Electron Beam Therapy - Current Status and Future Directions

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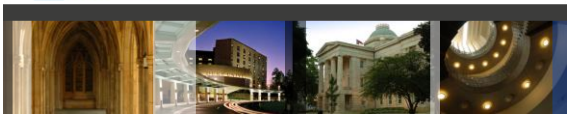
Duke University Medical Center

DukeMedicine

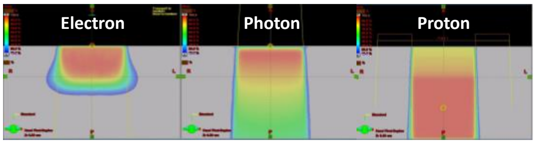


Conflict of Interest Disclosure

- None

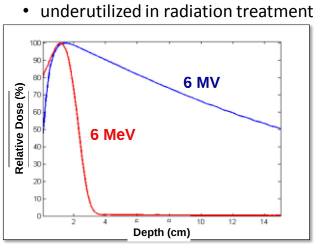
Outline

- Review of basic electron beam radiotherapy
- Special clinical procedures
  - Electron Conformal Therapy (ECT)
  - Electron Arc Therapy (EAT)
- Recent research developments
  - Modulated Electron Radiotherapy (MERT)
  - Dynamic Electron Arc Radiotherapy (DEAR)



Clinical electron beam therapy

- unchanged for decades
- underutilized in radiation treatment of cancer



- Electron interaction with matter is advantageous for the treatment of superficial disease
- Superficial tumors represent ~20% of all cancers*

*American Cancer Society, Inc. ***Cancer Statistics 2013 : A presentation from the ACS.***

Electron Beam Use

- Head (Ear, Eye, Nose, Scalp …)
- Neck Node boost (Pre-IMRT)
- Chest Wall
- Breast (Boost)
- Extremity
- Total Skin Irradiation

History of Electron Therapy
Accelerator Technology

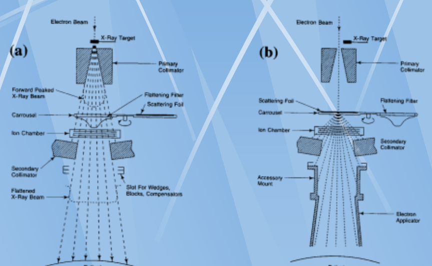
- Manufacturers Offer Comparable Electron Beams
  - New units mostly Elekta and Varian; Siemens similar quality beams
  - Multiple electron beams: 7-8 in range 6-20 MeV
  - Special modalities: High dose rate TSEI & Electron arc therapy


Varian Trilogy (www.varian.com)


Elekta Infinity (www.elekta.com)

Antolak History of Electron Therapy

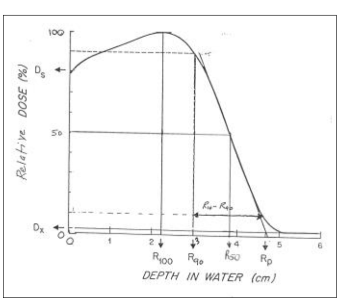
Electron Mode



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

Antolak Machines & Dosimetry

Electron beam PDD – TG25



- Surface Dose D_s
  - >80%
  - Increase with E
- Therapeutic range R_{90}
  - E/3.3
- Fall-off margin $R_{10} – R_{90}$
- Depth of max dose R_{100}
  - ~ constant for E > 12 MeV
- Practical Range R_p
  - E / 2
- Bremsstrahlung dose D_x
  - ↑ with E
  - Non-negligible for high energies

Electron Beam Profiles – mostly flat

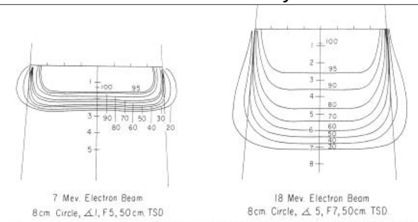


Figure 14.9. Comparison of isodose curves for different energy electron beams. [Reprinted with permission from: Tapley, p 86 (35).]

