Modern Pencil Beam Scanning (PBS)

Where We Are and Where We Are Going
Disclaimers

• No disclosures of any kind.

• The views in this presentation are my own and not necessarily endorsed by my employer or colleagues.

• Information is provided “as is” without warranty of any kind. The information in this presentation could include technical inaccuracies and/or typographical errors.
My Background in Dosimetry

• 2 years at MD Anderson Cancer Center
  – B.S. Medical Dosimetry
    • 85% of clinical training focused on photon based radiation therapy.
    • 15% of clinical training focused on proton based radiation therapy.

• 1 year at Banner MDACC
  – VMAT, IMRT, 3DCRT, SBRT, and more

• 2 years at SCCA Proton Therapy Center
Goals

• Share knowledge and information on proton therapy especially modern Pencil Beam Scanning (PBS).

• Educate my dosimetry colleagues and anyone else that may view this presentation on how PBS is used clinically today.

• Promote interest in proton therapy and proton therapy dosimetry.
Motivation

• With the unique perspective of being new to Proton Therapy I am impressed by how much I have had to learn to be successful and progressive in my short tenure.
  – My time in proton therapy has shown me how little I knew before I joined the field.

• Speaking with other dosimetrist with no proton experience shows me there is still a great opportunity for education.
Goals, Expanded

- Protons: Review the basics
- Protons: the road to now
- Why PBS
  - Passive Scatter vs Pencil Beam Scanning
- The Basics of PBS
  - Some not so basic things too!
- The PBS treatment planning
- How PBS is used Clinically
  - What does PBS excel at
  - What is possible with PBS
- The future of PBS
PROTONS 101

Let’s review some of the basics of protons and proton therapy before we dig into the specifics of Pencil Beam Scanning.
Protons 101

• Protons
  – Positively charged particles
    • Have a large resting mass
    • Encompassed by Coulomb field
      – Coulomb field is the \textit{electrostatic field around} an electrically \textit{charged particle} or body
      – Protons always interact with electrons or nuclei of atoms in matter
      – No significant deflection of protons off their path. Travel in a fairly straight line
      – \textbf{Each interaction is generally a very small amount of each particles kinetic energy loss}. The protons are \textit{continuously slowing down} until the \textbf{protons eventually stop completely}. 
Protons 101

• Stopping Power = energy loss per unit path length

• Stopping Power INCREASES as a proton slows down
  – Due to this, a proton loses a large amount of its energy immediately before the particle comes to rest.
    • This creates a dose deposition peak at the end of the protons range.
Protons 101

• Stopping Power \( \left( \frac{dT}{dx} \right)_{Y, T, Z} \)

  — rate of energy loss per unit of path length \( x \)

  • Charged particle of type \( Y \)
  • Having kinetic energy \( T \)
  • Traveling in a medium of atomic number \( Z \)

  — Units: MeV/cm or J/m
Protons 101

- Obligatory proton presentation BRAGG PEAK!!!
Protons 101

• **Range** = the *expected value* of the path length that a particle follows until it comes to rest in a specific medium.

  – Factors:
    • Particle type
    • Initial direction
    • Medium particle is traveling through
    • Initial energy

• The **initial energy** of proton particles *dictates how far they will travel* in a given medium.
Bragg Peaks of Common Proton Therapeutic Range

Varying initial energy allows control of where protons will stop.
Protons 101

- BRAGG PEAK vs Therapeutic Photon Energies
Protons 101

• A singular Bragg Peak covers a small, clinically insignificant area.
Protons 101

CTV

Relative Dose vs. Depth graph

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Protons 101

• A singular Bragg Peak covers a small, clinically insignificant area.

