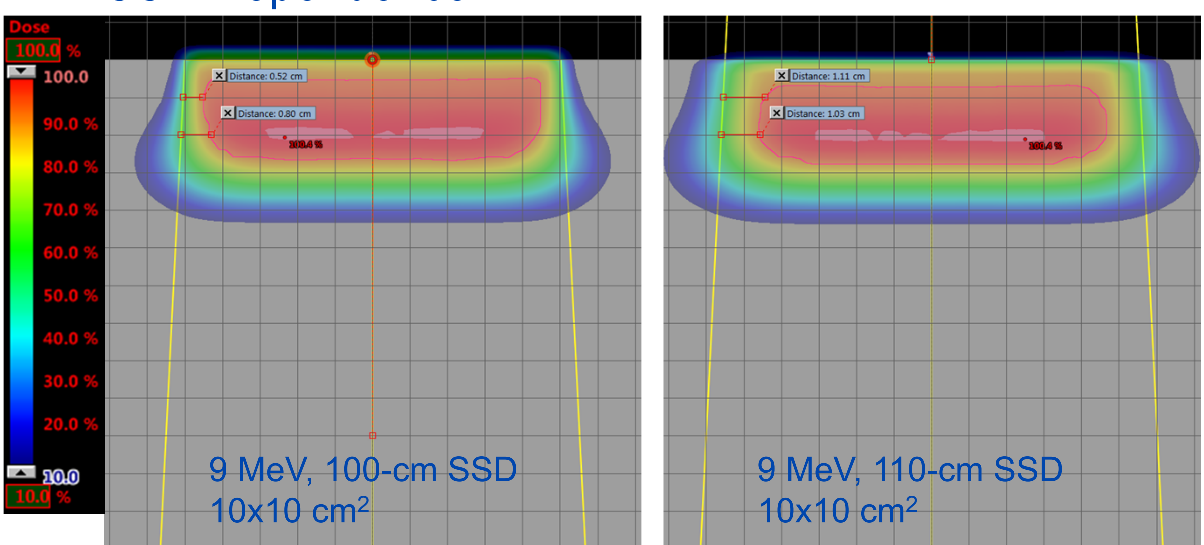
Review of Basic Electron Dosimetry

Electron Dose Distributions
SSD Dependence



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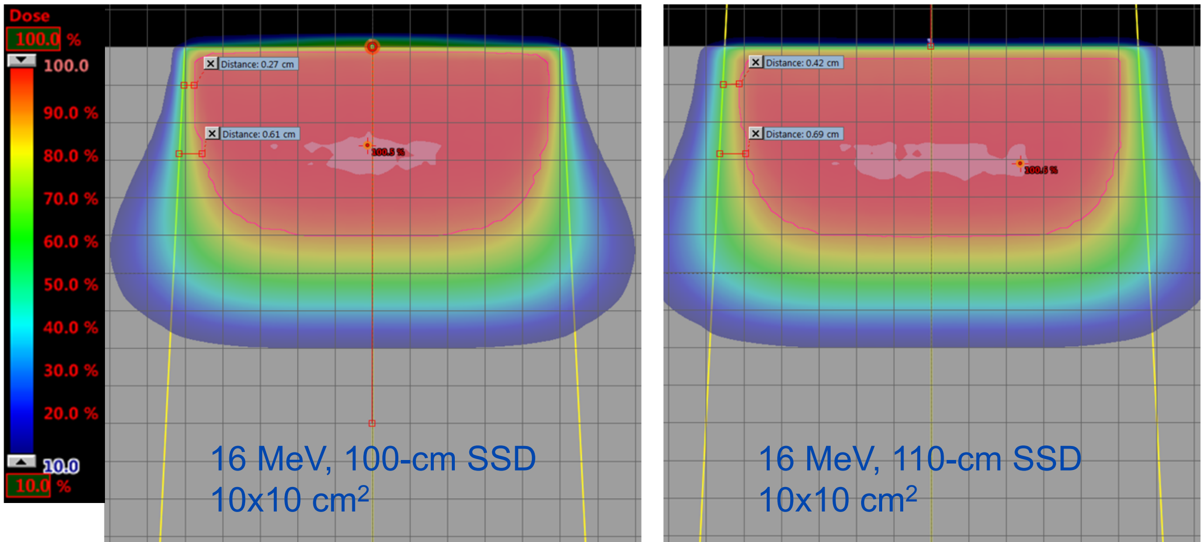
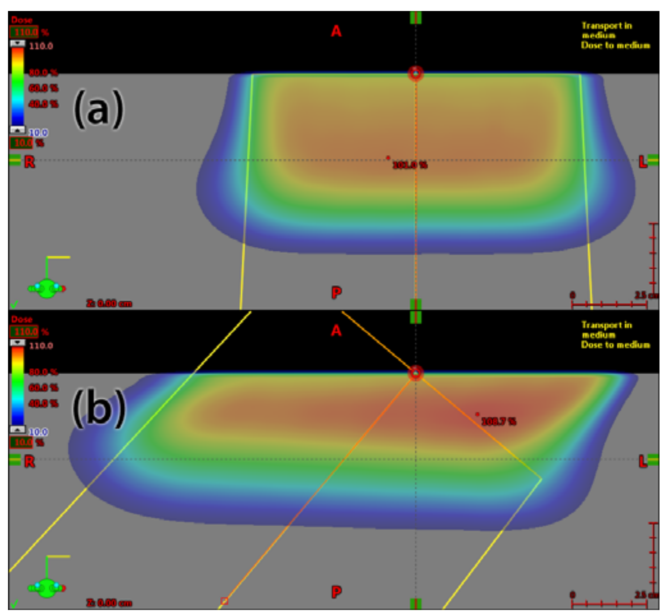
Review of Basic Electron Dosimetry

Electron Dose Distributions
SSD Dependence



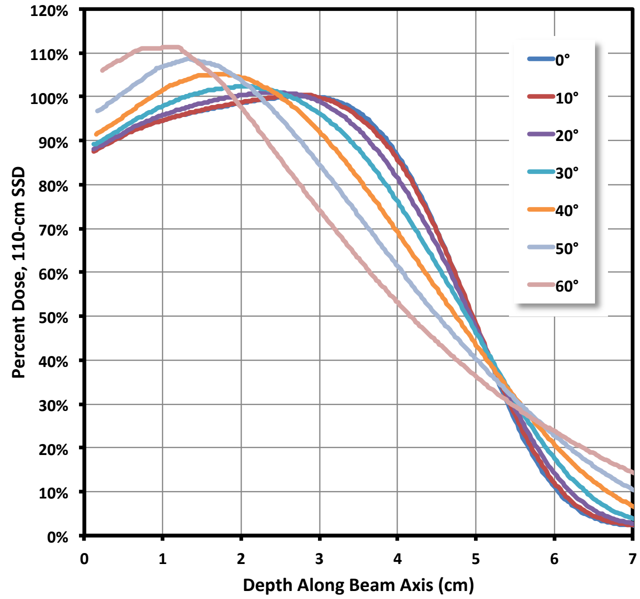
Electron Dose Distributions
Oblique Incidence

- 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



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Review of Basic Electron Dosimetry

Electron Dose Distributions Oblique Incidence

- 12-MeV, 10x10 cm^2, 110-cm SSD
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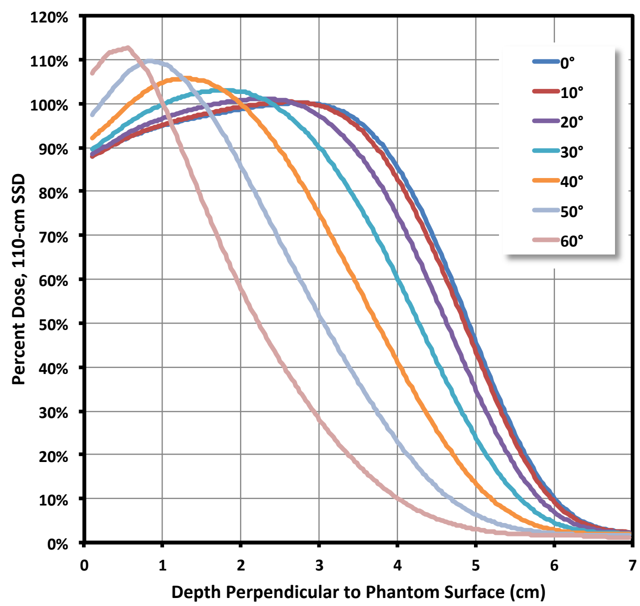

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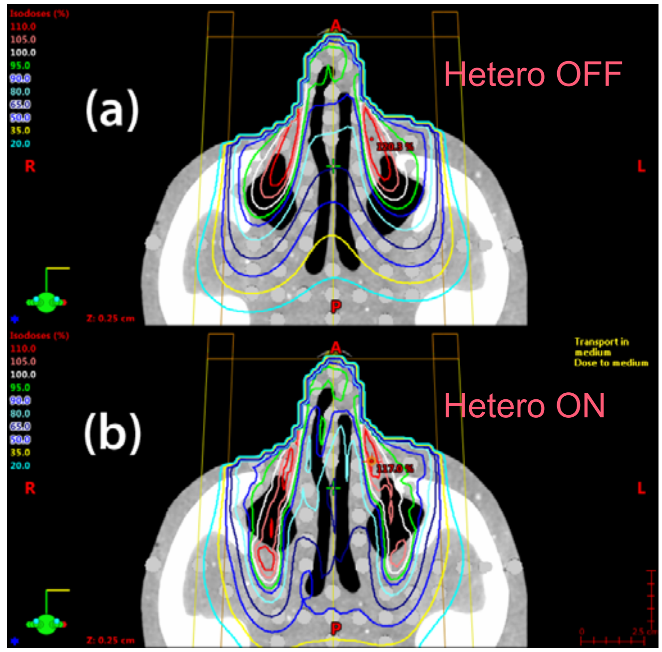
Review of Basic Electron Dosimetry

Electron Dose Distributions Heterogeneities

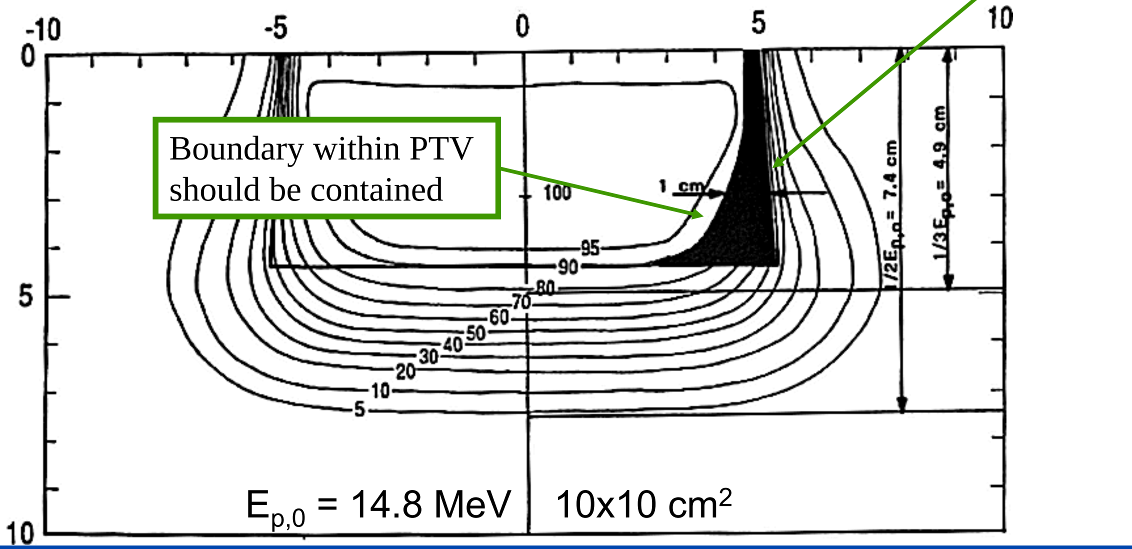
- 16-MeV 8×8 cm² field at 100-cm SSD
- Significant dose effects due to surface irregularities
- Internal heterogeneities make things even more complicated
- Important to know if your planning system can handle these effects



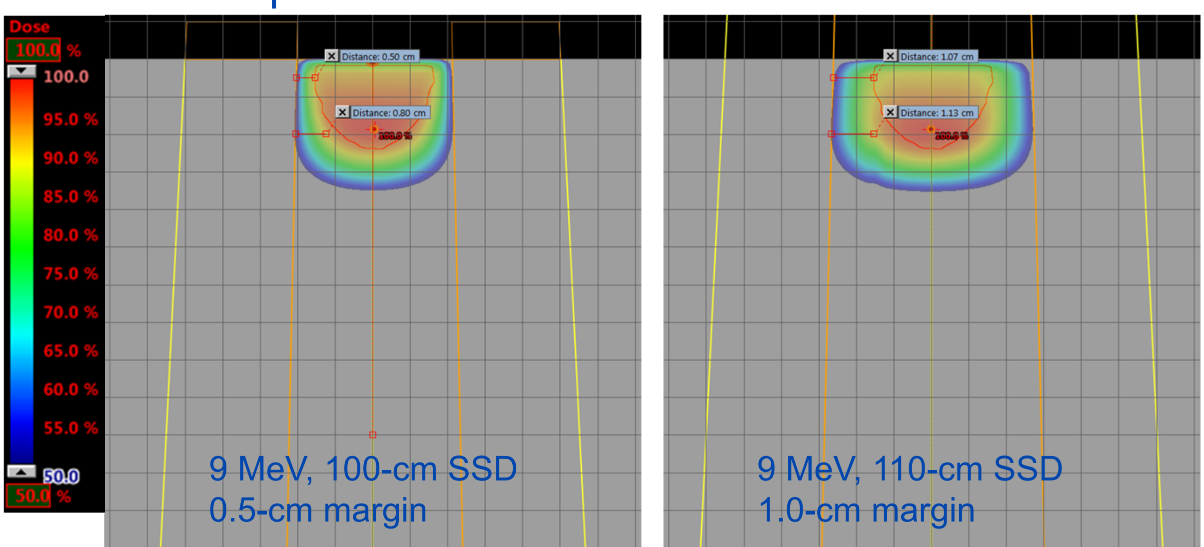
Custom Electron Treatment Devices

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

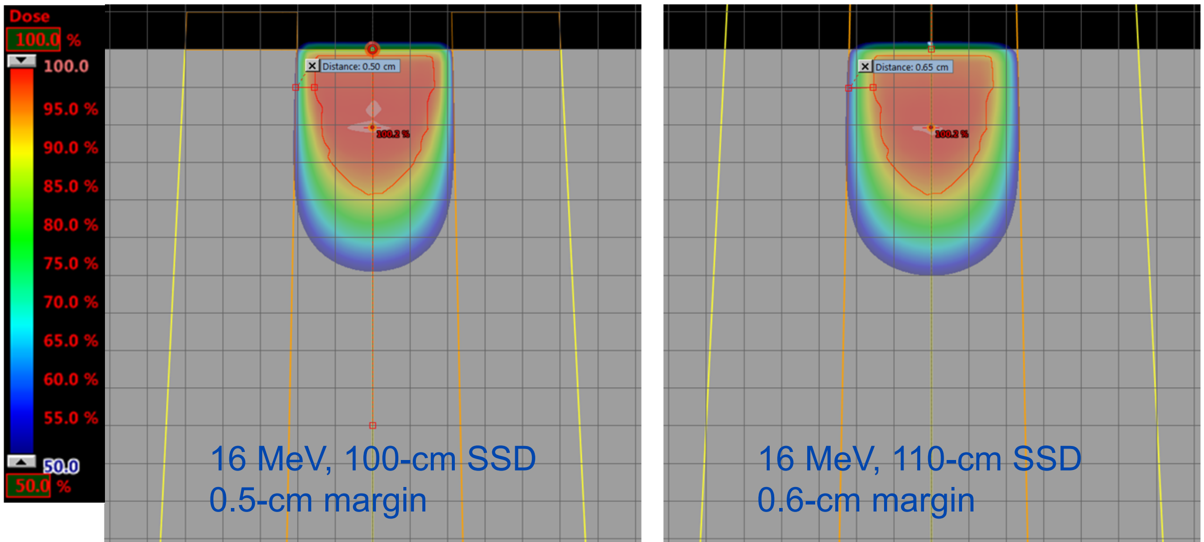
Electron Collimation:
Basic Rule for Target-Portal Margin