Expansion due to scattering
- Lower dose level
- Lower energy

Electron Beam MU Calculation

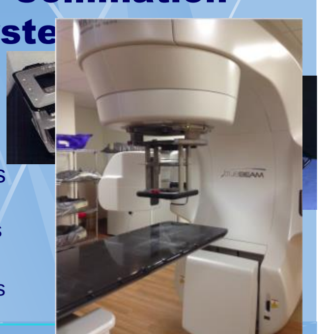
- Advanced electron dose calculation algorithms (pencil beam, Monte Carlo) are available in most TPS
  - Select proper electron energy
  - Visualize relative dose distributions
  - Accuracy in predicting output is limited.
- Most clinics determine MU using empirical formula based on measurement data

$$MU = \frac{Prescription\ Dose\ (cGy)}{CF_{SSD} \cdot OF_{Cone\_Cutout} \cdot IDL \cdot ISF}$$

CF_{SSD} = 1.0 cGy/MU for reference open cone @dmax
OF_{Cone_Cutout} = output factor for the cone and cutout
IDL = prescription isodose line
ISF = inverse square factor

Electron Collimation Syste

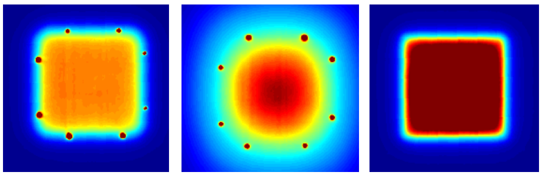
- Applicators with Inserts
- Variable Trimmers
- Intracavitary Cones
  - Intraoperative radiotherapy cones
  - Intraoral Cones
  - Transvaginal cones



Antolak Machines & Do

Electron beam: film measurements

10x10 cm^2 Cone | 10x10 cm^2 Jaw | 15x15 cm^2 Jaw + 10x10 cm^2 Cutout



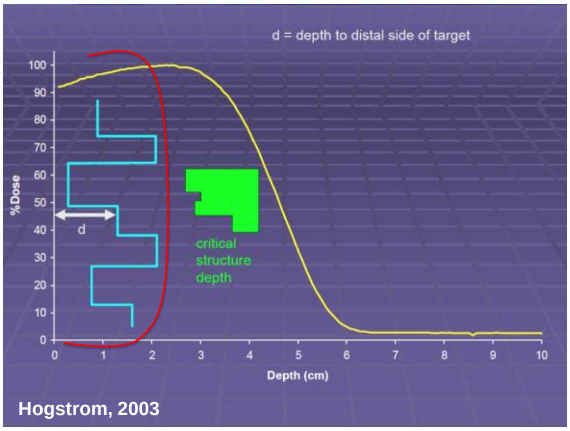
Penumbra=1.3 cm | Penumbra=5.0 cm | Penumbra=1.1 cm

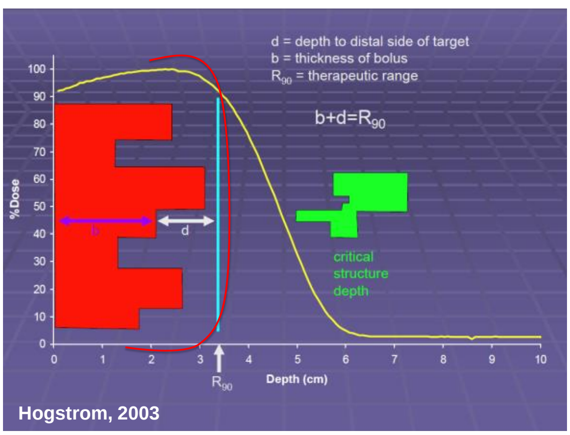
Electron Conformal Therapy (ECT)

ECT – one or a few electron beams

- Keep PTV within the 90% isodose volume
- Minimize dose to distal/underlying critical structures and normal issues
- Counterpart in photons: 3DCRT
- Bolus electron conformal therapy
  - Use tissue equivalent material to modulate the electron energy so 90% dose surface conforms to the distal edge of PTV