• To overcome this, multiple Bragg Peaks of varying energies and weighting can be combined. This summation of Bragg Peaks creates an area of uniformed prescribed radiation dose that is greater than or equal to the size of the target volume.
  – This effect is known as the **Spread-Out Bragg Peak (SOBP)**
Protons 101

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Protons 101

• Uncertainties
  – There are sources of error that are inherent in all forms of external beam radiation therapy:
    • daily patient positioning reproducibility
    • inter-fractional anatomic changes
    • intra-fractional organ motion
  – There are also proton specific uncertainties such as:
    • intrinsic proton range uncertainty
    • Hounsfield unit stopping power conversions
    • range degradation along the beam path
      – Dense tissues (i.e., bone) scatter protons more than less dense tissues.
      – Variations of tissue composition along beam path
        » Implanted materials
        • Dense metals
        » CT Artifacts
Protons 101

• **Range Uncertainty**
  – The uncertainty in knowing exactly where the Bragg Peak occurs in the patient.

• **Proton Plan Robustness**
  – Ensuring adequate target coverage even under Range and Geometric Uncertainties

*Robustness and Uncertainties are very extensive topics in proton therapy. For the sake of time and the focus of this presentation I am taking liberties and greatly simplifying these topics.*
TELL ME AGAIN WHY WE ARE DOING ALL THIS WORK?

Let’s take a second to center ourselves and regain our focus.

(Psst...We are all after the same goal!)
Ultimate Goal = Better Patient Treatments

- Motivation for improvement is DISEASE CONTROL and IMPROVING QUALITY OF LIFE

- Deliver more EFFECTIVE DOSE to the target volume while REDUCING DOSE TO NORMAL HEALTHY TISSUE that does not need to be irradiated.
• In terms of avoiding sequelae in irradiated normal tissues Rubin and Casarett demonstrated that there is **NO SAFE RADIATION DOSE**\(^{[1,2]}\).

• To address this problem there has been a tremendous response from the Medical and Scientific field.

  • **Non- Stop, Ongoing Research** to develop and advance **NEW TECHNOLOGIES** and **NEW TECHNIQUES** in radiation therapy.

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Images Courtesy of Matt Palmer, adapted from “Particle Therapy: Pager or Smartphone?”

LUNG: ~ 56%
HEART: ~ 67%
ELIMINATION OF UNNECESSARY RADIATION

Proton Therapy (IMPT)  X-Ray Therapy (IMRT)  Added Radiation w/ IMRT (X-Rays)

*25 Gy (25 Sv) of Unnecessary Radiation

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Images Courtesy of Matt Palmer, adapted from “Particle Therapy: Pager or Smartphone?”
ELIMINATION OF UNNECESSARY RADIATION

*25 Gy (25 Sv) of Unnecessary Radiation =

12,500 H&N CTs (2 mSv)
5,000,000 Intraoral X-Rays (0.002 mSv)
25,000x General Public Annual Limit (1.0 mSv)
UNNECESSARY RADIATION

As a general rule, the integral dose delivered to the patient will be 2–3 times lower with protons when compared to X-rays delivered by Intensity Modulated Radiation Therapy (IMRT).

Possibly even more important, is that a significant portion of this dose sparing can and does occur in adjacent Organs At Risk (OARs).
Let’s take a look at how we got to proton therapy as we know it today in the United States!

WHERE WE ARE AT
Photons

- **1895**
  - Wilhelm Roentgen discovers X-ray Beams

- **1898**
  - Curies announced the existence of radium

- **1928**
  - The first working linear accelerator constructed by Rolf Widerøe.
Proton Centers in the US

• 1931
  – Ernest Lawrence invented the **cyclotron**
  • Awarded the Nobel Prize in Physics in November 1939
    – "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"
Photons

• 1940
  – Kerst develops the Betatron
  • Electron beam therapy becomes a practical and useful therapeutic option.
Proton Centers in the US

• **1946:**
  – Robert Wilson, physicist, publishes work
    • Suggests using protons to treat cancer
      – Noted protons ability to deliver radiation to tumor while simultaneously decreasing radiation exposure to surrounding healthy tissue.

