Electron Beam Therapy for Superficial Radiation Therapy

Kenneth Hogstrom, Ph.D.
Louisiana State University-Mary Bird Perkins Cancer Center
Medical Physics and Health Physics Program

Conflict of Interest: Mary Bird Perkins Cancer Center currently has and has had previous research agreements with .decimal, LLC upon which I have participated regarding personalized treatment devices for electron beam therapy.

Learning Objectives

• Understand the availability of electron beam therapy planning and delivery technology.

• Understand the utility of electron beam therapy in the head, neck, limbs, and chest wall, as related to skin cancer or cancers requiring skin irradiation.
Scope of External Beam Modalities

- **Included:** electron beam therapy (EBT)
  - Conventional, fixed beam therapy for multiple sites
  - Bolus electron conformal therapy (BECT)
  - Intensity modulated BECT (IM-BECT)

- **Excluded:** other useful electron beam techniques
  - Total limb irradiation for lymphomas, sarcomas, etc. (Wooden et al 1996)
  - Total skin electron therapy for mycosis fungoides (Karzmark et al 1987)
  - Electron arc therapy for postmastectomy breast cancer (Hogstrom & Leavitt 1987)

- **Excluded:** other external beam modalities
  - kVp x-ray therapy
  - MVp x-ray therapy: Volumetric modulated arc therapy (VMAT) & helical tomo
  - Proton therapy or heavy ion therapy

Patient Specific Devices for Electron Beam Therapy

1. Cutout
2. Intensity Modulator
3. External Bolus
4. Skin Collimation
5. Internal Bolus
6. Internal Collimation
   (not covered, see AAPM TG25 1991)

It is necessary that:
- Dose algorithms accurately calculate dose in presence of these devices.
- These devices are easily modeled in the TPS.
- These devices are easily accessible for patient use.
Electron Beam TPS Requirements for Skin Cancer Patients

- Deficiencies in current treatment planning systems (TPS):
  - Inaccurately calculate dose at patient surface.
  - Lack tools for effectively and efficiently modeling most electron beam treatment devices.

- Dose algorithms should
  - calculate dose sufficiently accurate in presence of the patient specific devices used in electron therapy.
  - calculate dose sufficiently accurate in presence of patient heterogeneities.
  - Most current dose algorithms meet these requirements, but all do not for all cases. (Hogstrom et al 2021).

Dose Accuracy Comparison
PBA, PBRA, and eMC
Retromolar Trigone Phantom (Carver et al 2013, 2016)

<table>
<thead>
<tr>
<th></th>
<th>Trigone</th>
<th>Nose</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBRA</td>
<td>1.78%</td>
<td>1.52%</td>
</tr>
<tr>
<td>eMC</td>
<td>2.55%</td>
<td>3.30%</td>
</tr>
<tr>
<td>PBA</td>
<td>3.27%</td>
<td>6.01%</td>
</tr>
</tbody>
</table>
Dose Accuracy Comparison
PBA, PBRA, and eMC
Carcinoma of the Nose Phantom
(Carver et al 2013, 2016)

<table>
<thead>
<tr>
<th>Accuracy (1 sigma)</th>
<th>Trigone</th>
<th>Nose</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBRA</td>
<td>1.78%</td>
<td>1.52%</td>
</tr>
<tr>
<td>eMC</td>
<td>2.55%</td>
<td>3.30%</td>
</tr>
<tr>
<td>PBA</td>
<td>3.27%</td>
<td>6.01%</td>
</tr>
</tbody>
</table>

For greater details, see Hogstrom et al.’s Chapter 22 in the 2021 edition of Khan’s Treatment Planning in Radiation Oncology textbook.

Patient Specific Device #1: Cutout

- **Purpose:** To optimally shield tissues lateral to the PTV using an irregularly-shaped collimating cutout

- **Fabrication Options:**
  - In-house: Cerrobend cast around template, foam cut or 3D printed (Michiels et al 2018)
  - Ordered: .decimal Copper machined

- **Dosimetry Comparison:** Identical dose distributions within 2%/1 mm >99% points (Rusk et al. 2016)
Patient Specific Device #3A: Bolus, Uniform Thickness

• **Purpose**: To increase surface dose and decrease dose to structures distal to PTV.

