Electron Radiotherapy: Past, Present, and Future

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Therapy SAMS Session TH-A-500-1
AAPM Annual Meeting, Indianapolis, IN
August 8, 2013

ABSTRACT

Electron beams have been used for treating cancer patients for many years. However, with IMRT, IGRT, proton therapy, and new brachytherapy techniques coming to the forefront, does electron beam therapy still have a role in today's clinics? The physics of electron beam radiotherapy is fairly well understood, but it remains an underutilized modality at most facilities. After starting with a historical overview to provide an appropriate perspective, the session will discuss current technology for generating electron beams and measuring their dose distributions. General principles for planning electron radiotherapy, including both established and new techniques will be a significant focus. The use of electron beams in special procedures, such as total skin electron irradiation and intraoperative treatments, will be be discussed. Treatment planning requires accurate dose calculations, so dose calculation methodologies will be reviewed. Finally, we will briefly share our vision of the future of electron radiotherapy.

LEARNING OBJECTIVES

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

SUGGESTED READING MATERIAL

Background in Electron Beam Physics and Dosimetry

1. ICRU, "Radiation dosimetry: electron beams with energies between 1 and 50 MeV," Report 35, *International Commission on Radiation Units and Measurements* (September 15, 1984).
2. F. M. Khan, "Electron Beam Therapy," (1994) Chapter 14 in The Physics of Radiotherapy (Second Edition), Williams and Wilkins, Baltimore, MD, pp. 346-417.
3. K. R. Hogstrom, "Electron-beam therapy: Dosimetry, planning, and techniques," in *Principles and Practice of Radiation Oncology*, edited by C. A. Perez, L. W. Brady, E. C. Halperin, *et al* (Lippincott Williams & Wilkins, Philadelphia, PA, 2004) pp. 252-282.
4. K. R. Hogstrom and P. R. Almond, "Review of electron beam therapy physics," Phys. Med. Biol. 51, R455-489 (2006).

Electron Beam Dose Calibration

5. AAPM Radiotherapy Task Group 21, "A protocol for the determination of absorbed dose from high-energy photon and electron beams," Medical Physics **10**, 741-771 (1983).
6. P. R. Almond, B. M. Coursey, W. F. Hanson, M. Saiful Huq, Ravinder Nath, and D. W. O. Rogers, "AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams," Medical Physics, **26**, 1847-1870, 199.

Clinical Electron Beam Dosimetry

7. F. M. Khan, K. P. Doppke, K. R. Hogstrom, G. J. Kutcher, R. Nath, S. C. Prasad, J. A. Purdy, M. Rozenfeld, and B. L. Werner, "Clinical electron-beam dosimetry: report of AAPM Radiation Therapy Committee Task Group No. 25," Med. Phys. **18**, 73-109 (1991).
8. K. R. Hogstrom, "Clinical electron beam dosimetry: basic dosimetry data," in *Advances in Radiation Oncology Physics – Dosimetry, Treatment Planning, and Brachytherapy, Medical Physics Monograph No. 19, American Association of Physicists in Medicine,* edited J. A. Purdy (American Institute of Physics, Inc., Woodbury, New York, 1992), pp. 390-429.
9. A. S. Shiu, S. S. Tung, C. E. Nyerick, T. G. Ochran, V. A. Otte, A. L. Boyer and K. R. Hogstrom, "Comprehensive analysis of electron-beam central-axis dose for a radiotherapy linear accelerator," Medical Physics, **21**, 559-566, 1994.
10. K. R. Hogstrom, R. E. Steadham, P. F. Wong, and A. S. Shiu, "Monitor Unit Calculations for Electron Beams," in Monitor Unit Calculations for External Photon and Electron Beams, edited by J. P. Gibbons (Advanced Medical Publishing, Inc., Middleton, WI, 2000) pp. 113-125.
11. B. J. Gerbi, J. A. Antolak, F. C. Deibel, D. S. Followill, M. G. Herman, P. D. Higgins, M. S. Huq, D. N. Mihailidis, E. D. Yorke, K. R. Hogstrom, and F. M. Khan, "Recommendations for clinical electron beam dosimetry: Supplement to the recommendations of Task Group 25," Med. Phys. **36**, 3239-3279 (2009).
12. B. J. Gerbi, J. A. Antolak, F. C. Deibel, D. S. Followill, M. G. Herman, P. D. Higgins, M. S. Huq, D. N. Mihailidis, E. D. Yorke, K. R. Hogstrom, and F. M. Khan, "Erratum: "Recommendations for clinical electron beam dosimetry: Supplement to the recommendations of Task Group 25" [Med. Phys. **36**, 3239-3279 (2009)]," Med. Phys. **38**, 548-548 (2011).