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Proton Centers in the US

- **1954**
  - University of California at Berkeley
  - First patient treated with proton therapy

- **1962**
  - UCLA Medical Center obtains 1st Commercially Produced Linac

- **1954 - 1989**
  - Proton therapy continues to grow worldwide
  - Remember, cyclotrons or synchrotron were used primarily for research in particle or nuclear physics
    - The first proton therapy treatments were carried out in research facilities.

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Proton Centers in the US
Proton Centers in the US

• 1978
  – CT Based Treatment Planning
    • CT based treatment planning will end up being a big deal for proton therapy. It allows much more accurate calculation of stopping powers and thus more accurate placement of Bragg Peaks in patients. This ensures adequate target coverage and optimal healthy tissue sparing.
Photons

- 1986
  - 1,000 Medical Linear Accelerators in use in United States
Proton Centers in the US

• 1990
  – Loma Linda University
    • 1st hospital based Proton Center in United States
    • Treated with Passive Scatter Proton Therapy
      – Utilizes Brass Apertures and Wax Compensators to shape beam laterally and distally.

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Proton Centers in the US

• 1994
  – IMRT developed

• 1996
  – Paul Scherrer Institute, PSI
    • Villigen, Switzerland
  – Developed spot-scanning technique for proton therapy
  – First patient treated with spot scanning worldwide on November 25, 1996
Proton Centers in the US

• 2001
  – Francis H. Burr Proton Therapy Center
    • Harvard/Mass General Boston, Massachusetts
    • 2nd hospital-based proton therapy center in the United States

• 2003:
  – Midwest Proton Radiotherapy Institute
    • Indiana University Bloomington, Ind.
    • 3rd proton therapy center in the United States
Proton Centers in the US

• 2008:
  – MD Anderson Cancer Center
    • Houston, TX
    • 1st Site to treat with Pencil Beam Scanning in United States

• 2008
  – IBA received approval from U.S. FDA for PBS technique
    • Significant due to the fact that approximately 50% of proton centers in the US (and world) are built and maintained by IBA
Proton Centers in the US

• 2010
  – As of May 2010, there were 7 operational proton centers in the US.
Proton Centers in the US

• **2013:**
  - SCCA Proton Therapy Opens
  - Brings Proton Therapy to the Pacific Northwest
  - Seattle, WA
Proton Centers in the US

• 2015:
  – Scripps Proton Therapy Center
    • San Diego, CA
    • First proton center to open in the United States exclusively with PBS
The State of Proton Therapy

• The BIG Picture

– Less than 1% of radiation therapy treatments today are completed with Proton Therapy
– Studies estimate that ≥ 20% of radiation therapy patients would benefit from proton therapy.[1]
Proton Centers in the US

Active Proton Centers

- Active Proton Centers
- 2020?!
Proton Centers in the US

• **Today**
  - 25 Operational Centers
  - ≥ 12 under construction or in development
So, What Is the Big Deal?

- Proton Therapy is GROWING!
- PBS is the future of proton therapy
  - Going to need more dosimetrists just like YOU to either fill these positions or cross train and provide coverage.
The State of Proton Therapy

• Experts predict the number of patients treated per year with proton therapy will increase from 16,200 in 2015 to 300,000 in 2030.

• All the new centers or new treatment machines that are being built/installed are PBS exclusive.
  – Worldwide, all proton facilities currently planned or under construction shall also use scanning technology in the future.
Proton Therapy: Passive Scattering to Pencil Beam Scanning

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Proton Therapy Beam Delivery Methods:

The delivery method of clinical proton beams can be categorized in one of two ways:

- **Pencil Beam Scanning** (PBS)
  - Also referred to as *spot scanning*
  - First delivered in 1996

- **Passive Scattering**
  - **Uniform Scanning*** (US)
    - Technical note: US uses beam scanning delivery techniques. But, in terms modulation, and final dose distribution US closely resembles the dosimetric properties of passive scattering and is thus placed in the passive scattering grouping for the purpose of this presentation.
A quick overview of Passive Scattering proton therapy.