• **Usage**: Skin cancers in patients with flat skin surface overlying PTV & for lower energy electron beams having lower surface dose.

• **Availability**: Commercial non-patient specific (SuperFlab, Bolusil, Bolx, Elastogel, Thermoplastic, etc.) and patient specific (machined wax, molded FlexiBol, 3D printed materials)

Patient Specific Device #3B: Flat-top Bolus

• **Purpose**: To remove hot/cold spots in PTV dose distribution due to an irregular patient surface.

• **Usage**: Skin cancers of the nose and ear, and surgical defects (missing tissue bolus)

• **Availability**: decimal machined wax and in-house 3D printing

Patient Specific Device #3C: Conformal Bolus

• **Purpose:** To conform and circumscribe distal therapeutic isodose surface (90%) to distal PTV surface, minimizing dose to distal tissues.

• **Usage:** Skin cancers with disease at variable depths within 6 cm of skin surface.

• **Availability (Commercially):**
  - Bolus design software, e.g. BolusECT (.decimal) and MET (Adaptiiv)
  - Bolus fabrication, e.g. machined wax (.decimal) and in-house 3D printing.

Patient Specific Device #3C: Bolus Electron Conformal Therapy (BECT) Plan

- Scalp stage IV diffuse large B cell lymphoma: **9 MeV** bolus electron conformal therapy
- M. D. Anderson Cancer Center
Potential of BECT with Optimal e Beam for Postmastectomy Chest Wall Plan (Wang 2020)

- For select patients, electron beam therapy offers reduced heart dose, lung dose, and probability of secondary cancer relative to VMAT.
- See Wang (2020) and Opp et al. (2013) for more details.

Patient Specific Device #2: Intensity Modulator

- **Purpose:** To modulate intensity inside aperture (normally 1.00 inside) to be <1.00.
- **Usage:** Intensity modulated bolus electron conformal therapy (IM-BECT), field matching, or other techniques.
- **Availability:** Pending planning and fabrication technology transfer by .decimal using NIH SBIR grant.

(Hogstrom et al 2018, Hogstrom and Carver 2020)
Patient Specific Device #2: IM-BECT Plan (R Buccal Mucosa)

- **Bolus Only** 25 MeV
- **Bolus & IM** 25 MeV

Kudchadker et al 2002

Patient Specific Device #4: Skin Collimation

- **Purpose**: To spare tissue near edge of electron beams whose penumbra is large due to large air gap, small fields, or overlying bolus.

- **Usage**: Superficial PTVs near eyes or other structures to be restricted to low dose. Small PTVs, e.g. eyelids.

- **Availability**:
  - Current TPS allow manual creation, but lacks automation.
  - Fabrication is transitioning from manual to machined.
Patient Specific Device #4: Parotid Plan with Skin Collimation

• When will TPS automatically design skin collimation?
• When will TPS accurately calculate dose with skin collimation?

Patient Specific Device #4: Skin Collimator Fabrication

When will skin collimators be automatically fabricated?

• Current Manual Methods
  A: Pounded lead (ρ = 11.3 g·cm⁻³)
  B: Drip-molded Cerrobend (ρ = 9.4 g·cm⁻³)

• Future Machined Prototypes
  C: Milled brass (ρ = 8.7 g·cm⁻³)
  D: Printed bronze (ρ = 3.9 g·cm⁻³)*

*Lower density materials may be energy limited due to scatter off aperture wall.
Patient Specific Device #5: Internal Bolus

- **Purpose:** To fill internal air cavities to remove hot and cold spots caused by electron scatter.
- **Usage:**
  - Top: internal water bolus removes distal hot spot in inner ear.
  - Bottom: internal SuperFlab bolus removes cold spot lateral to nasal septum.
- **Availability:**
  - TPS limited to manual design of bolus or CT with fabricated bolus.
  - Fabrication is currently manual (e.g. SuperFlab, molded wax or silicone).
  - Small, irregular shape of bolus is well-suited for 3D printing.