Effect of Tissue Heterogeneity

13. K. R. Hogstrom, "Dosimetry of electron heterogeneities," in *Medical Physics Monograph No. 9: Advances in Radiation Therapy Treatment Planning,* edited by A. Wright and A. Boyer (American Institute of Physics, New York; 1983), pp. 223-243.
14. A. S. Shiu and K. R. Hogstrom, "Dose in bone and tissue near bone-tissue interface from electron beam," International Journal of Radiation Oncology Biology Physics," **21,** 695-702 (1991).

Electron Pencil-Beam and New Dose Algorithms

15. K. R. Hogstrom, “Evaluation of electron pencil beam dose calculation,” in *Radiation Oncology Physics, Medical Physics Monograph No. 15, American Association of Physicists in Medicine*, edited by J. G. Kereiakes, H. R. Elson and C. G. Born (American Institute of Physics, Woodbury, New York, 1987), pp. 532-561.
16. K. R. Hogstrom and R. S. Steadham, “Electron beam dose computation,” in *Teletherapy: Present and Future - 1996 Proceedings of the Summer School of the AAPM*, edited by J. Palta and T. R. Mackie (Advanced Medical Publishing, Madison, Wisconsin, 1996), pp. 137-174.

Electron Beam Treatment and Treatment Planning

General

17. K. R. Hogstrom, “Treatment planning in electron-beam therapy,” in *The role of high energy electrons in the treatment of cancer,* edited by J. M. Vaeth and J. Meyer (Karger, New York, NY, 1991) pp. 342.
18. F. M. Khan and M. D. McNeese, “Electron beam therapy,” in Levitt and Tapley's technological basis of radiation therapy: Practical clinical applications, edited by S. H. Levitt, F. M. Khan, and R. A. Potish (Lea & Febiger, Philadelphia, PA, 1992) pp. 80-93.

Electron Bolus and Conformal Therapy

19. W. H. Morrison, P. F. Wong, G. Starkschall, A. S. Garden, C. Childress and K. R. Hogstrom, “Water bolus for electron irradiation of the ear canal,” Int. J. Radiat. Oncol. Biol. Phys. **33**, 479-483 (1995).
20. D. A. Low, G. Starkschall, N. E. Sherman, S. W. Bujnowski, J. R. Ewton, and K. R. Hogstrom, “Computer-aided design and fabrication of an electron bolus for treatment of the paraspinal muscles,” Int. J. Radiat. Oncol. Biol. Phys. **33**, 1127-1138 (1995).
21. D. A. Low, G. Starkschall, S. W. Bujnowski, L. L. Wang, and K. R. Hogstrom, “Electron bolus design for radiotherapy treatment planning: bolus design algorithms,” Med. Phys. **19**, 115-124 (1992).
22. G. H. Perkins, M. D. McNeese, J. A. Antolak, T. A. Buchholz, E. A. Strom, and K. R. Hogstrom, “A custom three-dimensional electron bolus technique for optimization of postmastectomy irradiation,” Int. J. Radiat. Oncol. Biol. Phys. **51**, 1142-1151 (2001).
23. R. J. Kudchadker, J. A. Antolak, W. H. Morrison, P. F. Wong, and K. R. Hogstrom, “Utilization of custom electron bolus in head and neck radiotherapy,” J. Appl. Clin. Med. Phys. **4**, 321-333 (2003).
24. K. R. Hogstrom, J. A. Antolak, R. J. Kudchadker, C. M. Ma, and D. D. Leavitt, “Modulated Electron Therapy,” in Intensity-Modulated Radiation Therapy: The State of the Art, edited by J. R. Palta and T. R. Mackie (Medical Physics Publishing, Madison, WI, 2003) pp. 749-786.