WHAT IS PASSIVE SCATTERING OR CLASSIC PROTON THERAPY?
Passive Scattering (PS)

- PS is the delivery method referred to by the phrases *traditional* or *classical* proton therapy.
- Think of this as the exclusive method used from the beginning of proton therapy until 1996.
- Still in use today by many operating proton therapy centers.
Passive Scattering (PS)

1. Cyclotron or Synchrotron is used to accelerate protons to therapeutic energies.
   – Typically 70 – 250 MeV

2. Proton beam exists in a narrow mono-energetic state.

3. A modulator is used to bring the narrow mono-energetic proton beam to the desired energy.

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Passive Scattering (PS)

4. The energy specific beam now passes through one or two scattering devices.
   - This expands the narrow beam into a wide beam

5. Multiple beams of various discrete energies are selected for treatment. The cumulative effect of treating with all of these beams is the creation of a Spread Out Bragg Peak.
Passive Scattering (PS)

6. A custom target specific, beam specific aperture (collimator) is placed between the wide mono-energetic beam and the patient.
   - Usually made of thick brass
   - Used to shape the proton beam laterally
Passive Scattering (PS)

7. **Compensator** is placed perpendicular to beam line in front of patient (generally but not always).

   - Used to shape dose distally. Conforms maximum therapeutic dose to the distal (along the beam path) edge of the tumor.

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Passive Scattering (PS)
Passive Scattering (PS)

- Range Comp
  - Shapes dose distally
  - Compensates for inhomogeneities
  - Provides NO proximal conformality
  - Scatter from RC causes Hot+Cold spots in distribution
Passive Scattering (PS): Workflow

- Can be a very labor intensive forward planning technique. Imagine very complex 3DCRT.
  - Determine and create appropriate beam angles
  - Beam specific range and modulation uncertainty calculations
  - Create beam specific aperture
  - Create beam specific range compensator
  - Calculate Dose
    - Analyze lateral target margin
      - Edit aperture
      » Analyze lateral target margin
      - Repeat edits if necessary
  - Analyze beam specific distal and proximal target coverage
    - Adjust range and mod input and recalculate dose if necessary
  - Analyze distal target conformity and target coverage uniformity
    - Manually edit range compensator to eliminate hot and cold spots in target coverage
      » Re-calculate dose
      - Repeat
      - Repeat
      - Repeat
      - Repeat
      - Repeat
    - This could go on for hours....................
  - Analyze beam specific distal target coverage
    - There is a potential that you could have ruined the distal target margin with your manual edit to the range compensator
      » If so, start over from the beginning
  - REPEAT THIS PROCESS FOR EVERY BEAM
  - Analyze the composite plan dose
    - Return to individual beams and repeat above steps to ensure plan meets clinical goals
  - This can become even more complicated by complex planning schemes such as:
    - Match lines
    - Dose escalation
    - Match and Patch

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A quick overview of Pencil Beam Scanning proton therapy.

WHAT IS PENCIL BEAM SCANNING (PBS) PROTON THERAPY?
Pencil Beam Scanning (PBS)

• Precisely placing numerous pencil beams (of proton particles) into the target in order to cover the 3D volume with a uniform dose distribution.
  – Range (depth) dependent on the beam energy
  – Scanning magnets adjust the pencil beams position in both the X & Y direction

• The 3D volume is divided in several slices (LAYERS) perpendicular to the beams central axis. The dose in each layer is delivered by controlling simultaneously the pencil beam intensity and the location of the pencil beam SPOT in the X & Y direction.
Pencil Beam Scanning (PBS)

• **Pencil Beam**
  – A narrow, controlled beam of proton particles
    • Shaped and controlled with magnets

• **Spot**
  – Collection of mono-energetic protons, pencil beam, that are deposited at a given position.
    • Steering magnets precisely guide pencil beams to a predetermined position in the target

• **Layers**
  – For each beam, the 3D target volume is divided into several slices (layers)
    • Each layer is a collection of mono-energetic spots of various positions
Pencil Beam Scanning (PBS)

• Pencil Beam Size

Approximately 7 mm

Approximately 12 mm
Pencil Beam Scanning (PBS)
Pencil Beam Scanning (PBS)

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Image Courtesy of Marco Schippers, PSI; Innovative developments for proton therapy at PSI: beam delivery with SC magnets
Pencil Beam Scanning (PBS): How is it done?

