Proton Therapy Treatment Planning: Challenges and Solutions

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Proton treatment delivery
Passive scattering in practice

Range modulator wheel
Scatterer
Aperture
Compensator

Range compensator conforms dose to distal edge target volume; the aperture shapes field in lateral direction.

Brass aperture
Lucite range compensator

Proton treatment delivery
Scanning in practice

Physics of Proton Therapy

I. basic interactions
   - energy loss
   - scattering
   - nuclear interactions

II. clinical beams
   - percentage depth dose
   - lateral penumbra

Proton interactions: Energy loss

Primarily protons lose energy in coulomb interactions with the outer-shell electrons of the target atoms.

- excitation and ionization of atoms
- loss per interaction small \(\rightarrow\) ‘continuously slowing down’
- range secondary e\(^+\) <1mm \(\rightarrow\) dose absorbed locally
- no significant deflection protons by electrons

Bragg peak
Stopping power

Graph based on NIST data.

Proton interactions: Scattering

Primarily protons scatter due to elastic coulomb interactions with the target nuclei.

Approximation:
\[ \sigma \approx 0.02 \times \text{range} \]

Radial Spread in Water

Same general shape applies to different (relevant) materials.

Proton interactions: Nuclear

About 20% of the incident protons have a non-elastic nuclear interaction with the target nuclei.

- reduction of proton fluence with depth → shape Bragg peak
- secondaries:
  - charged \((p,d,n,\alpha,\text{recoils})\) ~60% of energy → absorbed 'locally'
  - neutral \((n,\gamma)\) ~40% of energy → absorbed 'surroundings'
- production of unstable recoil particles (activation)
  - radiation safety
  - dose verification using PET/CT

Nuclear interactions

Graph courtesy Harald Paganetti.

Proton Pencil Beam Algorithms

Hong et al, MGH 1996
Szymanowski et al, Institut Curie 2001

Beam Model
- dosimetry in water
- inhomogeneity correction
  - water equivalent thickness (wet)
  - HU stopping power

Graph courtesy Harald Paganetti.
Proton Pencil Beam Algorithm

**Beam Model**

- CAX Depth Dose (DD)
- broad beam
- pristine peak
- SOBP

**Radial Spread (RS)**

- multi coloumb scatter
  - beamline: degrader, nozzle elements (wet only)
  - compensator: material dependent scattering power
  - patient: wet only
- gaussian kernel

\[ \sigma^2_{\text{total}} = \sigma^2_{\text{line}} + \sigma^2_{\text{comp}} + \sigma^2_{\text{patient}} \]

Dose Calculation

- Dose from a pencil beam

\[ D_{pb}(x,y,z)=C(z) \times \frac{1}{2 \pi \sigma^2_{\text{ddf}}(z)} \times \exp \left( -\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2_{\text{ddf}}(z)} \right) \]

- Convolve DD with RS for each pencil
- Sum dose from all pencils

**Bortfeld Model of Pristine Peak**

*An analytical approximation of the Bragg curve for therapeutic proton beams*

- Thomas Bortfeld
  - University of Ulm, Germany (UOOG), Institute of Physics and Theoretical Biology, Ulm, Germany (UOOG), Institute of Physics and Theoretical Biology, Ulm, Germany
  - Accepted by Phys. Med. 1997

\[ D(z)=D_0 \cdot e^{-2z_0/\sigma^2} \cdot T(\beta(\gamma)) \times \exp \left( -\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2_{\text{ddf}}(z)} \right) \]

Analytical model of proton BP (up to ~ 200 MeV)

- accounts for energy spread
- empirical model of nuclear fragmentation (data fitting)
- numeric depth dose calculation of fitted BP
- assumption – range straggling 'constant' with depth

**SOBP**

Calculated versus Measurement

Proton beam dose calculation in water is generally very accurate!
Challenges in Proton Therapy Planning

1. Uncertainties:
   - Intrinsic basic physics uncertainty (I-values)
   - CT numbers (stopping powers; range),
   - Dose calculation errors due to complex inhomogeneities,
   - Intra-fractional organ motion,
   - Inter-fractional changes in anatomy and motion patterns,
   - Mis-registration of tissue compensators (passively scattered proton beams),
   - Uncertainties in immobilization devices and patient support devices

2. Evaluation of proton plans
   - How to evaluate a proton plan in the presence of various uncertainties?
     - PTV?
     - Error bars of dose distributions?

Intrinsic basic physics uncertainty makes the argument of “sub-millimeter precision” an issue, which deserves careful consideration.
HU-Stopping Power Conversion Uncertainties
Results in Range Uncertainties

Impact of CT Hounsfield number uncertainties on dose distributions
-3.5%  +3.5%

0% uncertainty

Individualized patient determination of tissue composition along the complete beam path, rather than CT Hounsfield numbers alone, would probably be required even to reach "sub-centimeter precision".

CT Artifacts and Hounsfield Numbers

"It is imperative that body-tissue compositions are not given the standing of physical constants and their reported variability is always taken into account" (ICRU-44, 1989).

Proton Range Uncertainties

The advantage of protons is that they stop.
The disadvantage of protons is that we don’t always know where…

Proton Range Uncertainty in the Presence of heterogeneities

Impact of Organ Motion on Proton Dose Distributions

Dong: ASTRO 2008

Dong/MDACC
Plan DVH Evaluation (PRV)
What you see is not what you always get..

Impact of Tumor Shrinkage on Proton Dose Distribution
Original Proton Plan
Dose recalculated on the new anatomy

Practical Solutions

Free breathing Treatment
Gated treated on exhale

Improving CT number accuracy and reducing metal artifacts with Orthovoltage CT imaging

Match and Patch Fields
- used to avoid OARs adjacent to target
- partition target into segments (sub-targets)
  - sub-targets treated with ‘sub-beams’
  - angle sub-beams to avoid OARs
- combined with other fields for dose uniformity

Match Fields
- match fields abutting each other
- penumbra matching penumbra

Patch Fields
- thru beam txt partial target
- residual txt with patch
- lateral penumbra (t-beam) ‘matched’ with distal falloff (p-beam)
- LPO beam (inferior) patched with SPO (superior)

Patch Field Selection
Patch Field Angle Selection
- optimal geometric coverage (\(G = 230^\circ\))
- avoid inhomogeneity along path (\(G = 205^\circ\))

Lacrimal Gland Carcinoma
(PTV 50.4)
- partition into sup + inf targets

Patch Field – Beam Angle Selection
Gantry 230°
Gantry 205°
Distal Blocking

- selective pullback of range to spare OARs
- pullback achieved with added compensator
- potential pitfalls
  - setup error or motion may nullify sparing
  - "simple" distal blocking may compromise target coverage
- assess robustness of approach

Distal Blocking

![Distal Blocking Diagram]

Things to remember!

- Proton beams stop - no exit dose
  - Although we don't know exactly where they stop
- Proton beams are more sensitive to
  - CT Hounsfield number/Stopping Power accuracy
  - Organ motion
  - Anatomy changes
- Proton plans are difficult to evaluate
  - "What you see is not what is delivered"
- Protons demonstrate excellent low dose sparing

Things to remember!

- Inter/Intra-fractional variations have far more significant consequences in patients treated with proton therapy
  - Approaches and data to deal with this issue is still lacking
  - Minimize it and develop strategies to deal with the residual motion
- Empirical approaches used in defining margins for range uncertainties, smearing, and smoothing are questionable
  - No real data exist to support any of these approaches
- Repeat imaging and reevaluation based on deformable registration may be necessary
  - In some cases repeat planning may be clinically beneficial

Final thought

What you see is not what you always get....