Electron Dose Distributions
SSD Dependence



Electron Dose Distributions
SSD Dependence



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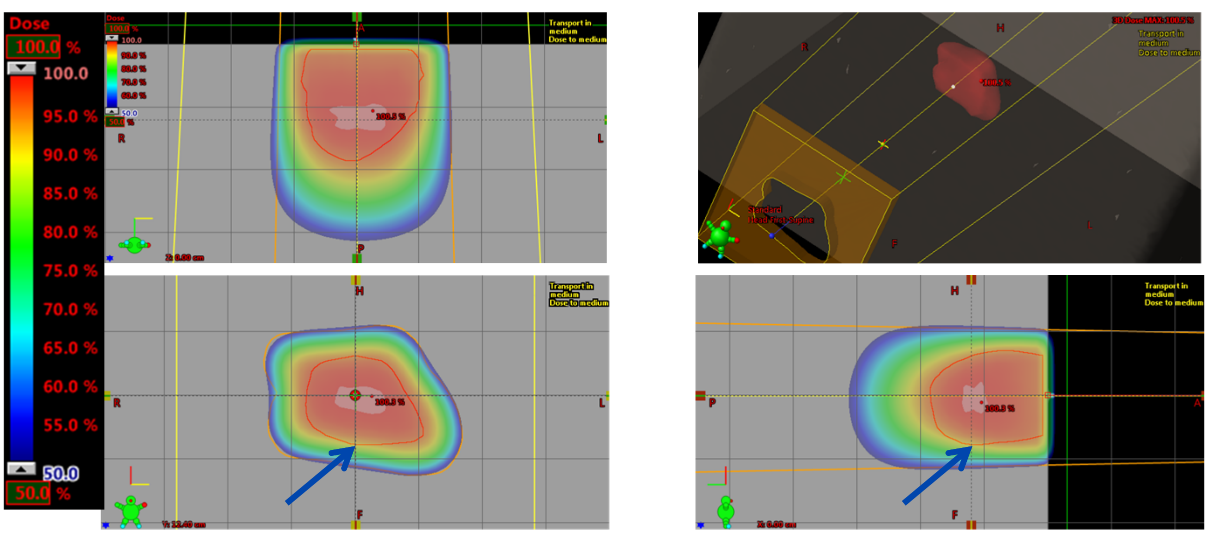
Applicator Aperture

Limitations of Uniform Margin Expansion



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Applicator Aperture

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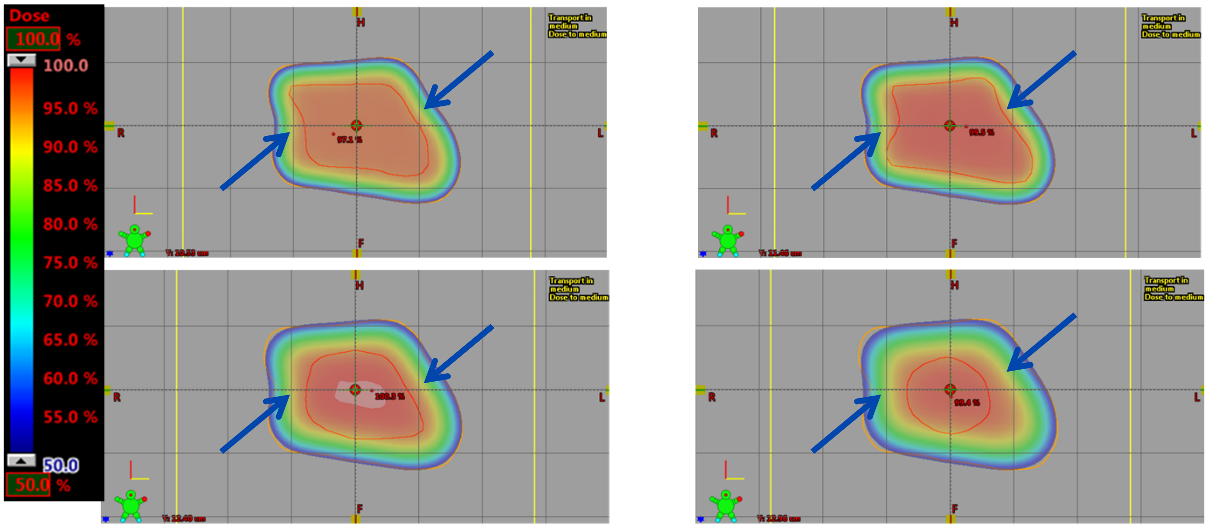
Limitations of Uniform Margin Expansion



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Applicator Aperture

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

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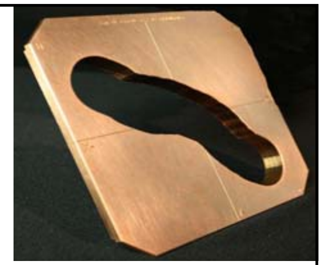
Applicator Aperture

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/

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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

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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

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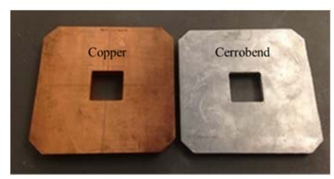
Applicator Aperture

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



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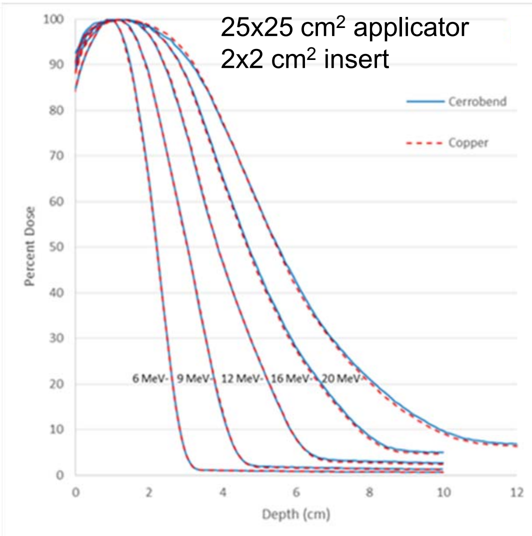
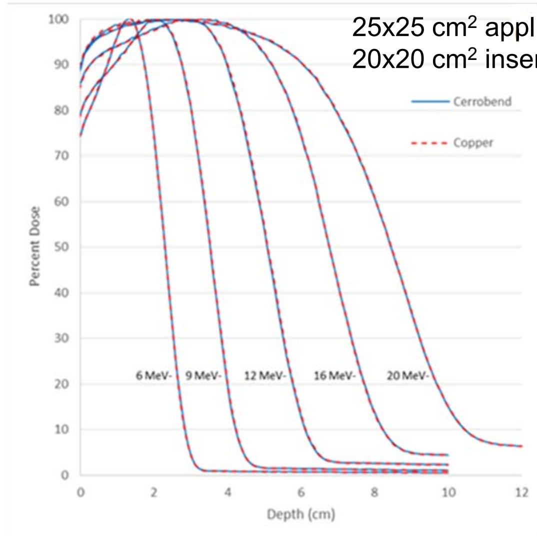
Applicator Aperture

B. D. Rusk MSc thesis, LSU

Percent Depth Dose Results: Copper vs Cerrobend

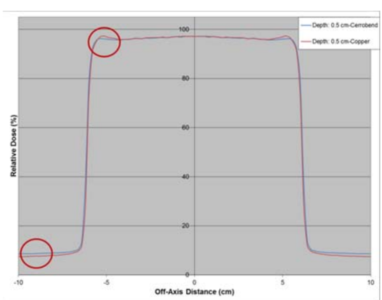


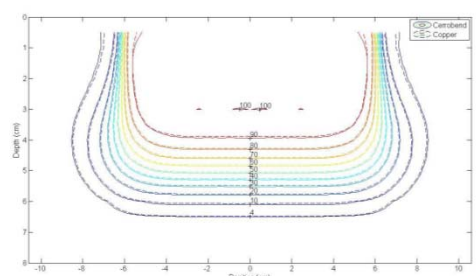


Applicator Aperture

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

Applicator Aperture

B. D. Rusk MSc thesis, LSU

Applicator Aperture

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

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Skin Collimation

Utility of Skin Collimation

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

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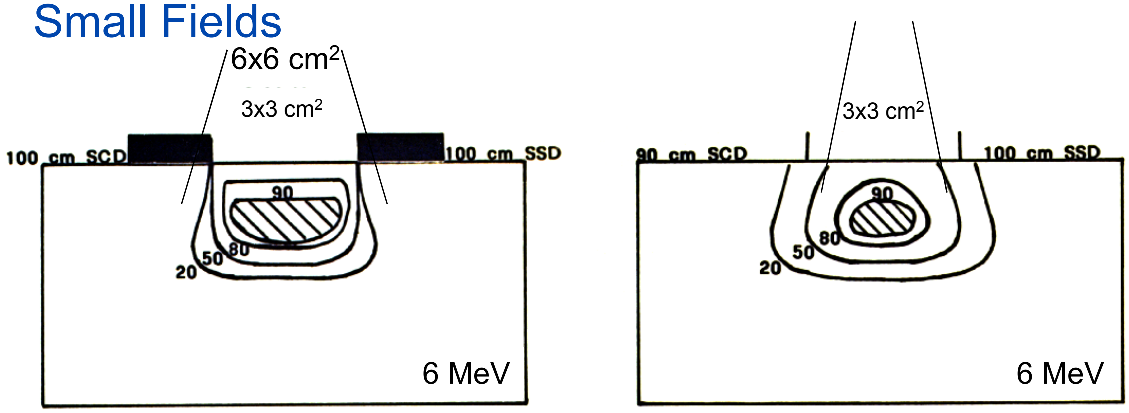
Skin Collimation