• Cyclotron or Synchrotron is used to accelerate protons to therapeutic energies.
  – Series of processes are performed to create a mono-energetic proton beam of a desired energy.
  – Typically 70 – 250 MeV

• **Magnets** are **used to shaped and steer** the proton beam through the transport system, to the treatment room, and ultimately to the patient.

• The proton beam exiting the transport system is a “pencil shaped beam”.
Pencil Beam Scanning (PBS)
Layer 1
Energy = 188.9 MeV
Relative Weight = 2.63%
Layer 2  
Energy = 185.4 MeV  
Relative Weight = 8.05%

Individual Layer Dose

Composite Dose:  
Current layer plus distal layers
Layer 3   Energy = 181.9 MeV
Relative Weight = 13.52%

Note: VARIABLE SPOT WEIGHTING
Larger spot diameter equals higher spot weight [MU/fx]; visual spots sizes are
Layer 4  
Energy = 178.5 MeV  
Relative Weight = 17.49%

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Layer 5   Energy = 175.1 MeV
Relative Weight = 14.09%
Layer 7   Energy = 168.4 MeV
Relative Weight = 8.16%
Layer 8  
Energy = 165.1 MeV 
Relative Weight = 6.03%
Layer 9  

Energy = 161.9 MeV

Relative Weight = 5.11%
Layer 10  Energy = 158.6 MeV
Relative Weight = 4.39%
Layer 11   Energy = 155.3 MeV
Relative Weight = 3.08%
Layer 12  
Energy = 152.1 MeV
Relative Weight = 2.16%

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Layer 13  Energy = 148.9 MeV
Relative Weight = 1.68%
Layer 14  Energy = 145.8 MeV
Relative Weight = 1.21%
Layer 15  
Energy = 142.7 MeV 
Relative Weight = 0.58%
PS vs PBS

A look at the pros and cons of each technique. A brief comparison of dose distribution between the two.

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PS vs PBS

Passive Scattering

Advantages

• Very sharp lateral penumbra due to use of apertures
• Potentially more robust for motion mitigation
  – Some techniques deliver the entire SOBP at once

Disadvantages

• Unable to conform dose to target proximally
• Increased treatment time
• Can be very arduous
  Forward planning
  – Time consuming
• Not conducive to multitasking
PS vs PBS

Pencil Beam Scanning

Advantages

• Robust Optimization
• Superior Dose distribution as compared to passive scattering
  – Decreased dose to NT
    • Greater reduction of side effects
  – Increased conformality
  – Increased uniformity in target coverage
    • Decreased hot spots
  – Removal of manual junctions/feathering
    • Removal of some complex and potentially not as robust/reproducible techniques such as patching
    • Greater uniformity and more robust
• Decrease # of Beams
  – Decreased planning time in many complex cases
• Faster turn around time from CT SIM to treatment
• Decreased treatment time
• Very easy to implement SIB
  – Variable spot weighting
• Conducive to use of templates and scripting

Disadvantages

• QA can be more intensive and challenging
• Increased lateral penumbra as compared to PS
  – This is likely to change in the future by planning PBS with apertures
## PS vs. PBS