Collimation

25. A. S. Shiu, S. S. Tung, R. J Gastorf, K. R. Hogstrom, W. H. Morrison and L. J. Peters, “Dosimetric evaluation of lead and tungsten eyeshields in electron beam treatment,” Int. J. Radiat. Oncol. Biol. Phys. **35**, 599-604 (1996).
26. K. R. Hogstrom, A. L. Boyer, A. S. Shiu, T. G. Ochran, S. M. Kirsner, F. Krispel and T Rich, “Design of metallic electron beam cones for an intraoperative therapy linear accelerator,” Int. J. Radiat. Oncol. Biol. Phys. **18**, 1223-1232 (1990).

Specialized Electron Beam Therapy Techniques

Extremities

27. K. K. Wooden, K. R. Hogstrom, P. Blum, R. J. Gastorf, and J. D. Cox, “Whole-limb irradiation of the lower calf using a six-field electron technique,” Med. Dosim. **21**, 211-218 (1996).

Electron Arc Therapy

28. K. R. Hogstrom and D. D. Leavitt, "Dosimetry of arc electron therapy," in *Advances in Radiation Oncology Physics – Dosimetry, Treatment Planning, and Brachytherapy, Medical Physics Monograph No. 19, American Association of Physicists in Medicine,* edited by J. A. Purdy (American Institute of Physics, Inc., Woodbury, New York, 1987), pp. 265-295.
29. D. D. Leavitt, "Physics of electron arc therapy," in *Medical Radiology—Radiation Therapy Physics*, edited by A. R. Smith, (Springer-Verlag, New York, 1995), pp. 139-154.

Total Skin Electron Therapy

30. AAPM Report No. 23, "Total Skin Electron Therapy: Technique and Dosimetry," in *American Association of Physicists in Medicine, AAPM Radiotherapy Task Group 30,* (American Institute of Physics, Inc., Woodbury, New York, 1987), pp. 55.
31. P. R. Almond, "Total skin/electron irradiation technique and dosimetry," in *Advances in Radiation Oncology* Physics – *Dosimetry, Treatment Planning, and Brachytherapy, Medical Physics Monograph No. 19, American Association of Physicists in Medicine,* edited by J. A. Purdy (American Institute of Physics, Inc., Woodbury, New York, 1987), pp. 296-332.
32. J. A. Antolak, J. H. Cundiff, and C. S. Ha, "Utilization of thermoluminescent dosimetry in total skin electron beam radiotherapy of mycosis fungoides," Int. J. Radiat. Oncol. Biol. Phys. **40**, 101-108 (1998).
33. J. A. Antolak and K. R. Hogstrom, "Multiple scattering theory for total skin electron beam design," Med. Phys. **25**, 851-859 (1998).

Intraoperative Electron Therapy

34. E. C. McCullough and P. J. Biggs, "Intraoperative electron beam radiation therapy," in *Advances in Radiation Oncology Physics – Dosimetry, Treatment Planning, and Brachytherapy, Medical Physics Monograph No. 19, American Association of Physicists in Medicine,* edited by J. A. Purdy (American Institute of Physics, Inc., Woodbury, New York, 1989), pp. 333-347.
35. C. E. Nyerick, T. G. Ochran, A. L. Boyer and K. R. Hogstrom, "Dosimetry characteristics of metallic cones for intraoperative radiotherapy," Int. J. Radiat. Oncol. Biol. Phys. **21** 501-510 (1991).
36. J. R. Palta, P. J. Biggs, J. D. Hazle, M. S. Huq, R. A. Dahl, T. G. Ochran, J. Soen, R. R. Dobelbower, and E. C. McCullough, "Intraoperative electron beam radiation therapy: Technique, dosimetry, and dose specification: Report of task force 48 of the radiation therapy committee, American Association of Physicists in Medicine," Int. J. Radiat. Oncol. Biol. Phys. **33**, 725-746 (1995).