Hogstrom, 2003





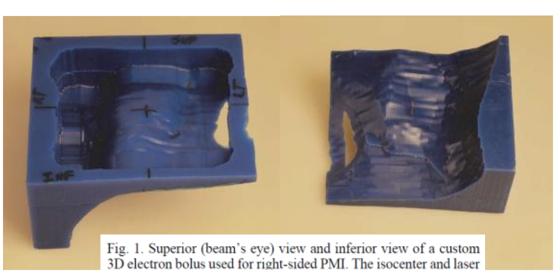


Fig. 1. Superior (beam's eye) view and inferior view of a custom 3D electron bolus used for right-sided PMI. The isocenter and laser

Perkins 2001 *A custom three-dimensional electron bolus technique for optimization of postmastectomy irradiation* IJROBP**51**

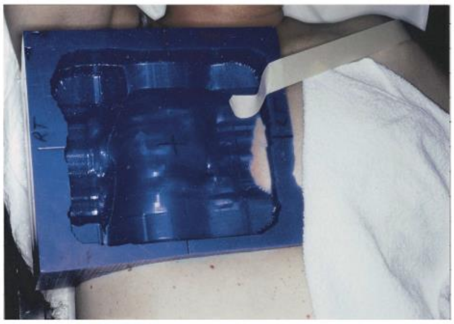


Fig. 2. The custom 3D electron bolus in treatment position. The patient is immobilized using the VAC-Fix system. The isocenter and laser markings for patient setup verification are shown. Superior (cranial), right (lateral), left (medial), and inferior (caudal) borders are labeled to assist in setup and verification.

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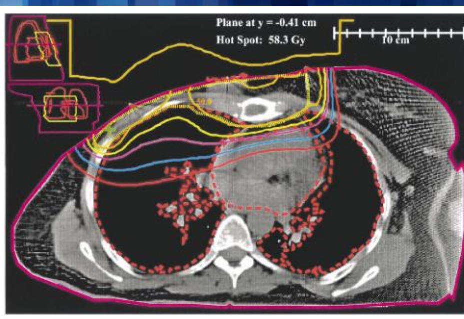

Fig. 7. Isodose distribution (Gy) using the custom 3D electron bolus technique for the same patient as in Figure 6. A dose of 50 Gy was prescribed to 100% of the given dose using 16-MeV electrons, and the bolus was designed to deliver 90% of the given dose to the target volume. The plan shows dose minimization to the ipsilateral lung and underlying cardiac tissues.

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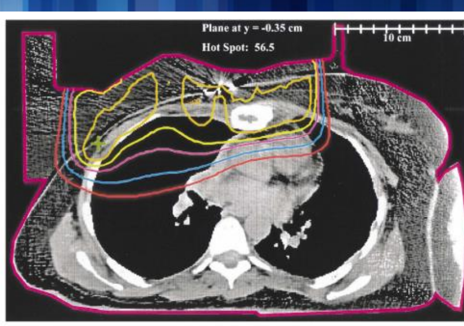

Fig. 8. Isodose distribution (Gy) using the custom 3D electron bolus technique for the same patient as in Figure 7. A dose of 50 Gy was prescribed to 100% of the given dose using 16-MeV electrons; the custom electron bolus was placed on the patient's skin and is visible in the CT image. To verify correct fabrication and positioning of the electron bolus, this dose distribution was compared to the dose distribution for the treatment plan shown in Figure 7.