Summary and Recommendations

1) Electron beam therapy can often offer individual patients the best dose plan for skin cancers.

2) Offering the best electron plan requires easy access to practical planning techniques and patient specific devices.

3) Planning technology has practical solutions for accurate dose calculations and bolus electron conformal therapy, and intensity modulation is on the horizon.

4) Planning technology needs improvement to easily design patient specific devices and to provide documented, accurate dose calculations in their presence.

5) Machined and 3D-printed patient specific devices continue to evolve. Cutouts and boluses are readily available; skin collimation and internal bolus are evolving; and internal collimation, other than eyeshields, has received little attention.
Slide 1: Title Slide; **Electron Beam Therapy for Superficial Radiation Therapy.**

Slide 2: The learning objectives for this talk are to understand the availability of electron beam therapy planning and delivery technology and to understand the utility of electron beam therapy in the head, neck, limbs, and chest wall, as related to skin cancer or cancers requiring skin irradiation.

Slide 3: This talk will discuss conventional, fixed electron beam therapy for multiple sites, as well as more recent bolus electron conformal therapy or BECT and the potential future technology intensity modulated BECT (IM-BECT). Time will not allow discussion of other useful techniques important for skin cancer, such as: total limb irradiation for lymphomas, sarcomas, etc. (Wooden et al 1996), total skin electron therapy for mycosis fungoides (Karzmark 1987), and electron arc therapy for postmastectomy breast cancer (Hogstrom and Leavitt 1987). Key references for these techniques are listed. Other modalities useful for skin cancers, such as kilovoltage x-ray therapy, megavoltage x-ray therapies, proton therapy, and heavy ion therapy, are excluded.

Slide 4: Fixed electron beam therapy benefits from multiple patient specific devices that are illustrated here. First is the orange beam-defining cutout; second is the yellow intensity modulator that fits inside the cutout; third is the blue electron bolus that rests on the patient surface; fourth is the gray skin collimation that also rests on the patient surface; fifth is the blue internal bolus that fills superficial air cavities; and sixth is internal collimation. The latter, which includes eyeshields, gum shields, and others, is omitted from today’s talk due to time limitations. To effectively use these devices, it is necessary that dose algorithms accurately calculate dose in their presence, that these devices are easily modeled in the treatment planning system (TPS), and that these devices are easily accessible for patient use.

Slide 5: Regarding the status of current TPSs for planning skin cancer treatment, there are deficiencies. Some do not accurately calculate dose at the patient surface, and all lack tools for effectively and efficiently modeling most electron beam treatment devices, requiring “workarounds”. Also, algorithms should calculate dose sufficiently accurate in the presence of the patient specific tools used in electron therapy and in the presence of patient heterogeneities. Most current dose algorithms meet these requirements, but all do not for all cases. (Hogstrom et al 2021)
Slide 6: This slide compares the dose accuracy for a bolus electron conformal therapy plan in a heterogeneous retromolar trigone phantom as reported by Carver et al (2013, 2016). Results for the Hogstrom pencil beam algorithm (PBA), the pencil beam redefinition algorithm (PBRA), and the Varian macro Monte Carlo algorithm (eMC) are compared. Histograms of dose differences, i.e. calculated minus measure dose, at measured dose points are plotted to the right. Ideally, no differences should exceed 5% or 3 mm, i.e. no white bars outside 5%. Only the PBRA meets these criteria; the eMC fails at only one point; and the PBA fails at only a few points. A good metric for comparing dose accuracy is the standard deviation of the Gaussian fit to the dose difference data, whose values are highlighted yellow in the table, showing the PBRA the most accurate.