### Base of Skull – Chordoma

<table>
<thead>
<tr>
<th>US</th>
<th>PBS</th>
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<tbody>
<tr>
<td>• 10 – 12 fields</td>
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</tr>
<tr>
<td>– 18 to 24 unique treatment devices (Apps+Comps) required</td>
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<tr>
<td>– Difficult Patched Field Technique</td>
<td></td>
</tr>
<tr>
<td>• Estimated 12 – 16 hours for average proton dosimetrist</td>
<td></td>
</tr>
<tr>
<td>• Completion time dictated by manual match line optimization speed</td>
<td></td>
</tr>
<tr>
<td>• 3 fields</td>
<td></td>
</tr>
<tr>
<td>– No unique treatment devices required</td>
<td></td>
</tr>
<tr>
<td>• Estimated 4-6 hours for average proton dosimetrist</td>
<td></td>
</tr>
<tr>
<td>• Completion time dictated by TPS optimizer calculation speed</td>
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</table>
## PS vs PBS

**Adult Craniospinal Irradiation (CSI)**

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<thead>
<tr>
<th></th>
<th><strong>US</strong></th>
<th><strong>PBS</strong></th>
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<tbody>
<tr>
<td></td>
<td>• 8 fields</td>
<td>• 3 fields</td>
</tr>
<tr>
<td></td>
<td>– 10 to 12 unique treatment devices (Apps+Comps) required</td>
<td>– No unique treatment devices required</td>
</tr>
<tr>
<td></td>
<td>• Estimated 12 – 16 hours for average proton dosimetrist</td>
<td>– More robust uniform junctions</td>
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<tr>
<td></td>
<td>• Completion time dictated by manual match line optimization speed</td>
<td>• Estimated 2-4 hours for average proton dosimetrist</td>
</tr>
<tr>
<td></td>
<td>• Treatment time 1- 1.5 hrs</td>
<td>• Completion time dictated by TPS optimizer calculation speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Treatment time 0.5 hrs</td>
</tr>
</tbody>
</table>
PS vs PBS

• PS
  – Best for smaller, contiguous targets
    • Limits planning to approximately <50% of disease sites
      – Have to come up with very complicated intricate techniques to overcome shortcomings

• PBS
  – Can treat 70 – 80% of disease sites. Even more??
    • Large treatment field sizes (ex: 40x30 field)
      – Non contiguous targets within same field
    • Simple, robust match-lines and junctions
    • SIB
    • MFO
    • Robust Optimization
PS vs PBS

Dose difference: PBS - US

Weighting: RAO = 60%, LAO = 40%

Uniform scanning plan is 18 - 21 CGE hotter in this region.
Uniform scanning plan is 8 - 12 CGE hotter in this region.
PS vs PBS

Dose difference: PBS - US
PS vs PBS

Dose difference: PBS - US
So, What Is the Big Deal?

- PBS
  - Putting Proton Therapy on par with IMRT
  - Ability to use inverse planning
    - Robust Optimization
  - Dose escalation
    - SIB
  - Lower production cost
  - Faster delivery
    - 10 - 15 minute treatment slots!?!?
      - IGRT + treatment
Intensity Modulated Proton Therapy (IMPT)

Here we will define and make sure we understand what is implied by some common (and commonly misunderstood) terms such as IMPT, PBS, SFO, SFUD, and MFO.

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WHAT IS IMPT, SFO, and MFO?

• What people commonly think of in the RADONC field when they hear IMPT is “IMRT but with Protons”
  – We Do That! But, it is a little complicated...
**WHAT IS IMPT, SFO, and MFO?**

- *My point of view*
  - All PBS proton therapy is technically IMPT
    - Even in SFO or SFUD
      - Treatment Planning Systems utilize variable spot weighting [MU/fx] to create a uniform dose distribution

- Let’s Dig Deeper!
• Single Field Optimization (SFO)
  – In IMPT using single-field optimization (SFO-IMPT), **each beam is optimized individually to deliver the prescribed dose to the target** while respecting the dose tolerances of normal tissue


  – Analogous with Single Field Uniform Dose (SFUD)
WHAT IS IMPT, SFO, and MFO?