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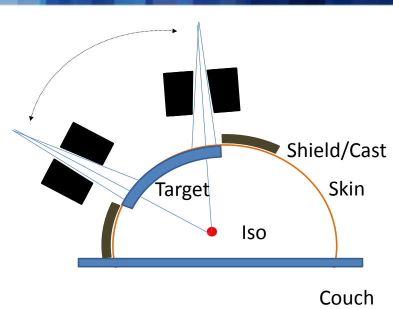
Advantages and disadvantages

- Requires no modification to the treatment machine
- Continuous energy distribution
  - 0.2 MeV / 1 mm
- Single treatment field

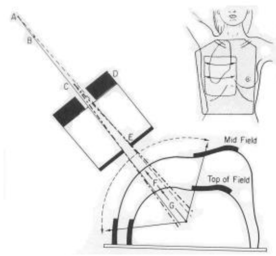
- Requires greatest energy
  - greater R_{90-10}
- Higher skin dose
- Additional CT and planning for QA required

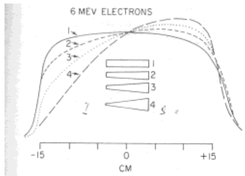
Hogstrom, 2003

Electron Arc Therapy (EAT)



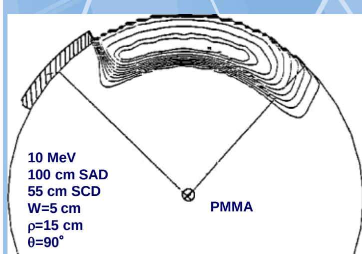
Electron Arc Therapy





*Leavitt D D et al, 1985 Electron ARC therapy: physical measurement and treatment planning techniques *IJROBP* **11** 987-999

Utility of Skin Collimation: Arc Electron Therapy



- Restores penumbra for electron arc treatments

McNeely 1988 *Electron arc therapy: chest wall irradiation of breast cancer patients* IJROBP **14**(6)

EAT for Chest wall Irradiation

- High rate local regional control (LRC)
- Minimal acute and late toxicities
- Decreased dose to heart and lung
- Elimination of a match line problem
- IMN included without difficulty
- Relative ease of treatment with reproducible execution

Gaffney 2001, *Electron arc irradiation of the postmastectomy chest wall with CT treatment planning: 20-year experience.* IJROBP **51**(4)

EAT - limitations

- Modification to the Linac
  - Customized cones of shortened length
- Modification to TPS
  - Different PDDs from standard beams
  - Bolus and cutout shape
  - Forward planning for multiple energies can be cumbersome
- Patient-specific cast/shield and bolus
  - Time consuming
- Experienced treatment team
- Difficult for wide spread use

Modulated Electron Radiotherapy (MERT)

MERT: uses multiple electron beams, each of differing energy and intensity pattern, to deliver a dose distribution that conforms the 90% dose surface to PTV

- Energy modulation
  - Bolus and Linac energy selection
- Intensity modulation
  - Cutout
  - Scanning beam
  - MLC

Ma 2003 *A comparative dosimetric study on tangential photon beams, intensity-modulated radiation therapy (IMRT) and modulated electron radiotherapy (MERT) for breast cancer treatment* PMB **48**(7)

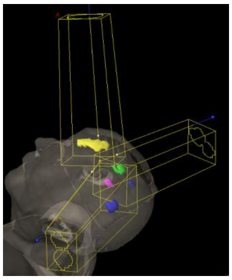
MERT – treatment planning

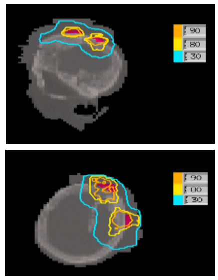
- Forward planning
  - weight optimization
- Inverse planning
  - Beamlet-based optimization
  - Monte Carlo simulation to account for actual aperture or MLC leaf sequences
  - Second optimization
    - weight optimization
    - Aperture fine tuning (DAO)
- Final dose calculation for the plan

MERT – treatment delivery

- MLC based delivery is preferred
  - No need to reenter room between segment
  - High positioning precision can be maintained through computer control
- With electron MLC (eMLC)
  - Prototypes of eMLC
  - Standard or short SSD (90 cm)
- With photon MLC (pMLC)
  - Short SSD (70 cm) to reduce in air scatter
- Bolus may be required for some segments due to coarse energy selection on linac