Utility of Skin Collimation
Small Fields



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

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Skin Collimation

Utility of Skin Collimation
Protection of Critical Structures

- Example: Maximum protection of eyes

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Skin Collimation

Skin Collimation Clinical Examples

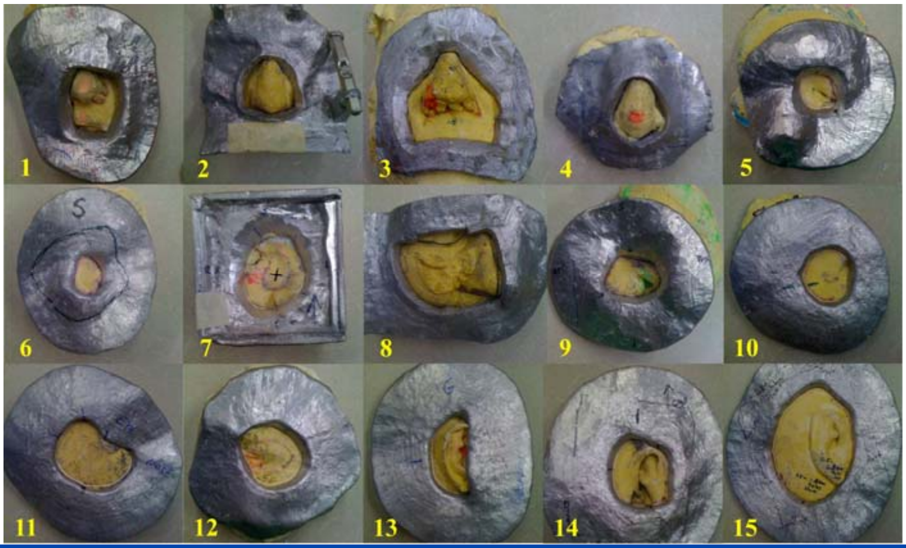


Figure 3.1 from RK Posey MSc thesis, LSU

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

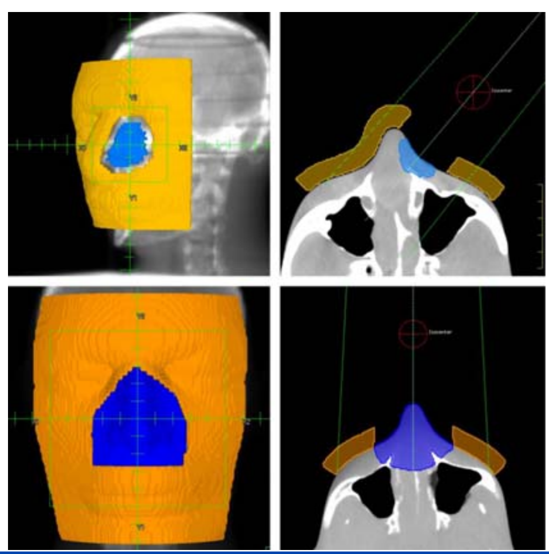


Figure 4.4 from RK Posey MSc thesis, LSU

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

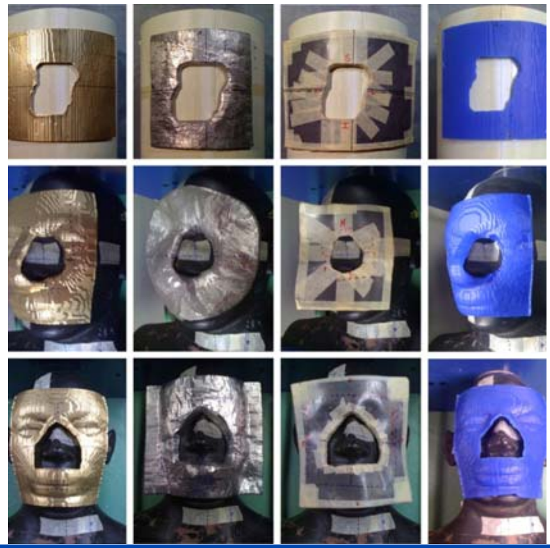
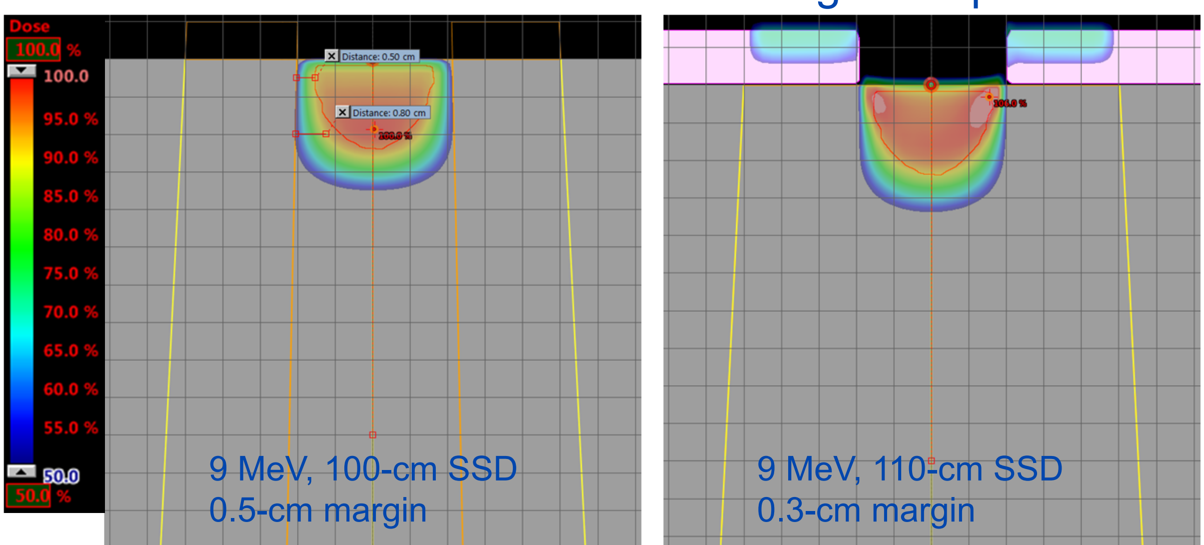
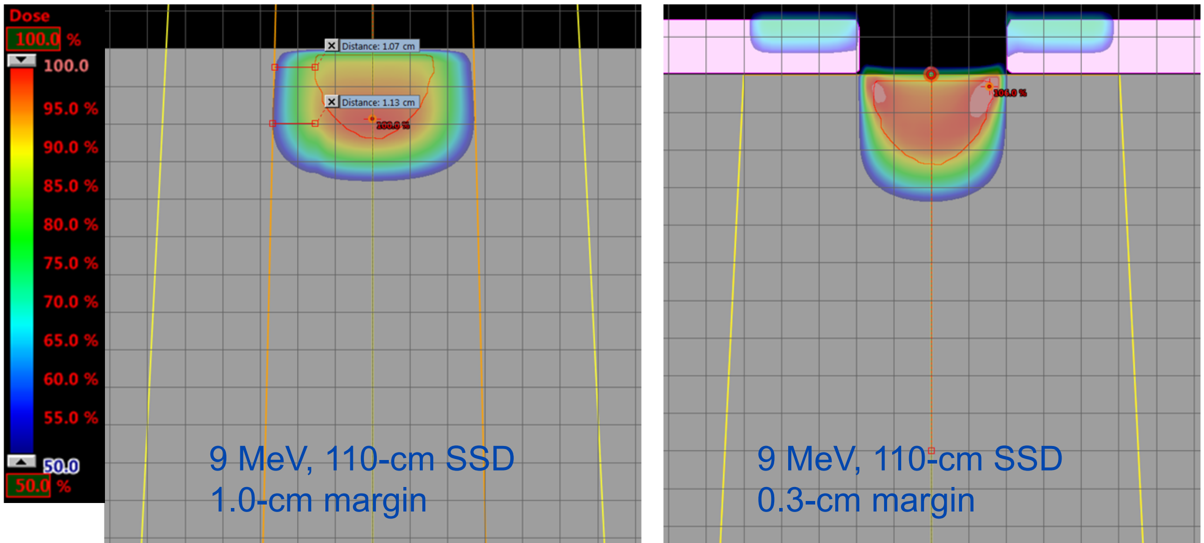


Figure 4.5 from RK Posey MSc thesis, LSU

Skin Collimation Treatment Planning Example



Skin Collimation Treatment Planning Example



Skin Collimation

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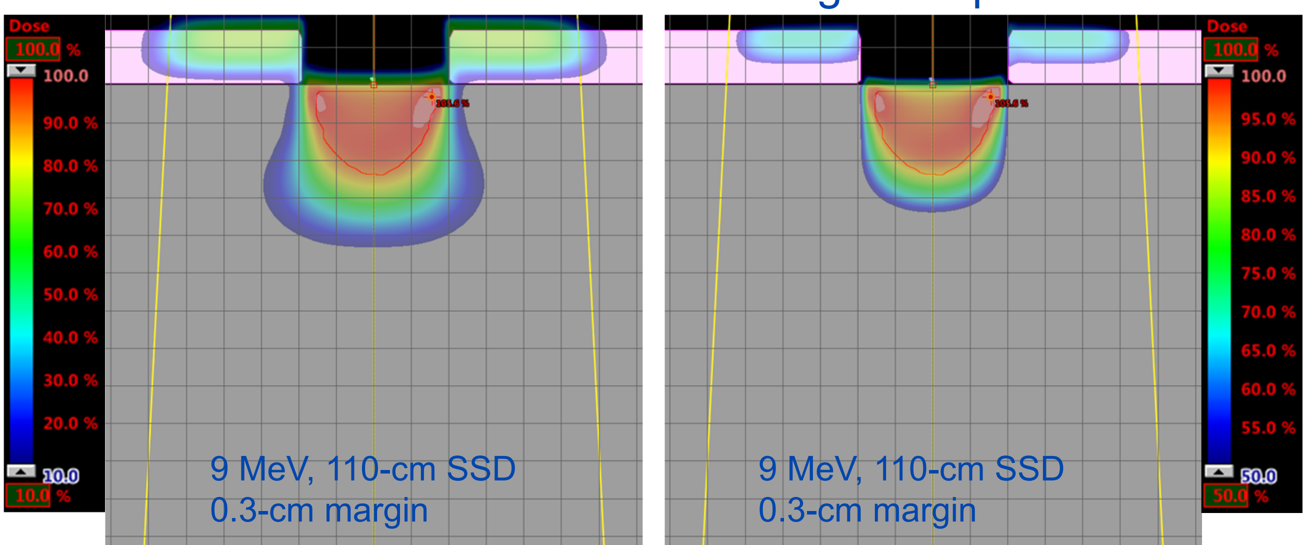
Skin Collimation Treatment Planning Example



Skin Collimation

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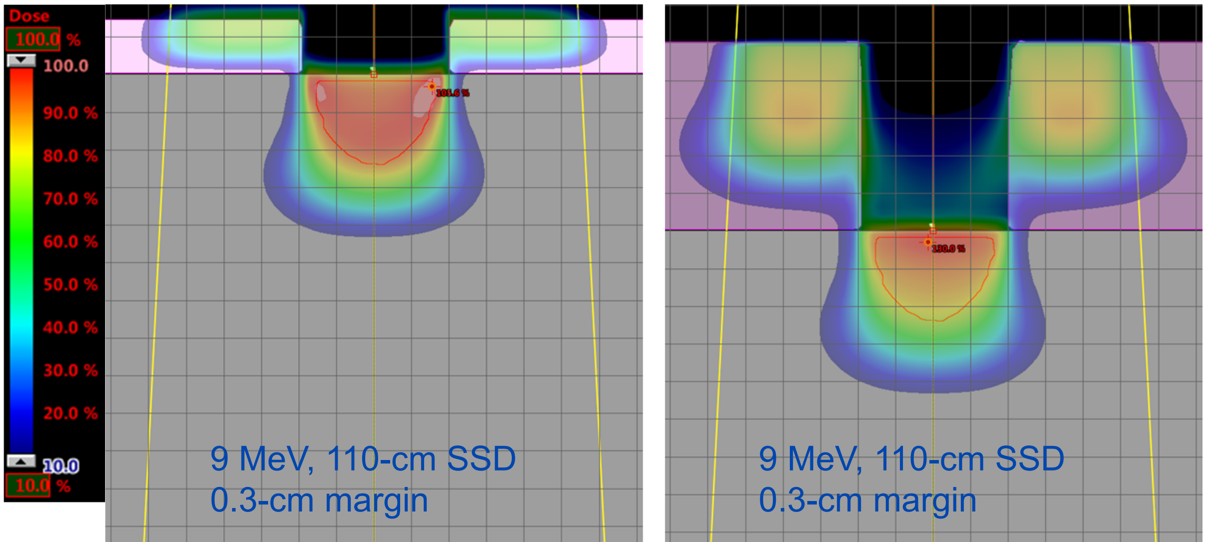
Skin Collimation Treatment Planning Example



Skin Collimation Edge Scatter

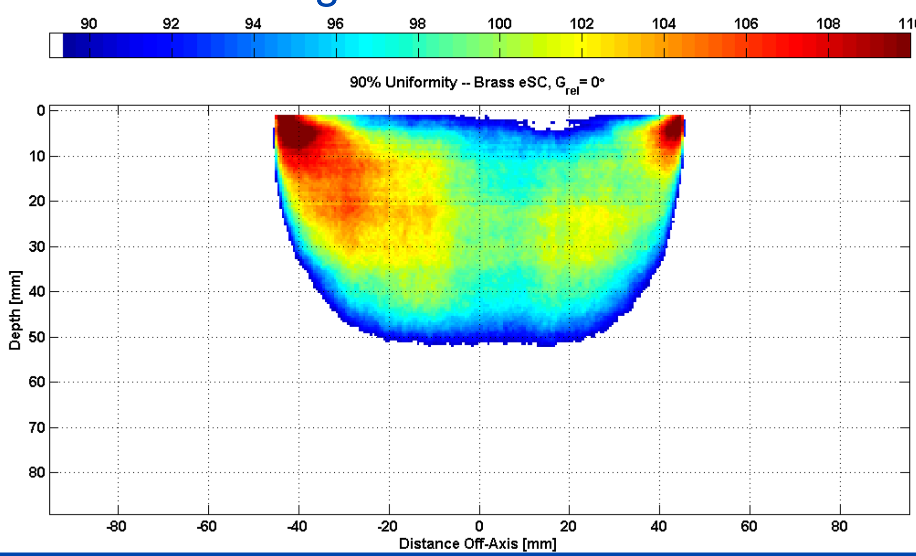
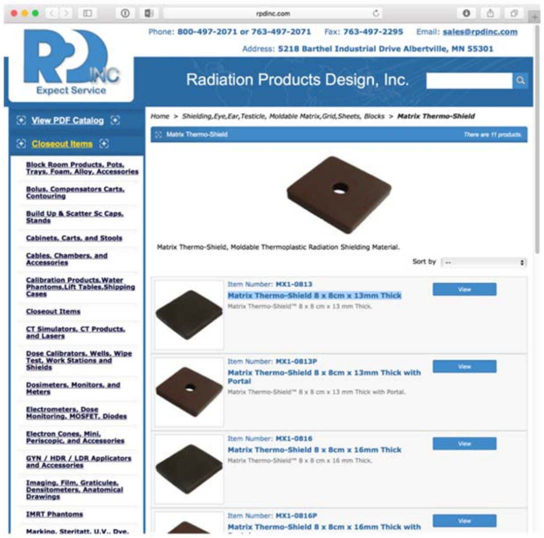


Figure 5.3 from RK Posey MSc thesis, LSU

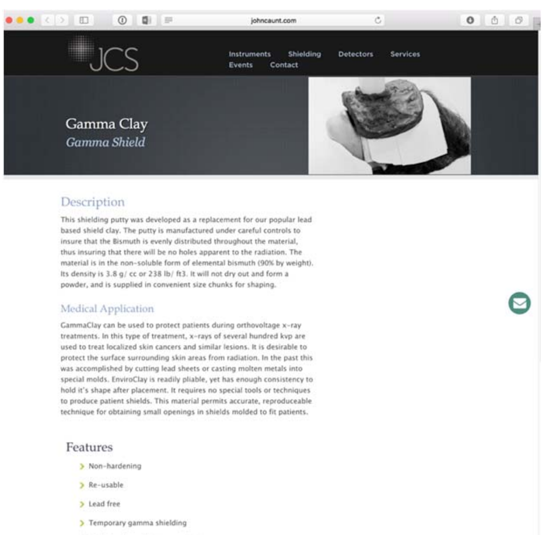
Skin Collimation

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

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Eye Blocks and Eye Shields

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

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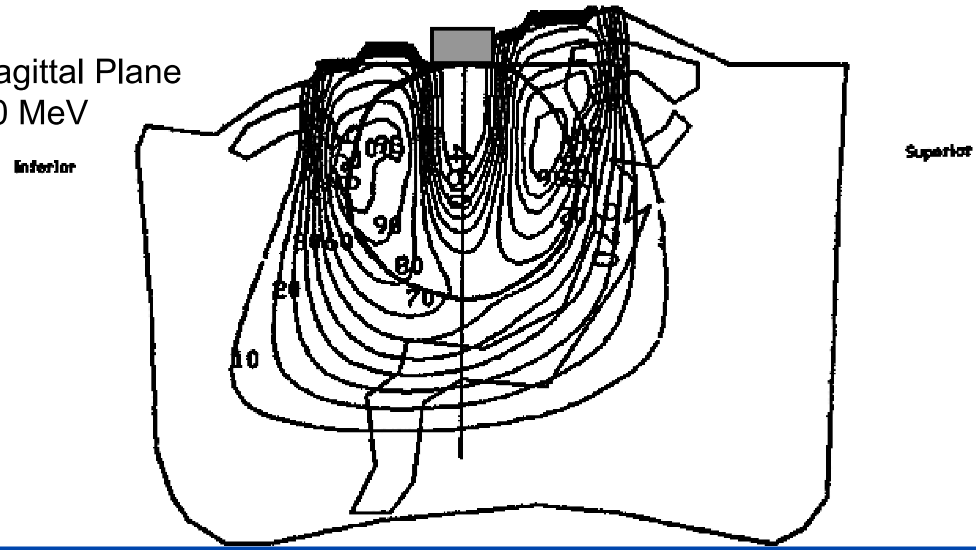
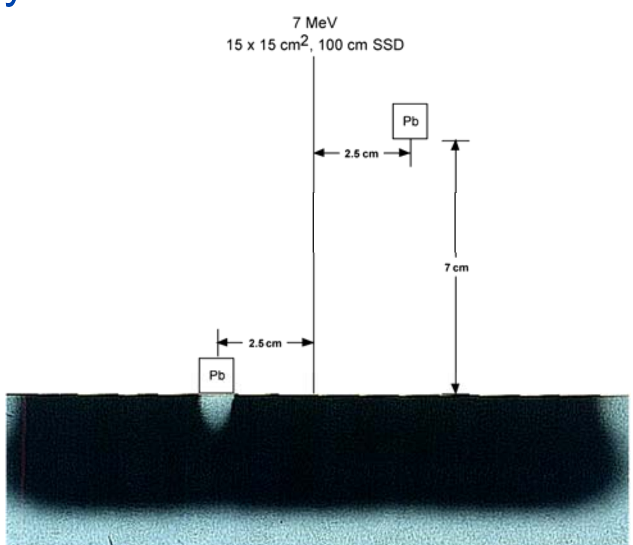
Eye Blocks and Eye Shields