Craniospinal Irradiation

37. M. H. Maor, R. S. Fields, K. R. Hogstrom and J. Van Eys, "Improving the therapeutic ratio of craniospinal irradiation in medulloblastoma," Int. J. Radiat. Oncol. Biol. Phys. **11**, 687-707 (1985).

Total Scalp Irradiation

38. S. S. Tung, A. S. Shiu, G. Starkschall, W. H. Morrison and K. R. Hogstrom, "Dosimetric evaluation of total scalp irradiation using a lateral electron-photon technique," Int. J. Radiat. Oncol. Biol. Phys. **27**, 153-160 (1993).

REVIEW QUESTIONS

1. What is the principle of side-scatter equilibrium? Explain how this principle affects the field-size dependence of depth dose and output. Explain how it can cause output to falloff faster than inverse square.
2. Discuss the energy dependence of the following depth dose quantities – D_s, R_{90}, R_p, and D_x.
3. Explain the field size dependence of depth dose, i.e. how it affects D_s, R_{90}, R_p, and D_x.
4. Discuss how penumbra depends on depth and air gap as a function of energy.
5. What is the square root method for depth dose?
6. What influence does air gap have on output and depth dose?
7. How does angled incidence affect depth dose and penumbra?
8. How does a sharp surface discontinuity affect the underlying dose distribution, i.e. where does the volumes of increased/decreased dose lie? Discuss the resulting clinical impact for the nose and ear.
9. Explain why abutted chest wall fields sometimes give significant lung dose, i.e., how the penetration of the dose distribution increased in lung tissue.
10. Discuss the influence of hard bone (e.g. mandible) on the underlying dose distribution. Is backscatter dose from bone clinically significant? Why is there an increased dose in bone, and is it clinically significant?
11. What is the relationship between lead thickness (mm) required to stop incident electrons and electron energy, $E_{p,0}$ (MeV)? List three clinical reasons for skin collimation and give a clinical example for each.
12. How does increased dose from electron backscatter depend on energy $(\bar{E}_z)$ at the tissue-lead interface? How can the patient be protected from backscattered dose from internal collimation?
13. Discuss the dose distribution behind a 1-cm diameter lead block, and how does it vary with energy and air gap? How can this type of block be used to treat retinoblastoma?
14. Define electron bolus. List three clinical reasons for electron bolus and give a clinical example for each.
15. Give two methods for verification of the intended use of electron bolus.
16. Explain the three different classifications of abutting electron fields and a clinical example of each. How is dose inhomogeneity resulting from field abutment minimized during the course of treatment?
17. In treatment of whole limb with electrons, six to eight fields (with falloff) spaced as evenly as possible around the limb's axis can be used. How does the depth dose change relative to that of a single beam? Why is arc therapy with a narrow field (e.g. 5-cm wide at isocenter) a poor option?
18. In electron arc therapy of the chest wall, explain how and why the depth dose changes relative to that of the unarced beam. Why is the width of the secondary electron insert narrower in the portion used to irradiate the superior part of the chest wall than the inferior part? Write the equation relating the field width, W, for treating a cross-sectional anatomy with a mean radius of curvature, ρ, to that of the central axis width, W_0, treating a cross-sectional anatomy with a mean radius of curvature ρ_0. Why is skin collimation required for electron arc therapy of the chest wall?
19. For total skin therapy using the Stanford technique, explain (1) why each patient is treated with two beams at gantry angles 90° $\pm\ \theta$, (2) why the light field edges from the two fields are separated by a large gap, and (3) why a 1-cm thick scatter plate directly in front of the patient improves dose homogeneity.
20. Describe the CT lookup tables and beam data input necessary to commission a pencil beam dose algorithm What comparisons with dose measurements would you make to verify proper data input prior to clinical use? What are the strengths of the Hogstrom pencil beam model in its clinical application? Under what circumstances will the algorithm have dose inaccuracies greater than 5%?