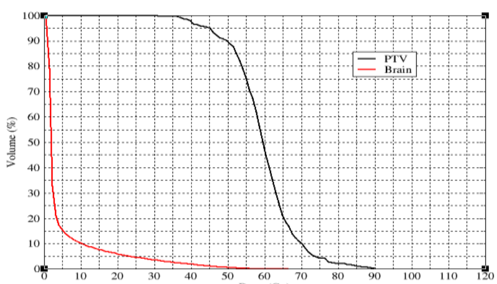
MERT – Scalp case 1





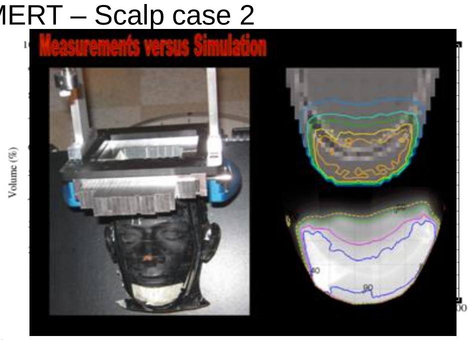
Eldib

MERT – Scalp case 1



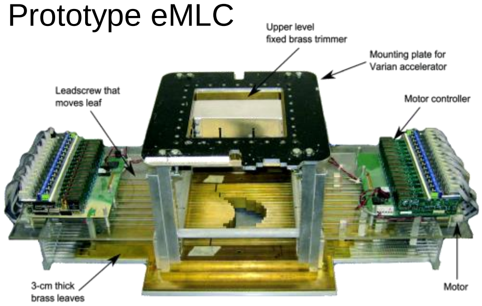
Eldib

MERT – Scalp case 2



Eldib

Prototype eMLC



Eley, J. G., K. R. Hogstrom, et al. (2011). "Potential of discrete Gaussian edge feathering method for improving abutment dosimetry in eMLC-delivered segmented-field electron conformal therapy." Medical Physics 38(12): 6610-6622.

Looking to the Future

Antolak

Commercial eMLC

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

Antolak

https://www.youtube.com/watch?t=66&v=F0BBbHRrjBg

Modulated Electron Radiotherapy

M.K. Fix, D. Henzen, P. Manser

INSELSPITAL
UNIVERSITÄTSSPITAL BERN
HOPITAL UNIVERSITAIRE DE BERNE
BERN UNIVERSITY HOSPITAL

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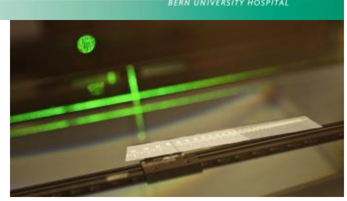
UNIVERSITÄT BERN

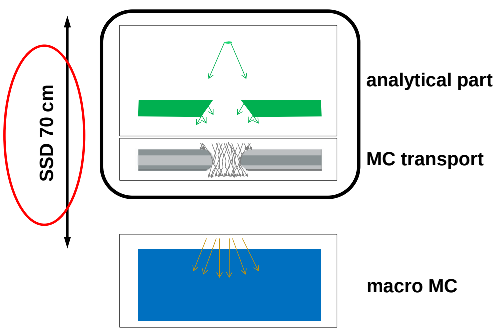


Enable modulated electron radiotherapy

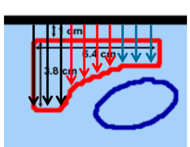
- Use an efficient beam shaping device
  - Multi-leaf collimator (MLC)
- Enable highly accurate and efficient dose calculation

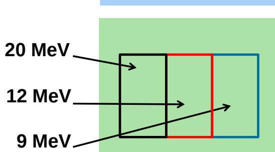
Photon MLC base MERT
using an MC based dose calculation framework