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

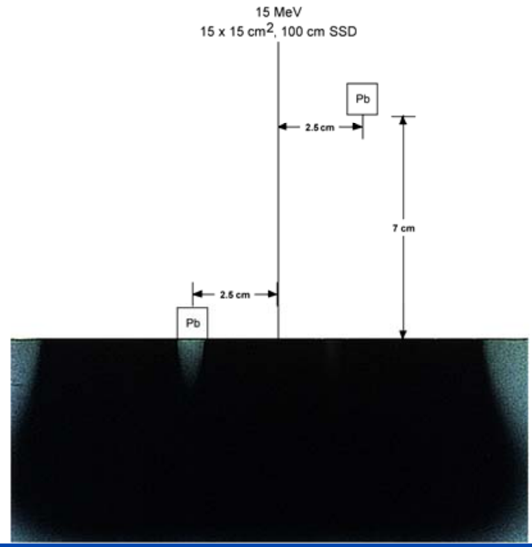
Sagittal Plane
10 MeV



Electron Collimation
Utility/Futility of Small Blocks



Electron Collimation
Utility/Futility of Small Blocks



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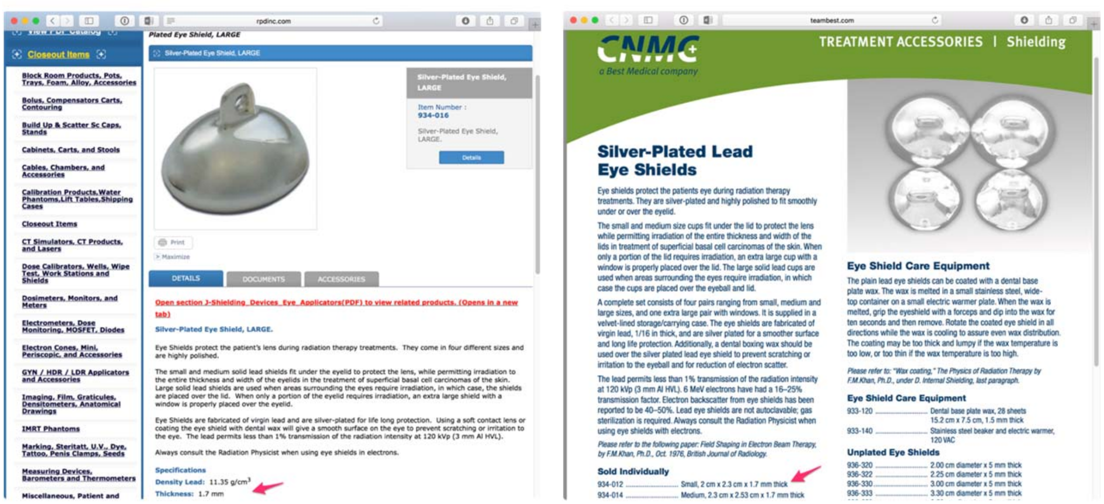
Eye Blocks and Eye Shields

Orthovoltage Eye Shields
Do NOT use for Electron Beams



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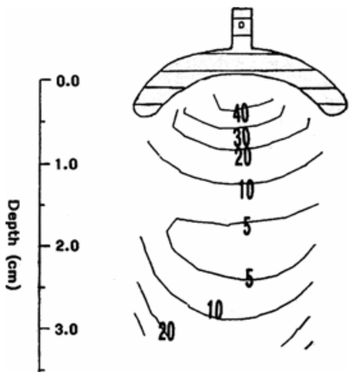
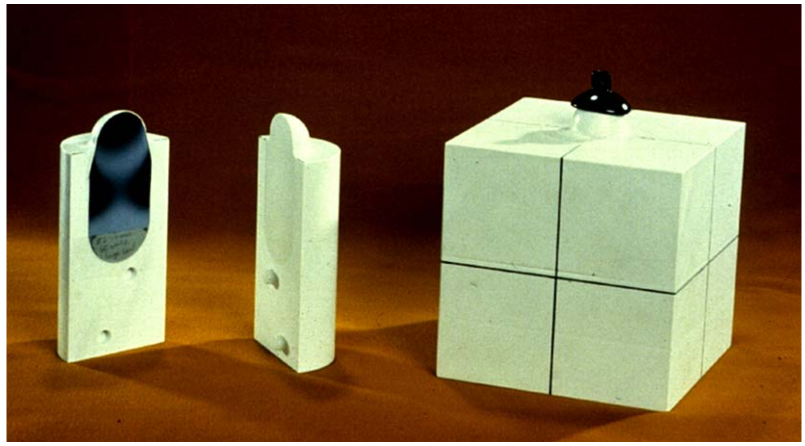
Eye Blocks and Eye Shields

Orthovoltage Eye Shields
Do NOT use for Electron Beams

Shiu et al





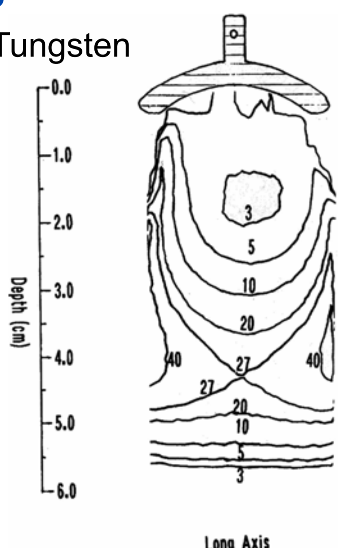
1.7 mm Pb equivalent to 1.9 cm water!

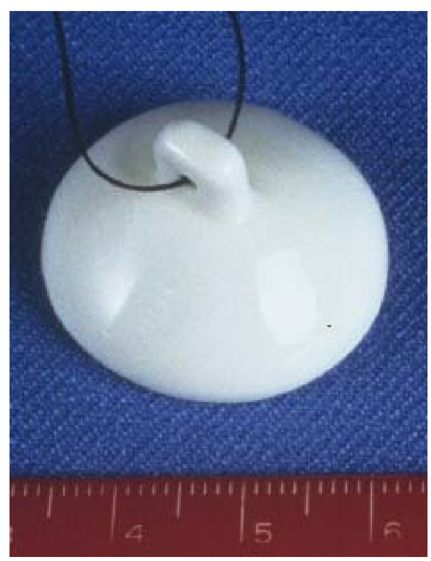
Eye Blocks and Eye Shields

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

Electron Collimation
Tungsten "Electron" Eye Shield

9 MeV - Tungsten



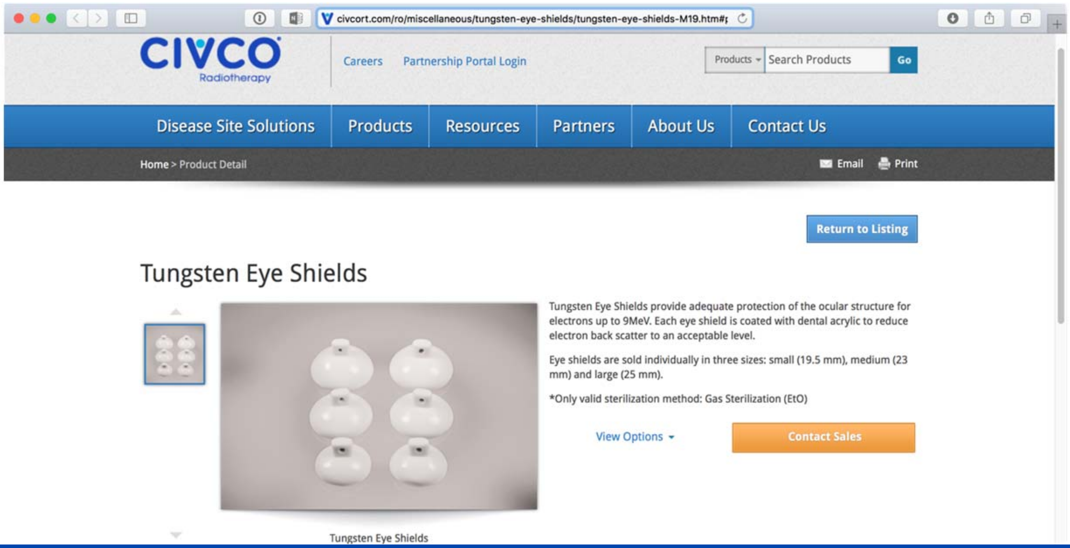


Tungsten rather than lead eye shields should be used for 6-9 MeV electrons.

Eye Blocks and Eye Shields

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

Commercial Electron Eye Shields



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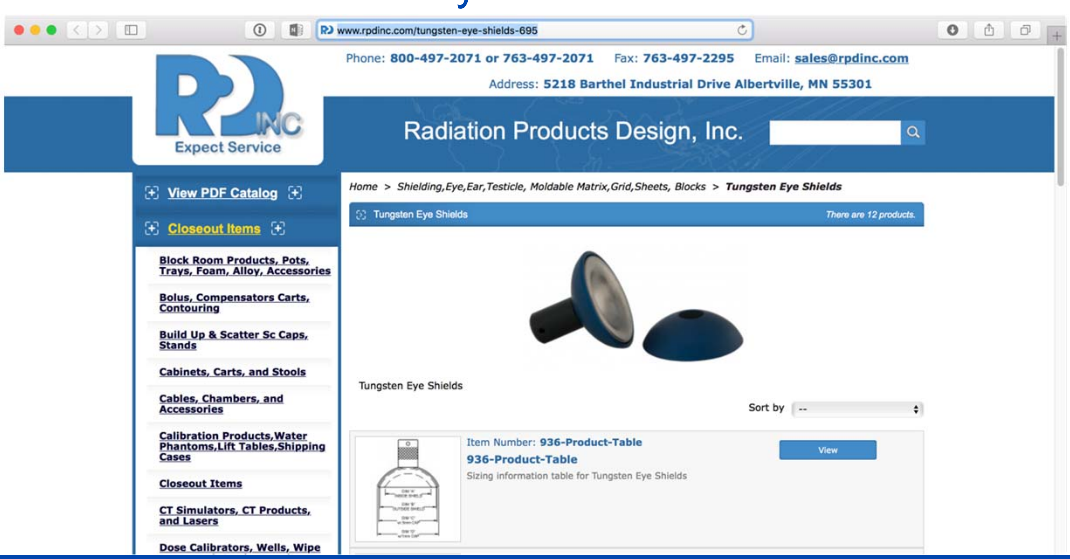
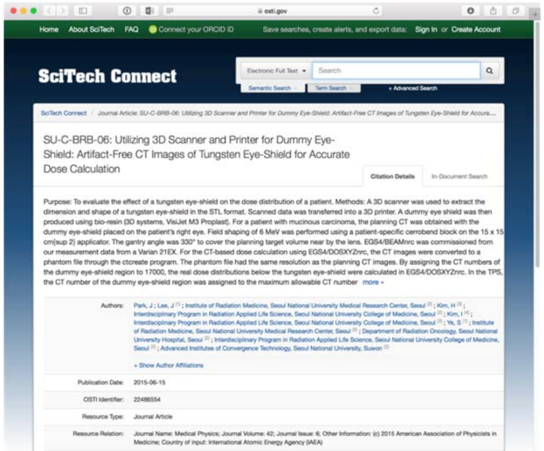
Commercial Electron Eye Shields



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



ncbi.nlm.nih.gov

Journal of Radiation Research, 2013, 54, 174–181
doi: 10.1093/jrr/rrs067 Advance Access Publication 21 August 2012

Application of a dummy eye shield for electron treatment planning

Sei-Kwon KANG*, Soah PARK, Taejin HWANG, Kwang-Ho CHEONG, Taejin HAN, Haeyoung KIM, Me-Yeon LEE, Kyoung Ju KIM, Do Hoon OH and Hoonsik BAE

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(Received 16 January 2012; revised 28 June 2012; accepted 10 July 2012)

Metallic eye shields have been widely used for near-eye treatments to protect critical regions, but have never been incorporated into treatment plans because of the unwanted appearance of the metal artifacts on CT images. The purpose of this work was to test the use of an acrylic dummy eye shield as a substitute for a metallic eye shield during CT scans. An acrylic dummy shield of the same size as the tungsten eye shield was machined and CT scanned. The BEAMnrc and the DOSXYZnrc were used for the Monte Carlo (MC) simulation, with the appropriate material information and density for the aluminum cover, steel knob and tungsten body of the eye shield. The Pinnacle adopting the Hogstrom electron pencil-beam algorithm was used for the one-port 6-MeV beam plan after delineation and density override of the metallic parts. The results were confirmed with the metal oxide semiconductor field effect transistor (MOSFET) detectors and the Gafchromic EBT2 film measurements. For both the maximum eyelid dose over the shield and the maximum dose under the shield, the MC results agreed with the EBT2 measurements within 1.7%. For the Pinnacle plan, the maximum dose under the shield agreed with the MC within 0.3%; however, the eyelid dose differed by –19.3%. The adoption of the acrylic dummy eye shield was successful for the treatment plan. However, the Pinnacle pencil-beam algorithm was not sufficient to predict the eyelid dose on the tungsten shield, and more accurate algorithms like MC should be considered for a treatment plan.