Slide 7: This slide compares dose accuracy for the PBA, the PBRA, and the eMC for a more challenging BECT plan in a heterogeneous nose phantom. Again, only the PBRA meets the 5% or 3 mm criteria; the eMC fails at only a few points; and the PBA fails significantly at multiple points. The standard deviations for the dose difference histograms, again highlighted in yellow in the table, show significantly less accuracy for the PBA, as expected. (Descriptions of these three algorithms and detailed discussion of their accuracies can be found in Chapter 22 of the new edition of Khan’s Treatment Planning in Radiation Oncology textbook, Hogstrom et al. 2021).

Slide 8: Let’s now look at patient-specific devices, the cutout first. Its purpose is to optimally shield tissues lateral to the PTV using an irregularly-shaped collimating cutout. Traditionally, this has been done by molding Cerrobend around a Styrofoam template, although today, one can use a 3D printer to fabricate the template (Michiels et al. 2018). A growing option has been to use .decimal Copper-machined cutouts in lieu of Cerrobend, which have been shown clinically equivalent within 2% or 1 mm by Rusk et al (2016). The top photo shows Copper and Cerrobend sets of beam commissioning cutouts, and the lower photos show patient-specific cutouts.

Slide 9: Next, let’s look at external electron bolus, which can provide increased surface dose, improved PTV dose uniformity, and decreased normal tissue dose distally. Uniform thickness bolus provides increased surface dose and increased sparing of distal normal tissue. It can be quite useful for skin cancers in patients with a flat or cylindrical surface and for lower energy electron beams, which have
lower surface dose. Commercial products include non-patient-specific ones such as SuperFlab, Bolusil, Bolx, Elasto-Gel, Thermoplastic, and others, and patient-specific ones fabricated using machinable wax, molded FlexiBol, and 3D printing materials. These boluses can be modeled in the treatment planning system or CT scanned to be part of the patient. The top picture show a postmastectomy chest wall Bolusil bolus. The lower left shows a molded FlexiBol bolus, and the lower right shows a 3D-printed Agilus-60 bolus, both useful for total scalp irradiation.

Slide 10: A second bolus type, flat-top boluses, are designed to remove hot and cold spots in the PTV dose distribution due to an irregular patient surface. Their thickness is optimized to best spare distal tissue. They are useful for skin cancers of the nose and ear. The pictures on the right show the treatment plan and the corresponding 3-D rendering of the bolus setup for a squamous cell carcinoma patient treated with an approximately flat-top bolus.

Slide 11: A third bolus type, used for electron conformal therapy, conforms and circumscribes the distal therapeutic isodose surface (typically 90%) to the distal PTV surface, minimizing dose to distal tissues. This is useful for skin cancers with disease at variable depths. As illustrated by the figures on the right, a variable thickness bolus modulates the range to conform the 90% isodose line to the PTV. Software for designing conformal boluses is currently available from two vendors, .decimal LLC and Adaptiiv. For bolus fabrication, .decimal mills machinable wax, and Adaptiiv utilizes in-house 3D printing.

Slide 12: This slide illustrates use of bolus electron conformal therapy for a partial scalp. A 9-MeV beam irradiates a stage IV diffuse large cell lymphoma. The transverse plane on the left shows the blue wax bolus conforming the 30 Gy surface to the distal PTV surface, minimizing dose to the brain. The sagittal slice in the center shows the same. The patient setup in the prone position with the blue wax bolus in place is shown on the right.

Slide 13: This slide illustrates bolus electron conformal therapy plans for postmastectomy chest wall irradiation using a sagittal-coronal, oblique electron beam. Both plans conform the red, 90% isodose line to the white PTV through use of the blue wax bolus. The left, 21.3-MeV plan shows that for select patients, such plans can offer reduced heart dose (highlighted by the red ellipse), reduced lung dose (highlighted in blue), and reduced probability of secondary cancer relative to those of a VMAT plan. However, the right figure shows even less heart and lung
dose if future electron beams were flattened by beam scanning rather than dual scattering foils, and if continuous beam energies were available, so that a 17.3-MeV beam could be used. For more details see Wang (2019) and Opp et al. (2013).