Beam model

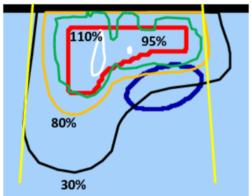


Segmentation



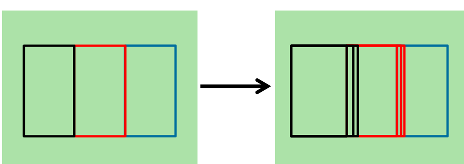


Patched segments



Feathering

20 MeV 12 MeV 9 MeV

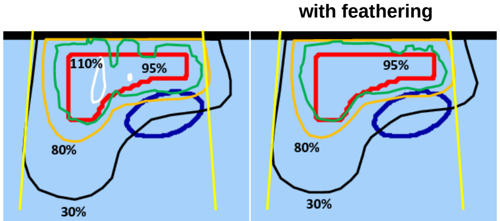


3 x 20 MeV
3 x 12 MeV
1 x 9 MeV

Feathering

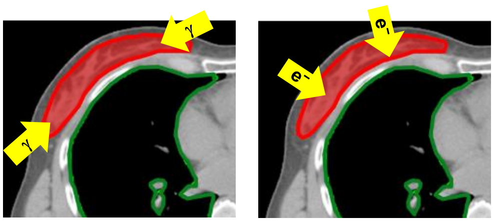
Patched fields

Patched fields with feathering



Application: breast

Standard | MERT

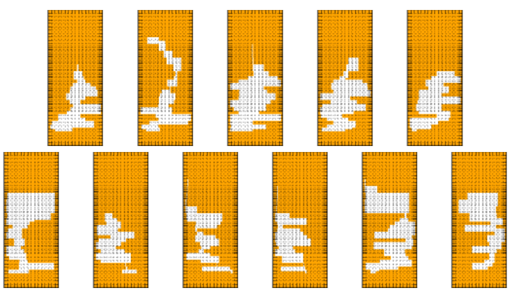


γ: 6 MV

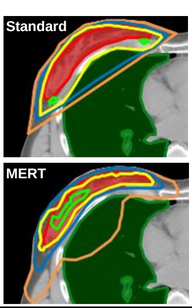
e^{-} : 6 / 9 / 12 MeV
12 segments

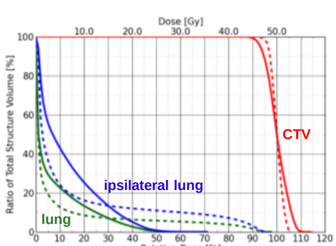
Application: breast

Segments



Application: breast

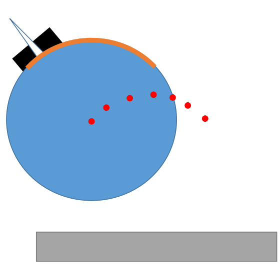




Dynamic Electron Arc Radiotherapy (DEAR)

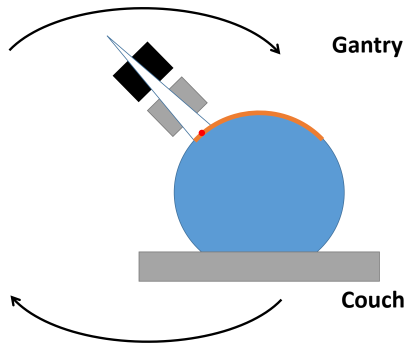
DEAR

- Electron radiation is delivered in ARC mode
- Electron applicator and cut-out are kept to provide lateral beam constriction
- Treatment couch is in simultaneous motion with gantry rotation to prevent collision. Beam always normal and SSD = 100 cm
- Couch motion, gantry rotation, and dose rate are modulated to produce desirable dose distributions



Rodrigues

DEAR design



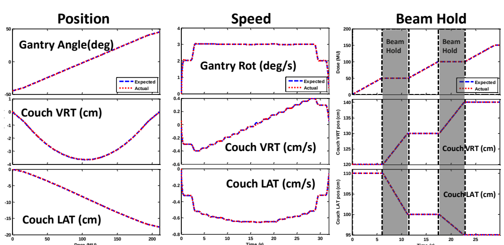
Rodrigues

Planning comparison – Chest wall irradiation

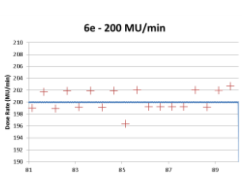
- DEAR: 6, 9, 12 MeV.
- Photons: 6X, tangent, no wedge