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Eye Blocks and Eye Shields

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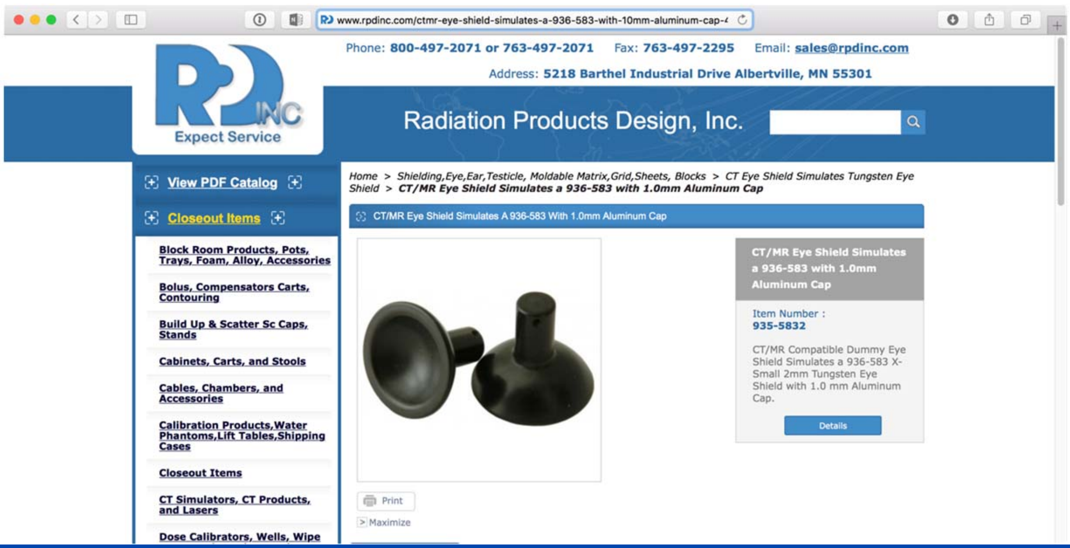
Dummy Eye Shields for Treatment Planning



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Eye Blocks and Eye Shields

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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

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Eye Blocks and Eye Shields

Custom Electron Treatment Devices

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

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Eye Blocks and Eye Shields

Bolus Electron Conformal Therapy (ECT)

Personalized Electron Beam Therapy
Using Custom Treatment Devices

2017 AAPM Annual Meeting, Denver, CO

Kenneth Hogstrom, PhD

Senior Medical Physics Advisor, Mary Bird Perkins Cancer Center
Professor Emeritus, LSU Medical Physics & Health Physics Program
Professor Emeritus, The University of Texas M D Anderson Cancer Center

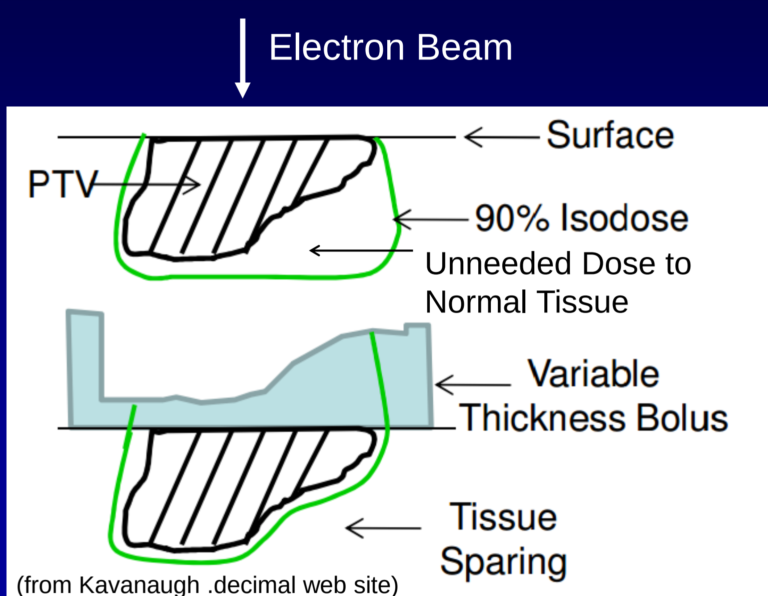
Bolus Electron Conformal Therapy

I. What is Bolus ECT?
II. Clinical Utilization of Bolus ECT
III. Planning Bolus ECT
IV. Bolus ECT Dose Calculation Accuracy
V. Delivering Bolus ECT (Fabrication & QA)
VI. Future – Potential for Intensity Modulation

Types of Electron Boluses

- Uniform-thickness bolus (e.g. chest wall, scalp)
  - Increases surface dose (low energy beams)
  - Spares distal tissues by providing continuously varying energies (6-20 MeV) from set of typically 7
- Flat-top bolus (e.g. nose or ear)
  - Smoothes skin surface (perpendicular to beam direction) reducing dose heterogeneities
- Variable-thickness bolus (all sites)
  - Thickness varies with off-axis position conforming therapeutic range (e.g. R_{90}) to distal PTV surface.

Utility of Variable Thickness Bolus

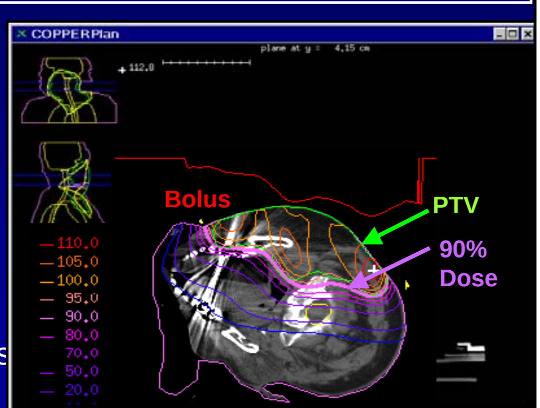


Bolus Electron Conformal Therapy (ECT)

What is Bolus Electron Conformal Therapy? (Hogstrom et al 2003)

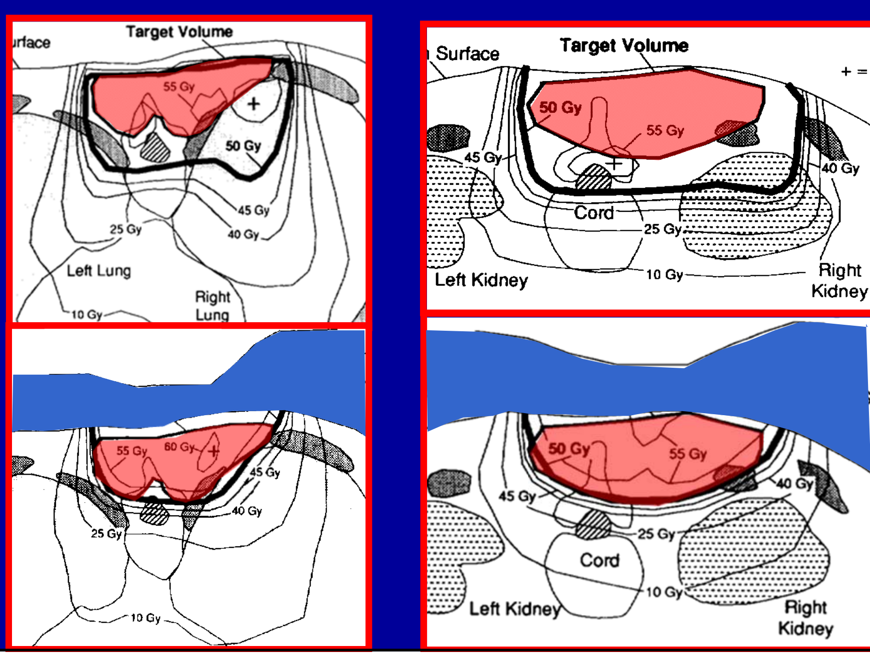
Bolus Electron Conformal Therapy (ECT) is the use of a single electron beam with variable thickness bolus that is designed for the following purposes:

- shaping the distal 90% dose surface to conform and contain the PTV,
- delivering minimal dose to adjacent (underlying) critical structures and normal tissues, and
- achieving as homogeneous dose distribution as possible to the PTV.

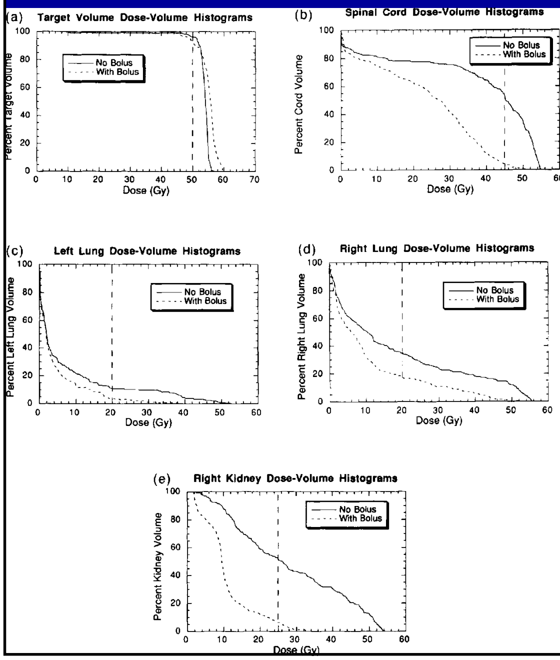


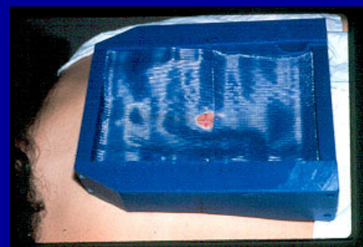
(Starkschall et al. 1994, 1995)

Bolus: Posterior Wall Sarcoma (Low et al. 1995)



Bolus: Posterior Wall Sarcoma (Low et al. 1995)





- Conclusions (bolus ECT vs. e⁻ only):
  - Bolus ECT greatly reduces dose to normal tissue.
  - Dose heterogeneity to PTV is increased.

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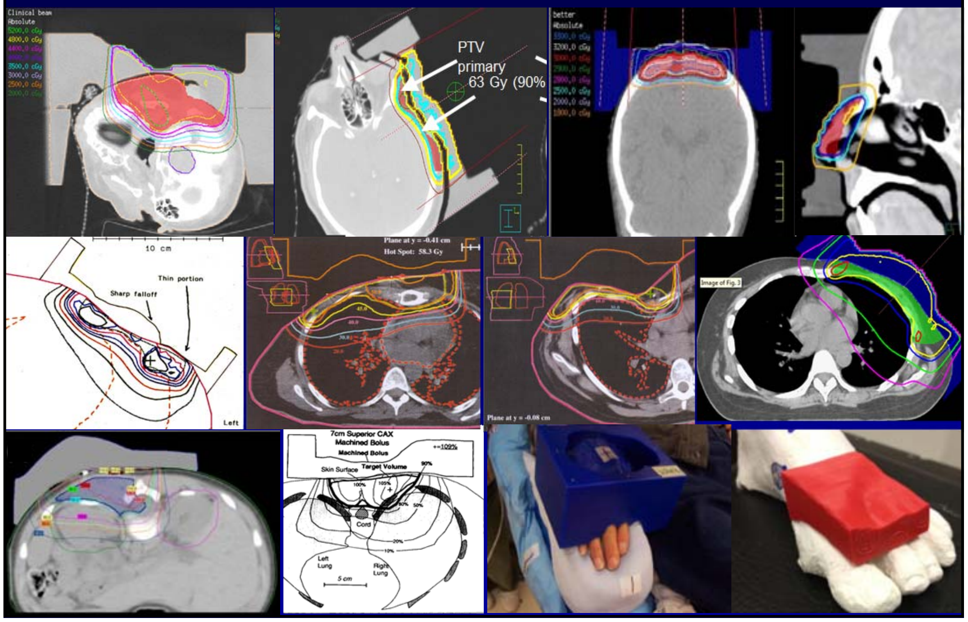
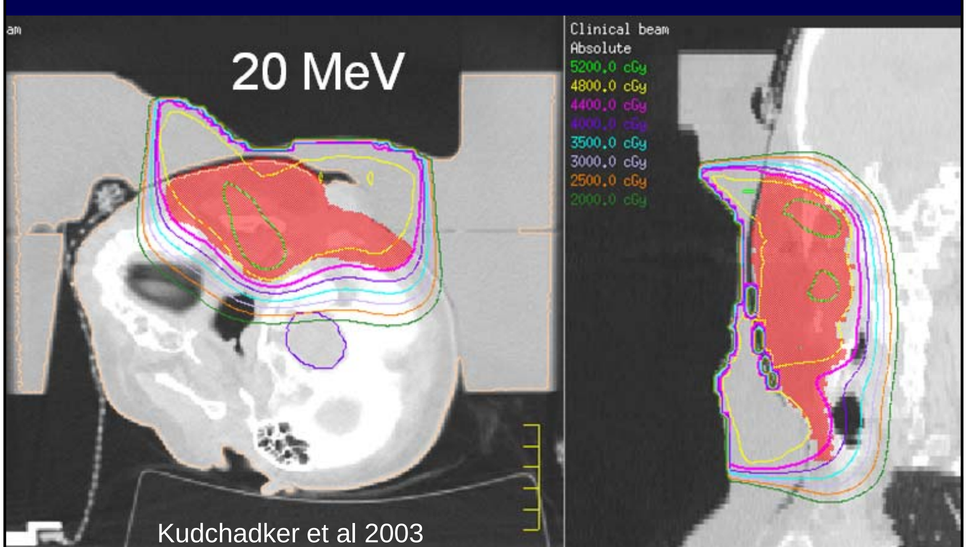
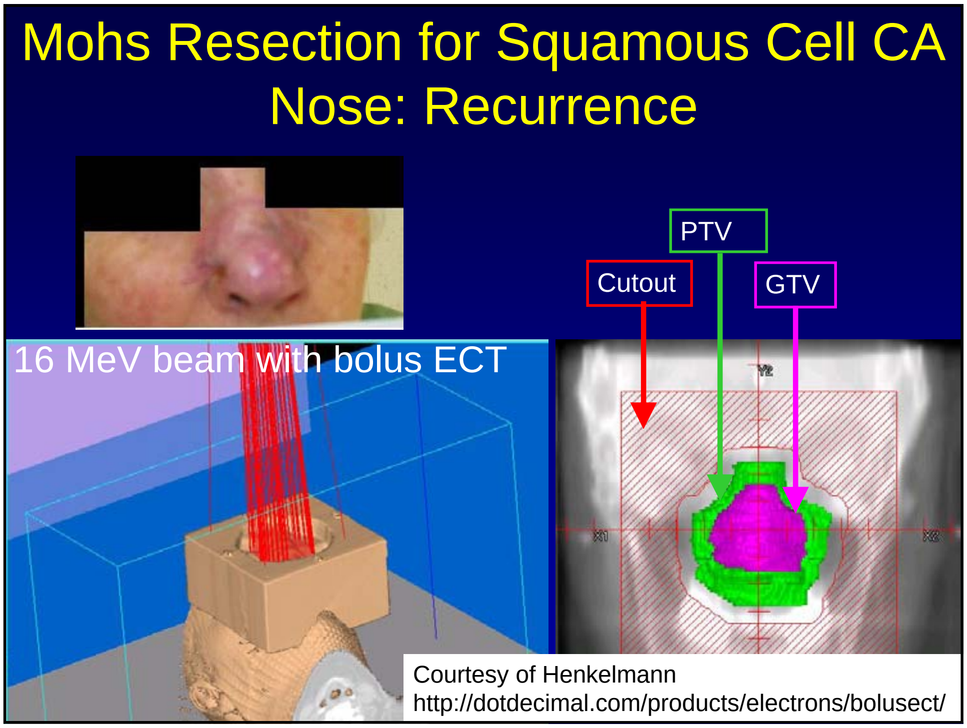
Bolus ECT: Clinical Examples by Treatment Sites