- Multi-Field Optimization (MFO-IMPT)
  - All spots from all fields are optimized simultaneously.
  - MFO-IMPT allows for superior dose distributions compared with either passively scattered proton therapy or SFO-IMPT.
  - MFO-IMPT is also the most complex form of IMPT, where a homogenous dose distribution can be achieved within diverse geometric targets while limiting the radiation dose to normal structures near the target.

**WHAT IS IMPT, SFO, and MFO?**

### SFO

<table>
<thead>
<tr>
<th>Function</th>
<th>Constraint</th>
<th>Dose</th>
<th>ROI</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Physical Composite Objective</td>
<td>Beam Set</td>
<td>Min Dose</td>
<td>PTV</td>
<td>Min Dose 7920 cGy, All beams</td>
<td>150</td>
</tr>
<tr>
<td>Min Dose</td>
<td>Beam Set</td>
<td>Uniform Dose</td>
<td>PTV</td>
<td>Uniform Dose 7920 cGy, All beams</td>
<td>100</td>
</tr>
<tr>
<td>Max Dose</td>
<td>Beam Set</td>
<td>Max Dose</td>
<td>PTV</td>
<td>Max Dose 7921 cGy, All beams</td>
<td>125</td>
</tr>
<tr>
<td>Max Dose</td>
<td>Beam Set</td>
<td>Max Dose</td>
<td>Patient</td>
<td>Max Dose 7921 cGy, All beams</td>
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</tr>
</tbody>
</table>

### MFO

<table>
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<tr>
<th>Function</th>
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<th>Description</th>
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<td>Patient</td>
<td>Max Dose 7921 cGy</td>
<td></td>
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</table>
WHAT IS IMPT, SFO, and MFO?

Low Risk Prostate
1.8Gy/fx * 44fx
2 Beams: Rt +Lt Lateral
SFO

Rt Lat

Lt Lat

Low Risk Prostate
1.8Gy/fx * 44fx
2 Beams: Rt +Lt Lateral
MFO

Rt Lat

Lt Lat
WHAT IS IMPT, SFO, and MFO?
WHAT IS IMPT, SFO, and MFO?

- Single Field Integrated Boost (SFIB)
  - In IMPT using SFO
  - Using the capability of variable spot weighting to create multiple uniform dose levels
Strengths of PBS Proton Therapy
HN – SFO vs MFO
SFO HN – Beam Dose
MFO/SFO HN Comparison

<table>
<thead>
<tr>
<th>Mean Dose (cCGE)</th>
<th>Parotid_R</th>
<th>Parotid_L</th>
<th>OralAvoidance</th>
<th>LarynHypopharynx</th>
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<tr>
<td>MFO</td>
<td>2007</td>
<td>1933</td>
<td>643</td>
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<tr>
<td>SFO</td>
<td>2135</td>
<td>3328</td>
<td>1502</td>
<td>1612</td>
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PENCIL BEAM SCANNING TREATMENT PLANNING WORKFLOW

A CLOSER LOOK AT THE PROCESS OF CREATING A PBS TREATMENT PLAN. HIGHLIGHTING THE DIFFERENCES AND SIMILARITIES BETWEEN PBS AND IMRT/VMAT PLANNING.
PBS WORKFLOW

1. PRE-PLANNING
2. TECHNIQUE [SFO vs MFO]
3. BEAMS
4. PBS SPECIFIC PLANNING PARAMETERS
5. PBS OPTIMIZATION – INVERSE PLANNING
6. PLAN EVALUATION
PBS WORKFLOW: PRE-PLANNING

• CONTOURING
  – ADJACENT ORGANS AT RISK
  – CUSTOM INVERSE PLANNING STRUCTURES
    • SPOT PLACEMENT STRUCTURES
    • OPTI/PLANNING STRUCTURES, RINGS, ETC
  – CT ARTIFACT
  – VARIABLE TISSUE
    • AIR POCKETS
    • COLLECTION OF FLUID
  – SURGICALLY IMPLANTED MATERIAL AND DEVICES
PBS WORKFLOW: Technique

