Session in Memory of Martin L. Rozenfeld, PhD

John A. Antolak and James A. Kavanaugh

AAPM SAM Therapy Educational Course
August 1, 2018

Introduction

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 Bjargard. Seated, left to right: Fearghus O’Foghlutha, Ben Galkin, Peter Almond, Jim Kereakes, and Leonard Stanton.

Session in Memory of Martin L. Rozenfeld, PhD

- Farrington Daniels Award, 1984

- 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
Personalized Electron Beam Therapy using Custom Treatment Devices

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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)

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

History of Electron Therapy
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-)

- 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)
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

Dose Calculation & Measurement Technology

- Electron Transport and Dose Calculations
- 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

- Collisonal energy loss
  - Electron - electron interactions
- Multiple Coulomb scattering
  - Electron - nuclear interactions
Percent Depth Dose (PDD)


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

9 MeV, 100-cm SSD
10x10 cm²

16 MeV, 100-cm SSD
10x10 cm²

Electron Dose Distributions

SSD Dependence

9 MeV, 100-cm SSD
10x10 cm²

9 MeV, 110-cm SSD
10x10 cm²
Electron Dose Distributions

SSD Dependence

16 MeV, 100-cm SSD
10x10 cm²

16 MeV, 110-cm SSD
10x10 cm²

Electron Dose Distributions

Oblique Incidence

- 12-MeV, 10x10 cm², 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 cm², 110-cm SSD
- Penetration increases relative to the beam direction

Electron Dose Distributions
Oblique Incidence

- 12-MeV, 10x10 cm², 110-cm SSD
- Penetration decreases relative to the surface normal
**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

$E_{p,0} = 14.8\text{ MeV}$
$10\times10\text{ cm}^2$

Beam edge defined by collimator

Boundary within PTV should be contained

Electron Dose Distributions
SSD Dependence

9 MeV, 100-cm SSD
0.5-cm margin

9 MeV, 110-cm SSD
1.0-cm margin
Electron Dose Distributions
SSD Dependence

- 16 MeV, 100-cm SSD
  - 0.5-cm margin
- 16 MeV, 110-cm SSD
  - 0.6-cm margin

Limitations of Uniform Margin Expansion
Limitations of Uniform Margin Expansion

Electron Collimation
Basic Rules for Collimator Thickness

- $t_{\text{Pb}} \text{ (mm)} = \frac{1}{2} E_{p,0} \text{ (MeV)} + 1$
- $t_{\text{Cerro}} = 1.2 \ t_{\text{Pb}}$

Examples:
- 8 MeV → 5 mm Pb → 6 mm Cerro
- 20 MeV → 11 mm Pb → 13 mm Cerro
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

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
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

<table>
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<tr>
<th>Machine</th>
<th>Varian Clinac 21EX 4/10</th>
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<tr>
<td>Energy</td>
<td>6, 9, 12, 16, 20 MeV</td>
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<td>SSD</td>
<td>100 and 110 cm</td>
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<td>Field Size (cm²)</td>
<td>Applicator Size (cm²)</td>
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B. D. Rusk MSc thesis, LSU
Percent Depth Dose Results: Copper vs Cerrobend

- 25x25 cm² applicator 2x2 cm² insert
- 25x25 cm² applicator 20x20 cm² insert

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

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

<table>
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<td>Applicator (cm²)</td>
<td>Applicator (cm²)</td>
<td>Applicator (cm²)</td>
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<td>6x6</td>
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<tr>
<td>20x20</td>
<td>N/A</td>
<td>0.996</td>
<td>N/A</td>
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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

Skin Collimation Treatment Planning Example

9 MeV, 100-cm SSD
0.5-cm margin

9 MeV, 110-cm SSD
0.3-cm margin
Skin Collimation Treatment Planning Example

9 MeV, 110-cm SSD
1.0-cm margin

9 MeV, 110-cm SSD
0.3-cm margin

Skin Collimation
Skin Collimation Treatment Planning Example

9 MeV, 110-cm SSD
0.3-cm margin

9 MeV, 110-cm SSD
0.3-cm margin

Skin Collimation Edge Scatter

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
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.

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
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

7 MeV
15 x 15 cm², 100 cm SSD

Eye Blocks and Eye Shields
**Electron Collimation**

**Utility/Futility of Small Blocks**

15 MeV
15 x 15 cm², 100 cm SSD

**Orthovoltage Eye Shields**

Do NOT use for Electron Beams
Orthovoltage Eye Shields
Do NOT use for Electron Beams

1.7 mm Pb equivalent to 1.9 cm water!

Electron Collimation
Tungsten “Electron” Eye Shield

9 MeV - Tungsten

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


Commercial Electron Eye Shields

Dummy Eye Shields for Treatment Planning

Application of a dummy eye shield for electron treatment planning

SriKumar Kang, Suth Pareek, Taegji Kwang, Kwang-Bi Cheong, Taegji Hahn, Hyeong Min, Hee Young Lee, Young Joo Kim, De Hoan Oh, and Hendrik Baal

Department of Radiation Oncology, Samsung Medical Center, Yonsei University College of Medicine, 50 Iljindeokro, Kangnam-gu, Seoul, 06205, Korea.


Email: us/documents/759867/ASTRO_Audit_2018-10.pdf

Sunlight can damage the lens and retina of the eye, and can cause cataracts.

CT/3D Eye Shield Simulates 0.95-0.97 mm Aluminum Cap

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CT/3D Eye Shield Simulates 0.95-0.97 mm Aluminum Cap
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