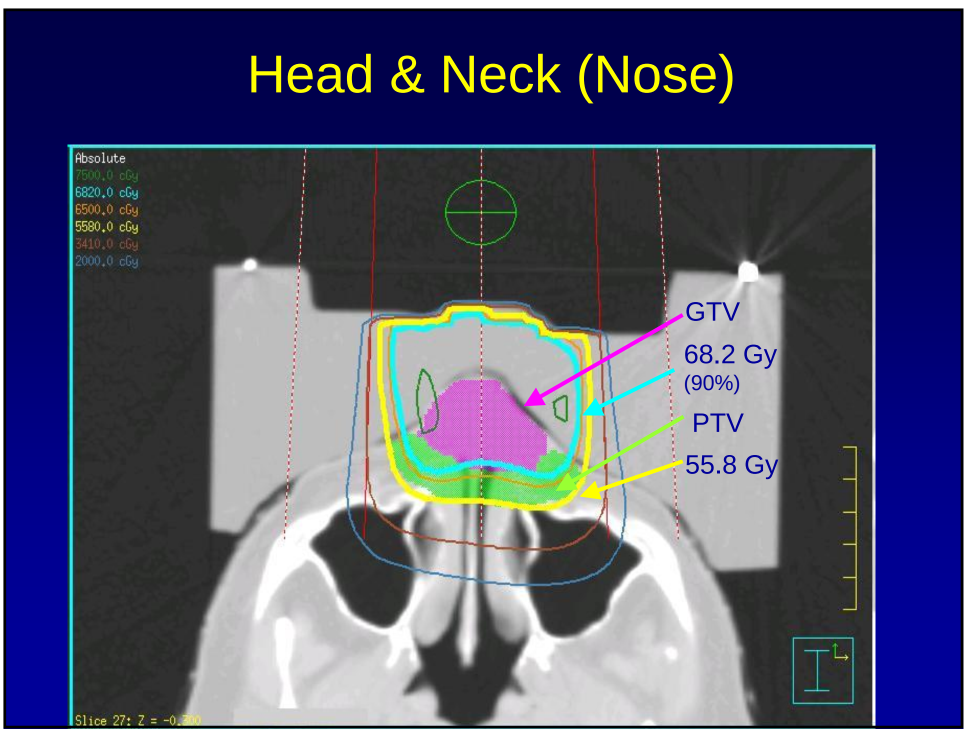
(see http://dotdecimal.com/products/electrons/bolusect/)

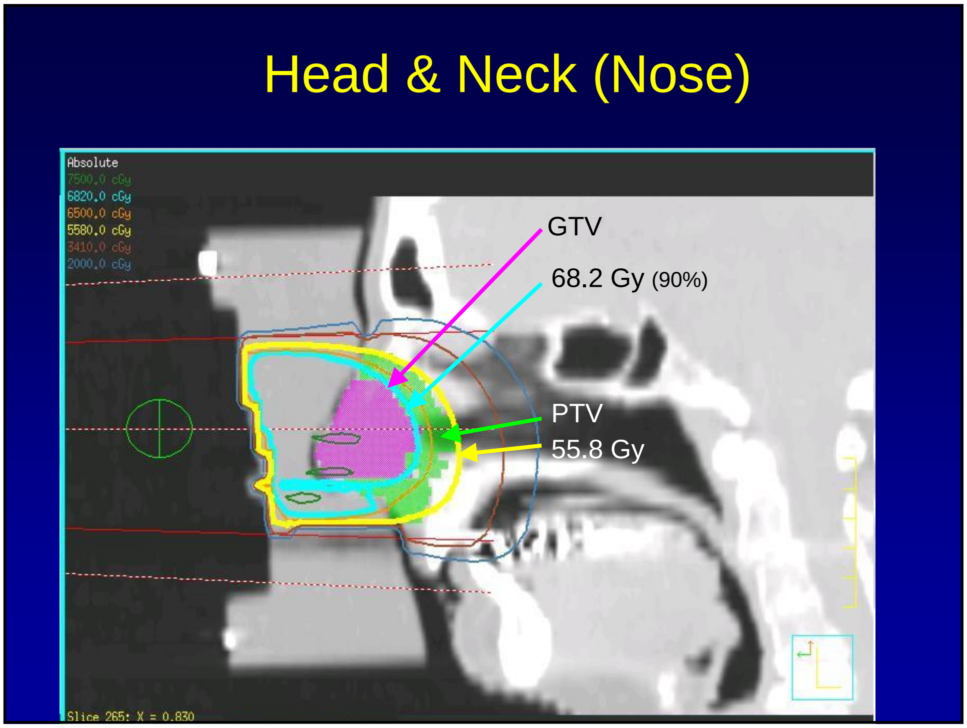


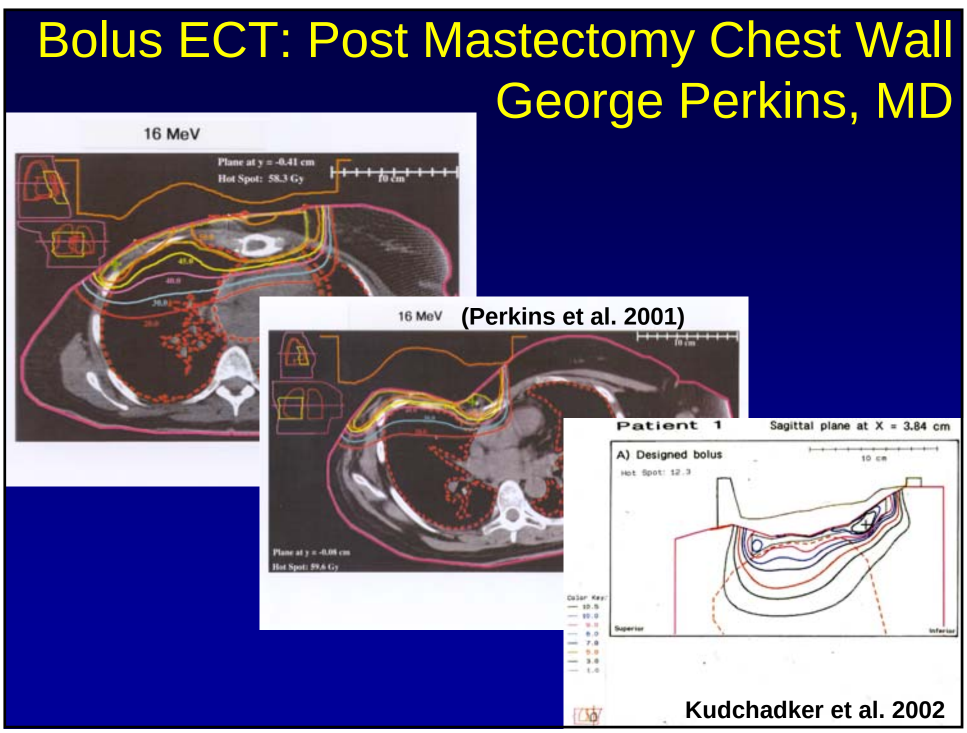
Head & Neck (Parotid Gland)




Mohs Resection for Squamous Cell CA
Nose: Recurrence
PTV
Cutout
GTV
16 MeV beam with bolus ECT
Courtesy of Henkelmann
http://dotdecimal.com/products/electrons/bolusect/


Head & Neck (Nose)
Absolute
7500.0 cGy
6820.0 cGy
6500.0 cGy
5580.0 cGy
3410.0 cGy
2000.0 cGy
GTV
68.2 Gy
(90%)
PTV
55.8 Gy
Slice 27: Z = -0.300

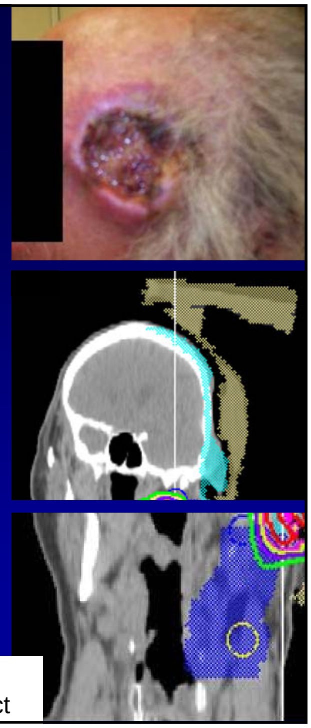




Bolus Electron Conformal Therapy (ECT)

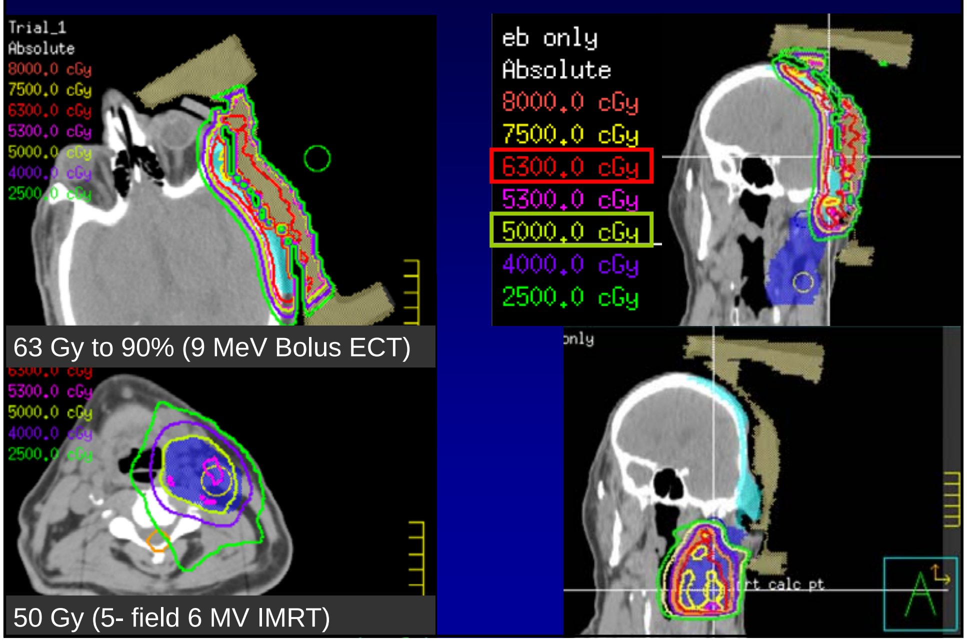
Mixed Beam
L Temple & Upper Neck

- Patient History
  - Recurrence (1 year post-resection) differentiated squamous cell CA: 7-8 cm tumor resection (+ margins)
- L Temple Prescription
  - 63.0 Gy (28 fx) to 90% isodose surface
  - Bolus ECT using L oblique 9-MeV e⁻ field
- L Upper Neck Prescription
  - 50 Gy (25 fx)
  - IMXT using 5-fields of 6MV x-rays
  - Abuts bolus ECT field (w/o bolus)



Courtesy of Henkelmann
http://dotdecimal.com/products/electrons/bolusect

L Temple & Upper Neck: Mixed Beam Plan

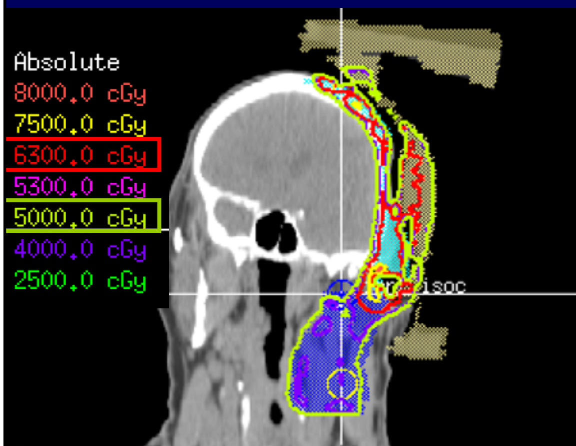


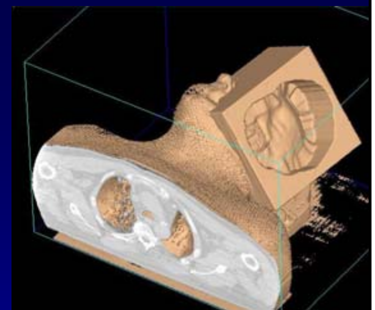
63 Gy to 90% (9 MeV Bolus ECT)

50 Gy (5- field 6 MV IMRT)

L Temple & Upper Neck: Mixed Beam Plan

9 MeV Bolus ECT + 6 MV IMRT





Bolus Electron Conformal Therapy

I. What is Bolus ECT?

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III. Planning Bolus ECT

IV. Bolus ECT Dose Calculation Accuracy

V. Delivering Bolus ECT (Fabrication & QA)

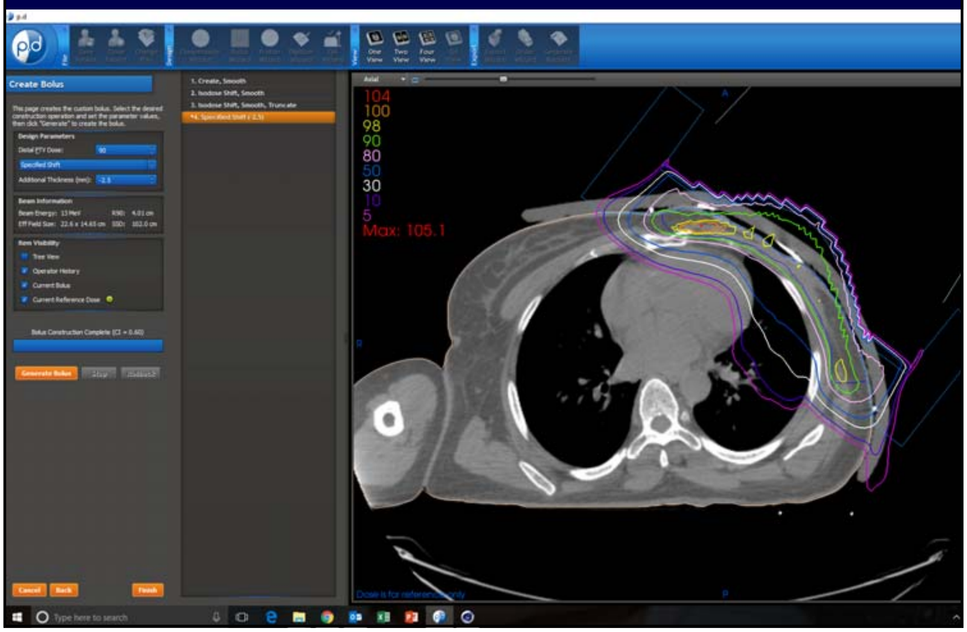
VI. Future – Potential for Intensity Modulation