Room View

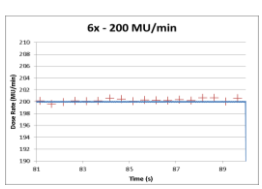
Patient View



Deliverability – Dose Rate Modulation

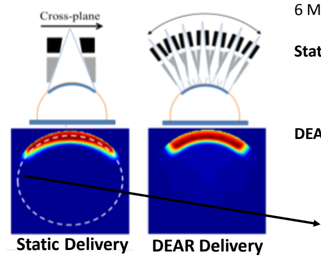


stdev = 1.6 MU/min



stdev = 0.2 MU/min

Dosimetry



Cylindrical phantom
6 MeV

Static Delivery
- $16x10\ cm^2$ cutout
- Gantry Angle 0^o

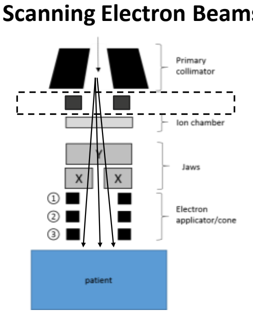
DEAR Delivery
- $3x10\ cm^2$ cutout
- Gantry Angle $315 - 45^o$

Penumbra (80% -20%)
Dose homogeneity

Dosimetry – Penumbra

In-plane: Similar for both plans
Cross-plane: DEAR 2x better than static delivery

Scanning Electron Beams



- Pair of magnets actively deflect electron pencil beam
- Improved PDD due to reduction of Bremsstrahlung tail
- Failure of scanning system → mistreatments

DEAR: virtual scanning mode

Scripted in word
Skeletonized in Matlab
6 MeV electron
D=1cm cutout
SSD=100 cm
Gantry=0
CR
148 CP (7MU/CP)
Beam hold (D->e)

Rodrigues

DEAR Summary

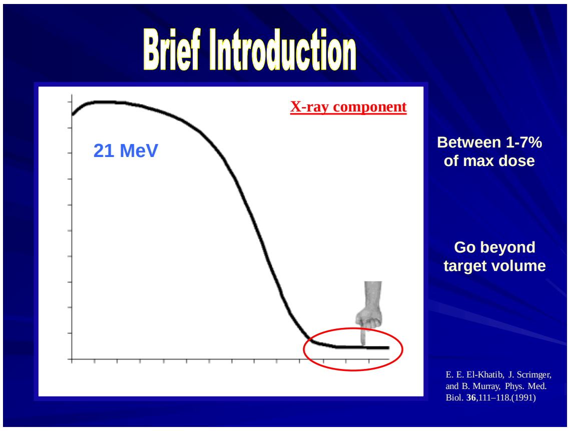
- DEAR can produce uniform dose distributions over large and curved targets while maintaining narrow penumbra
  - Treated area > cone size
- DEAR can be delivered with either fixed cone or eMLC
- DEAR delivery has high accuracy
  - Expected and delivered plans agree very well
  - Trajectory log file can be used as a QC tool
- Limitations
  - Conformal dose from single field
  - Not ready in clinical operation

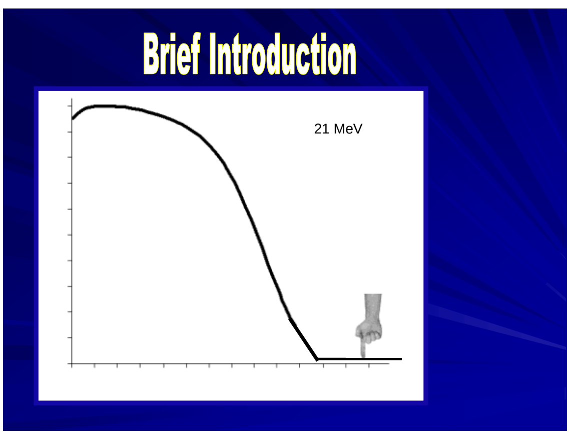
Rodrigues 2014 *Dynamic Electron Arc Radiotherapy (DEAR): a feasibility study* PMB **59**(2)