Slide 14: A potentially useful future device for electron beam therapy is the passive intensity modulator (Hogstrom and Carver 2018). It modifies the intensity inside the aperture from its normal, uniform value of one to values less than one versus off-axis position. Unlike passive x-ray intensity modulators, it modulates based on scattering rather than attenuating the beam. Electron intensity modulation should be useful for bolus electron conformal therapy, field matching, and other techniques. Its availability is pending planning and fabrication technology transfer by .decimal using an NIH SBIR grant. On the top right is a picture of an intensity modulator based on the recent patent by Hogstrom and Carver (2020). It consists of a copper insert whose cutout contains a machinable foam slab that is peppered with 6-mm tungsten pins of varying diameter. This device creates a downstream intensity distribution from 80-100%, illustrated by the iso-intensity plot beneath.

Slide 15: Kudchadker et al. (2002) first illustrated the utility of intensity modulation for bolus electron conformal therapy. The left dose plan illustrates how a steep gradient on the bolus surface creates an underlying volume of increased dose (or “hot spot”), as great as 120%. The right dose plan illustrates how using the intensity modulation plotted in the lower right image, along with a small bolus redesign, eliminates the hot spot while maintaining conformity of the 90% isodose surface in yellow to the dotted PTV. This is better appreciated in the comparison of the PTV dose volume histograms for the two plans in the upper right plot.

Slide 16: Skin collimation is a device used to spare tissue near the edge of electron beams whose penumbra has become too large due to large air gaps, small field sizes, or overlying bolus. It can be useful for treatment of superficial PTVs near the eyes or for small PTVs like the eyelids. The two pictures on the right show lead skin collimation protecting the eyes from electrons scattered from the overlying beeswax bolus used for treating carcinoma of the nose.

Slide 17: The sparing benefit of skin collimation is illustrated here, which compares dose plans used to treat the corner of a parotid PTV abutting the eye, outlined in yellow. Under a conforming electron bolus (shown by the red line), the left plan without skin collimation, would deliver significantly greater dose to the adjacent orbit and lens than the right plan, with skin collimation (shown in orange). The
greatly reduced orbit and lens doses are illustrated by dose volume histograms plotted on the right. This begs the question, when will electron planning systems have tools that automatically design skin collimators, rather than ‘workarounds’, and accurately calculate dose in their presence?

Slide 18: This slide compares current and evolving technologies for fabrication of skin collimation. The top two pictures show skin collimators manually fabricated using pounded lead on the left and dripped Cerrobend on the right. The lower left picture shows a prototype milled from brass by .decimal (Posey 2012), and the lower right shows one 3D-printed using a bronze filament (Craft et al 2020). The density of printed bronze, being less than half that of the other metals, might limit its use to energies below 10 MeV due to electron scatter from the cutout edges, although that should be sufficient for many skin cancers.

Slide 19: The final tool discussed is the use of internal bolus to remove hot and cold spots caused by electron scatter into or behind air cavities. The top two figures show how dose to the inner ear, which can be as large as 165% without bolus in the ear canal, being reduced to 130% with bolus filling the ear cavity (in this case saline solution). The remaining hot spot is due to the external ear and can be removed by external bolus. The bottom two figures show measured dose at points abutting the nasal air cavities being decreased by 10%, which can be increased by filling the nasal passage way with a custom internal bolus (SuperFlab in this case). Such cases should be a good application for using a molded or 3D printed flexible material.

Slide 20: The state of electron beam therapy for skin cancers can be summarized as follows:
1) Electron beam therapy can often offer individual patients the best dose plan for skin cancers.
2) Offering the best electron plan requires easy access to practical planning techniques and patient specific devices.
3) Planning technology has practical solutions for accurate dose calculations and bolus electron conformal therapy, and intensity modulation is on the horizon.
4) Planning technology needs improvement to easily design patient specific devices and to provide documented, accurate dose calculations in their presence.
5) Machined and 3D-printed patient specific devices continue to evolve. Cutouts and boluses are readily available; skin collimation and internal bolus are
evolving; and internal collimation, other than eyeshields, has received little attention.

References

• **References Non-Specific to Text and Slides (Historical, General Electron Beam Therapy Techniques)**

• **References Specific to Text and Slides**