Bolus ECT Treatment Planning Process

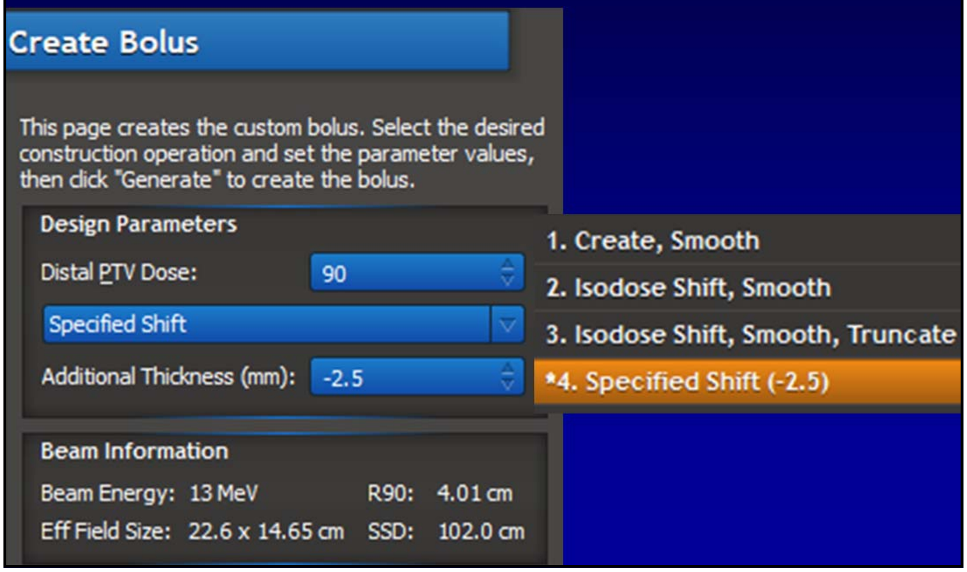
(highlighted steps are bolus specific)

- Perform planning CT scan of patient
- Plan w/o bolus in clinical TPS (e.g. Pinnacle or Eclipse)
  - Delineate PTV and prescription
  - Specify e⁻ beam angle (⊥ to distal PTV surface)
  - Specify e⁻ beam energy (R_{90}>max PTV depth)
  - Determine field shape (PTV + margin)
  - DICOM transfer plan w/o bolus to bolus design system
- Design bolus with .decimal p.d software (Low et al. 1992)
  - Create initial bolus (thickness = R_{90} – depth to distal PTV)
  - Calculate dose using PBRA and modify as needed
  - Transfer bolus to TPS for dose calculation & .decimal for milling

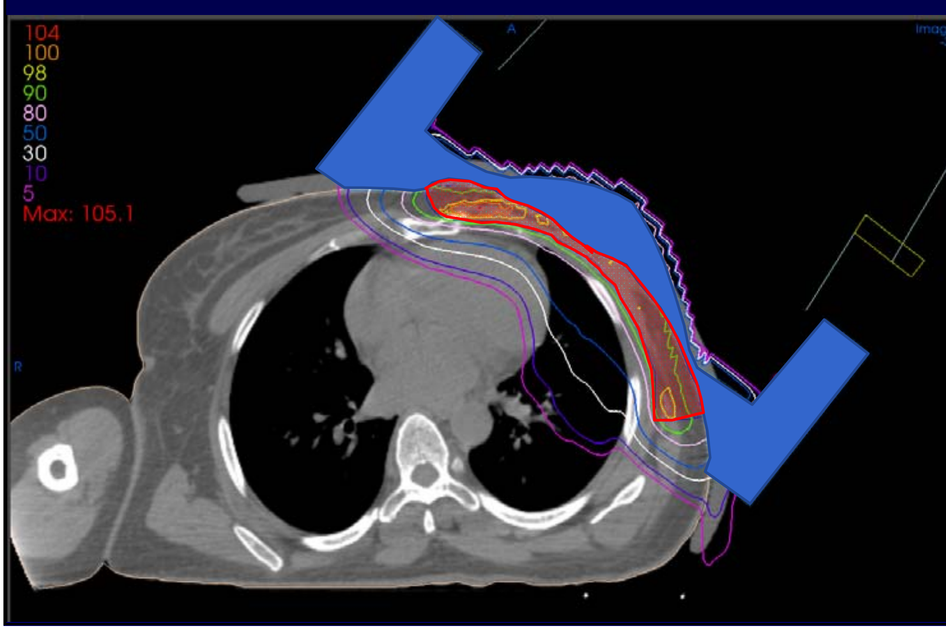
.decimal p.d BolusECT® Software



Bolus Design Using Operators (Low et al 1992)



Bolus ECT Dose Distribution



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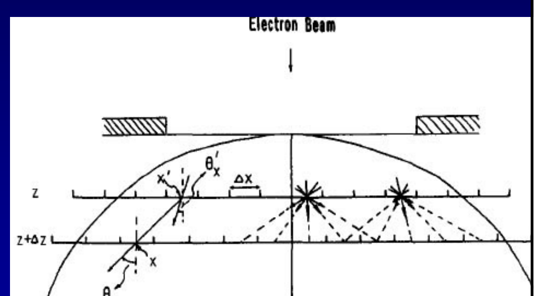
Pencil Beam Redefinition Algorithm (PBRA)

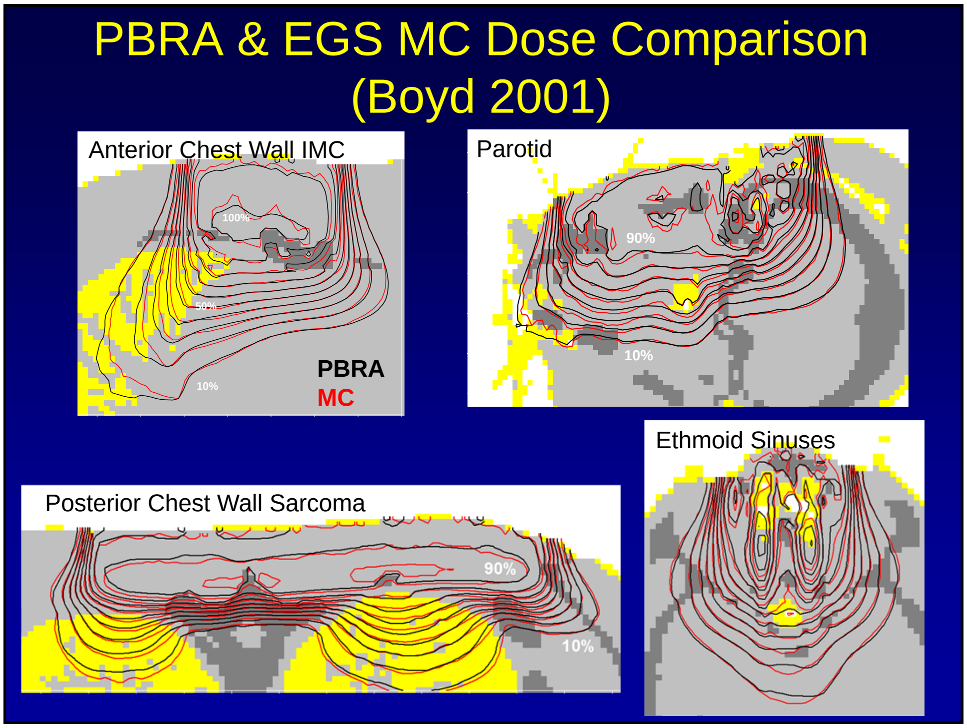
p.d uses PBRA for Dose Calculations

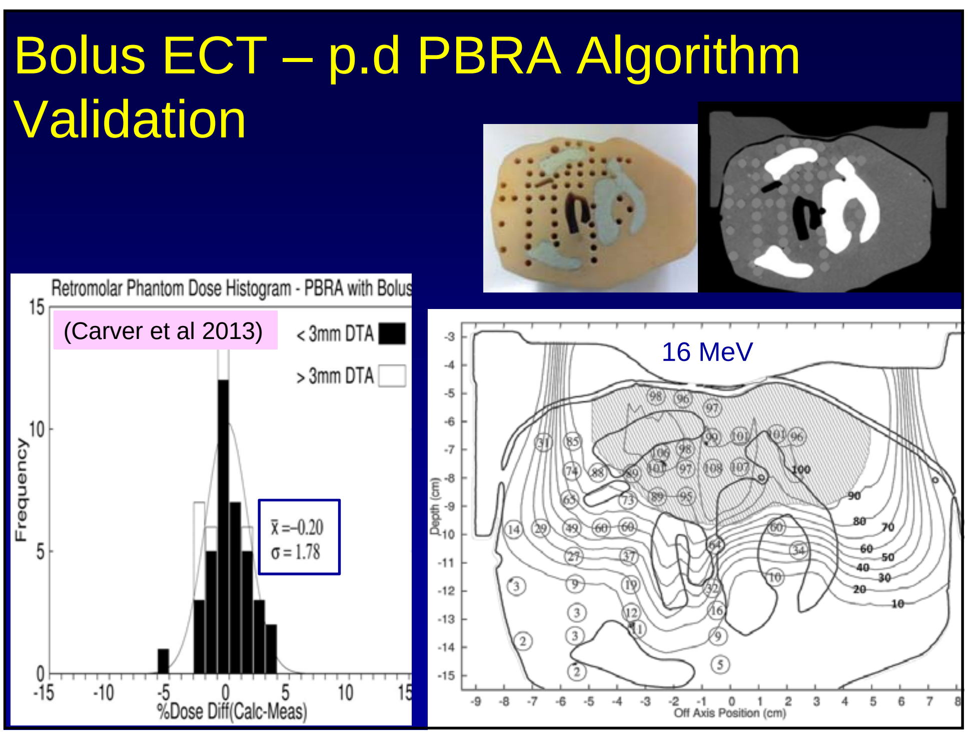
- Shiu and Hogstrom (1991); Boyd, Hogstrom, Rosen (1998); Boyd, Hogstrom, Starkschall (2001)



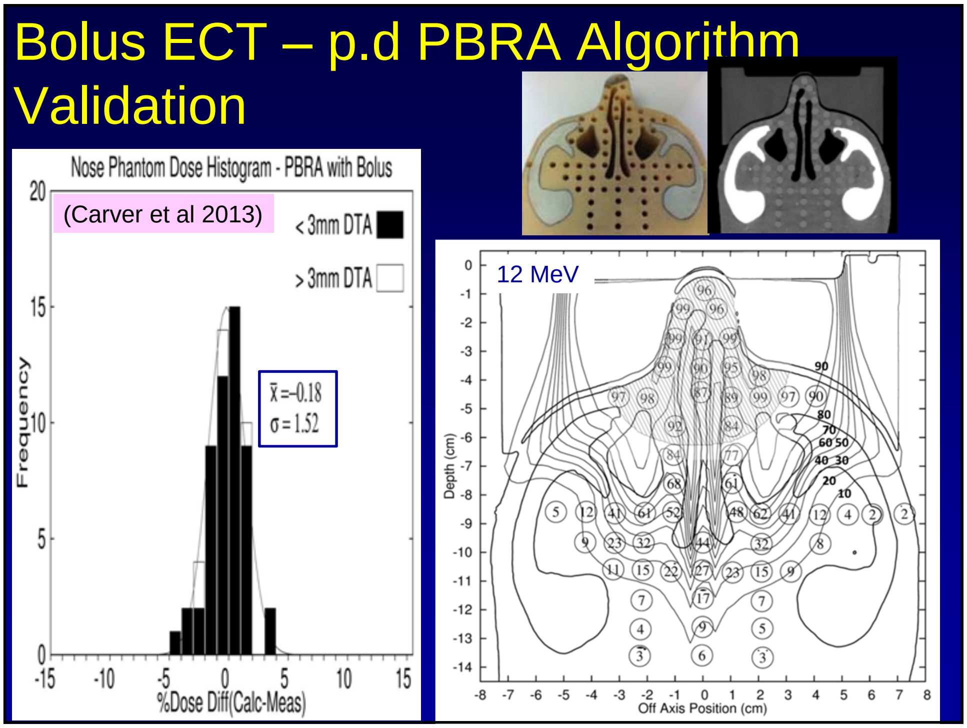
Advantages of PBRA

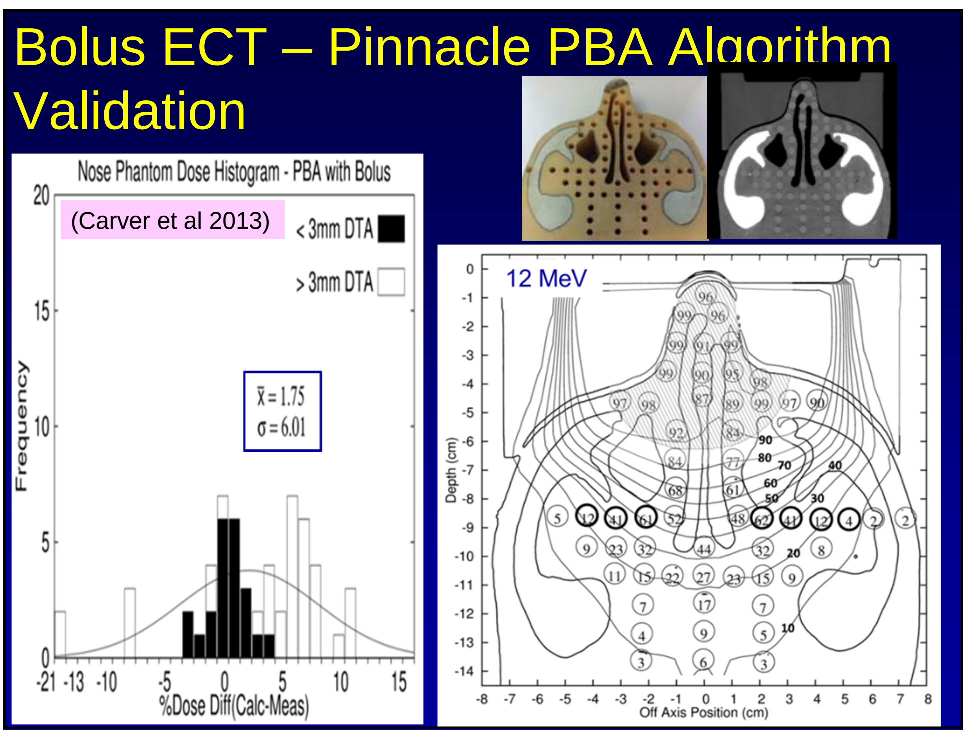
- Self commissioning for bolus design
- Faster, more precise, and more accurate than fast MC algorithm
- Accuracy is well documented





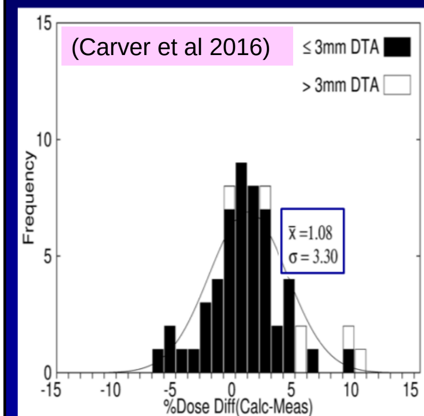
Bolus Electron Conformal Therapy (ECT)

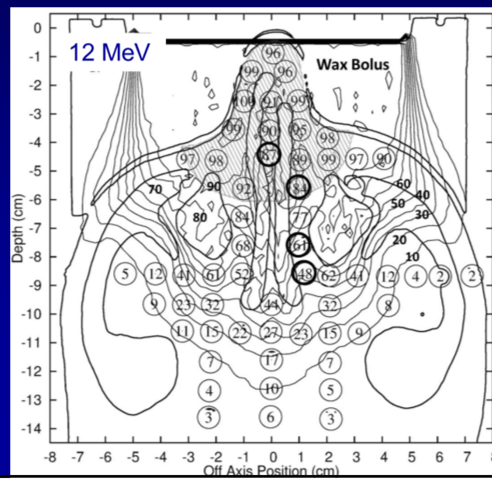




Bolus Electron Conformal Therapy (ECT)

Bolus ECT – Eclipse eMC Algorithm Validation (1% Stat)





Bolus ECT: Dose Calculation Accuracy

Dose differences (Calculated – Measured): Mean ± 1 SD

	Retromolar Trigone	Nose
p.d PBRA[1]	-0.20% ± **1.54%**	-0.18% ± **1.22%**
Eclipse eMC[2]	+0.01% ± **2.38%**	+1.30% ± **3.35%**
Pinnacle PBA[1]	-0.05% ± **3.14%**	-1.75% ± **5.94%**

[1]Carver et al. 2013 [2]Carver et al. 2016

Conclusions

- p.d PBRA is most accurate for bolus ECT planning.
- Eclipse eMC is sufficiently accurate for bolus ECT.
- Pinnacle PBA is marginally accurate for bolus ECT.