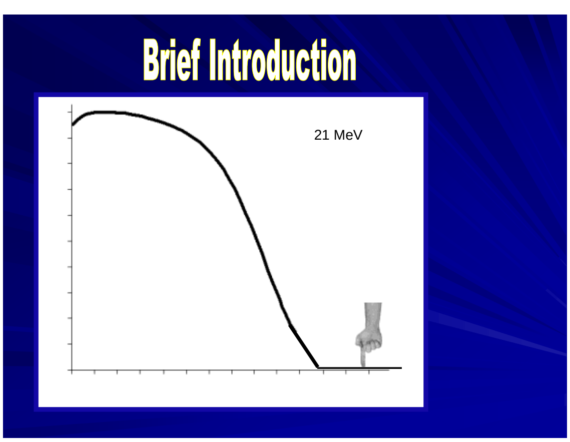
FOX CHASE Cancer center TEMPLE HEALTH

Investigation of the clinical potential of scattering foil free electron beams

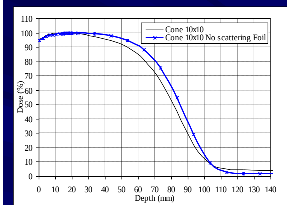
Ahmed Eldib
Fox Chase cancer center


Brief Introduction
X-ray component
21 MeV
Between 1-7% of max dose
Go beyond target volume
E. E. El-Khatib, J. Scrimger, and B. Murray, Phys. Med. Biol. 36,111–118,(1991)

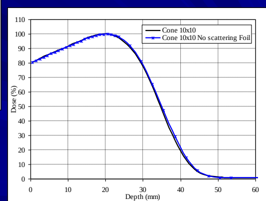

Brief Introduction
21 MeV


Brief Introduction
21 MeV

Percentage depth doses

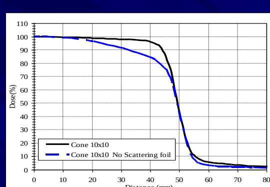


PDD for SFF 21 MeV beam compared to the conventional regular beams.

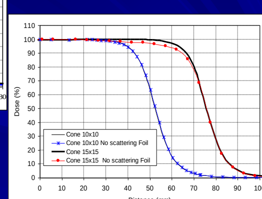


PDD for SFF 9 MeV beam compared to the conventional regular beams.

Profiles

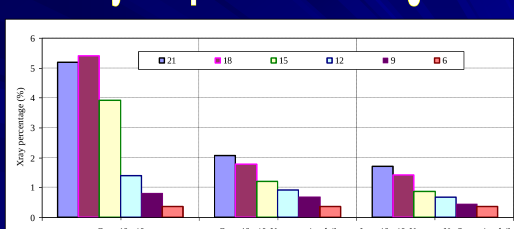


Profiles @Dmax for SFF 21 MeV electron beam compared to the regular beam



Profiles @Dmax for SFF 9MeV electron beam compared to the regular beam

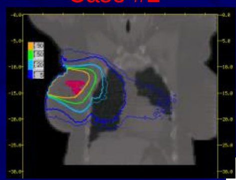
X-ray component Percentage



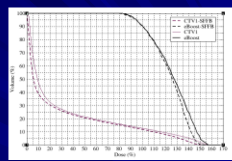
X-ray component percentage for all available energies using conventional beams compared to that excluding scattering foil and cone.

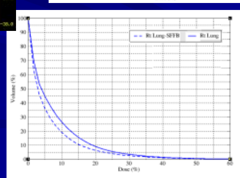
Tumor bed electron boost

Case #2



21MeV Electron boost plan
Thin line: Regular beam





Summary

Technology Complexity

Photons	Electrons	
FFF	SFF	
VMAT	DEAR	VMATe
IMRT	MERT	
ARC	EAT	
3DCRT	ECT	3D Printing

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In Memoriam of Jacques Ovadia

Reinvigorating Scientific Excellence

Electron Beam Therapy –

Past, Present and Future