SFO (Single Field Optimization)

OR

MFO (Multi Field Optimization)
PBS WORKFLOW: Beams

• Many considerations are taken into account when selecting beam angles
  – Looking for beams that will be to our advantage dosimetrically
  – Looking for ROBUST beams
    • Avoid beams that:
      – Would pass through variable tissues due to weight loss or swelling
      – Unnecessarily pass through high density implanted metal and devices
      – High heterogeneity interfaces
• Typical number of beams 2-4
PBS WORKFLOW: PBS SPECIFIC PLANNING PARAMETERS

• **Spot control**
  – Understanding where your spots are going
  – Robustness Issues
  – How spots are working for you and against you
PBS WORKFLOW: PBS SPECIFIC PLANNING PARAMETERS

Goughenour 2017
0.5 cm Target Margin
15 layers
656 spots

Normalized to 95% Coverage

0 cm Target Margin
12 layers
374 spots

Normalized to 95% Coverage
Goughenour 2017

Dose Difference:
2 cm - 1 cm

10 - 20% increase in dose

Dose Difference:
1 cm - 0.5 cm

Dose Difference:
1 cm - 0 cm

Note: 104% isodose line now present and expansive

Note: 124% isodose line now present and expansive
PBS WORKFLOW: PBS OPTIMIZATION – INVERSE PLANNING

• Clinical Example
  – HN; 3 dose levels SIB
  – 4 beams; LAO, RAO, LPO, RPO
    • All beams are not treating the entire target
  – Robust optimization utilized
  – Low dose gradients
  – “SFO-Hybrid”
# Inverse Planning: Spot Control

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<tr>
<th>Function</th>
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<th>ROI</th>
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## Inverse Planning: Typical Target and OAR Parameters

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Goughenour 2017
PBS WORKFLOW: Plan Evaluation

• Similar to any photon plan
  – DVH
    • Target goals
    • OAR constraints
  – Robustness
    • Ensuring adequate target coverage even under Range and Geometric Uncertainties
      – Also, evaluating potential for increased OAR doses
Clinical PBS Example That EXCITES ME

• Comprehensive Chestwall and Breast
Clinical PBS Example That EXCITES ME

45 Gy

5.4 Gy

10 Gy
Clinical PBS Example That EXCITES ME

- SFO technique
- Robust optimization
- Single en face beam
Clinical PBS Example That EXCITES ME
Clinical PBS Example That EXCITES ME

- Composite Plan: CW6040

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<tr>
<th>Dose</th>
<th>ROI/POI</th>
<th>Clinical goal</th>
<th>Value</th>
<th>Result</th>
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Clinical PBS Example That EXCITES ME

• Composite Plan: CW6040
Wrap Up: Future is Bright!
Wrap Up: Future is Bright!
PBS is in its infancy and it will only get better!

- Robust Optimization
- Dual Energy CT Scan Acquisition
  - Range Uncertainty Reduction
- PBS with Apertures
- LET/RBE optimization
- CBCT Availability
- Widespread MFO implementation
- Commercial availability Monte Carlo
- Proton Imaging
- Range Verification
- Spot Scanning Proton Arc Therapy
- Increased Research and Results
- Beamline/Delivery Optimization
- Advances in Motion Mitigation
SPECIAL THANKS: MY WIFE, Felicia
Special Thanks

• SCCA PTC Dosimetry Team

• SCCA PTC Physics Team

• Entire SCCA PTC Team

• Friend and colleague, Matt Palmer
Questions?

• alexander.goughenour@gmail.com
  – Subject: AAMD/dosimetry
• https://www.psi.ch/media/20-years-of-high-precision-combat-against-cancer
• https://www.varian.com/oncology/products/treatment-delivery/probeam-proton-therapy-system
• http://www.mevion.com/
• http://pronovasolutions.com/
• http://www.proton-therapy.org/howit.htm