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History of .decimal LLC Bolus Fabrication (Machineable Wax)

- MD Anderson Bolus ECT (Low et al 1992)
  - 1992-2000 in-house fabrication
  - 2000-2004 .decimal fabrication
- .decimal, LLC Offers BolusECT® (2009)
  - Free p.d device designing system (integrates with TPS)
  - Fabrication cost: $300-$1,000 (size & delivery)
- US Market
  - 350 institutions to date
  - 2,200+ boluses delivered to date (500 in 2016)

BolusECT® - Bolus Fabrication

- Bolus fabrication by .decimal, LLC (Sanford, FL)
  - p.d sends bolus file to .decimal for fabrication
  - Bolus milled from machineable wax block (Low et al 1994)
  - Delivery: 1-2 days

Blank Block of Wax

.decimal Farm of Milling Machines

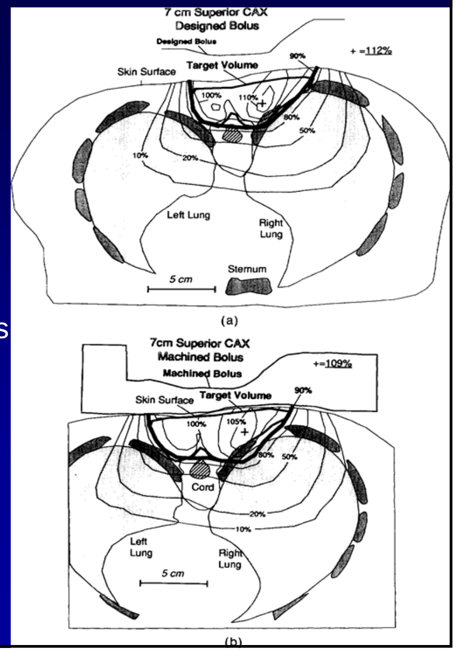
BolusECT® - Bolus Fabrication

Patient Surface

Beam Surface

Bolus ECT: Pre-treatment Quality Assurance (Low et al. 1995)

- Quality Assurance (factory)
  - .decimal verifies thickness before shipping
- Quality Assurance (clinic)
  - Acquire patient CT scan w/ bolus
    - Initially: CT simulator
    - Daily: Cone beam CT
  - Calculate dose with bolus on patient
  - Verify bolus fabrication and localization by comparing dose calculation with dose plan



Bolus Fabrication (3D Printing)

- Under development by 3D Bolus, Inc.
  - Bolus design using Su, Robar et al (2014) algorithms
  - Alternative business model for bolus ECT
- Planning
  - User purchases bolus ECT planning software
  - Compatible with TPS, but all dose calculations done in TPS
- Fabrication
  - User purchases 3D printer
  - User sets up 3D printing lab
  - User 3D prints bolus

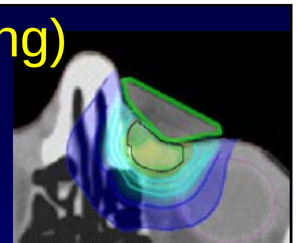
Bolus Fabrication (3D Printing) Challenges

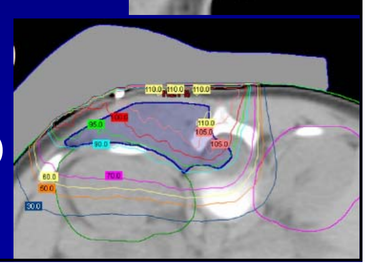
- Cost, space, & maintenance of 3D printer & supplies
- Long printing time for large boluses (0.5-2 days)
- Printing with accuracy and homogeneity
- Availability of commercial bolus design software

AXIOM 20 DUAL Direct Drive 3D Printer
$9,995.00
https://airwolf3d.com/shop/tall-desktop-3d-printer/

Bolus Fabrication (3D Printing) Clinical Bolus

- Patient Boluses
  - Limited published clinical examples
  - Primarily smaller boluses/field sizes
- Small Bolus
  - Inner canthi (Lukowiak et al 2017)
  - Pinna (Zhao et al 2017)
- Medium Bolus
  - Rhabdomyosarcoma (Su et al 2014)

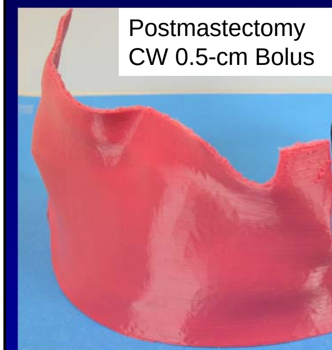




Constant Thickness Bolus

- Useful for MV x-ray & electron beam dose buildup

Postmastectomy
CW 0.5-cm Bolus



3D Printed PLA
Courtesy of James Robar

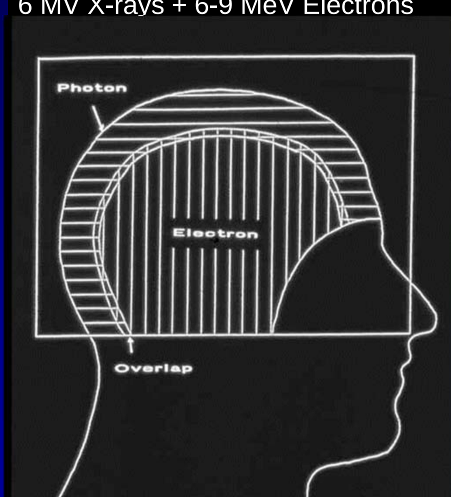
Reconstructed Breast
(Lee and Archer)

Partial Scalp irradiation
(Szal & Purdon)

.decimal Machineable Wax
http://dotdecimal.com/products/photons/uniform-thickness-bolus/

Total Scalp Irradiation Electron+X-ray Technique (Tung et al 1995)

6 MV X-rays + 6-9 MeV Electrons



0.6-cm Bee's Wax Bolus
Manually Constructed

Bolus Electron Conformal Therapy (ECT)

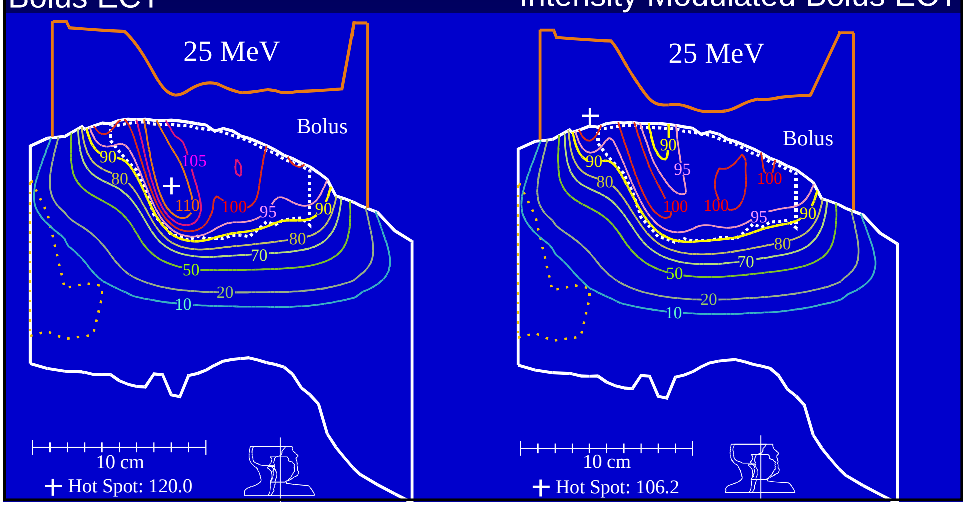
Bolus Electron Conformal Therapy

I. What is Bolus ECT?
II. Clinical Utilization of Bolus ECT
III. Planning Bolus ECT
IV. Bolus ECT Dose Calculation Accuracy
V. Delivering Bolus ECT (Fabrication & QA)
VI. Future – Potential for Intensity Modulation

Bolus Electron Conformal Therapy with Intensity Modulation

(Kudchadker et al 2002)

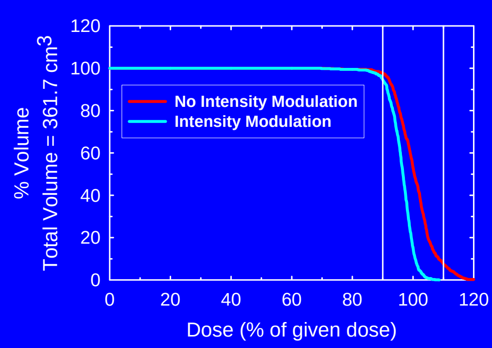
Bolus ECT | Intensity Modulated Bolus ECT

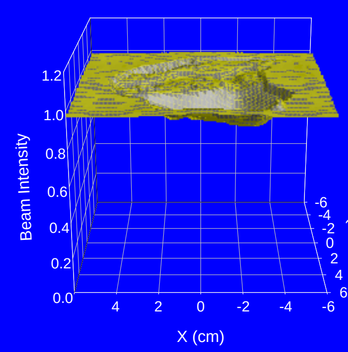


Bolus Electron Conformal Therapy with Intensity Modulation

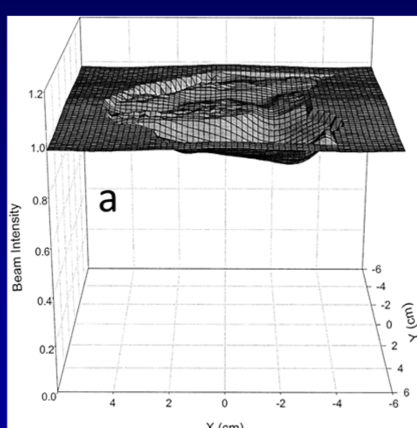
(Kudchadker et al 2002)

How can electrons be intensity modulated?

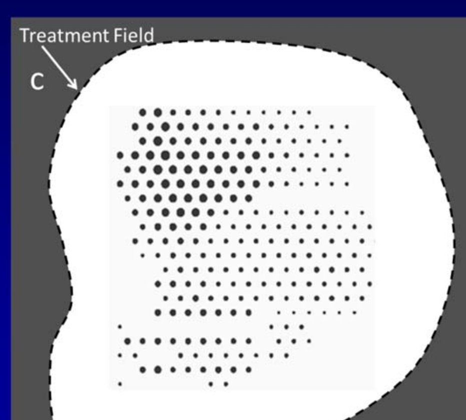




Patient Example Intensity Modulator (Chambers 2016)



Desired Intensity Modulation 20 MeV

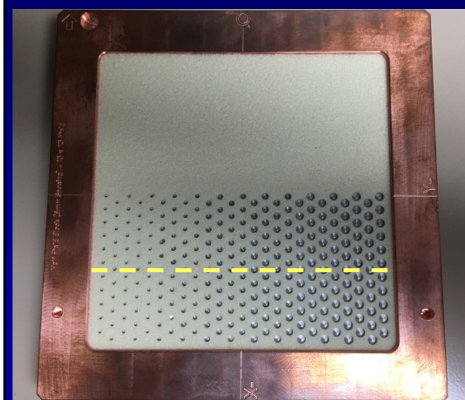


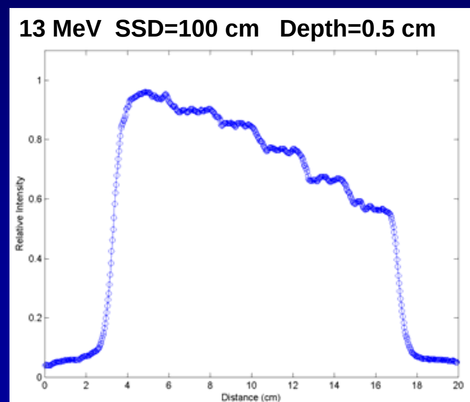
Intensity Modulator Design

Electron Intensity Modulation Proposed Method

(Hogstrom et al 2017, accepted, JACMP)

- Passive Radiotherapy Intensity Modulators for Electrons- PRIME (equivalent to compensators for x-rays)





Passive Electron Intensity Modulators

- Under development by .decimal LLC & MBPCC
  - Planning software
  - Passive delivery device (intensity modulator)
  - Clinical QA methods
- Potential Applications
  - Bolus ECT
  - Penumbra matching of electron fields of differing energy (segmented-field ECT)
  - SSD and irregular surface effects of electrons

Impediments to Bolus ECT Utilization

- Lack of equitable billing codes
- Competition with IMXT, which has
  - Slightly better PTV dose homogeneity
  - Comparable doses to nearby normal tissues
  - Greater chance of secondary cancer to distal tissues
  - Greater revenue stream
- Decreasing knowledge of electron therapy amongst radiotherapy staff
- Antiquated electron planning tools in TPS
- Greater ease of use of bolus design tools
  - e.g. managing unsmoothed juts in distal PTV surface

Summary: Bolus ECT

- Bolus ECT conforms the 90% dose surface to the PTV, significantly improving sparing of normal tissue.
- The utility of Bolus ECT for head and neck, postmastectomy chest wall, posterior chest wall, and extremities, is well documented in the literature (1995-present).
- BolusECT® has been commercially available for 8 years and used by ≈350 treatment centers. Free p.d software is compatible with most commercial TPS.
- PBRA and eMC algorithms are sufficiently accurate for bolus ECT; PBA algorithms are marginally accurate for some sites.
- Primary impediments to bolus ECT are lack of equitable billing codes, antiquated TPS tools, and IMXT.
- Future electron intensity modulators should improve PTV dose homogeneity.

Summary
Personalized Electron Beam Therapy Using Custom Treatment Devises

- Electron therapy can offer significant advantages, particularly for normal tissue sparing and reduced risk of 2° cancers (poor man's proton beam).
- Many tools (collimating inserts, skin collimation, eye shields, conformal bolus, and accurate dose calculations) exist for delivery of highly personalized electron therapy.
  - Most tools are commercially available
  - Treatment planning systems have failed to provide software that easily manages such tools and accurately calculates dose in their presence.